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Appendix A

Freshwater Creek Watershed Analysis

Mass Wasting Assessment

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SUMMARY

This mass wasting assessment contributes materially to the understanding of the effects that forest management practices have on landslide activity in the Freshwater Creek watershed. The study's findings point to correlations among forest practices, geology, slope gradient, landforms, landslide activity, and the potential for landslides to reach streams. Study results show that shallow landslides that initiated at roads or on hillslopes contribute sediment and debris to streams in approximately equal proportions. This finding suggests that the introduction of sediment to streams by landslides can be substantially reduced by modifications to current road construction practices and remedial action along existing roadways.

Large, deep-seated landslides are common in the watershed, but aerial photograph interpretation and field reconnaissance indicate that past clearcutting and road building practices have not substantively affected the stability of these features.

There are indications that conventional clearcutting practices lead to higher shallow landslide frequencies than partial cutting practices. While further study is called for, these results indicate that partial cutting on higher hazard sites could result in fewer shallow hillslope landslides, and that this technique may be an appropriate option for timber harvesting in some higher-hazard areas. Landslide rates in unlogged second-growth forests are less than in clearcut areas, however, landslide rates in standing timber may be underestimated due to the difficulty of identifying smaller landslides on aerial photographs in forested areas. Rough estimates made for large woody debris (LWD) inputs into streams by landslides indicate that landslides account for a minor component of total LWD input to streams in the Freshwater watershed. A sediment budget for sediment derived from landslides was developed and was provided to the channel module analyst for incorporation in the overall sediment budget for the watershed. Landslides are significant but are not the dominant source of sediment in the basin.

Two methods of analysis—empirical and deterministic—were used in this assessment. These two independent approaches produced similar findings, fostering confidence in the accuracy of the study results. The landslide hazard maps produced as a part of the study identify potential problem areas for road building and harvesting, as well as highlight the higher hazard areas where follow-up on-site geologic assessments typically occur.

RECOMMENDATIONS

- Implement a contingency plan for the assessment of landslides immediately after they occur. There is limited time available before vegetation obscures landslide features and limits data collection. The collection of morphological and geometric data on these landslides will assist in the development of landslide runout models and improve sediment budget estimates.

- Initiate a synoptic inventory of wood volumes deposited in streams by recent landslides throughout the PALCO ownership. This may improve estimates of LWD that could be expected from future landslide incidents.

- Conduct detailed landform mapping in one or more of the next watersheds scheduled for analysis to determine if additional field work and aerial photograph interpretation can improve the resolution of landslide hazard maps. If this approach is successful, detailed landform mapping could be considered in other watersheds.

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1.0 INTRODUCTION

1.1 PURPOSE

Mass wasting is a general term for a variety of processes by which large masses of earth material are moved by gravity either slowly or quickly from one place to another (American Geological Institute 1962). The term mass wasting as used in this analysis includes landslide processes, landslide effects, and the types of landslides present in the watershed. The term is not used in the broader sense that includes such processes as soil creep and minor rock fall. Sediment inputs from processes like soil creep and erosion from roads are addressed in the surface erosion module (Appendix B). The main purpose of the mass wasting assessment for the Freshwater Creek watershed analysis is to develop medium scale landslide hazard maps (Soeters and van Westen 1996) and landslide-related sediment budget estimates. The assessment evaluates the effects of past and present forest management activities on landslide activity.

The goal of the Freshwater watershed mass wasting assessment is to provide Assessment and Prescription Team members with an understanding of the following issues:

- Which areas in the watershed are sensitive to landslide activity?
- What types of forest management activities are associated with increases in landslide activity?
- How much sediment and large woody debris are delivered to streams by landslides associated with forest practices?

1.2 SCOPE OF WORK

The mass wasting assessment of the Freshwater Creek watershed analysis follows the approach outlined in the mass wasting methodology in: *Methods to Complete Watershed Analysis on Pacific Lumber Company Lands in Northern California* (PALCO April 2000). This report should be read in conjunction with that document; only brief summaries of the Mass Wasting methodology are provided in this report. Because the mass wasting assessment methods are still being refined, and because some of the mass wasting inventory work predates the April 2000 version of the watershed analysis methodology, the April 2000 version of the methodology was not followed in its entirety. Variances from the methodology and reasons for variance are described in the summaries of methods used.

The objectives of the mass wasting assessment are to identify and document the following:

1. The types and rates of landslides occurring in the watershed;
2. Landforms having similar inherent physical characteristics relative to landslide activity;
3. The effects of forest practices on landslide activity (rates) on different landforms; and
4. The relative contribution of sediment and large woody debris (LWD) to streams by landslides over the time-period covered by aerial photography (i.e., 1942-1997).

Two approaches were employed: empirical and deterministic analysis. Both approaches provide ratings of expected landslide hazard. The empirical approach determines expected road and hillslope landslide densities (i.e., the number of landslides per unit length of road or number of landslides per unit area). The deterministic approach calculates hillslope factor of safety (FOS) ranges for different geologic unit-slope combinations. The results of the empirical approach were used to estimate the amount of sediment contributed to the overall sediment budget in the watershed. Background landslide rate estimates and rough estimates of the amounts of LWD contributed by landslides to streams are also developed.

The mass wasting assessment has two phases. The first phase combines landform mapping with a historical aerial photography inventory and ground surveys of landslides. The landform map delineates and describes the extent and variety of morphologic landforms present in the watershed. The landslide inventory documents landslide frequencies, volumes, and delivery to streams. This phase also includes collection of soil samples and field data for deterministic slope stability modeling.

The second phase consists of data analysis and the development of landslide hazard maps and sediment budget estimates. As part of the empirical analysis, statistical tests are applied to identify significant relationships among terrain attributes, forest practices, and landslide frequency. The deterministic analysis uses a slope stability model (LISA), which calculates the FOS ranges for unique combinations of geology and slope for the Freshwater basin. LISA complements the empirical analysis, providing a quasi-independent procedure to assess the stability conditions in the watershed. The data on landslide volumes and delivery are used to develop a partial sediment budget that estimates the relative contribution of landslides to the watershed-scale sediment budget. Also included in this phase are estimates of background landslide rates in second-growth forests and rough estimates of LWD contributions to streams by landslides.

The products of the mass wasting assessment include nine maps that fall into six categories: (1) a landform map; (2) two landslide inventory maps, one each for shallow and deep-seated landslides; (3) two empirical, shallow-landslide hazard rating maps that display expected landslide frequencies for road and hillslope landslides, respectively, for each landform polygon; (4) two empirical, shallow landslide delivery maps that display an assessment of the potential for shallow landslides to reach streams from road and hillslope areas respectively; (5) a hillslope landslide hazard map derived from the deterministic (LISA) analysis, and (6) a composite landslide hazard map produced by combining the shallow and deep-seated landslide hazard maps. The first landslide inventory map displays the approximate initiation point of shallow debris-slides and debris-flows that started within harvested areas or at roads. The second landslide inventory map outlines the locations of possible deep-seated landslides and earthflows and assigns a qualitative hazard rating for the potential for forest practices to reactivate or accelerate movement. In addition, the geology map used for the mass wasting assessment a map showing the distribution and range of slope gradients (derived from a digital elevation model) in the basin, and a map combining the geology map with landslide locations are also provided. These maps are listed in Table 1-1.

Table 1-1: List of maps produced for the Mass Wasting Module.

Map number	Map Name	Explanation
A-1	Freshwater Geology	Depicts the distribution of geologic types in the basin. This map was compiled from mapping by Falls (1999a).
A-2	Slopes	This map displays the distribution of slope gradients in the basin.
A-3	Morphologic Landform Units	This map shows the types and distribution of landforms in the basin.
A-4	Shallow Landslide Inventory	This map shows the type and distribution of shallow landslides in the basin and identifies those landslides that appear to enter streams.
A-5	Deep-seated Landslide Inventory and Hazards	Shows the type, distribution, and estimated activity level of earthflows and large, deep-seated landslides. It provides qualitative hazard ratings for the potential for forest practices to reactive these features or increase rates of movement.
A-6	Empirical Landslide Hazards– Road Landslides	Average, shallow, road landslide densities (landslides per 100 ft of road) for the 1940-1997 period for each landform polygon.
A-7	Empirical Landslide Hazards– Hillslope Landslides	Average, shallow, hillslope landslide densities (landsides per acre of hillslope) for the 1940-1997 period for each landform polygon.
A-8	Empirical Landslide Delivery– Road Landslides	Average, shallow, road landslide, stream delivery frequencies (landslides per 100 ft of road) that reached streams for the 1940-1997 period for each landform polygon.
A-9	Empirical Landslide Delivery – Hillslope Landslides	Average, shallow, hillslope landslide, stream delivery frequencies (landslides per acre of hillslope) that reached streams for the 1940-1997 period for each landform polygon.
A-10	Deterministic (LISA) Landslide Hazards– Hillslope Landslides	Provides factor of safety ranges for shallow hillslope landslides for each geologic unit – slope association polygon calculated with the USFS DLISA model.
A-11	Composite Landslide Hazards	A map which combines shallow landslide hazard rankings for roads and hillslopes and high hazard areas for deep-seated landslides on a single map.
A-12	Composite Landslide Inventories and Geology	A map combining geology with the shallow and deep-seated landslide inventories.

2.0 CRITICAL QUESTIONS AND ASSUMPTIONS

The mass wasting assessment guides the development of information necessary to understand the landslide types and processes in the watershed. It is therefore critical that the analysis be based on the best available information. The approach used for the Freshwater watershed is based on and is directed by the following questions:

1. Which landforms or areas of the landscape are susceptible to landslides? What landslide frequencies and landslide types are associated with these landforms? How are they distributed throughout the landscape?

2. What morphologic or geologic attributes are associated with landslides?

3. What is the distribution of natural landslides in comparison with landslides related to forest practices?

4. What is the background[1] or natural rate of landslide activity?

5. Which forest practices contribute to landslide initiation? What are the relationships between landslide frequency and forest practices?

6. Which landslide locations deliver sediment to stream channels or other waters?

7. What is the rate of delivery of sediment by landslides to the stream system? How has the rate of delivery been influenced by forest practices?

8. What is the contribution of large woody debris (LWD) to streams by landslides?

A number of assumptions underlie the mass wasting module methodology and are used in conjunction with the critical questions to direct the investigation. These assumptions include the following:

1. Present-day landforms represent a landscape evolving in response to geologic, geomorphic, and climatic events. Landslides will occur naturally on some of these landforms and contribute to the development of new landforms (e.g., debris-flow fans).

[1] For this analysis, because there are no natural forests in the watershed, the background rate is taken as the rate of landslides occurring in older, second-growth stands.

2. Aerial photos can be used to interpret and document the history of forest practices and landslide activity associated with different landforms in a watershed over the duration of the photographic record. Although they often become obscured by vegetation, most landslides of significant size can be identified on aerial photographs. Documentation of the incidence and frequency of landslide events can be improved with the use of a time series analysis of aerial photographs and verification in the field.

3. The identification of relationships between landslides, landforms, and forest practices can indicate the relative potential for future instability. Landforms prone to landslides can be mapped based on physical characteristics (e.g., slope morphology, geology, and soils) as interpreted from aerial photographs, topographic maps, and geologic maps.

4. By understanding the soil, bedrock, and groundwater conditions and the effects of forest practices, and by applying physical (deterministic) models and/or empirical (statistical) tests, the likelihood and frequency of landslide activity on a landform can be estimated. In a similar fashion, the distances that landslides may travel and the likelihood that landslides will reach streams can be estimated.

5. Most landslides are initiated by natural events (e.g., earthquakes, rainfall). However, logging, road construction, and other forest practices can increase landslide activity.

3.0 WATERSHED CHARACTERISTICS

3.1 GEOLOGY

3.1.1 Regional Geologic Setting of the Freshwater Creek Watershed

Since the Mesozoic Era, the geologic development of northern California has been dominated by plate convergence. Coastal California north of Cape Mendocino is located on the leading edge of the tectonically active convergent margin of the North American plate. During the last 140 million years, subduction and the resulting continental accretion have welded a broad complex of highly deformed oceanic rocks to the western margin of the North American plate. These accreted rocks now make up the Franciscan Complex, which is composed of a variety of tectonostratigraphic terranes. Together, these terranes constitute the basement rocks of the north coast region of California (Carver and Burke 1992). Throughout the late Cenozoic, the combined effects of the eastward subduction of the Gorda Plate and the northward migration of the Mendocino triple junction have resulted in uplift of the Coast Ranges and erosion of the extensive forearc sediments of the Franciscian terranes (Nilsen and Clarke 1987). Today, Neogene sediments define the location of post-Franciscan deposition centers and rest unconformably on the older terranes. The younger sediments are preserved on shore in a series of down-dropped blocks associated with the structurally complex region north of the Mendocino triple junction and the greater Humboldt Bay region (Clarke and McLaughlin 1992; Nilsen and Clarke 1987; Carver 1987).

3.1.2 Geologic Units, Stratigraphy, and Structure

The geology of the Freshwater basin includes Cretaceous to Jurassic Franciscan and early Tertiary Yager terranes, that are overlain unconformably by the Middle Miocene, late Pilocene, and late Pleistocene Wildcat Group (Kilbourne 1985b; Falls 1999a). The Wildcat Group unconformably overlies the middle Miocene Bear River beds in the subsurface of the Eel River basin and Paleogene and older basement rocks elsewhere in the region (Ogle 1953; Hopps and Horan 1987; Ingle 1976; Clarke 1992). These geologic units are in turn overlain by Quaternary alluvial deposits, landslide debris, and a veneer of soil and colluvium. Artificial fill is also found locally throughout the watershed. The distribution of geologic units in the watershed is outlined on Map A-1, Freshwater Geology.

3.1.2.1 Franciscan Central Belt Terrane

The eastern 40% of the watershed is underlain by rocks of the Franciscan Central Belt terrane. In the Freshwater basin, Falls (1999a) divided the Franciscan Central Belt in to two sub-units as follows: a sub-unit of well consolidated, moderate to highly deformed sandstones, mudstones, and shales with localized areas of high shearing (a facies suite, referred to in this report as Franciscan sedimentary rock); and a sequence of pervasively sheared matrix with isolated blocks of greenstone, blueschist, graywacke, metagraywacke, serpentine, greenschist, mudstone, conglomerate, and chert. These blocks vary from several yards up to hundreds of yards in size. This second sub-unit, a facies suite, is referred to in this report as Franciscan mélange. These sub-units are separated by northwest-trending, northeast-dipping thrust faults (Falls 1999a). Franciscan Central Belt terrane is also exposed between the main fault strands of the Freshwater fault along the lower valley sides of Freshwater Creek, Graham Gulch, and McCready Creek.

3.1.2.2 Yager Terrane

The Yager terrane consists of dark gray indurated mudstones, shales, graywackes (sandstones), siltstones, and conglomerates, with interbedded limey siltstones. The finer-grained sediments weather to soft clayey materials and are poorly exposed, in contrast to the harder sandstones and coarser rocks that locally underlie ridge tops. Locally, rocks of the Yager terrane form boulders that are found in stream channels. The exotic blocks common to the older Franciscan rocks are not present. Most Yager terrane outcrops are found in valley bottom locations where streams have cut down through the softer Wildcat sediments to expose the underlying Yager. Ogle (1953) identified up to 2400 feet of Yager terrane rocks in Freshwater Creek. Falls (1999a) maps Yager terrane along Little Freshwater Creek, associated tributaries, and along Freshwater Creek in slivers of bedrock caught up in the Freshwater fault zone. In the watershed, Yager strata are characterized by a general northwest strike and a steep dip to the northeast.

3.1.2.3 Wildcat Group

The Wildcat Group crops out most extensively in the western 60% of the watershed. Within the study area, the Wildcat Group was originally mapped as undifferentiated by Ogle (1953) because of poor exposures, thick vegetation and lack of distinctive lithologies. Elsewhere on the south side of the Eel River and along the bluffs of the Eel, he recognized five formations within the group. These five formations, in ascending order are: the Pullen, Eel River, Rio Dell, Scotia Bluffs Sandstone, and Carlotta. The Carlotta is the generally coarser grained unit of the five formations. In the Freshwater watershed, the Wildcat Group is described as primarily poorly indurated mudstone, siltstone, claystone, fine-grained sandstone, and minor conglomerate. Massive mudstones and siltstones are the most dominant geologic materials. A basal conglomerate, and a pebbly sandstone are present in parts of Elk River and in Freshwater Creek. Kilbourne (1985b) describes the Wildcat Group as "moderately to poorly indurated, massive to poorly bedded, folded, compact, blue-gray clayey siltstones with smaller amounts of sandstone." Knudsen (1993) divided the Wildcat Group into upper and lower units. He defined the lower Wildcat unit as a sequence of offshore marine deposits of mudstone, siltstone, and fine-grained sandstone. The upper unit is described as composed of near-shore, bay, and fluvial facies and is interpreted as being correlative to the Falor Formation described to the northeast by Manning and Ogle (1953) and Carver (1987). In this informal subdivision, Knusdens' lower unit appears to roughly correspond to the lower four (essentially fine-grained) formations of the Wildcat as defined by Ogle (1953) and the upper unit would correspond to Ogle's coarser-grained Carlotta Formation. The informal stratigraphic subdivision proposed by Knudsen (1993) was carried forward by Falls (1999a).

The Wildcat Group is in fault contact with the Franciscan Central Belt terrane along the Freshwater fault. However, within the bedrock slivers in the fault zone, the Wildcat is mapped to lie unconformably on Franciscan Central Belt and Yager terranes. West of the Freshwater fault along Freshwater, Little Freshwater, and their tributaries, the Wildcat can be seen resting unconformably on Yager rocks. Where bedding attitudes can be measured, Wildcat sediments vary from essentially flat to a moderate to gentle dip to the north and west. Regionally, the section thickens to the west and north. The Wildcat Group records an eastward transgression of the sea during the late Miocene, progressive shoaling from bathyal or abyssal depths, then infilling of the basin from early Pliocene to early Pleistocene, followed by a westward progression of the shoreline during early to middle Pleistocene time (Nilson and Clarke 1987).

3.1.2.4 Previous Mapping of Late Neogoene/Quaternary Sediments

Because of the poor exposures of the late Neogene/Quaternary sediments on a regional scale and the lack of distinctive lithologies and marker beds combined with gradational contacts and possible interfingering of units, precise differentiation of these units is difficult. Portions of the Hookton Formation are described as an approximately 400-foot thick sequence of primarily non-marine sediments (Ogle 1953). The sands, silts, clays, and gravels in the Hookton are characterized by limonitic staining (Ogle 1953). Kelly (1984) mapped this geologic unit within the Freshwater Creek basin and limited its areal extent to the southwestern most, low-altitude, uplifted terrace deposits. However, Knudsen (1993) interpreted those exposures to be part of the Lower Wildcat Group, resulting in the absence of the Hookton Formation on recent geologic maps of the Freshwater watershed. Other areas of Hookton, mapped by Kilbourne (1985b), are found along high, gently sloping ridge crests in the western portion of the watershed and are described as "early to late Pleistocene, well to poorly sorted, gently folded, unindurated marine grading to non-marine sand, gravel, and silt that may be stratigraphically equivalent to the Falor Formation." However, the most recent geologic map of the Freshwater watershed, Falls (1999a) interperts the Hookton areas mapped by Kilbourne (1985b) as Upper Wildcat.

3.1.2.5 Alluvial Deposits

In the lower portions of the watershed, undifferentiated Pleistocene/Holocene (Quaternary) river terrace deposits are composed of poorly indurated, interfingering lenses of gravel, sand, silt, and clay. They are found along the main channel of Freshwater Creek (Ogle 1953; Falls 1999a). They are typically capped with thin, 2- to 10-foot thick deposits of unconsolidated, poorly sorted sands and sandy pebble conglomerate (Kilbourne 1985b). These stable, uplifted terrace deposits are found on alternating sides of the main channel of Freshwater Creek between Three Corners and the junction with the South Fork Freshwater Creek. They interfinger with more recent Holocene alluvial deposits of interbedded gravel, sand, silt, and clay that compose the floodplain and active channel of Freshwater Creek. Locally, relatively small terrace and active channel deposits occur along the mainstem of Freshwater Creek and its tributaries.

3.1.2.6 Landslide Deposits

Landslide deposits are found throughout the watershed**.** They vary in size from insignificant roadside debris-slides covering a few square yards, to very large, relatively stable, deep-seated landslides that underlie hundreds of acres. Landslide deposits can range in thickness from one foot to over 100 feet or more. They are composed of a generally heterogeneous mixture of bedrock debris, soil/colluvium, and sometimes organic debris that have moved down slope more-or-less as a relatively intact, though sometimes as a very fluid, mass. Landslides are further discussed in Section 6.0 of this report.

3.1.2.7 Colluvium/ Residual Soil

Colluvium and residual soils form veneers and blankets that cover most of the hillslopes in the watershed, except where bedrock is exposed. These deposits are generally relatively thin (veneers) on ridgetops and steep upper slopes; and increase in thickness down hillsides toward the bottom of slopes, where they can form thick accumulations (blankets). Residual soil forms from the mechanical breakdown and chemical weathering of the underlying bedrock or unconsolidated geologic materials. Colluvium is weathered material that has moved downslope by gravity-induced movement and accumulated on the hillside. Colluvial deposits can be up to 10 feet or more in depth. Shallow landslide deposits (e.g., debris-flow fans) are often considered a form of colluvium. For clarity, these deposits are not shown on the geologic map but should be assumed to be present as described above.

3.1.2.8 Artificial Fill

Artificial fill is present along the outside margins of most roads in the watershed. It is also present at most stream crossings and along the outside margins of landings and borrow pits. It is composed of soil/colluvium, bedrock materials, and local organic debris. Though not shown on geologic maps, its presence, as described above, should be assumed.

3.1.2.9 Structure

Structurally, the watershed is dominated by the Freshwater fault. This fault is part of a group of northwest-trending faults that are the on-shore expression of faulting associated with the Cascadia subduction zone. The Freshwater fault is represented by a zone of several fault traces that trend northwest-southeast through the central area of the watershed. The fault is characterized by Falls (1999a) as a normal fault along which bedrock blocks step down to the west in a regional context. Generally, the fault separates rocks of the Franciscan Central terrane on the east from Yager terrane and overlying younger Wildcat Group sediments on the west. Some Wildcat is exposed overlying Franciscan terrane east of the Freshwater fault in the north-central area of the watershed. Slivers of bedrock, underlain by either Central terrane or Yager terrane (both overlain by Wildcat rocks), are juxtaposed along the various fault traces within the fault zone. Falls (1999a) also maps an imbricate series of northwest-trending, northeast-dipping thrust faults in the eastern area of the watershed.

3.1.3 Geologic Mapping Used for this Analysis

Because of a long and continuing history of geologic mapping in the Freshwater watershed and adjacent areas, there are a number of geologic maps in existence. Due to the evolving nature and understanding of the geologic setting of the watershed, these maps are not always consistent with respect to geologic contacts (map unit boundaries), faults, or geologic descriptions. Hence, there can be differences from map to map. The most recent California Geological Survey[2] (CGS) map of the Freshwater basin was prepared by Falls (1999a). This map is currently the most detailed and likely most accurate geologic map for the watershed. However, it was not available in digital format at the time the preliminary Mass wasting assessment for the Freshwater watershed was carried out. The digital geologic map for the watershed stored in the PALCO geographic information system (GIS) and which was used for the preliminary mass wasting analysis comprised the common corners of four separate CGS geologic map sheets. These map sheets were the Arcata South quadrangle (Kelley 1984), the Iaqua Buttes quadrangle (Kelsey and Allwardt 1987), the Korbel quadrangle (Kilbourne 1985a), and the McWhinney Creek quadrangle (Kilbourne 1985b).

Areas mapped as Falor Formation on this composite geologic map correspond to the Upper Wildcat as mapped by Falls (1999a). The areas of Hookton Formation outlined on the composite geologic map included both the area of Hookton considered Lower Wildcat by Knudsen (1993), and those areas of Hookton considered Upper and Lower Wildcat by Falls. Some western portions of the area mapped as Franciscan sedimentary rocks on the composite map were mapped as Lower Wildcat by Falls. Areas of Franciscan sediments outlined on the lower valley floor of the Freshwater on the composite map are mapped as recent alluvium on Falls' 1999 map. Similarly, some areas of Franciscan Melange outlined on Falls' map were mapped as Franciscan sediments on the mid 1980's CGS maps. This particular difference appears to be a function of differences in geologic definition between the McWhinney and Iagua map sheets. The Wildcat areas mapped as undifferentiated on the mid 1980's CGS maps generally correspond to the Lower Wildcat as defined by Falls. Falls restricts the Upper Wildcat to gently sloping ridge crests and upper slope areas as was done on the earlier CGS geology maps for the Hookton and Falor formations. All maps show small units of unidentified lithology, generally within the Franciscan mélange.

The current version of the Freshwater mass wasting analysis uses the distribution of geologic units delineated on a digital version of the 1999 CGS map for the Freshwater (Falls 1999a). The digital version of this map was completed and released by the CGS in mid 2001. It is included as part of this analysis as Map A-1, replacing the original composite map.

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[2] The California Geological Survey was formerly known as the Department of Mines and Geology (DMG). For the sake of simplicity we have used the new name for this agency in this document including text references to documents or reports written when the agency was known as the DMG. However, in the list of references these documents are still identified as DMG publications.

3.2 SOILS

Detailed descriptions of the soils in the Freshwater watershed are found in the surface erosion module report (Appendix B). An engineering soil description summary is located in Section 8.0 of this report.

3.3 SEISMIC ENVIRONMENT

The Freshwater watershed is located about 30 miles northeast of the Mendocino triple junction. This junction marks the convergence of three tectonic plates, the North American, Gorda, and Pacific. These plates are bounded by the San Andreas fault, the Mendocino fault, and the Cascadia subduction zone. The northward extent of the San Andreas fault system defines the transform boundary between the North American plate and Pacific plate. The Mendocino fault defines the transform boundary between the Pacific plate and the Gorda plate. The Cascadia subduction zone defines the convergent boundary between the Gorda plate and the North American plate. Quaternary deformation in northern coastal California is the result of compression and lateral translation associated with the northward migration of the Mendocino triple junction and subduction along the Cascadia zone. Crustal deformation manifests itself through folding and thrust faulting (Kelsey and Carver 1988). Because of ongoing folding and thrust faulting, the on-shore region north of the Mendocino triple junction continues to experience rapid uplift; it is the most tectonically active region in the state (Prentice et al. 1992)

The Freshwater basin is situated amid a system of northwest-trending, eastward dipping thrust faults, reverse faults, and normal faults. These faults include the Freshwater fault zone, the Mad River fault zone, and the Little Salmon fault. Within the watershed, the Freshwater fault shows no evidence of activity since the late Quaternary (Falls 1999a). It is not listed as a probable seismogenitic source by Petersen et al. (1996). Located about three miles northeast of the Freshwater watershed is the active Mad River fault zone. The Mad River fault zone includes five principal thrust faults (Trinidad, Blue Lake, McKinleyville, Mad River, and Fickle Hill faults) and many minor thrust faults (Kelsey and Carver 1988). Kelsey and Carver (1988) proposed a net slip rate along the Mad River fault zone of at least 0.25 in./year of horizontal shortening since the late Pleistocene. Petersen et al. (1996) estimate that the Mad River fault zone is capable of generating a maximum moment magnitude (Mw) 7.1 earthquake and estimate a recurrence interval of about 2,000 years. The Little Salmon fault is located approximately 7 miles southwest of the Freshwater watershed. It has produced a minimum of three seismic events within the last 2,000 years (Dengler et al. 1992), the most recent being about 300 years before present (BP). Horizontal shortening for the Little Salmon fault is estimated at 0.1

in./year. Petersen et al. (1996) estimate the Little Salmon fault is capable of generating a Mw 7.1 earthquake and estimate a recurrence interval of about 270 years.

Humboldt County and the entire north coast of California lie within a seismically active region of North America (HEEC 1999); the seismic hazard for the entire county is considered high (OES 1975) and will remain high for the foreseeable future. Recent seismic hazard studies estimate that the likely Mw earthquake on the Cascadia subduction zone in northern California ranges from Mw 8.3 (Petersen et al. 1996) to Mw 8.4 (Toppozada et al. 1995). In the past decade, the north coast region has experienced four magnitude 6 or greater earthquakes: the August 1991 Honeydew earthquake (magnitude 6.0 to 6.2), and the three April 1992 earthquakes of the Petrolia event (magnitude 6.6 to 7.1).

Regional historical events, event frequencies, and magnitudes are described in detail by Dengler et al. (1992). They document numerous Modified Mercalli Intensity (MMI) VI or greater events occurring within and near the Freshwater basin since the early 1900s. Ground shaking intensities in the watershed varied from an estimated MMI IV for the Honeydew earthquake (McPherson and Dengler 1992) to MMI VII to VIII for the Petrolia events (Reagor and Brewer 1992). Toppozada et al. (1995) estimate that during an 8.4 earthquake on the Cascadia subsudction zone, the region could experience ground shaking intensities of MMI VII to IX. Predictions indicate that the greatest intensities, MMI IX, will be confined essentially to the alluvial terraces.

Large earthquakes and associated intense ground shaking can be a triggering mechanism for initiation of landslides or reactivation of preexisting landslides, as clearly demonstrated by the Honeydew and Petrolia events. In the epicentral area of the Honeydew earthquake, several apparently deep-seated landslides and earthflows were reactivated (McPherson and Dengler 1992). In addition, abundant small slides along roads, and some temporarily blocked stream channels were reported (Dunklin, 1992). Shaking intensities in the Honeydew epicentral area were estimated to be VIII. In the epicentral area of the main shock of the Petrolia events, shaking intensities were determined to be VII to VIII (Reagor and Brewer 1992) but locally could have been greater. Many landslides, rock falls, and debris-slides on coastal cliffs and throughout the inland hillside regions were triggered by the ground shaking. Prentice et al. (1992) report three large reactivated earthflows at or about the same place as reactivated earthflows reported by Lawson (1908) following the 1906 earthquake. These landslides are about 5 miles north of the epicentral area. Prentice et al. (1992) report that during ground reconnaissance, they observed ground cracks up to a few inches wide apparently associated with reactivation of large, deep-seated landslides. Studies by Keefer (1984) show that the minimum shaking intensity that triggers landslides is generally MMI VI to VIII, though sometimes intensities as low as IV to V can trigger landslides. As noted earlier, intensities of IV to VIII likely occurred in the watershed in response to the Honeydew and Petrolia events. If a great earthquake occurs on the California portion of the Cascadia subduction zone, intensities of VII to VIII are expected to occur on the hillside. Shaking intensities observed following large to major earthquakes (Scott 1971) on faults similar to the Little Salmon or Mad River faults suggest these nearby faults could generate ground shaking in the watershed equal to MMI VII and VIII to IX, respectively.

This information suggests that there is a potential for seismically induced landsliding to occur in the watershed in response to a large to major earthquake on either the Little Salmon fault, the Mad River fault zone, in the Cascadia subduction zone, or in the area of the Mendocino triple junction. Based on past performance, shallow landslides, fill settlement, and rock falls could be very common along roads and other hillside areas. Large deep-seated landslides could be initiated or reactivated (Dunklin 1992). The amount of movement is extremely difficult to estimate and could vary from very insignificant, indicated by ground cracks only a few inches wide, to the apparently significant displacements as noted by McPherson and Dengler (1992), Prentice et al. (1992), and Dunklin (1992). It should be noted that although the Freshwater watershed was subjected to ground shaking intensities apparently high enough to trigger shallow and deep-seated landslides during the Honeydew and Petrolia events, none were reported. This suggests that, at least with respect to earthquakes generated on faults some distance from the watershed, the slopes and landslides in the watershed may not be particularly susceptible to failure, and higher shaking intensities may be required to initiate movement. Information compiled by Youd and Hoose (1978) indicates that a search of the historic records up to about 1978 did not reveal reports of landslides (at least significant ones), on the hillsides in the watershed. This also suggests that seismically induced landslides in the watershed are not historically common.

Potential effects from intense ground shaking on management activities in the watershed could include failure of cut and fill slopes along forest roads. However, because of the improved construction practices required by the forest practice rules, fill slope failures would more likely occur along legacy roads than newer roads in the watershed. Where stream-crossing fills are thick enough, settlement of the road surface or slumping of the fill slopes could occur in response to intense ground shaking. Finally, there is the possibility that recent harvest activities could be a contributing factor in initiation or reactivation of a landslide on areas subjected to intense seismically-induced ground shaking. Such a landslide, if large enough, could deliver significant amounts of sediment to a stream. While this is possible, the past history of slope movement related to ground shaking in the watershed does not suggest that this is a common event, or that significant sediment volumes are delivered. While this does not discount the potential for a significant seismically induced landslide to occur, it points out that that the probability for harvest activities influencing such events in the watershed is very low.

Methods exist to qualitatively evaluate the stability of slopes and existing landslides, particularly deep-seated landslides, under seismic loading. It should be emphasized that peak events (meaning horizontal ground accelerations) are never used in the dynamic analysis of a slope or landslide. The standard of practice is to use accelerations in the range between 0.15 and 0.2g. However, the meaningful application of such methods requires detailed information well beyond the normal scope of landslide evaluations for forest practices applications. Methods mentioned in Renteria (1992) may be applicable on a generalized, regional-planning scale or for very site-specific high risk settings where an adequate amount of data are available to constrain the parameters for a seismic-slope stability analysis. However, the application of such methods for the seismic evaluation of a slope or landslide where such constrained parameters are not available to accurately characterize the slope in question would generally be less than meaningful.

3.4 GENERAL PHYSIOGRAPHY

The Freshwater watershed is represented by two quite different morphologic units separated by the Freshwater fault. The variability of the units on each side of the fault, in large part, reflects the underlying geology. East of the Freshwater fault, portions of the watershed exhibit the classic “ice cream” appearance of “soft” erosional hillside morphology typical of the Franciscan mélange. Rises or irregularities in this topography are usually associated with “knockers,” tectonically placed blocks of hard, sometimes exotic, rocks within the softer mélange material. Where mélange is absent, the topography is characterized by a "harder" appearance and relatively steeper slopes. Streams are more incised; local relief is moderate to high.

To the west of the fault are younger bedded rocks of the Yager terrane and Wildcat Group. This area is characterized by relatively low relief. Gentle slopes characterize the ridge crests in this area, with steeper slopes at or just below the ridge crests. Valley floors are somewhat wider than in the eastern area. There are many short streams that dissect the generally planar slopes, creating a more “fluted” appearance to the topography of this side of the watershed. In the lower reaches of the watershed, along Freshwater Creek, the topography becomes more and more dominated by the relatively flat surfaces of the stream terraces and the incised channel and associated steep bank of Freshwater Creek. Locally in the watershed, ridge crest erosion has resulted in “stream piracy” where streams have been captured and stream flow rerouted. The slope gradients shown on Map A-2 illustrate these patterns.

Carver and Burke (1992) and Prentise et al. (1992) have documented that the uplift rates are high (approximately 0.05 to 0.1 in./year) in the coastal areas of northern California. To illustrate the point further, consider that without erosion the hills within the watershed would have risen to an elevation of approximately 7,500 feet since the time the uplift first began, about 1.8 million years ago, when the present Freshwater Creek area was part of a broad coastal plain. As uplift and erosion continued over geologic time, the remnants of the coastal plain became ridge crests, some of which can still be found today.

4.0 BACKGROUND AND REFERENCE INFORMATION

4.1 REFERENCE MATERIALS

The following information was used for the mass wasting assessment in the Freshwater watershed:

- PALCO Freshwater topographic base map: 1:18,000 scale, based on a digital elevation model (DEM) stored in the PALCO GIS. This map has a 40-foot contour interval. It is our understanding that this digital elevation model is derived from United States Geological Survey (USGS) 1:24,000 medium scale topographic maps. This DEM has a reported 10 meter grid cell resolution, recalibrated by the USGS from an original 30 meter grid. The DEM was received from the USGS in December, 1999.
- Slope gradients from the DEM maximum, minimum, and mean DEM slope angles for each landform polygon derived from the PALCO GIS.
- CGS geologic map sheets: Arcata South quadrangle (Kelley 1984), the Iaqua Buttes quadrangle (Kelsey and Allwardt 1987), the Korbel quadrangle (Kilbourne 1985a), and the McWhinney Creek quadrangle (Kilbourne 1985b).
- CGS geologic and geomorphologic features, and relative landslide potential maps for the Freshwater watershed (Open-File Report 99-10, Falls 1999a; and, Open-File Report 99-10a, Falls 1999b). Aerial photographs used by the CGS for geological and landslide inventories were cross-referenced for shallow landslide identification and locations by Pacific Watershed Associates (PWA) staff and J. Falls. Any additional shallow landslide locations that were determined to be valid were added to the PWA database. The aerial photographs used by the CGS are listed in the marginal notes on Open-File Report 99-10, - Plate 1 (Falls 1999a). Tables 4-1 and 4-2 list additional aerial photography used for the Freshwater landslide inventories.
- PALCO GIS data layers:
  - forest cover.
  - geology— Falls, 1999, from digital files received in mid 2001 from the CGS.
  - morphologic landform mapping (the database used for this assessment includes polygon areas in acres and road lengths for each landform polygon derived from the PALCO GIS).

- Freshwater shallow landslide inventory (PWA 1999).
- Freshwater deep-seated landslide inventory

Table 4-1: List of PALCO aerial photographs used for the Freshwater shallow landslide inventory.

Year of Air Photography	Flight Line	Frame Numbers	Year of Air Photography	Flight Line	Frame Numbers
1942	CVL-6B	01-06	1987	h23	41-46
	CVL-6B	72-74		h24	43-51
	CVL-3B	37-43		h25	43-52
	CVL-9B	71-76		h26	41-54
1948	15	20-26		h27	39-49
(CDF-2)	16	186-190		h28	44-52
	17	52-55		h29	44-48
	33	80-85		h30	44-48
1954	12n	6-9	1994	17	70-79
	13n	128-134		18	67-76
	14n	13-18		19	63-75
	14n	121-129		20	64-77
1966	17b	34-39		21	65-79
	18	21-31		22	67-74
	19	83-94		23	66-73
	20	79-90		24	66-73
	21b	63-73	1997	17	68-79
	22	80-87	(HUM 97)	18	73-84
	23b	32-36		19	72-85
	24a	80-84		20	63-77
1974	17a	33-39		21	69-81
	18a	31-41		22	63-71
	19	72-83		23	63-68
	20	68-78		24	62-66
	21a	33-43			
	22	63-68			
	23a	33-37			
	24b	30-34			

Table 4-2: List of aerial photographs used for the Freshwater deep-seated landslide inventory.

Year of Air Photography	Flight Line	Frame Numbers	Year of Air Photography	Flight Line	Frame Numbers
1948	15	20-26	1997	97 – 17	70-77
(CDF-2)	16	186-187	(HUM 97)	97 – 18	74-78
	17	44-45, 52-55		97 – 19	73-84
	27	44-45		97 – 20	64-66
				97 – 21	69-70
				97 – 22	63-64

4.2 CHRONOLOGY

This section outlines the history and timing of the various components of the Mass Wasting assessment for the Freshwater Creek watershed.

4.2.1 Empirical Approach

The following chronology outlines the empirical analysis process:

- Pacific Watershed Associates (PWA) conducted a landslide inventory for the Freshwater watershed for PALCO in 1998 and 1999. All visible road landslides were verified in the field. This inventory addressed landslides occurring between 1940 and 1997.
- Golder Associates Inc. constructed a Morphologic Landform Unit (MLU) map for the Freshwater watershed in February 2000.
- The landslide inventory map and the MLU map were intersected to determine the frequency of landslides occurring on the various morphologic landform units (April 2000, June 2001).
- Landslide summaries were prepared showing the average landslide frequencies for individual landforms (April-May 2000, June 2001). Landslide frequency is expressed as the number of landslides per unit area of hillside or unit length of road over the 1940 to 1997 period of record. Landslide hazard maps showing historical hillside and road landslide densities and expected frequency of delivery of landslides to streams were developed and revised (May-December 2000). These maps were revised in mid 2001, after the CGS provided digital geology coverage for the Freshwater.
- Deep-seated landslide inventory (large earthflows and large landslides) and reactivation potential hazard maps were developed and revised by John Coyle (April-December 2000).
- Comparisons were made for the period of 1975-1997, by landform category, for areas of clearcut harvesting, thinned second-growth, and unthinned second-growth, to develop an estimates landslide density for these different types of landuse (May 2000, October 2001).

4.2.2 Deterministic Approach

The following chronology outlines the deterministic analysis process:

- T. Koler (PALCO) constructed a prototype MLU map in early 1999. This map served as the basis for selecting geotechnical sampling sites. Sample locations were selected by laying a stratified random sampling grid over the landform map. The sampling design attempted to ensure representative soil sampling and testing for the various landforms present in the watershed.

- During 1998 and early 1999, Hart Crowser Inc. and Golder Associates gathered geotechincal data and samples for different landforms using Williamson drive probes and soil augers.

- Hart Crowser and R. Prellwitz correlated drive probe data with blow counts obtained using an Acker SPT (1998-99).

- Laboratory results and blow-count data were used T. Koler (PALCO) to determine soil moisture and angle of internal friction for sampled sites (April-May 1999).

- Soil cohesion was determined by Prellwitz in early 1999 with the Chen and Giger method (1971).

- A revised MLU map was produced by Golder Associates in collaboration with Koler in early 1999. This map was used to group samples into the landform and slope class categories.

- The factor of safety (FOS) for the various landforms was determined by Koler using LISA, the U.S. Forest Service deterministic slope stability model (April-May 1999 and October 2001).

5.0 LANDFORM MAPPING – FREQUENCY AND SPATIAL DISTRIBUTION OF LANDFORMS

5.1 METHODS

This portion of the analysis produced a Morphologic Landform Map (Map A-3). The map shows the types and spatial distribution of various landforms present within the Freshwater watershed. This map is used in combination with the landslide inventory to generate landslide hazard maps for the basin.

The morphologic landform units (MLU) mapped within the Freshwater watershed boundary followed the guidelines and definitions outlined in the mass wasting module methodology (PALCO 2000), Appendix B. This landform mapping approach delineates landforms on a topographic map based on slope shape, slope gradient, and stream class if a stream is contained within a map unit. Slope shapes are defined as convex, concave or incised (convergent), planar, complex, and fans and/or terraces. The primary breaks used for slope gradient were 20 degrees and 30 degrees. Slopes less than 20 degrees were termed gentle, slopes between 20 and 30 degrees as moderate, and slopes greater than 30 degrees as steep. Fans and terraces typically have slopes gentler than 10 degrees, and these were mapped separately.

The morphologic landform map units (polygons) were delineated on a topographic map at a scale of 1:18,000, with a contour interval of 40 feet. This map was obtained from the PALCO GIS. The landforms were digitized into the GIS and then edited at a scale of 1:12,000. Due to the moderate resolution of the topographic map, small, unmapped inclusions of minor or sub-dominant landforms will likely occur in most landform polygons. For example, when a complex-gentle landform bounds a terrace/floodplain/fan landform, it is possible for the fan feature to extend up into the complex-gentle feature.

A manual scale was created to easily measure the maximum distances between contour lines for any given slope class. This scale was used to increase the rate at which the mapping was done and to maintain consistency throughout the mapping exercise. Of the 25 possible morphological landform unit categories defined in the mass wasting module methodology, only 12 were mapped in the Freshwater watershed. The remaining 13 possible landform types were not identified in the Freshwater basin; or if they were present, they were too small to delineate at the 1:18,000 scale used for mapping.

Minimum landform polygon size was limited to approximately 0.01 square inches (approximately 0.5 acres). The smallest polygons were typically concave headwall landforms at the head of first-order, Class 3 stream channels. Limited field checking and aerial photograph interpretation were carried out to verify landform boundaries and classification.

Landform polygons often contain more than one geologic unit because landform boundaries are generated independently; therefore, landform map unit boundaries do not necessarily correspond to geologic map unit boundaries.

5.2 VARIANCE TO MASS WASTING METHODOLOGY

The morphologic landform mapping approach utilized in the Freshwater conforms to the procedure outlined in Appendix B of the mass wasting module methodology (PALCO 2000). We did not carry out additional air-photo based terrain mapping as outlined in the prototype version of the mass wasting module methodology. Based on our experience developing landslide hazard maps from the morphologic landform maps (see Section 6.0), we did not feel it was essential to carry out additional landform (terrain) mapping to be able to produce an analysis of landslide occurrence, delivery, and hazard suitable for watershed-scale planning. Limited field verification indicated that the morphologic landform mapping provided a reasonably clear separation of landform types in the watershed, and a different type of terrain mapping (or terrain classification) would not likely have improved that separation. Indeed, a second set of landform (terrain) maps and derivative landslide hazard maps would likely cause more confusion than they would contribute to improved analysis. We do feel that it would be useful in the future to use aerial photography and more intensive field verification of map units to delineate and refine landform boundaries. Without this additional work, landform boundaries will often require site-specific field verification during timber harvest plan preparation or road location activities.

5.3 LANDFORM DISTRIBUTION AND RELATIONSHIPS TO UNDERLYING GEOLOGIC UNITS

Table 5-1 summarizes the distribution of morphologic landform units within the Freshwater watershed and stratifies them by the dominant underlying geologic unit. Map A-3 illustrates the distribution of the landform units in the watershed.

Table 5-1: Distribution of Landform Units by Geologic Unit

Landform	Geologic Unit	Area (acres)	% of Total Area	Mean Slope (°)	Maximum Slope (°)	Minimum Slope (°)
Convex gentle	Franciscan melange (KJfm)	2995	15.2	25	55	5
	Franciscan sediments (KJfs)	626	3.2	28	55	5
	Recent alluvium (Q)	2	0.0	11	25	5
	Alluvial terrace deposits (Qrt)	28	0.1	17	35	5
	Lower Wildcat (Twl))	3299	16.8	25	55	5
	Upper Wildcat (Twu))	68	0.3	19	30	5
	Yager Formation (Ty)	165	0.8	26	45	5
	Unidentified lithology (u) [2]	108	0.5	26	45	10
Convex moderate	Franciscan melange	38	0.2	35	65	5
	Franciscan sediments	153	0.8	39	65	5
	Recent alluvium	0	0.0	18	30	10
	Lower Wildcat	444	2.3	30	60	5
	Upper Wildcat	21	0.1	21	40	5
	Yager Formation	38	0.2	33	55	5
	Unidentified lithology	7	0.0	37	40	25
Convex steep	Franciscan melange	1	0.0	44	65	15
	Franciscan sediments	48	0.2	45	65	15
	Lower Wildcat	5	0.0	33	60	10
	Yager Formation	5	0.0	38	60	20
	Unidentified lithology	6	0.0	35	40	15
Incised moderate	Franciscan melange	1642	8.3	25	55	5
	Franciscan sediments	369	1.9	26	55	5
	Recent alluvium	183	0.9	11	85	5
	Alluvial terrace deposits	117	0.6	12	50	5
	Lower Wildcat	2436	12.4	24	50	5
	Upper Wildcat	51	0.3	18	40	5
	Yager Formation	263	1.3	20	55	5
	Unidentified lithology	34	0.2	29	45	15
Incised steep	Franciscan melange	63	0.3	35	65	5
	Franciscan sediments	87	0.4	37	65	5
	Recent alluvium	0	0.0	27	40	20
	Alluvial terrace deposits	1	0.0	28	35	20
	Lower Wildcat	632	3.2	30	60	5
	Upper Wildcat	8	0.0	24	40	5
	Yager Formation	44	0.2	33	50	5
	Unidentified lithology	2	0.0	42	45	20
Headwall	Franciscan melange	14	0.1	24	35	5
	Franciscan sediments	6	0.0	30	55	5
	Lower Wildcat	34	0.2	25	50	5
	Upper Wildcat	5	0.0	16	35	5
	Yager Formation	1	0.0	25	30	20
	Unidentified lithology	1	0.0	22	35	10

Table 5-1: Distribution of Landform Units by Geologic Unit

Landform	Geologic Unit	Area (acres)	% of Total Area	Mean Slope (°)	Maximum Slope (°)	Minimum Slope (°)
Planar gentle	Franciscan melange	1423	7.2	26	45	5
	Franciscan sediments	164	0.8	29	55	5
	Recent alluvium	1	0.0	20	30	15
	Alluvial terrace deposits	8	0.0	23	30	10
	Lower Wildcat	491	2.5	28	45	5
	Upper Wildcat	42	0.2	17	30	5
	Yager Formation	27	0.1	25	40	5
	Unidentified lithology	10	0.1	35	45	20
Planar moderate	Franciscan melange	140	0.7	35	50	5
	Franciscan sediments	98	0.5	36	55	5
	Recent alluvium	0	0.0	37	50	35
	Alluvial terrace deposits	1	0.0	31	60	5
	Lower Wildcat	477	2.4	21	40	5
	Upper Wildcat	8	0.0	32	55	5
	Yager Formation	33	0.2	40	45	5
	Unidentified lithology	8	0.0	32	60	5
Planar steep	Franciscan melange	12	0.1	41	55	10
	Franciscan sediments	55	0.3	23	40	15
	Recent alluvium	0	0.0	30	30	30
	Alluvial terrace deposits	0	0.0	36	60	5
	Lower Wildcat	123	0.6	40	60	5
	Yager Formation	15	0.1	41	45	40
	Unidentified lithology	0	0.0	38	60	5
Terrace/fan	Franciscan melange	6	0.0	15	35	5
	Franciscan sediments	4	0.0	10	85	5
	Recent alluvium	425	2.2	8	40	5
	Alluvial terrace deposits	387	2.0	17	35	5
	Lower Wildcat	83	0.4	20	45	5
	Yager Formation	14	0.1	10	85	5
Complex gentle	Franciscan melange	361	1.8	19	50	5
	Franciscan sediments	111	0.6	12	30	5
	Alluvial terrace deposits	21	0.1	19	50	5
	Lower Wildcat	731	3.7	14	35	5
	Upper Wildcat	256	1.3	37	45	10
	Yager Formation	1	0.0	27	35	25
	Unidentified lithology	0	0.0	17	50	5
Complex moderate	Lower Wildcat	86	0.4	20	30	5
	Upper Wildcat	2	0.0	21	40	5

[2] Most of the unidentified lithologies are small inclusions within the Franciscan melange.

Data on geology, distribution of landform units within geologic units, and landform slopes were derived from the GIS. Individual MLU polygons can overlap two and occasionally three geologic units. To simplify analysis, each landform polygon was subdivided into child polygons by intersecting the geologic unit polygons with the MLU polygons. The Freshwater basin is slightly less than 20,000 acres in area.

Convex, gentle slopes cover 37% of the watershed. Two geologic units are associated with convex-gentle slopes: the Franciscan Central Belt and the Wildcat Group. These two geologic units cover about 43% and 47% of the watershed, respectively. Convex-moderate slopes cover 4% of the watershed with convex-moderate slopes in the Wildcat accounting for 2% of the area. Convex-steep slopes account for about 0.3% of the basin area and are too rare to show definitive geologic formation relationships.

Incised-moderate landforms occupy about 26% of the watershed. A limited number of gently sloping streamside areas are included within the incised-moderate category, these situations typically occur where streams cross low-lying floodplain areas or alluvial terraces. Incised-moderate landforms in the Franciscan sediments and the Wildcat Group constitute 10% and 13% of the area, respectively. Incised-steep landforms account for 4% of the area, and most of these landforms (3%) are in the Wildcat Group.

Complex-gentle slopes account for 8% of the watershed area, with the complex-gentle slopes in the Wildcat Group covering 5% of the basin. Complex-gentle slopes in the Franciscan Complex comprise 2% of the watershed area. Complex-moderate slopes cover about 0.4% of the watershed and are limited to the Wildcat Group. No complex-steep slopes were mapped.

Quaternary terraces, floodplains and fans occupy about 5% of the watershed area.

Planar-gentle slopes account for 11% of the total basin area, with planar-gentle slopes in the Franciscan and Wildcat Group covering 8% and 3% of the watershed, respectively. Planar-moderate slopes in the Freshwater Creek watershed account for only 4% of the watershed area. Planar-steep slopes cover only 1% of the watershed, distributed among the Wildcat Group, the Franciscan sediments, and the Franciscan melange.

Headwall slopes account for less than 0.5% of the watershed area. The majority of these landforms occur within the Wildcat Group.

The GIS was used to derive average, minimum, and maximum DEM slope angles for each set of mapped landform-geologic unit association polygons (Table 5-1). The average DEM slopes generally fall within the slope class limits that define each landform type. The minimum and the maximum DEM slopes, however, often fall outside the slope class limits that define the landform type, because of inclusions of steeper or gentler slopes within some map units.

6.0 LANDSLIDE INVENTORIES AND ANALYSIS

6.1 SHALLOW LANDSLIDE INVENTORY METHODS SUMMARY

This portion of the mass wasting assessment produces a Shallow-Landslide Inventory Map (Map A-4), showing the types (road versus non-road related) and spatial distribution of shallow landslides in the watershed. The map distinguishes between landslides that reach streams and those that do not. The landslide inventory also produces a database that lists a series of attributes for the majority of shallow landslides identified in the watershed. Data are not included for very small, road-cut and hillslope landslides that may be visible in the field but cannot be seen or are very difficult to identify with certainty on aerial photographs.

The shallow-landslide inventory involved the identification of landslides on aerial photographs dating from 1940 through 1997, a 58-year period of record. All landslides identified in the field and/or on aerial photographs were plotted on the shallow landslide inventory map. All road landslides and a limited number of harvest area landslides were verified in the field. The original PWA shallow landslide inventory included locations for about 50 very small road-cut landslides and a few very small hillslope landslides (i.e., on the order of 1-10 yd^3) that were not included in the landslide database because no geometric data was collected. Data for landslides initiating in or at road-cut slopes were not recorded unless the landslide was large enough to reach a stream (only four landslides reaching streams began at road-cuts). The majority of road landslides in the data set started at or in road fills. With the exception of these very small landslides, geometric and classification data (landslide dimensions, type, forest practices at the point of origin, etc.) were collected for all landslides visible on the aerial photographs or identified in the field. In the case of the field-verified landslides, the geometric data were collected in the field. Simple summary statistics were applied to the landslide data to identify spatial and temporal patterns in landslide activity, as well as distributions of landslide size and type.

6.2 VARIANCE FROM THE MASS WASTING METHODOLOGY

The information collected corresponds in general with the data list outlined in PALCO (2000); but because the landslide inventory preceded this version of the methods, there are some differences. These differences arise because the landslide data were originally collected to identify, quantify, and direct mitigation of sediment sources in the watershed that might pose a risk to streams and not for the broader objectives of watershed analysis.

The landslide data set includes estimates of transport (depletion) zone dimensions, but does not include estimates of deposition (accumulation) zone dimensions. Data on stream classes and lengths of streams affected by landslides were not recorded, except for eight channelized debris-flows (debris torrents). The majority of landslides that reached streams did not travel down those streams.

The Freshwater landslide inventory includes a large number of landslides that are smaller than the minimum 300 yd^2 size recommended for inventory by the mass wasting module methodology. Approximately 48% (104 of 217) of the road landslides and 36% (82 of 227) of the hillslope landslides recorded in the Freshwater landslide inventory database were smaller than the 300 yd^2 minimum size limit. This count does not include very small landslides noted above located in the field during the PWA landslide inventory but not included in the landslide inventory database.

6.3 SHALLOW LANDSLIDE INVENTORY RESULTS AND DISCUSSION

The most common types of shallow landslides identified in the Freshwater watershed consist of debris-slides and debris-flows. The landslide inventory database includes 444 shallow landslides in the Freshwater basin that occurred between 1940 and 1997, these landslides are mapped in Map A-4. Most of these landslides came to rest on hillslopes some distance below their point of initiation or entered streams and stopped almost immediately. Only eight (or 3%) of the landslides that reached streams traveled any distance down a stream channel. The length of stream traversed by these eight channelized debris-flows averaged about 320 feet and ranged from about 170 to 540 feet. Approximately 80% of the landslides initiating on road fill slopes or on hillslope areas reached streams. If only larger landslides are considered (i.e., landslides >300 yd^2 or >400 yd^3) then the percentage of landslides reaching streams increases to about 90%. Frequency distributions for shallow-landslides for the air photo period 1942 to 1997 are shown in Figures 6-1 to 6-6.

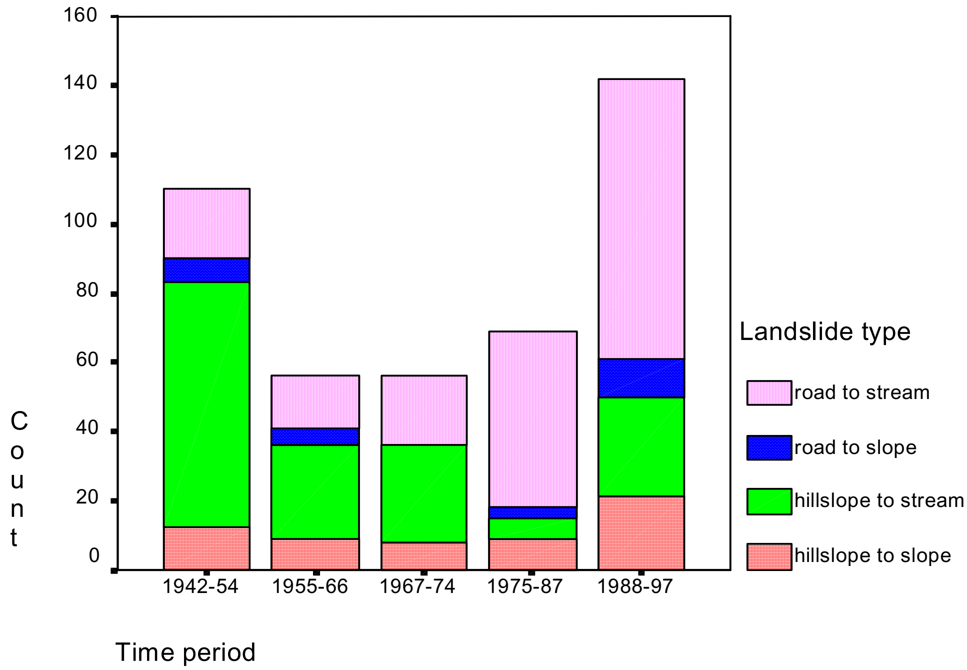

Figure 6-1: Landslide distribution over time (all landslides).

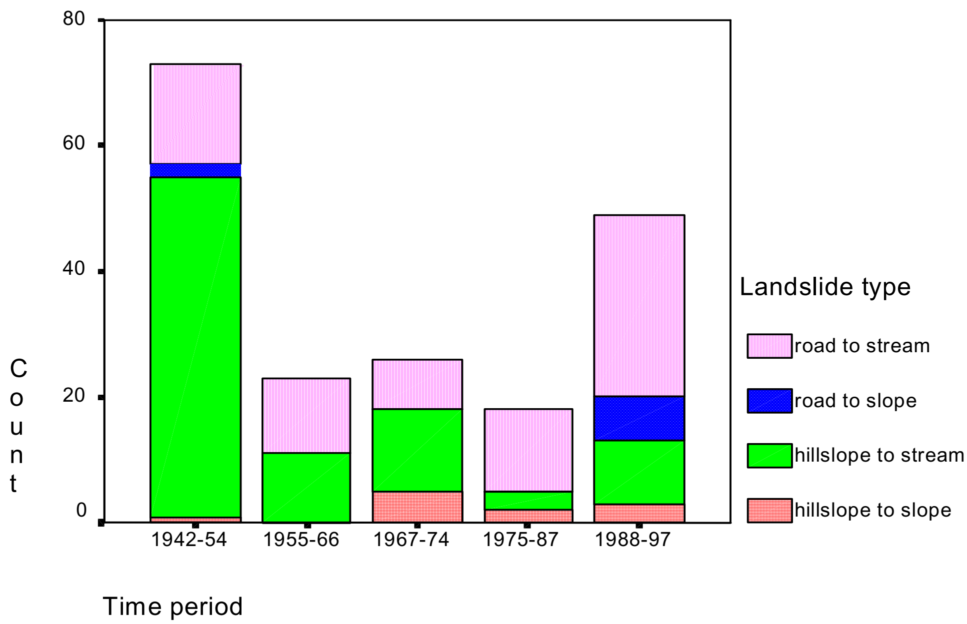

Figure 6-2: Landslide distribution over time (landslides >400 cubic meters).

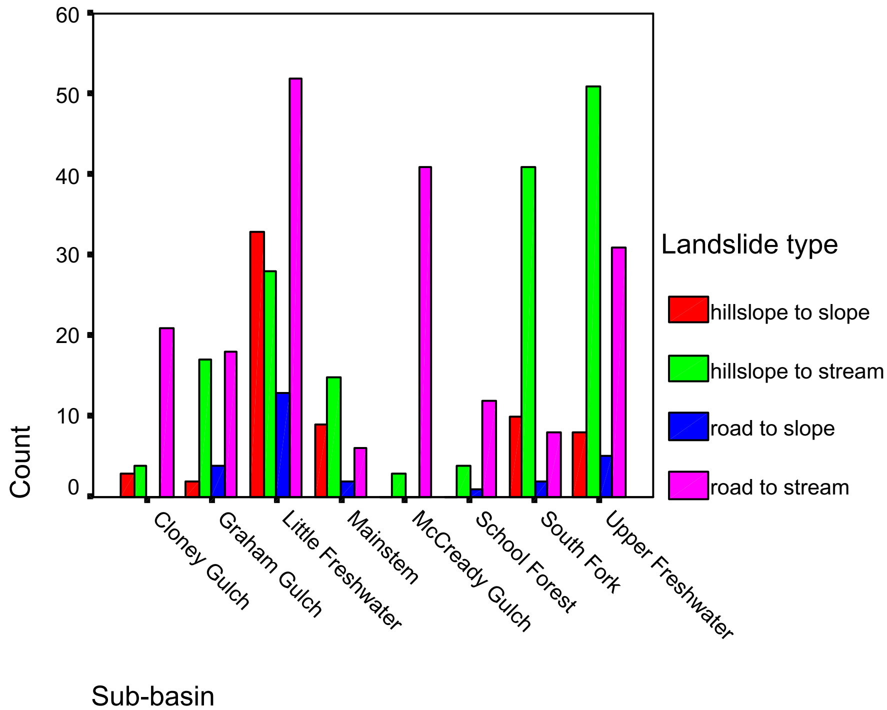

Figure 6-3: Landslide distribution by sub-basin 1942 – 1997.

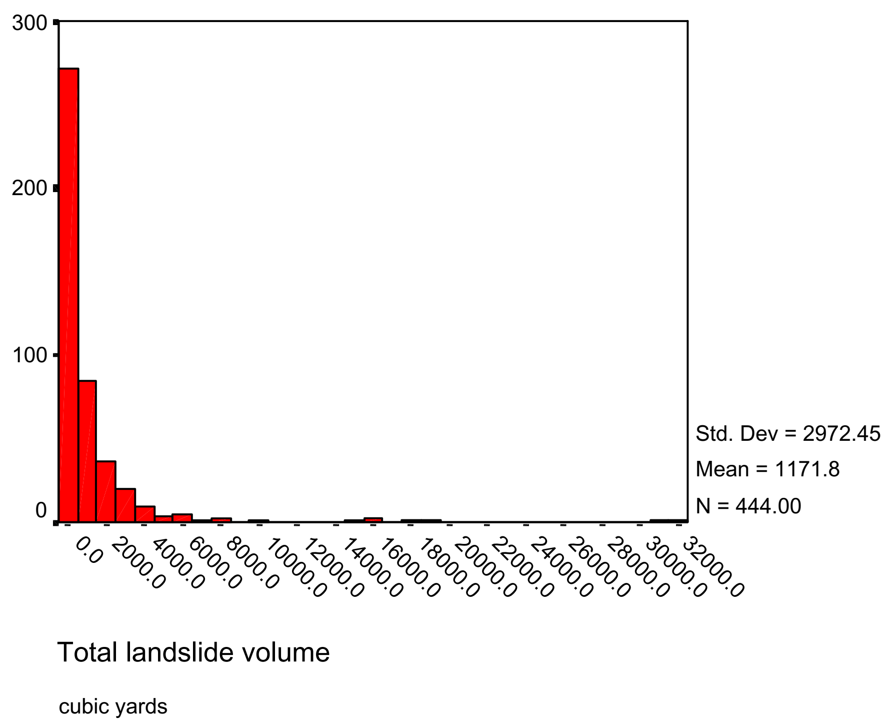

Figure 6-4: Landslide distribution by total volume.

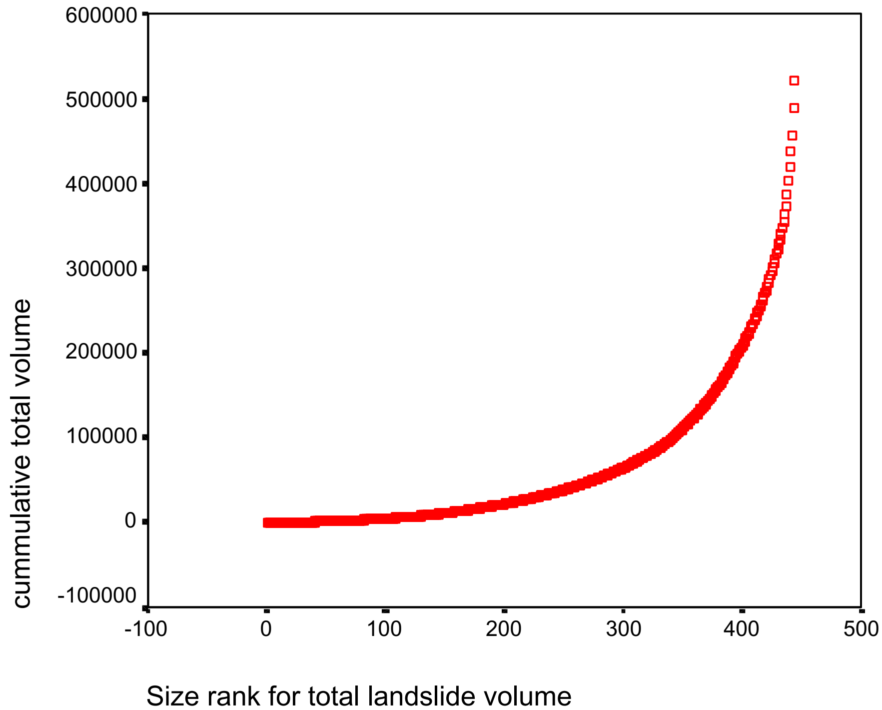

Figure 6-5: Landslide size rank versus total cumulative volume.

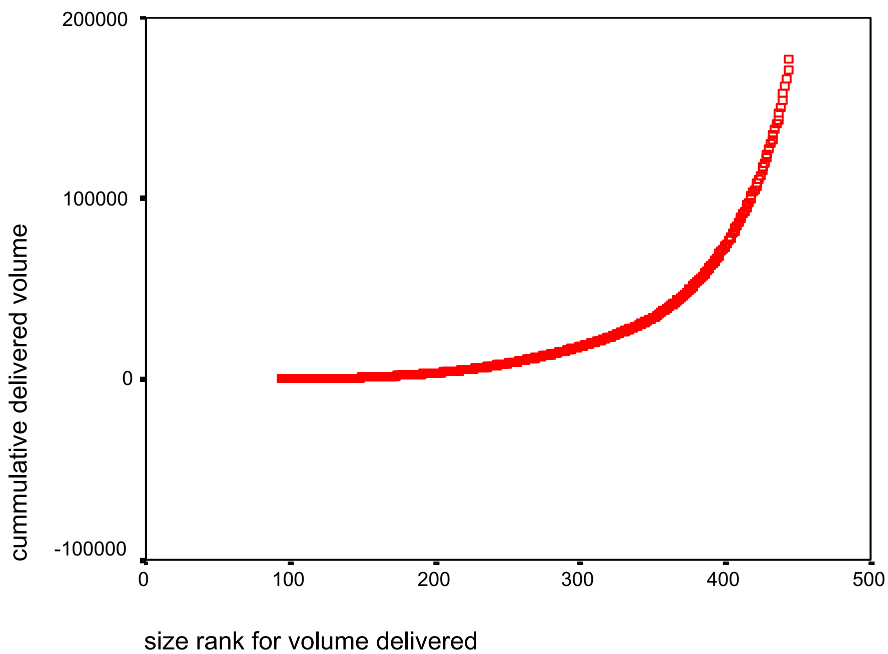

Figure 6-6: Landslide size rank versus cumulative volume delivered.

Landslides initiating at roads appear to be more common than landslides starting on hillslope areas at some distance from roads (58% versus 42%). When landslides larger than 300 yd^2 are compared, however, then road landslides are slightly less common than hillslope (non-road) landslides (44% versus 56%). This difference arises from the fact that whereas the identification of hillslope landslides relied primarily on aerial photograph interpretation, a number of very small landslides initiating in road fills were identified in the field during walking traverses along roads. Typically, a landslide must be 300 to 500 yd^2 or larger to be clearly visible on an aerial photograph in recently logged areas and 2,000 yd^2 or larger to be visible in well-forested areas. Landslide size distributions are presented in Figures 6-4 to 6-6.

Landslide activity in the Freshwater basin is not uniformly distributed over time (Figures 6-1 and 6-2). There was a large peak of landslide activity in the aerial photograph period ending 1954 (most of these events occurred sometime between 1948 and 1954), and again in the 1988 to 1997 aerial photograph period (most of these occurred sometime between 1994 and 1997). Visual comparison of landslide distributions over the period of record with existing rainfall records (see rainfall plots in the Hydrologic Change Assessment, Appendix C) shows some correspondence with major rainstorm events. The most recent period of increased landslide activity likely corresponds to a period with large and very large storms. Some of the non-uniform distribution of landslide activity could be due to a varying history of road building and harvesting over the period of record.

6.4 DEEP-SEATED LANDSLIDES METHODS

During interpretation of stereoscopic aerial photographs, heavy forest cover can conceal the presence of deep-seated landslides, or can make recognition of the spatial extent of landslides difficult to determine with any degree of certainty. Because of the constraints that forest cover places on aerial photograph identification of large deep-seated landslides, the best aerial photographs to use are photographs taken shortly after an area has been harvested. With this in mind, two years of coverage were utilized, 1948 and 1997, to map large, deep-seated landslides in the Freshwater watershed. The 1948 coverage was used in the eastern area of the watershed because that year of coverage followed a period of extensive clearcutting in the eastern portion of the watershed and coincidentally was readily available in PALCO's aerial photograph archive. The lack of tree cover provided an excellent view of the landscape. This resulted in a high degree of confidence in interpretation and mapping of the spatial extent of the landslides recognized. The 1997 aerial photographs were used to map deep-seated landslides in the western part of the watershed. This coverage was used because it was taken a few years after harvesting began again in that portion of the watershed. Although clearcut areas were less extensive on the

1997 aerial photographs, the smaller harvest units and various silivicultural systems utilized exposed sufficient ground surface that large deep-seated landslides could be recognized and their extent interpreted and mapped with a high degree of confidence.

During the review and interpretation of aerial photographs, topographic and geomorphic features indicative of deep-seated landslides were identified and plotted on a 1:18,000 scale topographic base map. These features included the head of the landslide, lateral margins, and the toe of the landslide. The crown of the landslide was also mapped. Mapping of the crown along with the head of the landslide delineated the headscarp of the landslide. A list of topographic and geomorphic features suggesting or indicative of deep-seated landslide processes is included in the mass wasting module methodology (PALCO 2000). Each landslide was numbered, and the photo-pair it was observed on recorded. Landslides were classified as to type using the nomenclature of Crudden and Varnes (1996). The certainty of identification was also noted as either definite, probable, or questionable. An estimate of the current relative stability (or activity level) was also assigned to each landslide. The range of options included active, dormant historic (currently inactive but could be reactivated), dormant mature (relict/essentially stable), and relict. Finally, the potential for reactivation of the entire landslide mass was visually estimated from aerial photographs and maps. Consideration was given to attempt to evaluate the potential for reactivation of a portion of any given deep-seated landslide deposit; however this was considered impractical. In order to accomplish this the landslide deposit would need to be "microzoned". The scale and accuracy of the base map would preclude truly meaningful zonation on a regional scale. In addition, without a tightly defined use, hazards and risk at a microzoned scale can not be meaningfully assessed.

Approximately four days were spent in the field reviewing the deep-seated landslide mapping and associated hazards. This tally does not include several additional days of field review and reconnaissance of deep-seated landslides for timber harvest plans, also carried out in the Freshwater watershed. There were no deviations from the Mass Wasting methods that would result in significant implications for the interpretation of the aerial photographs with respect to the type and distribution of large deep-seated landslides in the watershed.

It is important to note that the locations shown for the deep-seated landslides mapped for this study are approximate. The locations are as accurate as can be expected using aerial photograph interpretation and manual transfer to the base map. This is especially true in areas of inexact topography on the base map. It is expected that ground reconnaissance for individual timber harvest plans will, at times, refine the locations of some of the deep-seated landslides mapped for this study.

A qualitative hazard rating was assigned to each deep-seated landslide. These hazard ratings varied from a very low to a very high potential for reactivation or acceleration of movement. Criteria for each hazard class are provided in Table 6-1. In addition to the criteria presented in Table 6-1, the interpretation for potential for reactivation or acceleration of movement assumes that future forest management practices will be less intrusive than the forest practices that occurred in the past in this watershed. It is our judgment that the small clearcut and partial cutting practices currently being applied in the area will have a very low potential to reactivate the entire mass of relict deep-seated landslides. Inactive (dormant-historic) deep-seated landslides are judged to have a low to moderate potential for reactivation. Inactive earthflows are judged to have a moderate potential for reactivation. Active landslides have either a high or very high rating for continuing to move or accelerate. The rating system takes into account the history of clearcut harvesting and the effect harvesting had on the reactivation of deep-seated landslides in the watershed. Our review of aerial photographs and field reconnaissance shows that historically, large portions of the watershed were clearcut including entire deep-seated landslides and adjoining areas. These deep-seated slides were subjected to intense management, far beyond the levels of activity permitted under current rules. Yet, there is very little, if any, evidence that past management activities had a significant, or even a minor, influence on the overall stability or reactivation of the entire mass of the overwhelming majority of landslides in the watershed – this in spite of great earthquakes, such as the 1906 San Francisco event and the more recent Honeydew and Petrolia events, and several intense and prolonged rainstorms that have occurred in the watershed over the last several decades.

Table 6-1: Landslide hazard ratings for earthflows and large deep-seated landslides.

Landslide Hazard Rating	Criteria for qualitative landslide hazard classes based on activity level
Very Low (VL)	Relict earthflows and relict large deep-seated landslides.
Low (L)	Dormant-mature deep-seated landslides and dormant-mature earthflows.
Low-Mod (LM)	Dormant-historic (inactive) deep-seated landslides.
Moderate (M)	Dormant-historic (inactive) earthflows.
High (H)	Active deep-seated landslides. Active earthflows.
Very High (VH)	Steep toes of active deep-seated landslides or active earthflows along stream edges or stream escarpments.
N/A	Earthflows or deep-seated landslides in grassland areas. No forestry practices will be applied in these areas.

The qualitative hazard classes outlined in Table 6-1 relate to the potential for forest practices (harvesting or road building) to reactivate or increase the rate of movement of earthflows and large, deep-seated landslides. The hazard interpretations are conservative and are based on observations of little or no apparent influence of past clearcutting and road building practices on these features. These ratings likely overestimate the hazard associated with smaller clearcuts and partial cutting activities. Any areas where foresters or others encounter field evidence of recent slope movement (instability) not identified on the large landslide hazard map should be considered high hazard areas. On-site geologic investigations of higher hazard areas would be appropriate where proposals for logging or road building overlap these features or could be affected by such features.These interpretations do not address the potential for shallow landslides on these features. There may be shallow landslide activity associated with active earthflows and active deep-seated landslides especially in the steep terminal zones of active deep-seated landslides. In general, shallow landslide hazard is dealt with by the shallow landslide hazard maps.

6.5 VARIANCE TO MASS WASTING METHODOLOGY

Our deep-seated landslide inventory methodology varied from the mass wasting assessment methods (PALCO, 2000) in several respects. We used only two sets of aerial photographs, rather than several sets. As discussed earlier, these photo sets were chosen because they were taken shortly after harvest activities and, therefore, afforded the best opportunity to see the morphology of the land surface without the concealing effects of tree cover. Deep-seated landslides are not ephemeral features in the landscape; their identifying characteristics persist over decades and centuries; therefore, review of sequential aerial photos is not necessary. Sediment delivery to streams was not estimated because deep-seated landslides, unless active, are not delivering sediment. In the case of deep-seated landslides, harvest activities in almost all cases have no bearing on the origin of the landslide because the landslide occurred long before the first timber harvesting occurred in the area.

The terminology for landslide activity levels of Keaton and DeGraff (1996) was used in this report in preference to the terminology outlined in the Mass Wasting methodology. The terminology of Keaton and DeGraff has recently been adopted for use with deep-seated landslides on the PALCO ownership and is generally more descriptive than the terminology outlined in the mass wasting module methodology. In this case, the term inactive as used in the mass wasting module methodology is comparable to the term dormant-historic of Keaton and DeGraff. Similarly, the terms relict and dormant-mature of Keaton and DeGraff are comparable to the term relict as used in the mass wasting module methodology.

6.6 DEEP-SEATED LANDSLIDE INVENTORY RESULTS AND DISCUSSION

The following sections outline the findings of the deep-seated landslide inventory and the interpretations of that inventory.

6.6.1 Type and Size

Deep-seated landslides are common in the Freshwater watershed; 241 definite, probable, or questionable deep-seated landslides were identified or recognized, some of which were confirmed during a limited field reconnaissance. These are shown on Map A-5. They are quite variable in type, size, and activity level. The variability appears to be related, in part, to the underlying bedrock type, distribution, and structure.

Deep-seated landslides are represented by two general types: rockslides and earthflows (Nomenclature from Cruden and Varnes [1996]). Rockslides are landslides with a failure surface that passes into and then through the bedrock that underlies the overlying veneer of residual soils and colluvial deposits. Movement occurs along the failure surface or relatively thin failure zone. As movement occurs, the landslide mass remains more or less intact. Earthflows are characterized by a distinct basal failure surface, but within the landslide mass there are also ephemeral and discontinuous failure surfaces. Movement along these internal failure surfaces results in dismemberment of the slide mass. As earthflows move, the landslide mass becomes a mixed mass of rock and earth debris that "flows" like a very viscous fluid. Composite landslides are landslides that display geomorphic features characteristic of two types of landslides. A common example would be a rotational/translational landslide that, as the landslide continues to move down slope, becomes an earthflow.

Deep-seated landslides in the watershed range in size from about 100 to 7,500 feet wide and 150 to 11,000 feet long. Like length and width, thickness is quite variable. At a minimum, deep-seated landslides are by definition, for this report, at least 10 feet thick. Maximum thickness is difficult to estimate, but larger landslides can be tens to hundreds of feet thick

The activity level of most of the deep-seated landslides in the Freshwater watershed is best characterized as dormant-historic (after Keaton and DeGraff 1996). That is, they currently demonstrate no evidence of active movement and may have been relatively stable for an extended period of time. These landslides could be reactivated under current environmental conditions or by poorly planned management practices.

Dormant-mature deep-seated landslides are judged relatively stable and not likely to be reactivated unless there is a major change in current environmental conditions (e.g., extreme rainfall conditions for years). These dormant-mature landslides are found in the watershed but are rare. Probably the best example is the very large landslide located in the northern portion of the watershed on the east side of Cloney Gulch. Although an entire landslide mass can be judged dormant-mature, it is possible for local portions of the landslide mass, particularly areas of steep slopes and locations near streams, to be reactivated while the remaining landslide mass remains stable.

Active deep-seated landslides currently demonstrate active movement or instability. They are also rare in the Freshwater watershed. There are three known active deep-seated landslides in the Freshwater watershed: one is an earthflow in Graham Gulch; the second is located in the upper mainstem of Freshwater Creek (PWA 1999); and the third, a small, probable deep-seated landslide was observed affecting the main haul road in the southern area of the watershed near a recently stabilized landslide. This recently stabilized landslide is located in the southern area of the watershed, near the upper reaches of South Fork Freshwater Creek. Placement of the fill, waste material from a nearby quarry, may have initiated movement in the landslide. It was stabilized by removal of the fill.

In conclusion, it appears that the majority of deep-seated landslides in the watershed are relatively stable. Because of a lack of topographic or geomorphic evidence that would allow the majority of the non-active landslides to be classified as dormant-mature they are classified as dormant-historic. This suggests that they may be sensitive to management practices. In fact based on the history of past management and other environmental events (earthquakes and storms) the deep-seated landslides classified as dormant-historic have shown little proclivity for reactivation. The watershed has been subjected to intense management, very wet winters, and strong ground shaking, yet there is little evidence that any of these factors, separately or collectively, have had more than a very minor effect with respect to reactivating the existing deep-seated landslides. Thus they appear to be relatively stable. The steep-slope areas of some deep-seated landslides can be a location for renewed movement of deep-seated landslide activity. However, in spite of past management activities (and sometimes intense management activities) obvious or dramatic evidence for reactivation of deep-seated landslides in these steep-slope areas is rare. This suggests that management activities (especially as conducted today) are not likely an important factor in the development of deep-seated landslide activity and resulting associated sediment delivery.

6.6.2 Relationship of Large Deep-Seated Landslides to Bedrock Geology

Bedrock geology exerts a strong influence on the distribution of the size and type of landslides found in the watershed. As previously discussed the western half of the watershed is underlain by relatively moderately consolidated, fine-grained rocks of the Wildcat Group. In contrast, the eastern half is characterized by slivers of relatively coherent interbedded sandstone and shale of the Franciscan sediments intercalated with a large area of relatively weak Franciscan melange terrane. This distribution of strongly contrasting bedrock materials exerts a powerful influence on the distribution of the size and type of landslides found in the watershed. In the western area underlain by the Wildcat Group, deep-seated landslides tend to be relatively small and of the rockslide type, either translational or rotational style failures. Earthflows are extremely rare. In contrast, in the eastern portion of the watershed where melange terrane is prevalent, large earthflows are the dominant type of deep-seated landslide. The largest deep-seated slides are located in this area of the watershed, as are the known active deep-seated landslides.

Large masses of material move slowly within the mélange. Under "natural conditions," landslide processes are likely regulated by heavy rainfall and tectonic uplift. In years of heavy rainfall, groundwater storage plays a significant role by decreasing the overall hillslope stability.

6.6.3 Sediment Delivery from Deep-Seated Landslides – Background Discussion

Sediment delivery to watercourses from deep-seated landslides can occur by several processes. These can include sheet wash and erosion or shallow- or deep-seated movement of the entire deep-seated landslide deposit.

The ground surface of a deep-seated landslide deposit, like any other hillside surface, is subject to erosional processes such as raindrop impact, sheet wash (overland flow), gully/rill erosion, and stream erosion. Under these conditions, sediment entrainment and transport are likely the same as on adjacent hillsides not underlain by landslide deposits. However, the earth materials within the landslide are disturbed and are therefore weaker than undisturbed materials. Yet once a soil has developed, the fact that the slope in question is underlain or not underlain by a deep-seated landslide would make little difference to sediment generation by erosion processes that act at the soil surface. Of course, fresh unprotected surfaces that develop in response to recent or active movement could become a source of sediment until the bare surfaces are covered with leaf litter and/or become vegetated.

Movement of a portion or all of a deep-seated landslide can result in delivery of sediment to a watercourse. However, movement would need to be on slopes immediately adjacent to or in proximity to a watercourse, and of sufficient magnitude to result in enough displacement of the toe of the landslide or portion thereof for delivery to occur. A deep-seated landslide that toes out on a slope far from a stream or moves only a short distance downslope will generally deliver little or no sediment to a watercourse. Also, movement would need to be of sufficient magnitude to actually push the toe of the landslide into the watercourse or result in oversteepening of the toe, sufficient to make it unstable enough to initiate failure of the toe and so deliver sediment to the stream.

Generally, ground cracking at the head of a large, deep-seated landslide does not equate to immediate sediment delivery at the toe of the landslide. Past movement of large deep-seated landslides creates some void spaces within the landslide mass. Though movement can be clearly indicated by the ground cracks, many times the toe may not respond or show indications of movement until some of the void space within the landslide is “closed up.” This would be particularly true in the case of very large, deep-seated landslides that exhibit ground cracks that are only a few inches to a few feet wide. Compared to the entire length of the landslide, the amount of movement implied by the ground crack could be very small. This, combined with the closing up or “bulking up” of the landslide, would not generate much, if any, movement at the toe of the landslide. Significant movement represented by large, wide ground cracks would generally need to occur for sediment delivery to occur at the toe of the landslide.

A large, active landslide over time could and can deliver large volumes of sediment. Delivery generally occurs in a conveyer-belt like process with movement delivering earth materials to the creek bank and/or into the creek. These materials are then removed by fluvial processes, increasing sediment in the channel. Actual delivery can occur by oversteepening of the toe of the landslide and subsequent failure into the creek or by the landslide pushing out into the creek, followed by erosion of the toe of the landslide. Sediment delivery could also occur in a catastrophic manner. In such a situation, large portions of the landslide essentially fail and move into the watercourse “instantaneously.” These types of deep-seated failures are relatively rare and usually occur in response to unusual storms or seismic ground shaking. However, it appears that a large landslide in Graham Gulch did fail in just such a manner (pers. comm., Danny Hagan 2000) in the late 1940s or early 1950s. This landslide is a very significant source of sediment that affects both Graham Gulch and downstream segments of Freshwater Creek.

It is very important not to confuse normal streambank erosion at the toe of a large landslide with actual movement of the landslide. That is, toe erosion by streams should not be assumed to indicate that a deep-seated landslide is active. Before making such a connection, the landslide surface should be carefully explored for evidence of significant movement, such as wide ground cracks or displaced roads. It is also important to realize that in many instances only a portion of a deep-seated landslide will be reactivated if reactivation occurs. Thus, although a landslide may be very large, reactivation does not necessarily mean that the entire landslide mass is actively moving.

Rates of movement of deep-seated landslides in the Northern California Coast Ranges are not well documented for rockslides. For earthflows, however, some rates have been published. Studies of earthflows and earthflow like failures by Kelsey (1978), Iverson and Major (1987), and Swanston et al. (1995) show that rates of movement can vary from about 0.5 to 13 feet per year. In addition, it has also been shown that rates of movement can be strongly influenced by the amount of yearly or individual storm rainfall amounts.

7.0 EMPIRICAL RELATIONSHIPS BETWEEN LANDFORMS, LAND USE, AND SHALLOW LANDSLIDES[3]

Four separate interpretations were made for landforms and shallow landslides in the mass wasting assessment. The first was the expected landslide density (i.e., landslide hazard) for each unique landform or combination of landforms present in the watershed. The second interpretation was the likelihood or potential for a landslide initiating in a particular category or group of landforms to reach a stream and introduce sediment and debris into the stream. The third task was to estimate background landslide rates for the basin. The fourth task was to make estimates of the amount of LWD that may be contributed to streams by landslides. This section of the analysis also produced four separate landslide hazard maps. Maps A-6 and A-7 are empirical landslide hazard maps for road and hillslope areas respectively (i.e., landslides per 100 feet of road and landslides per acre over the period 1940 to 1997). Maps A-8 and A-9 are empirical landslide delivery maps for road and hillslope areas respectively and use the same landslide frequency units as Maps A-6 and A-7. The approach used follows the methodology in the mass wasting module (PALCO 2000) and is summarized below.

As part of their program to update the geology map for the Freshwater watershed, the CGS (Falls 1999b) produced a separate qualitative landslide hazard map. That map, Open-File Report 99-10a - Plate 2 (Falls 1999b), is available from the CGS. A comparison of the PALCO and CGS hazard mapping approaches is presented in Attachment A-2.

7.1 METHODS

The landslide inventory map, the geologic unit map and the MLU map were intersected in the PALCO GIS to determine the frequency of landslides occurring on the various morphologic landform-geologic units (child polygons).

An evaluation of landslide hazard or estimated frequency (density) of future landslides is made by relating the occurrence or frequency of landslides (e.g., landslides/acre or landslides/100 ft for roads) to specific landforms and geologic features (terrain attributes). The landslides documented in the landform database and used for this analysis include those original[4] landslides with depletion zones that are greater than or equal to 100 square yards from the landslide inventory identified in the field or visible on the aerial photographs between 1940 and

[3] This analysis focuses on shallow, rapid, translational landslides.

[4] The term 'original' indicates the first occurrence of the landslide noted on aerial photographs or in the field.

1997. Landslides that showed repeated activity at the same location where only counted once; this constraint excluded 17 repeat events from the analysis. The 100 square yard constraint excluded 68 small landslides from the analysis[5]. The analysis of landslide frequency over time in Section 6.3 and the sediment budget estimates in Section 9.0 are for the period 1942 to 1997. For this portion of the analysis, however, we included recorded landslides for the period 1940 to 1997 to provide as much opportunity as possible to identify landforms with higher densities of landslides. The 100 square yard depletion zone constraint for minimum landslide size and the original landslide constraint were applied so that landslide density data and relationships can be compared among watersheds. These constraints will be used in all watersheds on Pacific Lumber timberlands.

Shallow landslide density values are based on planimetric landform polygon areas not slope area; this approach tends to slightly inflate shallow landslide density values on steep slopes relative to gentle and moderate slope gradients.

Simple exploratory data analyses (means plots, figures in this report, and tabular analyses) were used to identify preliminary relationships between morphologic landform categories, geologic units, slope angles, and landslides for hillslope areas and roads (i.e., landslides per acre or landslides per 100 ft of road). This simple, univariate analysis facilitates identification of relationships between individual terrain attributes (e.g., landform, slope angle, geology) and landslide frequency that might be obscured by multi-variate analyses.

A relatively new type of statistical analysis known as CHAID (Chi-squared Automatic Interaction Detector) was then used to group the data into a limited number of multi-factor categories with similar hillslope (post-harvest) or road landslide densities. CHAID is a non-parametric, multi-variate procedure known as segmentation modeling (Magidson J./SPSS 1993). This procedure uses chi-squared statistics to divide a sample population into two or more distinct groups based on the best predictors of a dependent variable. Segments defined by the analysis do not overlap. Both dependent and predictor variables can be treated as categorical (nominal or ordinal) or continuous variables. The procedure merges categories of a predictor variable that are not significantly different at each segmentation level. The analysis produces easy-to-read tree diagrams that identify predictor variables and present statistics for each separate group or cell of the dependent variable. These categories are used to generate landslide hazard classifications that document the mean densities of landslides occurring on hillslopes and along roads. CHAID was used for this purpose by Pack (1995) in a study of landslides related to

[5] These constraints were not applied to the shallow landslides included in the sediment budget analysis (see Section 9.0).

logging roads in the interior of British Columbia and by Rollerson et al. (1997) on Vancouver Island to explore relationships between terrain attributes and post-logging landslide activity. One advantage of CHAID over more traditional multi-variate statistical methods is that the geologist can manually intervene and prune branches of the tree that appear contrary to geologic or engineering logic. Illogical terminal nodes (cells) on some branches of a decision tree may occur because they contain only a limited number of samples and are therefore biased by anomalous values.

The sample element for this analysis is based on landform map polygons (or child polygons when landform polygons are intersected with other polygon-based maps, such as geology). Polygons have different sizes but can be considered geologic entities that should not be spilt in an arbitrary fashion. If each polygon is treated as a single sample, smaller polygons and larger polygons weigh equally in the analysis. To offset this factor all polygons (samples) are weighted by dividing each polygon area by a nominal minimum polygon area (e.g., 1000 ft^2) and then incrementing the number of records for each sample (polygon) by the quotient value to generate an appropriate number of pseudo-replicate samples.

One of the tasks of the mass wasting assessment is to estimate background or natural landslide rates. To do this, comparisons are made for the period of 1975-1997 for landslide frequencies, by landform type for areas subject to clearcut harvesting or thinning, or that are designated as uncut second-growth. Timber harvesting is assumed to produce shallow, non-road landslides. Some of these landslides, however, would have occurred even if the basin had not been logged. Since there are no unlogged areas in the watershed, it is impossible to provide an exact estimate of the natural rate for shallow landslides. To provide a background rate, landforms and landslides for the period 1975-1997 were partitioned into three categories: clearcut areas, areas of second-growth commercial thinning, and areas of uncut second-growth (these categories were derived from the forest cover layer in the PALCO GIS). Areas for different landform-forest cover combinations were generated by intersecting the forest cover, and landform layers in the GIS. We then tabulated the numbers of shallow landslides that appear to occur in each landform-forest cover combination and calculated landslide density values (landslides per acre) for each combination (Table 7-2). The second-growth landslide rates are the best estimate we can currently make for background landslide rates. Root strength, root distribution, and hydrologic conditions in older second-growth are likely approaching if not actually achieving natural background levels. Some of the shallow, non-road landslides may be related in part to road drainage, but there is no viable way to make this distinction on aerial photographs, and such relationships are often very difficult to clarify in the field. The 1975 to 1997 aerial photograph period was used because there were reasonably large areas of older (40 to

60-year-old) second-growth forest present in the watershed during this time, and the area was subject to both small and large rainstorms during this period. We should also note that even though the minimum landslide size constraint of a 100 square yard depletion zone was applied to this tabulation, it is quite possible that some small landslides that exceed this minimum size limit may not have been visible on aerial photographs of second growth areas or areas of commercial thinning. Consequently, the landslide densities reported for these areas may be somewhat lower than would be found with an intensive ground inventory.

The likelihood for delivery of sediment and/or LWD to streams by landslides is estimated for each landform type. The "landform sediment and LWD input potential" for different types of landforms can vary throughout a watershed depending on the proximity of a given map polygon to a stream. In this case, for each landform type, we estimated the average likelihood of landslides reaching streams by dividing the number of landslides (road and hillslope) that reach streams by the total number of landslides (i.e., landslides that deliver/total landslides = % landslides that deliver). We used CHAID to group landform types with a similar likelihood of delivery and to separate landform types with a different likelihood of delivery. To maintain a large data set, we grouped road and hillslope landslides together.

LWD input estimates for number of trees and volumes of LWD generally follow the conceptual approach outlined in the mass wasting module methodology. These estimates are based on expected riparian strip widths, tree counts and timber volumes derived from the Freshwater Detailed Riparian Plot Inventory data set. Also used are average widths and frequencies of shallow hillslope landslides that reached streams over the 1942 to 1955 period and cumulative stream lengths for Class 1, 2, and 3 streams. Scenarios and estimates for LWD input to streams related to future landslides are presented in Section 7.6.

7.2 VARIANCE TO MASS WASTING METHODOLOGY

The analysis carried out in this section follows the more quantitative of the two approaches outlined in the mass wasting module methodology for the development of landslide hazard maps.

There is currently no specific approach outlined in the methodology for estimating background landslide rates, but direction to do this is provided: "estimate background or natural landslide rates for each landform for the period of aerial photograph record" (PALCO 2000). We were not able to estimate background rates for the entire aerial photograph record, but rather for the last approximately 23 years of record (1975 to 1997). We believe the approach we used was appropriate for the data available at the time the analysis was carried out.

The approach for estimating the likelihood of delivery of landslides to streams varies from that outlined in the mass wasting module. The methodology suggests using or developing a runout model similar to those discussed by Benda and Cundy (1990), Fannin and Rollerson (1993), Kennard (1994), and Millard (1999). Because the landslide data set collected for the shallow landslide inventory does not include runout distance (accumulation zone) data, we were not able to take this approach. In addition, the Benda and Cundy model generally applies to channelized debris-flows (debris torrents), which are rare in the Freshwater watershed. The methodology goes on to state that until the utility of these types of models is evaluated for PALCO timberlands, the analyst can develop a qualitative set of criteria for estimating landslide runout and likelihood of entry of landslides into streams.

Most landslides in the Freshwater watershed travel relatively short distances (average depletion zone distance ≈100 ft), and most travel down relatively uniform, open slopes until they either reach streams, or stop on gently to moderately sloping (but often relatively narrow) toe slope areas above streams. Consequently, we felt that the probabilistic approach outlined in the methods section above was equally, if not more suitable, than either the runout model approach or the qualitative approach. It is certainly easier to apply when producing hazard maps that display or estimate the likely frequency of landslide delivery to streams.

The methodology for estimating future inputs of LWD from landslides to streams outlined in the methodology is a conceptual approach. The methodology states that the approach will be developed and refined over time. The approach used in the Freshwater analysis generally follows the conceptual ideas outlined in the mass wasting module. We vary from the proposed methodology in that estimates of LWD inputs from upslope areas are not included because they are expected to be minor and/or unpredictable.

7.3 HILLSLOPE LANDSLIDE RESULTS AND DISCUSSION

Comparison of mean hillslope landslide densities to general morphologic landforms shows that terrace, fan complexes, and headwall areas apparently experience no landslide activity. Inspection of the database shows some shallow landslides occurring on headwall areas but these are smaller than the minimum size used for this analysis. Complex and incised slopes tend to have moderate landslide densities. Convex and planar slopes have slightly higher landslide densities (Table 7-1, Figures 7-1).

Table 7-1a: Hillslope landslide density – landform attribute relationships (landslides per acre).

Variable	N	$N_{weighted}$	Mean (ls/ac)	Std. Deviation
landform				
Convex	722	350633	0.010	0.045
Incised	1592	257912	0.008	0.053
Headwall	124	2672	0.000	0.000
Planar	573	136416	0.011	0.058
Terrace/fan	147	39968	0.000	0.000
Complex	137	68218	0.009	0.023
landform-slope category				
Convex gentle	514	317303	0.008	0.032
Convex moderate	189	30518	0.021	0.077
Convex steep	19	2811	0.124	0.236
Incised moderate	1280	221474	0.006	0.038
Incised steep	312	36437	0.021	0.103
Headwall	124	2672	0.000	0.000
Planar gentle	277	94163	0.005	0.031
Planar moderate	225	33292	0.025	0.090
Planar steep	71	8961	0.029	0.099
Terrace/fan	147	39968	0.000	0.000
Complex gentle	128	64402	0.009	0.023
Complex moderate	9	3816	0.011	0.032
geologic unit				
Franciscan melange (KJfm)	616	291154	0.004	0.022
Franciscan sediments (KJfs)	366	74857	0.016	0.073
Recent alluvium (Q)	68	26630	0.000	0.000
Alluvial terrace deposits (Qrt)	117	24429	0.000	0.000
Lower Wildcat (Twl)	1578	384425	0.013	0.053
Upper Wildcat (Twu)	159	20025	0.004	0.043
Yager Formation (Ty)	323	26346	0.015	0.083
Unidentified lithology (u)	68	7955	0.011	0.083
slope class (degrees)				
0-10	123	33242	0.000	0.000
10-20	650	143635	0.005	0.025
20-25	748	265299	0.007	0.040
25-30	857	266061	0.009	0.039
30-35	507	93636	0.012	0.059
35-40	264	37278	0.023	0.085
40-45	95	10402	0.042	0.135
>45	50	6267	0.049	0.169

When these landforms are segregated on the basis of slope, landslide densities tend to increase as slope angle increases within a particular landform category (Table 7-1a, Figure 7-2). Similarly, when the data for all landforms are combined, there is an apparent strong relationship between DEM slope angle and landslide density, with landslide density increasing as DEM slope angle increases. This increase is most noticeable above 30 degrees (Table 7-1a, Figure 7-4).

Inspection of Table 7-1a shows that landslide densities tend to be lowest in areas underlain by unconsolidated Quaternary sediments (floodplain, fluvial terrace, and fan deposits). Intermediate landslide densities occur in the Franciscan melange and Upper Wildcat. The Franciscan sediments and Lower Wildcat, Yager and unidentified lithologies within the Franciscan melange exhibit moderate landslide activity (Table 7-1a, Figure 7-3).

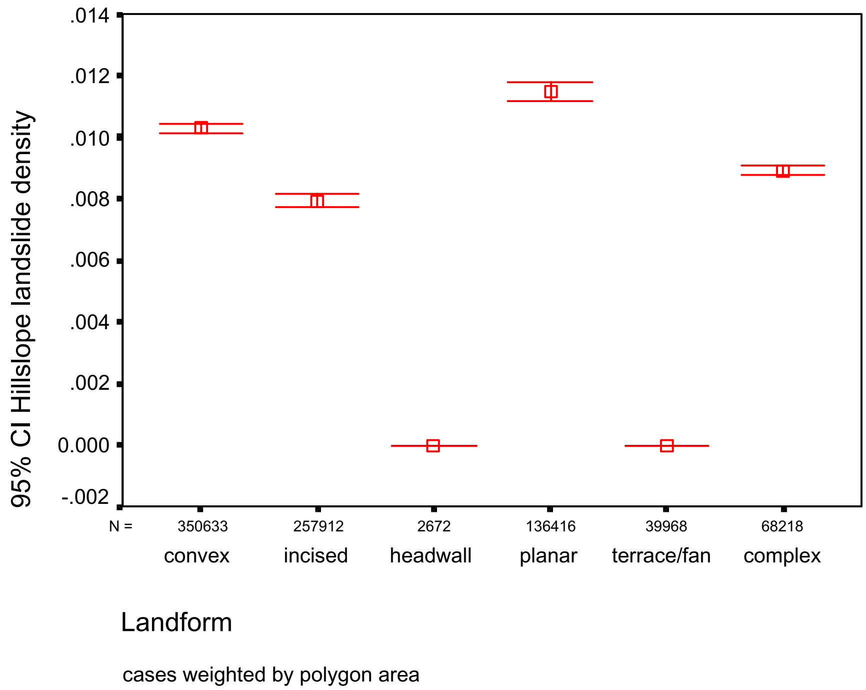

Figure 7-1: Hillslope landslide density by general landform.

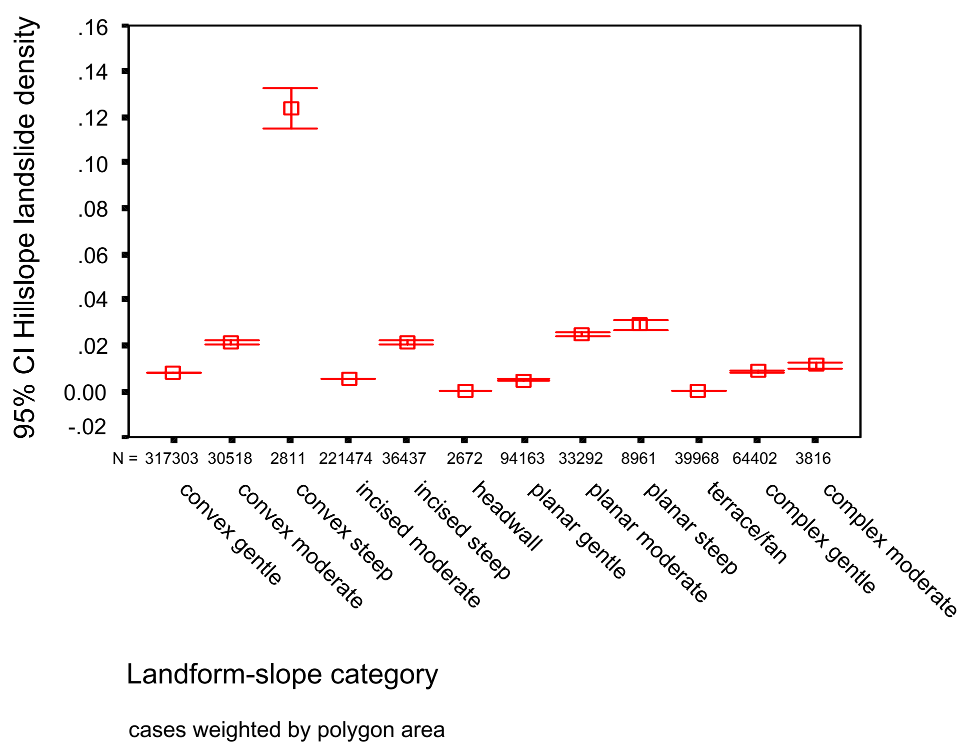

Figure 7-2: Hillslope landslide density by landform/slope category.

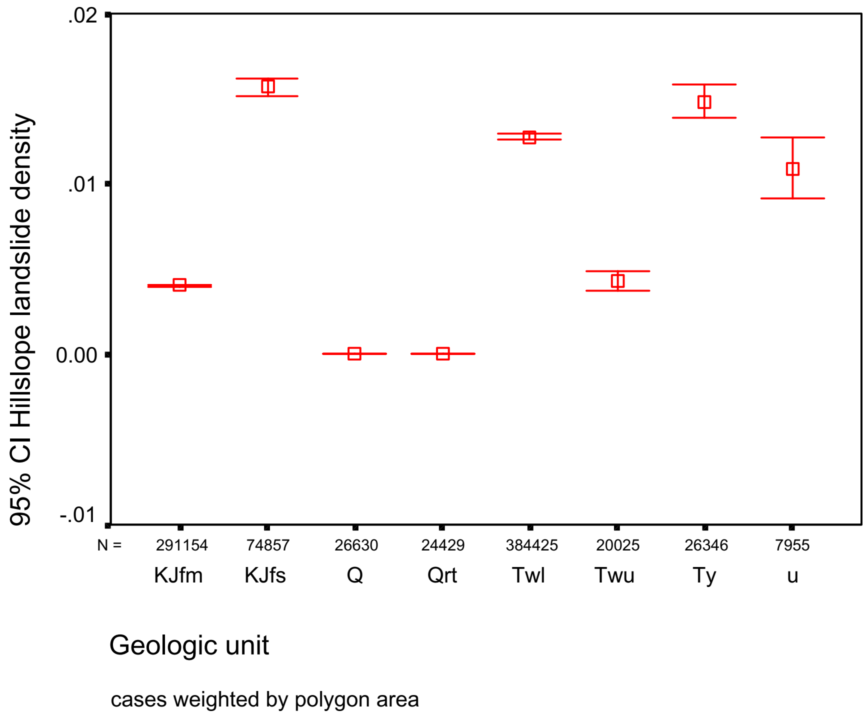

Figure 7-3: Hillslope landslide density versus geologic unit.

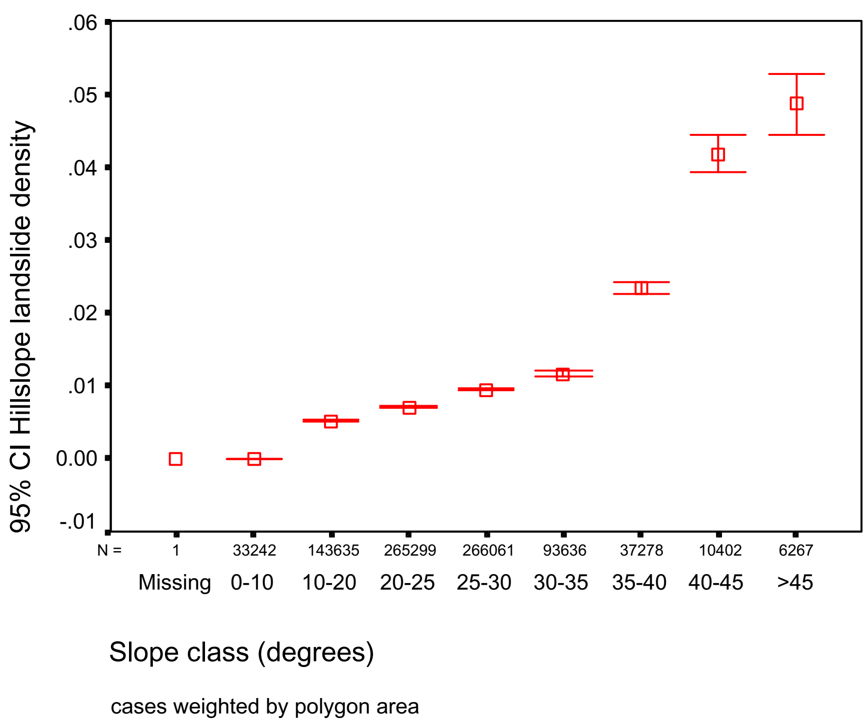

Figure 7-4: Hillslope landslide density versus slope class (degrees).

The variances (standard deviations) listed in Table 7-1a for various terrain attribute categories are quite high, but they are not unexpected for landform-landslide density data where the majority of landform polygons have no landslides and a lessor number of polygons have one or more landslides.

Initial analysis of the landform polygon based DEM slope, geologic unit and landslide density data using CHAID (Figure 7-5) resulted in a separation of polygon groups based on geology and DEM slope class. This analysis selected various combinations of geologic units as the best predictor followed by various combinations of slope classes. In some cases slope classes were further subdivided on the basis of mean slope angle but this did not improve the overall classification tree.

When the morphologic landform categories were included in the analysis CHAID selected landform as the most useful predictor variable, followed by slope and geology in varying combinations. However, because of the CGS's reluctance to accept the morphologic landform mapping approach, PALCO decided not to use the results of the second analysis to develop a landslide hazard map. Instead, the results of the first CHAID analysis which used only DEM slope and geology were used to produce a landslide hazard map. This map (Map A-7) indicates the expected densities for shallow hillslope landslides (landslides per acre) for the different slope-geologic unit associations identified by the analysis. The shallow hillslope landslide hazard classes derived from the CHAID analysis and used to generate the shallow hillslope landslide hazard map are summarized below in Table 7-1b

Table 7-1b: Shallow hillslope landslide hazard classes and characteristics summary.

Hazard Class	Characteristics from CHAID tree (landforms excluded from the analysis)
Very low <0.002 ls/ac	• Qrt and Q for all DEM slope angles • Twu and KJfm with DEM slope angles less than 25°
Low 0.002-0.01 ls/ac	• Twu and KJfm with DEM slope angles from 25° to 30° • Twl and u with DEM slope angles less than 35° • Ty and KJfs with DEM slope angles less than 35°
Moderate 0.01-0.05 ls/ac	• Twu and KJfm with DEM slope angles greater than 30° • Twl and u with DEM slope angles greater than 35° • Ty and KJfs with DEM slope angles greater than 35°
Very high	• Mapped shallow hillslope landslide locations (not part of CHAID analysis)

To estimate approximate background rates of landsliding in the Freshwater, we tabulated landslide occurrences on clearcut (non-merchantable), commercially thinned second-growth, and unthinned second-growth for the 23-year aerial photograph period between 1975 and 1997. Table 7-2 lists landslide occurrences and densities (landslides per acre for landslides with depletion zones greater than or equal to 100 square yards) for shallow hillslope landslides recorded for the 1975 to 1997 period in the Freshwater watershed for generalized landform types and forest cover believed to have been present during this time period. Headwall areas may be underrepresented in the landform database, so the landslide densities tabulated for headwall areas may be high. When viewing Table 7-2, interpret the term "planar slopes" to mean all slopes that are not incised or headwall landforms (i.e., convex, complex, and planar slopes).

Preliminary analysis of the data for the Freshwater watershed suggests that landslide activity on steeper (i.e., >30°) DEM slopes was higher in areas subject to clearcut harvesting than where commercial thinning or no harvesting was conducted during the same time period (Table 7-2). Irrespective of harvest history or harvesting technique, landslide rates appear lower on moderately to gently sloping landforms. The thinned and unthinned second growth stands range in age from about 30 to 60 years.

The results displayed in Table 7-2 should be interpreted with caution. The forest cover layer in the PALCO GIS database represents a snapshot in time, it has not been updated for about 10 years, and the areas in each forest cover category change with time. The areas for partial cutting present on the forest cover layer in the PALCO GIS (Table 7-2) are comparable to those shown in Table 3-8 of the surface erosion appendix of the Freshwater watershed analysis report for the period 1975 to 1997 (6717 acres versus 6737 acres). However, the area recorded as non-merchantable in the PALCO GIS does not compare well with the values for clearcut harvesting reported in Table 3-8 (4113 acres versus 2968 acres). If the acreage values recorded in Table 3-8 of the surface erosion appendix are used instead of those in the PALCO GIS, then the apparent landslide densities for the period of record are 0.008 landslides per acre for clearcut areas and 0.001 landslides per acre for partially cut areas. Irrespective of these discrepancies, this preliminary tabulation indicates that partial cutting results in landslide rates that are substantially lower than those that occur with clearcutting.

We have no data for natural forests so we cannot make any estimates of the difference between landslide rates after clearcutting and those in natural forest areas. We assume that rates in natural forests would vary among different landforms and would likely be similar to rates in uncut second-growth forests, but at present, we cannot substantiate those assumptions. The landslide frequency results for unthinned second-growth stands provide a preliminary estimate of background rates of landsliding in the Freshwater watershed. The intermediate landslide densities for unthinned second-growth tabulated in Table 7-2 may in part reflect a tendency of foresters to avoid harvesting in areas where there is residual evidence of earlier landslide activity. These results may also reflect the likelihood that at the beginning of the period of record a greater proportion of the watershed was occupied by unthinned second-growth stands than is indicated by Table 7-2.

Table 7-2: Landslides per acre for the 1975-97 aerial photograph period using the landforms as recorded at the landslide initiation point from aerial photograph interpretation.

Forest cover from the PALCO GIS	Generalized landform-slope categories from landform database	Total acres	Inferred forest cover from landslide database	Inferred landform from landslide database	Number of landslides	Landslides per acre
Non-merchantable			Clearcut 1-30 years			
(≤30 year old stands)	H	11		Headwall	13.0	1.18
	Im	865		Incised moderate	3.0	0.004
	Is	264		Incised steep	4.0	0.015
	Pg	2512		Planar gentle	0.0	0.000
	Pm	400		Planar moderate	1.0	0.003
	Ps	62		Planar steep	4.0	0.065
	Total	4113		Total	25.0	0.006
Second growth thinned			Second-growth thinned			
(≥30 year old stands)	H	27	(≥30 year old stands)	headwall	1.0	0.032
	Im	2033		Incised moderate	3.0	0.001
	Is	359		Incised steep	0.0	0.000
	Pg	3581		Planar gentle	0.0	0.000
	Pm	627		Planar moderate	2.0	0.003
	Ps	89		Planar steep	2.0	0.023
	Total	6717		Total	8.0	0.001
Second growth unthinned			Second-growth unthinned			
(≥30 year old stands)	H	9	(≥30 year old stands)	headwall	1.0	0.111
	Im	1197		Incised moderate	4.0	0.003
	Is	136		Incised steep	4.0	0.029
	Pg	2161		Planar gentle	0.0	0.000
	Pm	298		Planar moderate	1.0	0.003
	Ps	55		Planar steep	1.0	0.018
	Total	3857		Total	13.0	0.003

Note: The landslide inventory database uses slightly different landform descriptions than the landform mapping; consequently, the landforms-landslide combinations in this table do not necessarily correspond directly with those in table 7-1a. The landforms listed as inferred are an interpretation of what the landslide landform descriptions would be called under the MLU classification system. Landslides used in this tabulation have depletion zones greater than or equal to 100 square yards. The forest cover inferred for each landslide occurrence was interpreted from the air photo on which the landslide was identified. Forest cover information for landforms is derived from the forest cover layer in the PALCO GIS. The slope breaks between gentle and moderate slopes and moderate and steep slopes are 20° and 30° respectively. Second growth commercial thinning on PALCO lands usually results in ≥60% canopy retention (J. Adams, pers. comm. 2001).

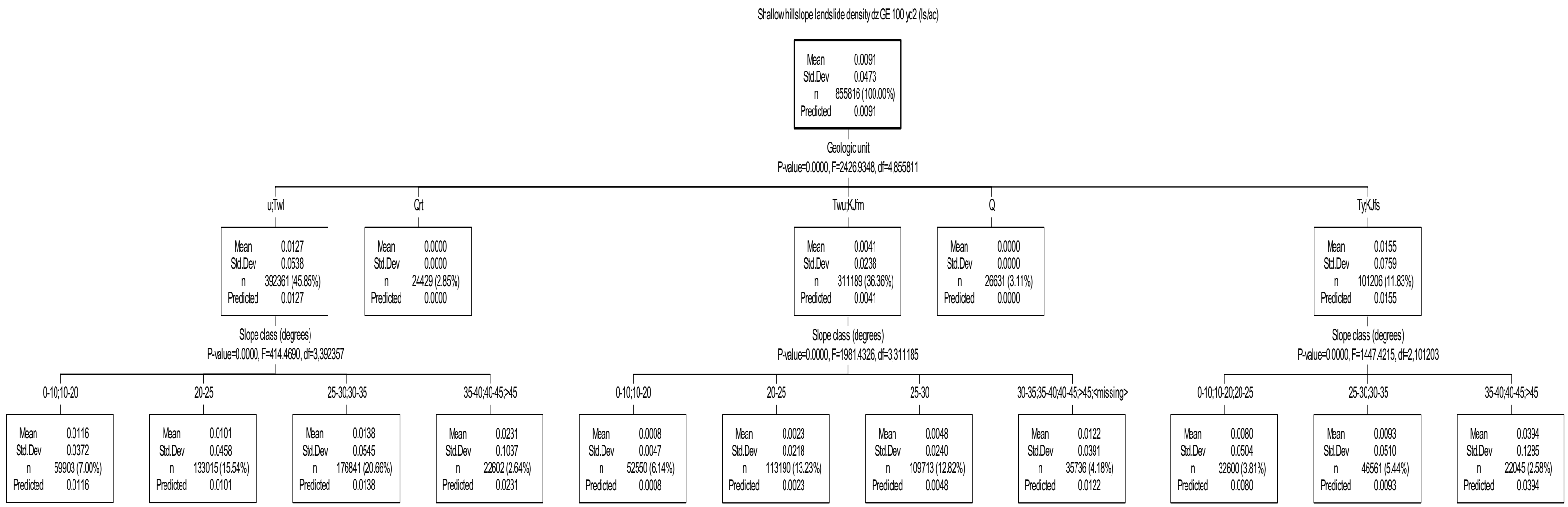

Figure 7-5: CHAID segmentation tree for hillslope landslides (landslides/acre).

7.4 ROAD LANDSLIDE RESULTS AND DISCUSSION

Comparison of mean road landslide densities (Table 7-3a, Figure 7-6) to the general morphologic landform categories shows that terrace and fan complexes experience no road landslide activity. Headwall landforms tend to experience the highest road landslide densities. Incised and planar slopes show intermediate road landslide densities. Convex and complex slopes are associated with slightly lower values than incised and planar slopes.

The segregation among road landslide densities is greater when the landform categories are combined with general slope categories (i.e., planar-gentle, planar-moderate, planar-steep) with a trend of increasing road landslide density for the steeper slope classes (Table 7-3a, Figures 7-6 and 7-7). When landforms are categorized in this manner, incised-steep units and moderate and steeply sloping planar slopes appear to have higher landslide densities than headwall slopes, however the range in headwall slope road landslide densities and small number of samples suggests that this difference is not significant. Similarly, the low road landslide density recorded for steeply sloping convex landforms is likely a function of small sample size.

Differences of road landslide densities among the various geologic units in the basin are very evident (Figure 7-8). Franciscan sediments and Lower Wildcat sediments have the highest road landslide frequencies followed by the Yager, Upper Wildcat and the Franciscan melange. There are no road landslides recorded for Quaternary sediments or for unidentified lithologies within the Franciscan melange (Figure 7-8). The road landslide densities associated with the Yager and the unidentified lithologies should be viewed with caution because of the very small number of road segments (samples) occurring in these geologic units. The low road landslide densities associated with some geologic units may in part be a function of the general association of these units with gentle to moderately sloping terrain.

Inspection of Figure 7-9 and Table 7-3a shows a general increase in road landslide density as slope angle increases with a substantial increase above a DEM slope angle of 30°. Above 40° there is a decrease in road landslide density. It is likely that this apparent decrease is a function of the small sample size in the steeper slope classes, however it could be a function of the use of different (more cautious) road construction techniques on steeper slopes.

As can be seen in Table 7-3a, the variance (standard deviation) for road landslide densities among the various terrain attribute categories is quite high. These variances are expected for this type of data and are similar to those found for the hillslope landslide–landform density comparisons.

Table 7-3a: Road landslide density – landform attribute relationships (landslides per 100 ft).

Variable	N	$N_{weighted}$	Mean (ls/100 ft)	Standard Deviation
Landform				
Convex	354	17128	0.012	0.046
Incised	629	7522	0.019	0.097
Headwall	26	113	0.030	0.204
Planar	266	5709	0.020	0.080
Terrace/fan	50	2194	0.000	0.000
Complex	86	5830	0.013	0.033
Landform/slope class				
Convex gentle	280	16003	0.011	0.035
Convex moderate	71	1042	0.032	0.125
Convex steep	3	83	0.000	0.000
Incised moderate	528	6635	0.016	0.086
Incised steep	101	886	0.049	0.153
Headwall	26	113	0.030	0.204
Planar gentle	153	3942	0.010	0.050
Planar moderate	97	1465	0.041	0.124
Planar steep	16	302	0.055	0.088
Terrace/fan	50	2194	0.000	0.000
Complex gentle	81	5425	0.012	0.033
Complex moderate	5	405	0.016	0.034
Geologic unit				
Franciscan melange (KJfm)	357	12190	0.005	0.029
Franciscan sediments (KJfs)	150	2986	0.016	0.063
Recent alluvium (Q)	32	1025	0.000	0.000
Alluvial terrace deposits (Qrt)	37	1482	0.000	0.000
Lower Wildcat (Twl)	731	18527	0.023	0.084
Upper Wildcat (Twu)	55	1643	0.004	0.009
Yager Formation (Ty)	30	378	0.009	0.014
Unidentified lithology (u)	19	265	0.000	0.000
DEM Slope class (degrees)				
0-10	38	1741	0.000	0.000
10-20	233	7853	0.011	0.045
20-25	364	12399	0.013	0.058
25-30	409	11236	0.012	0.056
30-35	248	3601	0.030	0.109
35-40	93	1302	0.036	0.098
40-45	18	225	0.030	0.151
>45	8	138	0.024	0.034

Segmentation of road landslide density into discrete groups using CHAID results in the use of geologic unit categories as the most significant predictor variable (Figure 7-10, Table 7-3b). Geologic unit combinations are further separated by slope classes derived from mean DEM polygon slope angles. Although not shown, further CHAID analysis, which included landform categories, resulted in a decision tree that used landform followed by slope class to subdivide geologic categories. This second analysis indicated that landform categories are useful in the segregation of landslide activity across the landscape; however, this analysis was not used due to the reluctance of the CGS to accept landform mapping as a tool for developing landslide hazard maps.

The results of the initial CHAID analysis (Figure 7-10) were used to produce a landslide hazard map (Map A-6) depicting the expected frequency of shallow road landslides (landslides per 100 ft of road) on different geologic unit and slope ranges. The shallow road landslide hazard classes derived from the CHAID analysis and used to generate the shallow road landslide hazard map are summarized in Table 7-3b below.

Table 7-3b: Shallow road landslide hazard classes and characteristics summary.

Hazard Class	Characteristics from CHAID tree (landforms excluded)
Very low <0.01 ls/100 ft	• KJfm, Twu, u and slopes <25° • Q or QRt
Low 0.01-0.02 ls/100ft	• KJfm, Twu, u and slopes >25° • Twl and slopes<30° • Ty and KJfs and slopes <27°
Moderate 0.02-0.05 ls/100ft	• Twl and slopes >30° • KJfs and Ty and slopes >27°
Very high	• Mapped shallow road landslide locations (not part of CHAID analysis)

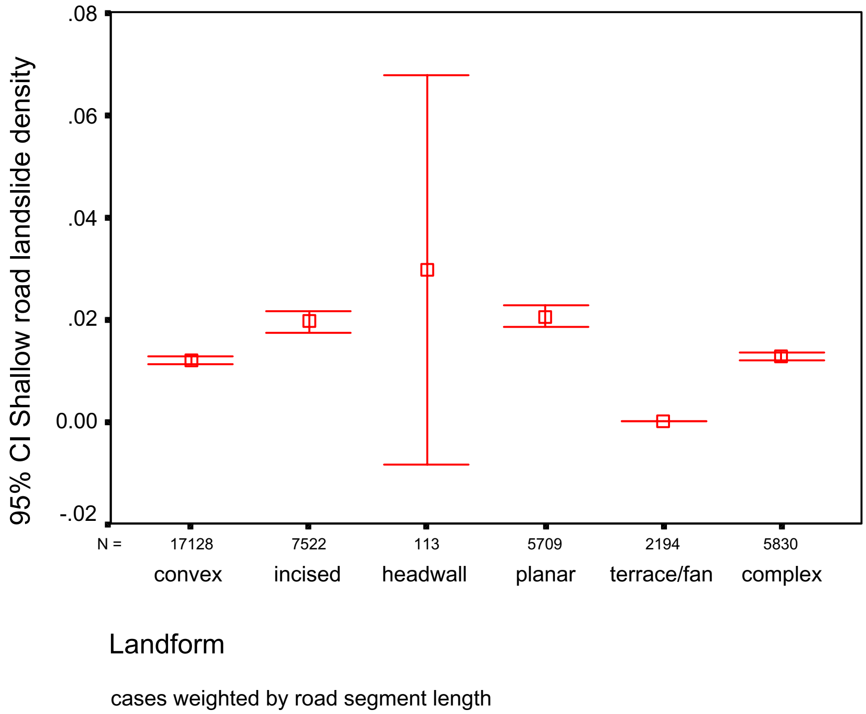

Figure 7-6: Road landslide density versus general landform category.

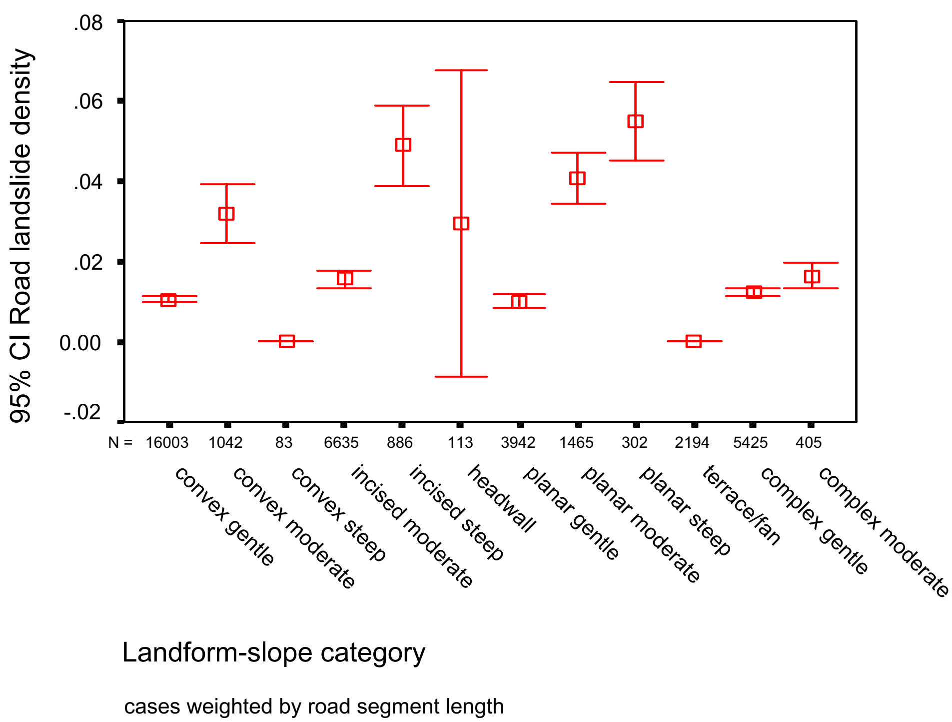

Figure 7-7: Road landslide density versus landform/slope category.

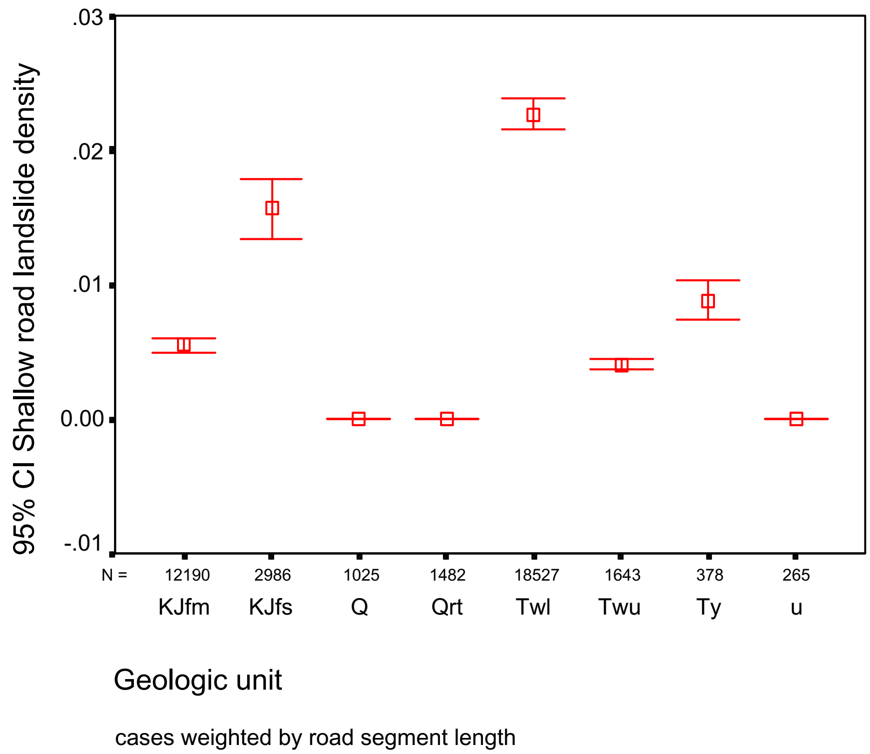

Figure 7-8: Road landslide density versus geologic unit.

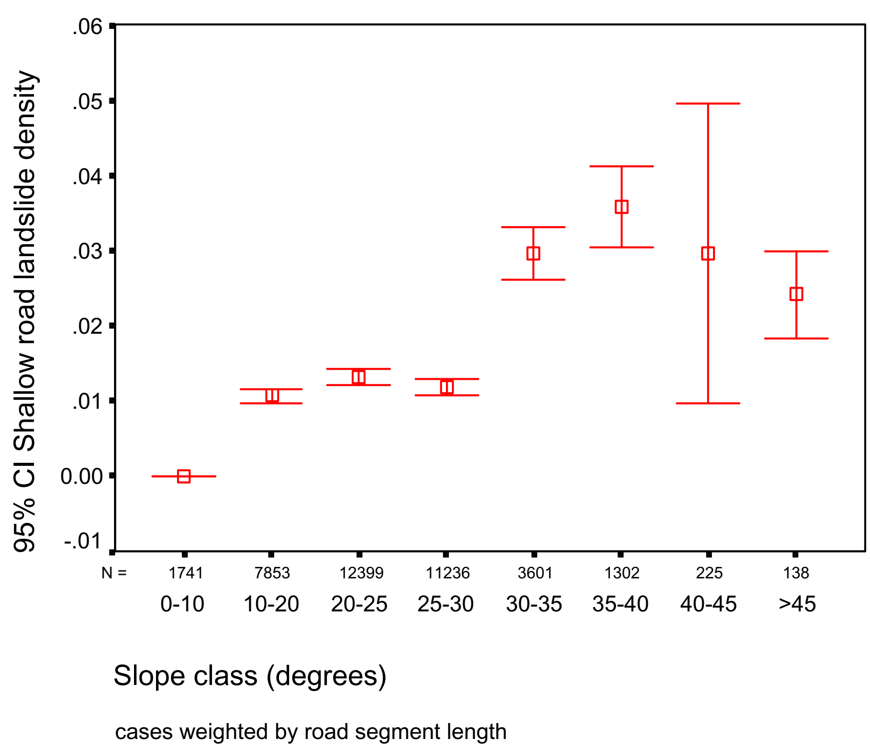

Figure 7-9: Road landslide density versus slope class (degrees).

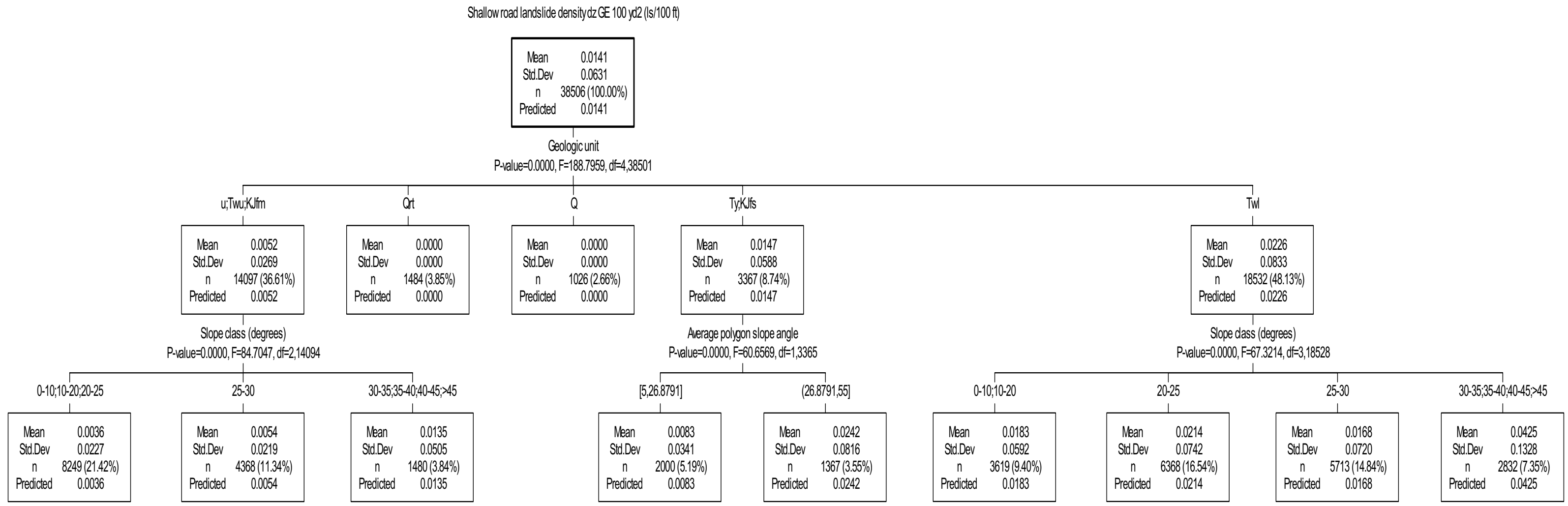

Figure 7-10: CHAID segmentation tree for road landslides with depletion zones GE 100 square yards (landsides/100 ft of road).

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7.5 POTENTIAL FOR LANDSLIDES[6] TO REACH STREAMS

The likelihood for delivery of sediment to streams by original landslides with depletion zones greater than or equal to 100 square yards (landslide runout potential) was estimated for each air photo interpreted landform category, topographic map interpreted landform category and for other geographic and morphologic attributes (e.g., slope angle and geologic unit). There are some significant differences for the likelihood of delivery among the various attributes. Analysis of the landslide data using CHAID (Figure 7-11) indicated that the air photo interpreted landform categories generated by PWA staff provided the best separation of landslides that deliver and do not deliver to streams. The highest delivery percentages or probabilities occurred with moderately steeply sloping incised units and with landslides initiating on the edges of stream channels (94%). Headwall areas were second highest with 76% of the landslides delivering to streams and planar slopes followed at 46%. When the air photo interpreted landform category was removed from the data set CHAID (Figures 7-12) then selected geologic units as the best predictor and separated these categories into two classes. The Franciscan, Yager and Upper Wildcat geologic units were grouped into one category with a 95% likelihood that landslides initiating in these areas would reach streams. The analysis showed a 76% likelihood that landslides initiating in areas of Lower Wildcat would reach streams. There was no delivery of landslide debris to streams from floodplain, terrace, and fan landforms as no landslides initiated on these landforms. The analysis showed no significant relationship among other morphologic landform units or slope angle and the potential for landslides to reach streams.

The different results between the air photo and map based morphologic landform categories likely occur for two reasons. One, differences in landform designations will have occurred between geologists because the map and air photo interpretations were made independently. Secondly, the relationship between landform and landslides is more apparent and likely more accurately identified on aerial photographs as landform boundaries are typically more distinct on aerial photographs than topographic maps. Maps A-8 and A-9, the empirical landslide delivery maps for shallow road and hillslope landslides, utilize the geologic delivery relationships displayed in Figure 7-12 as the air photo landform interpretations are not delineated on a map.

[6] This discussion refers to shallow rapid translational landslides (i.e., debris-slides, debris-flows).

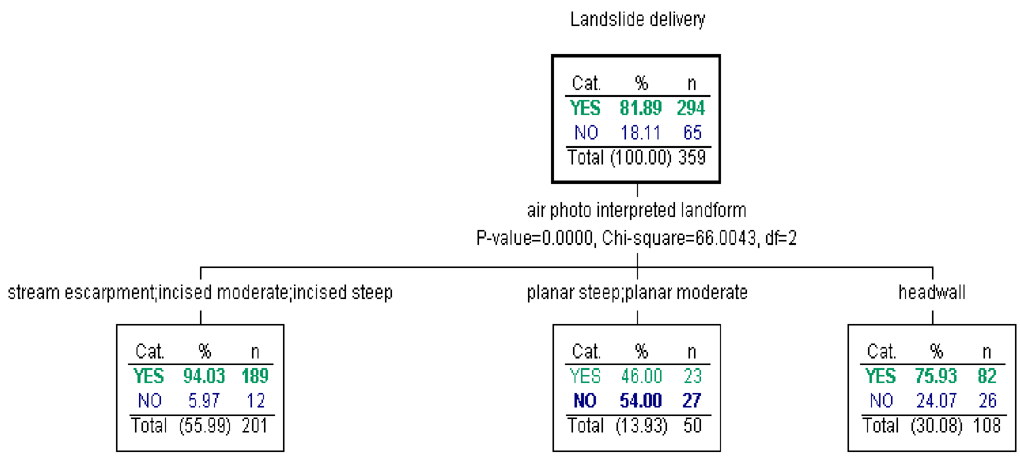

Figure 7-11: Percentage of landslides reaching streams from air photo interpreted landforms.

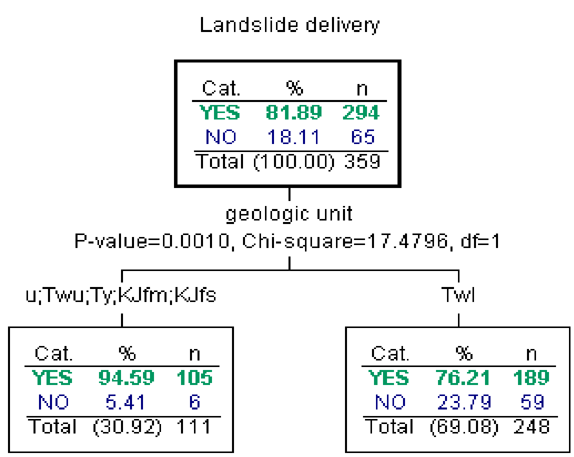

Figure 7-12: Percentage of landslides reaching streams from different geologic units.

This analysis is based on the 359 original landslides in the Freshwater landslide database that have depletion zones greater than or equal to 100 square yards. As noted earlier, the calculation of landslide densities, and in this case the percentage of landslides reaching streams, is dependent on the minimum size of landslide used in the analysis. Because landslides smaller than 100 square yards are not included in the analysis and because many of the smaller, revegetated (older) road and hillslope landslides in the basin were probably not identified either on aerial photographs or in the field, the delivery values outlined above may overestimate or underestimate the likelihood of smaller landslides reaching streams. No landslides initiated on terrace and fan complexes, so there is a negligible likelihood that these landforms will generate landslides that reach streams.

7.6 LANDFORM SEDIMENT AND LARGE WOODY DEBRIS INPUT POTENTIALS FOR STREAMS

7.6.1 Large Woody Debris Input Estimates for Landslides

The Channel Module (Appendix E) provides data that allow us to segregate the LWD contributions of landslides from other geomorphic processes, such as streambank erosion, that are contributing LWD to stream channels. The in-channel surveys of LWD carried out as part of the Channel Module field program examined the net accumulation of LWD from all streamside and hillslope processes (sources) including landslides. Data from this work are summarized in Section 7.0 of the Channel Module and suggest that only about 3% of the LWD in mainstem stream channels comes from landslides. Of this 3% contribution, field observations indicate that a majority is from small streamside landslides. Thus, LWD from more distant landslides probably represents a very small contribution to the total LWD input to the mainstem channels.

It is possible to use the mass wasting data to make a very simplistic, "order-of-magnitude" estimate of possible future LWD recruitment from hillslope (non-road) landslides[7]. We do not know with certainty the type of forest cover or LWD accumulations (logging slash) that were present along the paths of landslides that have occurred in the past, nor do we know with certainty what it will be in the future. We can assume, however, that in the future there will be some landslides that travel downslope and through stands retained as riparian buffers. Field observations in the Freshwater and other areas indicate that many of these landslides will entrain relatively little LWD, as second-growth harvesting tends to leave fewer pieces of LWD than old-growth harvesting, or these landslides will occur in or travel through plantations too young to provide significant LWD. However, we also know that many of the forested riparian strips that will be retained along streams in the future are already composed of older second-growth trees, and these trees will become larger with time. Landslides passing through these riparian buffers will likely entrain LWD and deliver it to stream channels.

[7] We are making an optimistic assumption that improved design and remedial work will limit road landslides to a nominal number in the future.

We know the approximate width of the path of non-road landslides (mean=93 ft, standard deviation=110 ft) that have reached streams over the last 55 years, the frequency with which these landslides have occurred, and the approximate number of trees and average wood volumes in existing riparian forests. Table 7-4 provides a matrix of the estimated number of trees and volumes of LWD that could be entrained by an average landslide moving through riparian forests of varying widths. We assume that most of the trees in the buffer are carried into the stream channel by the landslide. Based on field observations and experience in other areas, this simple model ignores the volume of LWD potentially lying on the forest floor as much of it will be sufficiently decomposed that a landslide moving through a riparian forest will easily break this material into smaller pieces. Similarly, we can discount the contribution of upslope LWD because of plantation age, or as we have observed many times in the field, much of this material will either be broken into smaller pieces or will be deposited alongside the landslide on the slopes above the stream. Clearly, some larger pieces of upslope woody debris will reach the stream, but the exclusion of this contribution from the estimate is offset to some degree by those trees within the riparian strip that resist uprooting, or are pushed to the side by landslides and are not carried into the stream.

Table 7-4: Estimates of trees and LWD volume in riparian buffers.

Stream Class	Riparian buffer width	Nominal (average) area of a riparian buffer affected by a single landslide	Estimated volume of LWD entrained from a riparian buffer by a single landslide[1]	Estimated number of trees entrained from a riparian buffer by a single landslide[2]
Scenario 1				
Class 1	100 ft	10,000 ft^2	2,320 ft^3	20 trees
Class 2	30 ft	3,000 ft^2	700 ft^3	6 trees
Class 3	10 ft	1,000 ft^2	230 ft^3	2 trees
Scenario 2				
Class 1	170 ft	17,000 ft^2	3,940ft^3	34 trees
Class 2	130 ft	13,000 ft^2	3,200 ft^3	26 trees
Class 3	30 ft	3,000 ft^2	700 ft^3	6 trees

[1] These estimates are based on data collected during LWD surveys of riparian forests in the Freshwater (Freshwater Detailed Riparian Plot Inventory Data) for trees with a DBH >10 in.

[2] These estimates are based on data collected during LWD surveys of riparian forests in the Freshwater (Freshwater Detailed Riparian Plot Inventory Data) for trees with a DBH >10 in.

As part of the landslide inventory, the type of stream (ephemeral, intermittent, and perennial) affected by each landslide was recorded, but stream class was not recorded. Stream class information was not available when the landslide inventory was done, so we cannot directly relate landslide frequency to stream class. The lengths of Class 1, 2, and 3 streams in the Freshwater watershed are estimated as 37 miles, 78 miles, and 166 miles, respectively, for a total of 281 miles of stream[8]. Over the 55 years between 1942 and 1997, approximately 160 shallow hillslope landslides reached streams. If we assume that hillslope landslides in the Freshwater are uniformly distributed among stream classes, then there have been about 0.6 landslides per mile of stream channel in 55 years, or 0.01 landslides per mile of stream channel per year. Significant lengths of the mainstem Freshwater (a Class 1 stream) are bounded by broad floodplains and gently sloping toe slope areas, where landslides can stop before they reach a stream. Consequently, this approach may overestimate the amount of LWD that will be delivered to Class 1 stream channels by landslides and underestimate the amount that will be delivered to Class 2 and 3 streams. Nonetheless, if we conservatively assume that future landslides will occur at the same rate, then we can make a rough estimate of the average rate of introduction of trees per mile of stream per year, or LWD volume per mile per year.

When we assign nominal riparian strip widths of 100, 30 and 10 feet to Class 1, 2, and 3 streams, respectively (Scenario 1 in Table 7-4)[9], the estimates are as follows (note: ls=landslide):

- [(37 miles)(20 trees)(0.01 ls/mile/yr) + (78 miles)(6 trees)(0.01 ls/mile/yr) + (166 miles)(2 trees)(0.01 ls/mile/yr)] / 281 miles = 0.05 trees/mile/year, or 15.4 trees per year for the whole watershed, or 847 trees over a 55-year period.

- [(37 miles)(2320 ft^3)(0.01 ls/mile/yr) + (78 miles)(700 ft^3)(0.01 ls/mile/yr) + (166 miles)(230 ft^3)(0.01 ls/mile/yr)] / 281 miles = 6.4 ft^3/mile/yr, or 1786 ft^3 per year for the whole watershed, or 98,241 ft^3 over a 55-year period.

If we assume that changes in management practices allow us to reduce the rate of landslides by half, then the landslide-induced LWD introduction rate to streams would be 0.03 trees/mile/year or 3 ft^3/mile/yr. In all likelihood, some trees will be broken into several pieces by the force of a landslide so the number of individual pieces of LWD will likely be higher than the estimated number of trees.

If we assume wider riparian strips along streams, the amounts of LWD generated by landslides will change. For example, if we assign riparian strip widths of 170 feet, 130 feet and 30 feet to Class 1, 2, and 3 streams, respectively (Scenario 2 in Table 7-4), we see the following outcome:

- [(37 miles)(34 trees)(0.01 ls/mile/yr) + (78 miles)(26 trees)(0.01 ls/mile/yr) + (166 miles)(6 trees)(0.01 ls/mile/yr)] / 281 miles = 0.15 trees/mile/year or 43 trees per year for the whole watershed or 2,355 trees over a 55-year period.

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[8] Stream class length estimates are derived from the stream class map in the PALCO GIS.
[9] These values come from the current PALCO Habitat Conservation Plan.

- [(37 miles)(3940 ft^3)(0.01 ls/mile/yr) + (78 miles)(3200 ft^3)(0.01 ls/mile/yr) + (166 miles)(700 ft^3)(0.01 ls/mile/yr)] / 281 miles = 18 ft^3/mile/yr or 5,115 ft^3 per year for the whole watershed, or 281,370 ft^3 over a 55-year period.

Scenario 2 does not consider that as the riparian strip is made wider, more trees will be pushed to the side of the landslide mass and so will not be introduced into the stream. Also, at least on gently sloping areas, the movement of smaller landslides may be retarded somewhat by standing timber and so less material may reach the stream edge.

Both the empirical data on landslide related LWD in mainstem streams (i.e., about 3%), and the simplistic, "order-of-magnitude" estimates presented here, indicate that landslides contribute relatively minor quantities of LWD to the total amount of LWD present in and along stream channels.

7.6.2 Landform–Landslide Input Potential

The landform sediment and LWD input potential for streams is a function of the interaction of expected landslide density for either shallow road or shallow hillslope landslides occurring on a specific landform or landform–attribute combination, and the likelihood of landslides reaching streams from that landform (landslide runout potential). A very simple calculation is used to estimate the likely densities of shallow landslides from roads or hillslope areas that may reach streams (i.e., landslides per 100 ft of road or landslides per acre that may deliver to streams), where:

(landslide density)(likelihood of landslides reaching streams) = landslide delivery density

The expected landslide densities and likelihood of landslides reaching streams developed with CHAID in Sections 7.3, 7.4, and 7.5 are used in this calculation for each landform polygon in the landform database for both road and hillslope landslides. The resulting values are used to generate two semi-quantitative (empirical) landslide delivery maps portraying expected shallow road landslide and shallow hillslope landslide stream delivery densities on a polygon by polygon basis (Maps A-8 and A-9). These landslide delivery density values and landslide delivery maps represent landslides occurring during the period of aerial photograph record from 1940 to 1997. These values could be converted to a yearly rate; for the purpose of this analysis, we did not do that because landslide occurrences tend to be episodic, not regular. In our opinion, summing landslide events over a relatively long period of record is a more appropriate way to portray landslide hazard.

8.0 DETERMINISTIC ANALYSIS

8.1 METHODS

Deterministic analysis was carried out using the Level I Stability Analysis (LISA) model to complement the empirical methods described above. The deterministic approach provides a second and complementary screening tool to evaluate whether the empirically derived results are "reasonable." It can also provide valuable information to geologists conducting on-site geological or geotechnical assessments.

In the deterministic approach, the morphologic landform map is the basis for developing or classifying a set of "deterministic" ratings. A stratified random sampling system, based on a landform map, was used to select sites for soil physical property testing and sampling. The soil physical properties sampled included soil shear strength (e.g., friction angle and cohesion), soil unit weight, and moisture content. Variations in soil physical properties are derived using methods described by Renteria (1992). Soil depth was determined using the Williamson drive probe and field methods described in Hall et al. (1994). Bulk soil samples were collected, described in the field, and tested in a materials laboratory for particle size distribution and Atterburg limits. Frequency distributions for slope-stability variables are generated through a deterministic evaluation of samples collected for each landform by applying the methods described by Hammond et al. (1992) and Koler (1998). Failure probabilities are calculated stochastically for each polygon type. Reliability of the frequency distributions is calculated using the protocol by Remboldt (1997). The analysis focused on shallow, translational landslides. The analysis also included a stochastic probabilistic analysis for predicting slope failure for different silviculture and rainfall conditions.

The product from the deterministic approach was a second landslide hazard map for hillslope landslides, with hazard ratings tied to changes in silviculture and hydrologic conditions. The results of the deterministic analysis can be used to corroborate the empirically derived landslide hazard ratings.

In the deterministic analysis, we applied the standard-of-practice for acceptable factors of safety in limit equilibrium analysis as established in the last century by several noted authorities in soil and rock mechanics, including Karl Terzaghi the "father of soil mechanics." These authorities give a detailed explanation of how the limit equilibrium analysis is applied and what factors of safety may be appropriate for slope stability evaluations. For the interested reader a number of standard references on the subject are included in the list of references at the end of this report.

8.2 VARIANCE TO MASS WASTING METHODOLOGY

The deterministic approach included two variations to the methodology outlined in PALCO (2000), and that was the addition of a time-series analysis of groundwater flux and evapotranspiration in response to clearcutting, prior to and ten years after a "wet year." The hydrological "wet year" applied in this analysis was the 1996-1997 water year followed by average monthly rainfall. The groundwater flux was evaluated with the assumption that there was no interception and all rainfall amounts entered the soil column with discharge amounts calculated from estimated soil- specific yields. Evapotranspiration was modeled with the Pennman-Montieth equation utilizing stomatal conductance via the Leaf Area Index. Also, as is discussed below the final landslide hazard map was based on the deterministic rather than the probabilistic version of LISA

8.3 RESULTS AND DISCUSSION

8.3.1 Soil Physical Properties

A summary of soil physical properties for the watershed is presented in Table 8-1. Nearly 500 soil units were identified in our fieldwork at 63 randomly selected sites. Just over 200 samples were collected for identification and classification purposes. The soil sampling and analysis approach follows the methods outlined in PALCO (2000).

Table 8-1: Soil physical properties summary for the Freshwater Creek Watershed.

Landform	Geologic Unit	Soil Depth (ft)	Unified Soil Classification	Dry Unit Weight (pcf)	Friction Angle (degrees)	Cohesion (psf)	Moisture Content (%)
Complex	Franciscan	1 to 5	GC, SM, ML, CL, CH	80 to 113	20 to 38	0 to 50, 0 to 100	12 to 27
Complex	Wildcat	1 to 10	ML, MH, CL	84 to 98	28 to 32	0 to 100	17 to 24
Planar	Franciscan	1 to 7	SC-SM, ML	83 to 102	28 to 35	0 to 50, 0 to 100	14 to 25
Planar	Wildcat	1 to 10	ML, MH	84 to 97	28 to 32	0 to 100	18 to 24
Convex	Franciscan	1 to 9	GM, SC, ML-CL, ML, MH, CL, CH	72 to 107	25 to 35	0 to 50, 0 to 100	18 to 32
Convex	Wildcat	1 to 12	SC, ML, MH, CL	83 to 103	28 to 32	0 to 50, 0 to 100	17 to 32
Incised	Franciscan	1 to 8	GP-GM, SC, ML, CL	72 to 111	25 to 38	0 to 50, 0 to 100	12 to 32
Incised	Wildcat	1 to 10	ML, MH, ML-CL	81 to 99	28 to 32	0 to 100	17 to 26
Terrace	Franciscan	--	--	--	--	--	--
Terrace	Wildcat	2 to 8	GM, ML	88 to 113	30 to 38	0 to 50, 0 to 100	11 to 24

Laboratory analyses indicate that the soils throughout the watershed are dominantly non-plastic silts. Limited areas of coarse-textured soils are found on all landforms overlying the Franciscan Complex. Convex and terrace landforms underlain by the Wildcat geologic unit also contain some gravels and sands. In addition to the laboratory analyses of the soil, physical properties including dry unit weight, moisture content, and friction angles were also derived by field penetration tests. This method of determining physical properties by penetration tests was developed by Arthur Casagrande in the 1930s and 1940s followed by engineering work developed by the US Department of the Navy and are described in several soil mechanics texts (e.g., Lambe and Whitman, 1969 – see page 148 ; Terzaghi and Peck, 1967 – see pages 289 to 360; and Bowles, 1984 – see pages 186 to 188.). Cohesion was derived from field measurements using the methods described in Hall et al. (1994). In general, friction angles are lower and cohesion values are slightly higher for soils developed from Franciscan rocks. The dry unit weight for soils in the watershed averages 90 pounds per cubic foot (pcf). Moisture contents are higher for convex and incised landforms but averaged about 20% for all landforms. Soil depths vary from ridge crest to valley floor and from landform to landform, but the mean soil depth is about 4 feet. Additional data are outlined in PALCO's Engineering Soils Catalogue .

8.3.2 Stochastic Analysis for Predicting Slope Failure

Frequency distributions for each parameter used in the slope stability calculations were constructed as part of the deterministic evaluation. The deterministic approach was evaluated using sensitivity analysis. Sensitivity analyses such as these are useful in determining which variables have the greatest effect on the final stability calculation. We found that the three most important parameters for the Freshwater assessment are slope gradient, soil depth, and groundwater ratio (ratio of the groundwater apparent thickness to the soil apparent thickness). All other parameters were relatively insensitive.

We field checked 42 landslides to evaluate the reliability of these conclusions. Detailed field and office evaluations were carried out on 33 of the 42 landslides. The fieldwork included the measurement and mapping of the subsurface soil unit geometry, soil physical properties, spatial and stratigraphic soil unit relationships (including soil depth), and the subsurface geometry of groundwater. The office analysis included iterations of the Modified Bishop method of slices (MOS), block method, and Janbu MOS for each of the 33 landslides. This was a forensic process to discover how the landslides had become unstable and failed so that this information can be applied in predicting future slope failure and for the prescription process.

In our forensic work, we first used the Modified Bishop MOS because the conventional wisdom among local geologists includes the assumption that many landslides (especially the deep-seated landslides) have a failure zone that is rotational. The Modified Bishop MOS results showed that this is not the case because the modeled factor of safety never reached a threshold of failure. We next used the block method and the Janbu MOS to model mass failure along a planar failure zone. Our results from this modeling were successful in that the modeled results were identical to our field observations: translational failure is the most common failure zone geometry, and the modeled factor of safety reached a threshold of failure. This an important finding because the infinite slope equation, the governing equation in the stochastic analysis, assumes a "thin" soil depth relative to slope length failure zone which is translational.

Part of the forensic analysis was also to verify strength parameters of the landslide mass, and identify the influence of the groundwater on overall slope stability. Friction angles and soil cohesion values were field measured and checked via laboratory testing with a triaxial compression test.

Groundwater fluctuations in response to rainfall and silviculture were modeled using the 100-year rainfall record, a groundwater flux equation, and the Penman-Montieth evapotranspiration equation. These fluctuations may have a direct effect on hillslope stability. Our objective, therefore, was to apply the data in our stochastic model to find predicted probabilities of slope failure where actual slope mass movement occurred. The result of this work is displayed in Table 8-2.

Table 8-2: Mass wasting hazard ratings from stochastic slope stability analysis.

MLU	P[FOS<1]*	Hazard Rating
All Terraces, Fans, etc.	0%	Very Low
All Complex	0%	Very Low
Convex Gentle	1%	Low
Headwall Swales Gentle	4%	Low
Planar Gentle	3%	Low
Convex Moderate	5%	Low
Incised 1 Moderate	2%	Low
Incised 2 Moderate	2%	Low
Incised 3 Moderate	3%	Low
Headwall Swales Moderate	7%	Low
Planar Moderate	11%	Moderate
Convex Steep	21%	High
Incised 1 Steep	8%	Moderate
Incised 2 Steep	11%	Moderate
Incised 3 Steep	11%	Moderate
Headwall Swales	20%	High
Planar Steep	23%	High

* Probability that the factor of safety will be less than one.

P[FOS<1]	Hazard Rating
0% – 2.9%	Very Low
3.0% – 7.9%	Low
8.0% – 15.9%	Moderate
16.0% – 24.9%	High
25.0% - 30.0%	Very High
30.0% and greater	Extreme

In the stochastic analysis, we evaluated different silviculture and hydrologic conditions for each landform. Our results showed that landform stability is insensitive to rainfall, with the exception of steep complex, steep headwall swales, and steep planar landforms. Modeling the groundwater flux through each polygon of interest derived the insensitivity to rainfall conclusion. In our analysis, we made the assumptions that all harvesting was clearcut, that all rainfall infiltrated to the groundwater storage area, and that groundwater flow was controlled by hydrologic parameters appropriate for the soil type as well as the discharge characteristics. The rainfall component of the model was derived from our 100-year (plus) rainfall record. The initial stochastic modeling, using average rainfall, showed little slope movement above background levels of 1 to 3% (very low hazard rating) after clearcutting. We then applied the most recent major storm activity (1996-1997 water year) that resulted in significant mass wasting to find our probabilities of slope failure. The results corresponded well with Fall's field observations (Falls 1999b; pers. comm. with Falls, 2000) and with the empirical results. Selected landform (e.g., headwall swales) may be subject to increased landsliding following clearcut harvest, whereas most others show little or no response to harvest.

The CGS objection to the use of the morphologic landform classification and map resulted in the removal of the landform factor from the deterministic analysis. Consequently landform polygons were considered only as DEM slope polygons and so were no longer suitable as a vehicle for carrying out probabilistic LISA (i.e., inferences about likely hydrologic conditions are derived from the landform map). Consequently, the analysis defaulted to DLISA, the deterministic version of LISA. This analysis produced a series of mean factor of safety values for different geologic units and slope angles (Attachment A-1 Table A-1-1) based on the available soil sample data. These factor of safety values (FOS) were grouped into five FOS hazard categories (Table 8-3). These values were inserted into the landform-landslide database with one FOS value assigned to each landform polygon based on the combination of geology and slope class represented by that landform polygon. The FOS values were then compared to the shallow hillslope landslide density values (ls/ac) in the database as a way of calibrating the FOS categories to actual landslide density values (Table 8-3 and Figure 8.1). The distribution of these categories in the Freshwater watershed is shown in Table 8-4 and Figure 8.2. The FOS values in the landform-landslide database were then used to generate a DLISA landslide hazard map (Map A-10). Visual comparison of the DLISA map to the empirical shallow hillslope landslide hazard map indicates that the two are quite similar. To have two quasi-independent analyses that use different methods producing similar results is encouraging and increases our level of confidence in the analysis.

Because these results are comparable, we can recommend that consideration be given to extending the deterministic landslide hazard mapping to other watersheds within PALCO ownership at this time based on existing geotechnical soils data, geologic units and GIS derived slope polygons. This approach could provide timely prioritization of higher hazard THP areas for on-site geologic investigations. We should point out that application of this approach to landscapes underlain by extensive deep-seated landslide deposits should be subject to further validation or calibration as both shallow and deep-seated landslide inventories come available through the watershed analysis process. The natural heterogeneity of the geologic materials on slopes comprised of deep-seated landslide deposits may preclude the use of simple deterministic models so validation or calibration on an ongoing basis is recommended.

Table 8-3 Factor of Safety Calibration – Freshwater basin

Factor of safety hazard category	Mean FOS ranges	$N_{weighted}$	Mean ls/ac	Std. Deviation
1	>1.5	178221	0.004	0.022
2	1.5-1.3	264625	0.007	0.040
3	1.3-1.0	269332	0.010	0.043
4	1.0-0.8	89695	0.012	0.053
5	<0.8	53946	0.030	0.109

Table 8-4 Area distribution of Factor of Safety Hazard Category map polygons

Factor of safety hazard category	Mean FOS ranges	Number polygons[10]	Sum of acres	% of Sum of area
1	>1.5	789	4099	21
2	1.5-1.3	745	6086	31
3	1.3-1.0	876	6195	31
4	1.0-0.8	477	2063	10
5	<0.8	409	1241	6
Total		3296	19684	100

[10] Note that these numbers represent the number of geologic unit-landform child polygons generated by intersecting the landform and geologic unit maps not the number of original landform polygons.

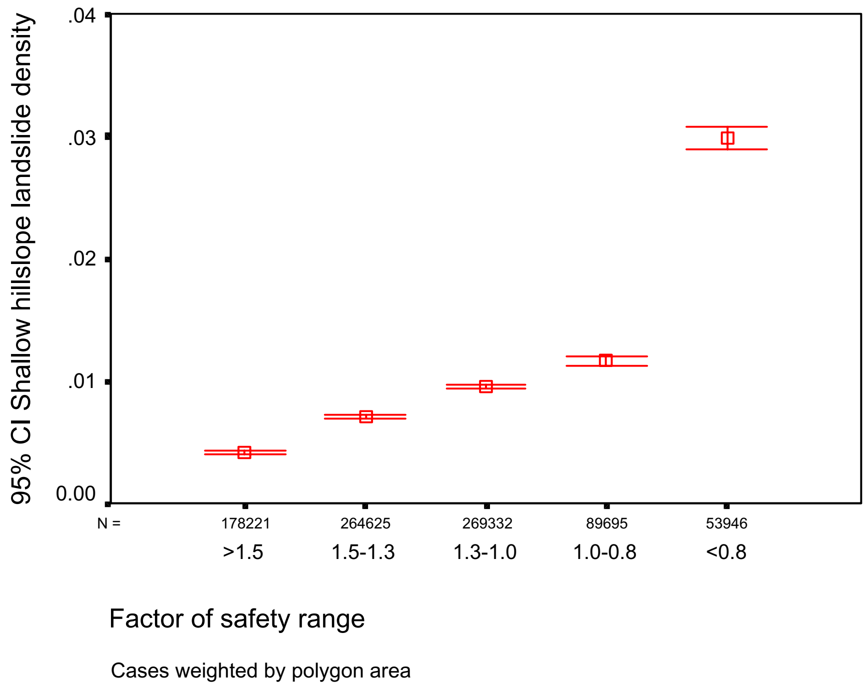

Figure 8-1 Factor of safety mean values versus shallow hillslope landslide density (ls/ac)

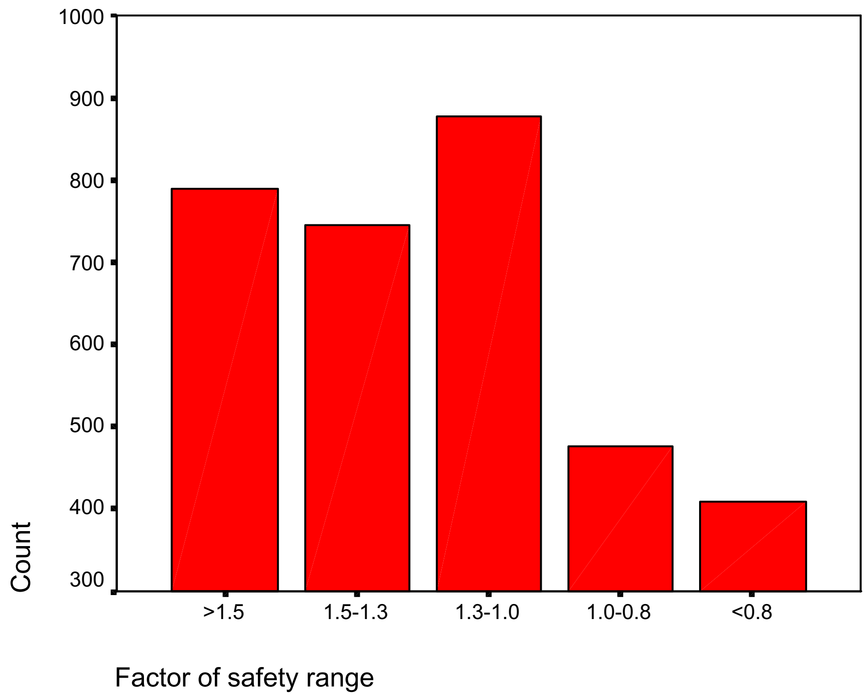

Figure 8-2 Mean factor of safety distribution by number of map unit polygons

9.0 LANDSLIDE SEDIMENT BUDGET ESTIMATES

The amount of sediment contributed to streams by landslides is estimated as part of the development of the overall sediment budget for the watershed. There are two parts to the sediment budget developed for landslides: (1) the amount of sediment introduced directly into streams or deposited along stream margins by the initial landslide event; and (2) the amount contributed by subsequent surface erosion along the landslide track. This analysis addresses sediment inputs from shallow landslides initiating at roads and on hillslopes.

9.1 METHODS

Landslide sediment budget estimates are based on simple field measurement (i.e., hip chain and clinometer surveys) of a moderate number of road and hillslope landslide depletion zone volumes and aerial photograph estimates of the dimensions of the remainder. Landslide volumes were converted to mass (tons) using dry unit weight (tons/yd^3) values derived from the analysis of soil samples collected for the deterministic analysis. Sediment budget estimates were developed for a range of particle size classes (silt and clay, fine sand, medium to coarse sand, and gravel) based on the proportions of these size classes in the soil samples.

Particle size distribution varies slightly between soils from the Franciscan and Wildcat geologic units, so particle size values were pro-rated by the percent coverage of these two geologic units within the various sub-basins in the Freshwater watershed.

The estimates of tons of sediment delivered to streams by landslides were partitioned by the point of landslide origin (road versus hillslope), by sub-basin and by aerial photograph interval for the period 1942 to 1997 (see Tables 9-1 and 9-2). Any landslides visible on the 1940 and 1942 aerial photographs were treated as occurring before 1942 for the purposes of the sediment budget estimates (four landslides are visible on the 1940 and 11 on the 1942 aerial photographs).

Table 9-1: Estimated tons of sediment delivered by hillslope landslides 1942-1997[1].

Sub-basin	1942-54	1955-66	1967-74	1975-87	1988-97	1942-97
Cloney	1310		370			1680
Graham Gulch	7100	7660	600		4160	19520
Little Freshwater	7020	2360	1760	230	7470	18840
Mainstem Freshwater	960	50		730	1290	3030
McCready Gulch				50		50
School Forest		230		20	20	270
South Fork Freshwater	35020	1420	1610	180		38230
Upper Freshwater	25840	6490	9210	740	1770	44050
Totals	77250	18210	13550	1950	14710	125670

[1] Sediment values are rounded to the nearest 10 tons.

Table 9-2: Estimated tons of sediment delivered by road landslides 1942-1997.

Sub-basin	1942-54	1955-66	1967-74	1975-87	1988-97	1942-97
Cloney	640		60	2110	590	3400
Graham Gulch		4940	60	370	1010	6380
Little Freshwater	660	530	460	2850	14340	18840
Mainstem Freshwater	1120	90			2720	3930
McCready Gulch			1990	7200	990	10180
School Forest			5400	950	340	6690
South Fork Freshwater	6560	2550			860	9970
Upper Freshwater	17380	4140	1050	170	2310	25050
Totals	26360	12250	9020	13650	23160	84350

The landslide sediment delivery estimates were provided to the channel module analyst for incorporation in the overall watershed sediment budget and, except for the summary tables provided, are not discussed in detail in this section. These estimates include only shallow landslides and do not include sediment delivery estimates for deep-seated landslides. Sediment estimates from stream erosion of the toes of any active deep-seated landslides were included in the channel module. Similarly, direct sediment contributions from any minor streambank landslides (not included in the landslide inventory described in Section 6.0) that were recorded during the channel surveys are included in the sediment delivery estimates developed from the stream channel survey data. Sediment contributions from small streamside landslides are also described in Table 13 in PWA (1999).

Surface erosion estimates for landslide scars were developed using an approach applied in an earlier sediment source study of the Freshwater (PWA 1999). These estimates assume that revegetation of landslide scars occurs within five years and that after that time surface erosion is negligible. During the period of revegetation, surface erosion is assumed to occur at an average rate of 0.2 in. per year on steep to moderately sloping surfaces of the depletion zone of the landslide. Surface erosion on the gently sloping accumulation zone is assumed to be negligible. The surface erosion rate is based upper limits of surface erosion recorded on exposed soil surfaces in nearby areas (e.g., 0.01-0.18 in./year in the Redwood Creek watershed; Marron et al. 1995). Only landslides that reach streams are considered to have a direct pathway for the delivery of eroded sediment to streams (i.e., shallow landslides from roads and hillslides that enter streams, and small streamside landslides). Landslides that did not enter streams are not included in the sediment budget calculations for surface erosion on landslide scars. The analysis assumes that 30% of the sediment eroded from the surface of a landslide scar will reach streams, and the remainder will be deposited on depressional or level areas on the landslide surface. The three assumptions that rapid revegetation, negligible surface erosion in accumulation (deposition) zones, and the estimate that about 30% of the sediment released by surface erosion will reach streams all conform with our field observations. Our field observations indicate that much of the sediment released by surface erosion is deposited at other locations on landslide surfaces. We also observed that shallow landslides in the Freshwater, especially accumulation zones, revegetate very quickly. For the current sediment budget, estimates for surface erosion on landslides were grouped by sub-basin, photographic time-period, and frequency of landslides within those time periods. As for the sediment budget estimates for direct input of sediment, estimates of eroded sediment were segregated into particle size classes on the basis of geology. Both shallow road and hillslope landslides were grouped into a single surface erosion category. These estimates were provided to the channel analyst for incorporation in the watershed sediment budget.

9.2 VARIANCE TO MASS WASTING METHODOLOGY

The sediment budget approach used for landslides in the Freshwater watershed followed the methodology outlined in the mass wasting module with one variation. The particle size divisions used were: silt/clay (<0.075 mm), fine sand (>0.075–2.0 mm), medium to coarse sand (>2.0–4.7 mm) and gravel (>4.75 mm). These values vary slightly from the values listed in the mass wasting module (i.e., <0.1 mm, >0.1–2 mm, >2–8 mm, >8 mm). These values were adopted, as they are the particle size divisions used for the soil samples collected for the deterministic analysis, which of necessity followed standard geotechnical analysis procedures.

The methods to estimate surface erosion on landslide scars did not vary from the methodology because there is no detailed methodology described in the mass wasting or elsewhere in the watershed analysis methodology.

9.3 RESULTS

We compiled landslide sediment input estimates for the various sub-basins in the Freshwater watershed. In total, 343 landslides (160 hillslope and 183 road landslides) reached streams in the Freshwater watershed over the 55-year period of record between 1942 and 1997. On average, 40% of the volume of these landslides entered streams. The average volume of sediment and debris delivered to streams was about 400 yd^3, or approximately 480 tons per landslide. Road landslides were smaller on average than non-road landslides (360 yd^3, versus 660 yd^3, respectively). These sediment input estimates are spread out over time as defined by the photo periods utilized for the landslide inventory and are summarized in Tables 9-1 and 9-2. About 60% of landslide-derived sediment reaching streams comes from landslides that began on hillslope areas, and the remaining 40% by landslides that initiate at roads.

As seen in Tables 9-1 and 9-2 and Figure 6-3, the delivery of landslide-derived sediment to streams is episodic rather than continuous. The estimates in Tables 9-1 and 9-2 should be viewed as an upper limit for direct (instantaneous) input of sediment by landslides into streams because varying amounts are available for immediate downstream transport, especially in smaller first and second-order streams. Our field observations indicate that the incorporation of both large and small woody debris in the landslide mass creates an erosion-resistant woody matrix that often immobilizes sediment in the deposition zone of shallow landslides. These deposition zones tend to re-vegetate within a few years. Consequently, stream erosion of the deposition zone is inhibited, especially when the effect of vegetation is combined with the effect of embedded woody debris. We would expect slow release of sediment over a long period, as the woody debris embedded in the landslide mass in and alongside these small streams slowly breaks down.

Except for one large, active earthflow in Graham Gulch and another in the upper mainstem of Freshwater Creek (PWA 1999), we are not aware of any significant and visible input of sediment into streams by deep-seated landslides in the Freshwater watershed. The large, recently stabilized deep-seated landslide in the southern area of the watershed near the upper reaches of South Fork Freshwater Creek (mentioned earlier in the discussion on large landslides) is not considered a significant sediment source. Small streams traverse or abut a number of large features identified on aerial photographs and topographic maps as possible large, dormant, deep-seated landslides in the Freshwater watershed (see Map A-5). With respect to sediment budgeting, the bank erosion estimates and minor streamside landslide sediment input estimates recorded by the stream channel surveys (including post-harvest entrenchment of small hillside streams) should capture any significant background input of sediment from these deep-seated landslides.

The total sediment yield for the 55-year period of record for surface erosion on landslide scars is estimated to be approximately 2,970 tons, or 1% to 2% of the total estimated sediment yield from landslides. This amount of sediment is minor in comparison with other sediment sources in the watershed. It is our opinion that the amount of surface erosion that may or may not occur on exposed landslide surfaces is much less than the errors inherent in estimates of landslide volumes and estimates of the amount of sediment injected directly into streams by the original landslide events. As described above, the landslide surface erosion estimates were tabulated by sub-basin and aerial photograph time-period based the frequency of landslides occurring during those periods. These estimates were provided to the stream channel analyst for incorporation in the watershed-scale sediment budget.

10.0 CONFIDENCE IN ANALYSIS

We have a moderate level of confidence in our findings. The database of available information on landforms and landslides for analysis is quite large. An extensive shallow landslide inventory that included substantial ground verification of landslide locations was prepared before the signing of the PALCO Habitat Conservation Plan and was made available to the study (PWA 1999). We were also fortunate in having a recent geologic map completed by the CGS (Falls 1999a), this map included the locations of many large, deep-seated landslides. Geotechnical field work to sample, identify, and classify soils, subsurface geometry, and soil shear strength for each landform improved our level of confidence in the analysis.

10.1 ESTIMATES OF LANDSLIDE FREQUENCIES AND BACKGROUND LANDSLIDE RATES WITH RECOMMENDATIONS TO IMPROVE DATA

Despite our confidence in this study, it does have some limitations. The shallow landslide inventory underestimates the numbers of very small landslides, especially older, smaller landslides because these are difficult to identify on aerial photographs or in the field. This applies to both roads and harvested hillslope areas, but is less a problem for roads as in this case all roads were walked. Similarly, smaller landslides (1,000-2,000 yd^2) in areas of advanced second-growth timber are difficult to identify on aerial photographs. The figures illustrating landslide size distributions (Figures 6-4 to 6-6), however, indicate that from the standpoint of estimating sediment introduction to streams, this is not a major issue as smaller landslides contribute very little to both the cumulative volume of all landslides and the overall sediment budget.

Estimates of background landslide rates are approximate because of the difficulty of identifying small landslides in advanced second-growth areas on aerial photographs. Section 7.3 compares clearcut areas with areas of unthinned second-growth for the approximate period 1975 to 1997. It is reasonable to assume that landslide rates in these second-growth forests are approaching natural landslide rates; however, natural landslide rates could be higher or lower. The apparently lower landslide rates in areas of thinned second-growth compared to unthinned second-growth somewhat suggests that a larger baseline area or a longer period of record may be needed before estimates of background landslide rates from second-growth can be considered robust. Improving estimates of background rates will improve our estimates of the effects of forest management on landslide rates and sediment introduction into streams.

Most estimates of sediment introduction from hillslope landslides were made from aerial photographs, so the absolute volumes are only estimates. In particular, there is no reliable way to estimate landslide depths from aerial photographs; therefore, depth estimates were made from landslide area-depth relationships derived from field measurements of a smaller set of road and hillslope landslides. These geometric estimates are consistent among landslides, as one person made all the aerial photograph estimates. Similarly, field estimates of landslide volumes introduced into streams are only visual estimates. Zones of depletion were measured on the ground for more recent road landslides using simple field survey methods (hip chain and clinometer), but the portion of the accumulation zone that entered a stream was visually estimated. Estimates of landslide volume derived from field measurements should be viewed with caution, as accurate depth estimates are difficult to make in the field because of the chaotic, broken surface of many landslides both in the zone of depletion and in the zone of accumulation. In addition, the field surveyor can make only rough estimates of the likely elevation and morphology of the pre-landslide hillslope surface. Landslide volume estimates are most sensitive to variations in estimated depths. The rapid revegetation of landslides in the area also reduces the accuracy of field measurements. There is only a limited amount of time (i.e., 3 to 5 years) when reasonably accurate field measurements can be made. After that time, it can be difficult to distinguish the margins of a landslide from surrounding unaffected areas, and accurate depth estimates become more difficult. Improving these estimates will help prescription writers clearly identify those management practices that will most effectively reduce sediment introduction into streams.

We recommend that in the future PALCO consider surveying suitable landslides in the field while they are still young enough for reasonable field estimates of length, width, and depth to be made. These data will be valuable for future watershed analysis studies.

We also recommend that in the future landslide locations be plotted directly onto the landform map (if used) prior to digitizing, rather than on a separate topographic base map (landslide locations should be retained on a separate layer in the GIS). Because of plotting errors, both for landslide locations and for landform boundaries (both were plotted manually onto separate topographic base maps), it is possible for a landslide to be plotted outside the landform polygon that it actually occurs within. This potential error source explains some of the variation in landslide densities among different landform categories noted in our assessment. Apparent plotting errors will also occur because some landforms are too small to map or identify so they do not show on the landform map, yet they can be identified in the field at the landslide location or on aerial photographs. Direct plotting of the landslide locations from the aerial photographs to the landform map should resolve some of these issues. Where possible, we made minor adjustments to landslide location records so that they were plotted inside appropriate landforms; however, we do not believe that we accounted for all cartographic variances in landslide and landform location. Improving the correspondence between landforms and landslides will improve landslide hazard map accuracy and so reduce the need for on-site geologic investigations.

10.2 LANDFORM MAPPING RESOLUTION WITH RECOMMENDATIONS TO IMPROVE PROCEDURES

The morphologic landform unit boundaries are based solely on contour line intervals and spacing on a topographic map. Initial landform mapping was done at a scale of 1:18,000. After digitizing by the PALCO GIS department, the map was printed at a scale of 1:12,000 and returned for editing. The increase in scale allowed smaller landforms to be mapped, increased the editing time, and likely resulted in some variation in landform delineation. If landform mapping is done in other watersheds in the future, it would be helpful to carry out the initial line work at the largest suitable scale and to edit at that same scale. This should provide greater consistency in landform delineation across individual map areas.

Landform boundaries reflect contour line spacing and morphology but do not necessarily delineate exact locations of change in slope. For example, the boundaries for incised units containing watercourses were digitized using a GIS query. This resulted in a standard polygon width of 200 to 300 feet for all incised units. For some of the field-checked map units containing Class 3 watercourses, however, the actual unit width was 50 to 100 feet. The actual field width for incised units containing Class 1 watercourses was usually wider than the 200-300 feet default used in the digitizing process.

Because of generalization issues created by landform units overlapping geologic unit boundaries, we recommend that the landform units be delineated on a topographic map that is also a geologic base map. Geologic boundaries should be used as primary landform polygon boundaries. This will eliminate the problem of landform boundaries crossing geologic unit boundaries. For example, when a convex, gentle slope overlaps two geologic units, the map will show two separate landforms. This modification to the mapping approach should improve correlations between landforms, slopes, and underlying geology and should result in more accurate landslide hazard maps.

It is important to note that more recent geologic work has been done in the Freshwater watershed (Knudsen 1993; Falls 1999a). Minor inconsistencies have been observed between the geologic base map provided by PALCO and some of this more recent geologic mapping. For example, Kelly (1984) mapped the Hookton Formation in the southwestern part of the watershed, but in 1993 Knudsen interpreted the Hookton Formation to be the lower member of the Wildcat Group. Falls (1999a) also considered it the lower member of the Wildcat Group. This analysis considered it to be part of the Hookton Formation. These differences, as noted, were minor and we do not believe that doing this affected our analysis or conclusions.

We originally intended to conduct detailed landform (terrain) mapping on an experimental basis to determine if it added significantly to the resolution of derivative landslide hazard maps. This was not done; as noted above, however, we have reasonable confidence in our results. Still, it would be valuable if this approach were completed in one or more of the next watersheds undergoing analysis. If detailed landform mapping significantly improves the resolution of the landslide hazard maps, it should be considered for the remaining watershed analyses. Improving the resolution of the landslide hazard maps should reduce the need for on-site geologic investigations.

10.3 STOCHASTIC ANALYSIS

The one area for improvement is the application of a stochastic model for road-related stability. The mass wasting assessment currently does not include a stochastic model for road-related stability assessments. In recognition of this, PALCO retained the services of R. Prellwitz to refine his Stability Analysis for Road Access (SARA) for the timberland watershed analysis. SARA is a sister to LISA, both of which were developed, tested, and adopted by the U.S. Forest Service as the agency's slope stability tools for watershed and transportation planning (see Hammond et al. 1992; Hall et al. 1994). This model will help assess road-related slope stability problems stochastically. In the meantime, the empirical method used in our assessment is fully adequate, although it lacks forensic capabilities.

11.0 RECOMMENDATIONS FOR MONITORING AND OTHER STUDIES

There are a few issues that the mass wasting assessment did not or could not address that might benefit from monitoring or future study. These are described below.

Better data from future landslide occurrences in the basin could be obtained by conducting investigations (i.e., field surveys) in a timely manner. Determination of specific management factors (e.g., uncontrolled road drainage, overloading by roadside berms) that may contribute to landslide initiation is not feasible on older landslides, as field evidence of these factors tends to be very transitory. We recommend implementing a contingency plan that would see investigation and assessment of landslides immediately after they occur. Over time, this approach would provide data on the types of management practices that most likely result in landslide initiation. It would also provide more accurate estimates of landslide size and volume for sediment budgeting and runout modeling. This information should improve both the utility and appropriateness of prescriptions.

A synoptic inventory of wood volumes deposited in streams (e.g., wood volume per unit length of stream channel) by recent landslides across the PALCO ownership could provide a reasonable estimate of the LWD volumes that can be expected in the future from individual landslides. As many streams in the future will be bounded by forested riparian reserves, these investigations should focus on landslides that have traveled through standing timber (i.e., 40- to 60-year-old second-growth stands or natural riparian forests). Given the apparent minor contribution of landslides to LWD recruitment in streams, this task is not considered a high priority. It is unlikely that this information will have a direct or highly beneficial effect on the utility and appropriateness of prescriptions.

Future landslide inventories should include the collection of morphologic and geometric data as well as soil, rock, and groundwater parameters along the entire path of any recent landslides. These data will assist in the development of landslide runout models and may improve sediment budget estimates. We suggest that there is some merit in carrying out a specific study to develop landslide runout models and/or estimates for the entire ownership rather than leaving this task to individual watershed analysis projects. This information may improve landslide runout predictions, but it is unlikely that it will have a direct effect on the utility of prescriptions developed as a part of a watershed analysis. It will help with site-specific prescriptions developed as part of THP geologic investigations. A major benefit of this recommendation is that this task will be done once and not repeated in a less inefficient manner during each watershed analysis.

All mass wasting monitoring efforts should have as their goal development of new information that can: (1) assess the effectiveness of developed prescriptions in reducing sediment delivery to streams, and (2) guide refinement of existing prescriptions or suggest new prescriptive approaches following future watershed evaluations in the basin.

12.0 SUMMARY

The Freshwater mass wasting assessment shows strong relationships between landslide densities along roads and in harvest areas and morphologic landform type (slope morphology), slope gradient, and specific geologic units. There is a definite correspondence between the landslide hazard estimates derived from the deterministic analysis with those developed through the empirical approach. The potential for landslides to reach streams has a relationship to general morphologic landform category, but further work on landslide runout relationships would be helpful.

Active deep-seated landslides are rare in the watershed, but inactive and relict features are common. There is no compelling evidence on aerial photos or in the field that suggests that forest management practices have had a substantive effect on the activity levels or rates of movement of these features.

The empirical and qualitative landslide hazard maps (Maps A-3 to A-8) developed from this assessment provide a useful tool for identifying those portions of the Freshwater basin that are at risk from landslides. They can also help identify those higher hazard sites where on-site geologic investigations are necessary to select site-specific management practices consistent with higher levels of landslide hazard. Site-specific field keys should be used to supplement the hazard maps. Where on-site geologic review is conducted, the resulting recommendations for prescriptions will generally be superior to prescriptions based solely on the landslide hazard maps.

There are initial indications in the data set for the Freshwater watershed that partial cutting (specifically commercial thinning) will result in lower hillslope landslide frequencies than conventional clearcutting on steeply sloping areas (i.e., slope gradients >60%). For other landforms, these data do not indicate a substantial effect of any harvest technique on landslide rates. The initial findings on partial cutting and clearcut landslide densities need refinement and further validation. The findings suggest, however, that partial cutting will be a viable option for forest harvesting on some higher hazard sites where clearcutting may be inappropriate. Landslide rates in older second-growth are lower than those occurring in clearcut areas and similar to those occurring in areas of partial cutting. Landslide rates in older second-growth may be underestimated, because smaller landslides in standing timber are often difficult to identify on aerial photographs.

The simple landslide-generated LWD input estimates made as part of this analysis indicate that the contribution of LWD to streams by landslides is minor in comparison to other processes such as natural mortality, windthrow, and streambank erosion.

Road and hillslope landslides appear to be approximately equal contributors of sediment and debris to streams. This finding suggests that modification to road construction practices and appropriate remedial action along existing roads could substantively reduce the amount of sediment delivered to streams by landslides. Shallow landslides can introduce substantial quantities of sediment into streams in the Freshwater watershed, but review of the other components of the watershed analysis indicates that other sediment sources are often more important. Riparian buffers along larger streams should reduce the number of landslides occurring on steeper slopes in these areas.

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ATTACHMENT A-1 DLISA FACTOR OF SAFETY VALUES

Table A-1-1 Mean Factor of Safety Values for Geologic Unit by Slope Angle

KJfm		KJfs		Ty		Twl		Twu		Qrt	
Slope (°)	FOS	Slope (°)	FOS	Slope (°)	FOS	Slope (°)	FOS	Slope (°)	FOS	Slope (°)	FOS
5	6.0	5	6.1	5	6.3	5	5.9	5	6.8	5	6.0
10	3.0	10	3.0	10	3.2	10	2.9	10	3.4	10	3.0
15	2.0	15	2.0	15	2.1	15	2.0	15	2.3	15	2.0
20	1.5	20	1.5	20	1.6	19	1.5	20	1.7	20	1.5
20	1.5	20	1.5	25	1.2	20	1.5	22	1.5	25	1.2
23	1.3	23	1.3	29		20	1.5	23	1.5	29	
25	1.2	25	1.2	29		22	1.3	25	1.4	29	1.0
29	1.0	29	1.0	29		22	1.3	26	1.3	29	
29	1.0	29	1.0	30		25	1.2	26	1.3	30	
29	1.0	29	1.0	30	1.0	29	1.0	29	1.2	30	1.0
30	1.0	30	1.0	31	1.0	28	1.0	29	1.2	31	
30	1.0	30	1.0	34		29	1.0	29	1.2	34	
31	0.9	31	1.0	35	0.9	29	1.0	30	1.1	35	0.8
32	0.9	33	0.9	40	0.8	30	1.0	30	1.1	40	0.7
34	0.9	34	0.9	45	0.7	30	1.0	31	1.1	45	0.6
35	0.8	35	0.8	50	0.6	31	0.9	34	1.0	50	0.6
40	0.7	40	0.7	55	0.6	31	0.9	34	1.0	55	0.5
45	0.6	45	0.7			34	0.8	35	1.0		
50	0.6	50	0.6			35	0.8	38	0.9		
55	0.5	55	0.6			40	0.7	40	0.9		
						45	0.6	45	0.8		
						50	0.6	50	0.7		
						55	0.5	55	0.7		

ATTACHMENT A-2 COMPARISON OF PALCO AND CGS LANDSLIDE HAZARD MAPPING APPROACHES

Attachment A-2: A comparison of PALCO and CGS landslide hazard mapping approaches

Independent of the landform, landslide inventories, and hazard mapping completed by PALCO for the Freshwater watershed analysis, the CGS carried out geologic mapping and landslide hazard mapping in the Freshwater watershed. The CGS and PALCO independently developed landslide hazard maps that take a slightly different approach and have a different format. Presented below is a comparison (Table A-2-1 and following text) of the two mapping approaches.

Table A-2-1: Hazard map attributes for the PALCO and CGS approaches to landslide hazard mapping.

Attribute	PALCO	CGS
Landslide hazard map types	There are six separate interpretive maps: Two maps display quantitative hazard or density ratings for shallow landslides originating at roads (landslides per 100 ft of road) and in harvest areas (landslides per acre) respectively for the period 1940 to 1997. Two additional maps show quantitative ratings for the expected frequency of shallow road and hillslope landslides (landslides per 100 ft of road or landslides per acre*)* that deliver directly to streams. Landslide density values are dependent on the minimum size of landslide selected for study. These maps do not separate expected background landslide frequencies from expected management-related landslide frequencies. The fifth map is the DLISA landslide hazard map that displays color-coded FOS ranges. These FOS ranges are calibrated to shallow hillslope landslide density values for the watershed. The sixth map provides qualitative landslide hazard ratings for large deep-seated landslides and earthflows. This approach clearly defines the source and type of specific landslide hazards. A disadvantage of this approach is that the user must review several maps to get a clear sense of the different types of landslide hazards that may be present in an area. At the request of the CGS a final map was produced which integrates the road and hillslope shallow landslide hazard maps and the deep-seated landslide hazard map on a single map sheet (Map A-11). This map displays a single hazard rating based on the highest of either the shallow road or hillslope landslide hazard for a given map polygon and is cross-hatched to display the higher hazard classes from the deep-seated landslide hazard map. Shallow landslide locations are shown on all the maps to indicate local potentially high hazard areas.	A single map which integrates qualitative landslide hazard interpretations for the relative potential for both shallow road and *shallow* hillslope landslides as well as qualitative hazard ratings for large, deep-seated landslides and earthflows. The landslide hazard map is interpretive but not entirely subjective. That is, it is based in part on watershed-specific field observations of landslide locations after logging or road building and the landscapes where these landslides appear most common. No ratings are given for the likelihood of delivery of landslides to streams. The advantage of the CGS approach is that the user needs to refer to only a single landslide hazard map. The disadvantage is that the relationships of specific hazards to roads, harvest areas, deep-seated landslides and likelihood of landslide delivery to streams are obscured. As with the PALCO approach, there is no separation of background versus management-related landslide activity. The USGS uses a similar landslide hazard rating system. Visual comparison of the CGS map with the PALCO maps indicates that the qualitative ratings on the CGS integrated map tend to be more conservative than the ratings on the individual empirical and deterministic landslide hazard maps as well as the ratings on the qualitative deep-seated landslide hazard map. The CGS ratings are not calibrated to known landslide density values or ranges.
Base information	The basic information includes a landform map, a geologic map (Falls, 1999), a topographic map, average, maximum and minimum slope angles derived from the PALCO DEM, landform polygon areas, and an air photo landslide inventory of shallow landslides for both roads and hillslopes (non-road areas) for a 57-year air photo record (1940-1997). All shallow road landslides were verified in the field; a limited number of shallow hillslope landslides were verified in the field. A separate shallow landslide inventory map is	A single-base geologic map with bedrock types, fault traces, shallow landslide locations, large deep-seated landslides and earthflows depicted on a topographic base map. Generalized areas, suspected or known to have been subject to debris slide activity in the past are identified with stippling on the map. The stippled areas on the base geologic map are qualitatively interpreted as sites of possible future landslides, not just past occurrences. Similarly, inner gorges are identified with

Table A-2-1: Hazard map attributes for the PALCO and CGS approaches to landslide hazard mapping.

Attribute	PALCO	CGS
	produced and is overlaid on a slope-geology polygon map generated by intersecting the landform and geology maps and is retained as a separate layer in the GIS. Landslide density values are determined by overlaying the shallow landslide inventory map on the slope-geology child polygon map, tabulating the number and type of landslides occurring in each landform polygon, and then calculating landslide densities on a per acre and unit length of road basis. A similar process was used to generate the DLISA landslide map with FOS ranges being applied to the slope-geology child polygon layer in the GIS. A separate, large, deep-seated landslide map was produced from air photo, map interpretation and limited fieldwork.	linear symbols on the map. The geologic data was compiled from existing published data and field mapping. The inventory of shallow landslides for both roads and hillslopes (non-road areas), is air photo based and spans a 57-year air photo record (1940-1997). Additional field identified landslides were added for the period 1997 through 1999. All shallow landslides occurring after 1997 and some pre-1997 landslides were verified in the field. The map is intended to show the relationship of the underlying geology and geologic structure to landslide features.
Landform types, polygons and mapping.	As is typical for landform mapping, landforms of varying types are shown covering the entire map area. Landforms (morphologic landform units – MLU's) are interpreted from a 1:18,000 scale topographic map (originally 1:24,000 scale) on the basis of slope and surface morphology as depicted on that map. Consequently, the landform map will only be as accurate as the topographic base map. The MLU landform polygons are defined by specific morphologic, slope gradient and stream class criteria described in the mass-wasting module methodology Appendix B. There was limited field validation of the MLU polygon boundaries. Inspection of the map shows a limited number of inclusions of gently sloping terrain in steeper MLU polygons and vice versa. The landform map does not depict surficial material types or geomorphic processes.	A comprehensive landform map is not produced. There are stippled areas on the geologic map indicating known or suspected debris slide source areas (debris slide slopes) that can be viewed as a form of landform mapping. Specific polygon boundaries, however, are not drawn around these areas. Polygon outlines are drawn around the locations of known or suspected earthflows or large, deep-seated landslides. These larger features can be considered a landform type. Additionally, the location of certain geologic features (e.g., inner gorges) are depicted on the map with on-site symbols but do not form discrete landform polygons. There are many areas on the CGS geology map where no landform is delineated.
Shallow landslide inventory	Includes all visible landslides on aerial photographs for the period 1940-97 and/or landslides identified during extensive walking traverses of roads. The PALCO shallow landslide inventory does not include landslides that occurred after 1997 because these landslides are outside the period of study defined for the Freshwater watershed analysis. Landslide locations on the landslide inventory map are transferred from the aerial photographs to the base map manually not by photogrammetric methods. Consequently, there is no correction for location as it may be influenced by air photo distortion. Similarly, landslides identified in the field but not on visible aerial photographs are manually plotted on the inventory map. The landslide inventory includes a database of landslide size information and information on delivery of landslide debris to streams cross-referenced by the landform type and polygon within which the landslides occurred. Cross-referencing with the CGS landslide map was carried out in cooperation with the CGS. A limited number of landslides that are visible on the aerial photographs used by the CGS and that were depicted on the CGS map were added to the PALCO shallow landslide inventory. Landslides plotted on the CGS map but not verifiable on the aerial photographs used by the CGS were not plotted on the PALCO shallow landslide inventory map. These differences occurred because the CGS had access to and reviewed some air photo records that were not used for the PALCO shallow landslide inventory. The CGS also included a limited number of post-1997 landslides on their map. At the request of CGS, a map showing composite landslide inventories and geology was produced (Map A-12).	Visible landslides were identified on an air photo record for the period 1940 to 1997. A limited amount of field-checking was carried out to field verify landslide locations and to add landslides that had occurred after the 1997 air photo date. The inventory was supplemented by field reviews of timber harvest plans, and associated roads, as well as geologic mapping conducted over a 4-year period (1995 through 1999). Landslide locations follow the same manual plotting approach used for the PALCO inventory. A comparison of the preliminary PALCO landslide inventory to the CGS geologic/landslide map found that a large number of landslides identified by the PALCO landslide inventory were not plotted on the CGS map. Many of these are likely smaller shallow road or hillslope landslides that are difficult to see on aerial photographs or were on PALCO aerial photographs that the CGS did not review. Some landslides plotted on the CGS geologic map could not be verified on the aerial photographs used by the CGS. As the CGS geologic map had already been submitted for printing, the map could not be updated to reflect this new information. Consequently, there is not an exact correspondence between the CGS shallow landslide locations and the PALCO shallow landslide inventory. The CGS is producing a separate digital landslide inventory map.

Table A-2-1: Hazard map attributes for the PALCO and CGS approaches to landslide hazard mapping.

Attribute	PALCO	CGS
Large landslide inventory map	This map was developed through air photo review of historical clearcut logging so that as many earthflows and large, deep-seated landslides as possible could be identified. These landslides are often most easily identified and mapped on aerial photographs taken shortly after an area has been clearcut logged. They can be difficult to identify on aerial photographs showing an extensive second-growth forest cover. A number of possible landslides, particularly in Franciscan geologic units were identified that are not depicted on the CGS large landslide map. This variation is likely because the CGS did not have on file some of the immediate post-logging air photo records that are in the PALCO air photo library. Limited field checking was carried out to verify landslide locations. There are, however, situations where landslide features are more easily identified on aerial photographs than in the field; consequently, field investigations do not always generate a positive verification of landslide presence or absence. An accompanying database identifies the landslide activity level for each large landslide. This activity level is depicted on the map. There are significantly less deep-seated landslides depicted on the CGS geology map than the PALCO deep-seated landslide map. We understand that the CGS is in the process of updating the deep-seated landslide locations on their map (J. Falls, pers. comm., 2002)	The CGS map was developed through air photo review of historical clearcut logging to identify as many large landslides as possible. Limited field checking was carried out to verify landslide locations. Both potential large landslide source areas (i.e., headscarp slopes) and the likely landslide mass are mapped as distinct features on the CGS geologic map. Landslides are identified as likely or questionable on the map by the use of a query (?) symbol for questionable landslide features. The activity levels of earthflows and large, deep-seated landslides are identified by the map symbology. Solid polygon lines indicate active landslides and dashed lines indicate inactive landslides. The large landslide inventory was supplemented by field review of timber harvest plans, and associated roads, as well as geologic mapping conducted over a 4-year period. Both the PALCO and CGS large landslide locations were plotted manually on the topographic base map by the geologists carrying out the work. The outlines of these large landslides were not transferred by photogrammetric means so location and extent will not be precise Like landform boundaries, the polygon outlines for these features should be regarded as approximate.
Landslide hazard map polygons	The shallow landslide hazard map polygons are composed of child polygons resulting from the intersection of the geology and landform polygons depicted on the original landform map and the geology maps. The large deep-seated landslide map polygons are the same as those on the deep-seated landslide hazard map. The hazard ratings are based on the activity level (i.e., relic, dormant and active as defined in this report) and specific morphological features of the landslides (e.g., steep headscarp depletion zones versus gently sloping accumulation zones). A table listing these criteria is provided in the body of this report. It should be noted that the activity level of these deep-seated landslides can change with significant but short-term changes in climate (CGS, pers. com., Nov. 2000), so the activity level noted on the landslide map is relative to the date of map production. The activity level of the deep-seated landslides is based on a set of morphologic criteria outlined in Keaton and DeGraff, 1996.	The large landslide polygons from the geologic map are retained as polygons on the hazard map. On the basis of interpretation of historical shallow landslides, slope gradient and morphologic (curvature) changes on the topographic map, additional hazard polygons are added to the map. There is limited field verification of the locations of the hazard polygon boundaries. Inspection of the map shows some inclusions of gently sloping terrain in steeper hazard units and vice versa. The large landslide areas on the hazard map are given a hazard rating that is one level higher than surrounding undisturbed areas. The large landslides are given a higher hazard rating than the surrounding areas because of an assumed potential for reactivation or all or part of the landslide mass. For example, in an evaluation conducted for the State Office of Emergency Services, CGS found that 35 percent or more of the storm-related landslides that occurred during the winters of 1995 through 1998 were located in areas of previously mapped as large deep-seated landslides (Bedrosian 1999, 1995).
Landform and hazard map polygon boundaries	These boundaries are derived from office interpretation of topographic contours on a 1:18,000 scale topographic map derived from a USGS 10 meter DEM, following the slope gradient and morphologic criteria noted above. Fieldwork to refine polygon boundaries was limited. Polygon boundary locations may not represent exact field locations of landform boundaries. These boundaries, like most geologic map boundaries, are approximate and the field locations of landform boundaries will likely vary in the range of $\pm$10 to $\pm$100 ft from that portrayed on the landform or landslide hazard maps. The term “approximate” refers to map boundaries that are gradational over short distances or that can be only approximately located. We should also note that the field observer should never assume that even such simple features as roads, are accurately plotted on topographic base maps.	There was field-checking of geologic boundaries and geologic unit characteristics and limited field-checking of the locations of shallow and deep-seated landslides. As with the PALCO maps, CGS polygon boundary lines are based on the best judgement of a single geologist as interpreted from a topographic base map. Interpretation of slope gradient and other morphologic features used to generate geologic, landform and hazard maps will only be as accurate as the accuracy of the original topographic base map. Consequently, these lines are not precise and will imitate but not exactly replicate real-world locations of slope and morphologic change. Like the boundary lines on the PALCO maps these boundaries should be regarded as approximate (i.e., vary in the range of $\pm$10 to $\pm$100 ft) with respect to landform and landslide hazard boundaries or changes in slope viewed or identified in the

Table A-2-1: Hazard map attributes for the PALCO and CGS approaches to landslide hazard mapping.

Attribute	PALCO	CGS
	Although the criteria defining landform types are specific, there will be some variation in polygon definition by different mappers. This variation is limited within a single watershed by having only one geologist carry out the landform mapping and by consultation among geologists who are working in different watersheds. There may be some opportunity to automate landform delineation by using slope and shape algorithms within the GIS but this was not done in Freshwater. Computer generation of landform polygons even if it can only be done for preliminary landform delineation would help reduce differences among mappers.	field.
Hazard class criteria and hazard class assignments	The PALCO shallow landslide hazard maps rely on an objective, empirical approach based on landslide density values (landslides per acre or landslides per 100 ft of road). Landforms are grouped into hazard classes or associations with similar landslide densities. These groupings are generated by a segmentation (decision tree) algorithm (CHAID: Chi-squared Automatic Interaction Detector) to identify optimal splits in the data. The analytical approach and results are described in detail in the body of the report. Because the hazard maps are generated in a GIS using specific criteria developed by the statistical analysis, hazard classifications for unique combinations of geology, slope and morphology are objective and constant across each hazard map. The colors on the landslide hazard map are picked arbitrarily to highlight the trend from lower to higher landslide densities. We should note that the hazard statistics for landslide frequency are based on the population of mapped landform and geology polygons drawn for each specific watershed so the landslide frequency statistics reflect the character of the mapped geology, slopes, landforms and associated landslide activity in each specific watershed. This approach to landslide hazard mapping falls into what has been termed univariate or multi-variate probabilistic analysis (Resources Inventory Committee 1996) depending on whether the data is analyzed using univariate or multi-variate statistics. A discussion of these approaches, excerpted from the aforementioned reference, is appended at the end of this comparison.	The CGS hazard map is based on generalized qualitative criteria (Falls 1999b) and is described as a relative landslide potential rating by the CGS. A brief description of this approach follows this table and is largely excerpted from the mass-wasting methodology Section 5.6.1. The criteria for the CGS hazard map have been excerpted from Falls (1999b) and are presented below. The CGS landslide hazard maps, like the PALCO landslide hazard maps, are prepared to aid in resource management and general land use planning. They are not intended, nor should they be used for, evaluation of specific sites. Site-specific evaluations often require detailed engineering geologic studies, and at times, soil engineering investigations of the underlying soil and bedrock, for proper planning of specific projects.

Discussion of Hazard Mapping Approaches

Relative landslide potential is a landslide hazard classification developed and used by the CGS for ranking the relative stability of various map areas. This approach is termed subjective geomorphic analysis or subjective rating analysis (Resources Inventory Committee 1996), depending on the specificity of the defining criteria. The approach involves the delineation of map polygons based on one or more terrain attributes and the development of a set of subjective defining criteria (an algorithm) used to assign a single landslide hazard class to each map polygon in a watershed.

The more specific the criteria, the more repeatable the stability assignments. Typically, combinations specific to the study area of geologic material, slope range (e.g., 30° to 35°), surface morphology (e.g. concave, convex, and planar slopes), geomorphic process and soil moisture conditions are specified in a tabular format and are applied to a pre-existing landform map in a systematic fashion. It is important that the defining criteria are as specific as possible. If not, there is a reasonable chance that interpretations by a single geologist for specific combinations of geology, slope and morphology will vary across a map area. Similarly, if criteria are not specific, it is likely that different geologists will produce different hazard assignments from the same base geologic, landslide, and topographic information.

Field observations and knowledge of a specific study watershed will influence hazard assignments so there should be specific documentation of how and where this influence occurs. Similarly, it is important to document how experience or observations in other nearby watersheds may influence or bias hazard interpretations in the study watershed.

Applied carefully, the approach ensures consistent landslide hazard rating assignments across a map area. The approach is very flexible and can be effective at a variety of scales and degrees of effort; however, it is very reliant on the skills and experience of the mapper. The approach has been widely applied in many jurisdictions around the world. The most notable example of this type of mapping for forestry purposes on the west coast of North America is in British Columbia where extensive areas of public and private forest lands have been classified for the potential for landslides following forest harvesting and road building.

The subjective geomorphic analysis methodology has been in use in California for some 30 years in both urban and rural areas. The method has been peer reviewed and has the concurrence of the California State Mining and Geology Board. The USGS uses a similar rating system.

The CGS system assigns a relative potential for landsliding rating[11] between the extremes of stable, flat valley bottom slopes and actively sliding material (lowest relative strength), as described below:

The CGS map (Open-File Report 99-10a, Plate 2, Falls 1999b) is derivative, based on the following: (1) the occurrence and distribution of landslides, other types of slope failure, and features indicating slope instability (Plate 1, Open-File Report 99-10); (2) the geology of the area, including bedrock types and lithologic properties relative to slope stability and distribution

[11] The following discussion is excerpted in large part from the marginal notes attached to Plate 2, Open-File Report 99-10a, California Department of Conservation, Division of Mines and Geology. Relative Landslide Potential Map Freshwater Creek, Humboldt County, California. James N. Falls. 1999.

of the various earth materials as well as the structural framework, such as the folded and faulted strata found throughout the region; and (3) the relative behavior of slopes within the area as interpreted from analysis of historic aerial photographs and recent field observations.

Studies of the stability of specific sites commonly require development of quantitative data through laboratory testing of field samples. This level of testing was not done for this regional evaluation. In producing the map, the CGS assumed that actively sliding material has the lowest relative strength, and thus, the highest relative potential for landsliding of all the geological materials underlying the slopes. Recent alluvial deposits in the valley bottom were assumed to possess the least potential for landsliding because of their flat slope. The relative potential for landsliding between these extremes was evaluated subjectively based on air photo interpretation, field observations, and the following principals:

- The broad apparent stability characteristics of geological materials underlying the slopes and adjacent lower-lying slope areas, as expressed in their natural exposures and their observed responses to alteration by land use activities. For example, slopes that exhibit abundant evidence of landsliding or downslope creep of the soil are considered oversteepened relative to the strength of the materials that underlie them.

- Steepness of slopes, whether or not landslides are apparent.

- The presence of active or intermittent natural influences that tend to cause slope failure. These include gravity, climatic conditions, fluvial processes, and the tendency of certain soils to shrink and swell under varying moisture conditions.

These criteria are combined to yield a five-value scale used on the relative landslide potential map to indicate the comparative capacity of slopes within the map area to resist failure by landsliding. These five classes and a set of general criteria are outlined in the following table.

Probabilistic univariate analysis uses objective probabilistic statistical methods to produce a quantitative link between terrain stability/landslide hazard classes and actual observed performance of slopes. A quantitative correlation extends the relative univariate analysis by assuming that the probability of future landslides can be predicted from the frequency of landslides in similar terrain units over a given time period.

In this method, a statistical correlation is sought between the probability of occurrence and a single terrain attribute or a prescribed combination of several terrain attributes (multi-parameter classification). The probability of occurrence is usually a spatial distribution, although in some cases where the landslide density map can be correlated with a time period, it is also expressed as a temporal probability of occurrence. The probabilistic univariate analysis is usually applied on the basis of terrain polygons.

Relative landslide potential classes – CGS Freshwater map.

Class Number	Class Descriptor	Class Criteria[12]
1	Very Low	Landslides and other features related to slope instability are very rare to nonexistent within this area. Included are low-lying valley bottoms and alluvial floodplains. Poorly consolidated weak sediments underlie many of these units, but these materials are relatively stable due to the flatness of the slope.
2	Low	This area includes gentle to moderate slopes underlain by relatively competent material that is considered unlikely to mobilize under natural conditions. Mass wasting in these areas is not common. Included are broad ridges and stream terraces. The ridges are underlain by relatively competent rock and are generally stable. Moderately consolidated sediments underlie the terraces. These materials lack the strength to support steep slopes but are generally stable due to the flatness of the slopes.
3	Moderate	Moderately steep, relatively uniform slopes are generally underlain by competent bedrock and have evolved through erosion by running water, rather than by landsliding. Slopes within this area may be at or near their stability limits due to weaker materials, steeper slopes, or a combination of these factors. Old landslides within these areas have been extensively modified by erosion and are not easily distinguished from surrounding relatively stable terrain.
4	High	These areas are characterized by steep slopes and include most landslides in upslope areas, whether apparently active at present or not, and slopes upon which there is substantial evidence of down slope creep of surface materials. Included are debris slide slopes and areas where weak rocks or adverse bedding are likely to exist. Evidence for debris slides or recent movement may not be clearly present in all of these areas.
5	Very High	Areas include active landslides, areas of “disrupted ground,” debris slide/flow source areas, and inner gorges. Slopes are very steep. Also included are areas that would be classified as “high”, except that a concentration of landslides suggests that the area is potentially more unstable.

This method is practical because it is simple to implement and test. Selection of relevant terrain attributes and definition of classes, however, requires careful and thorough work. A potential source of error, which is common to all statistical methods, is the quality and detail of the landslide frequency data on which the correlations are based. A further potential source of error is the delineation and classification of polygons by the mapper during the data collection phase. Because mapping variability can influence the resultant landslide frequencies correlated with a particular multi-parameter terrain class, combining individual terrain types into generalized classes reduces this problem somewhat, and tends to smooth over differences between mappers.

The probabilistic univariate analysis method has been used in a number of forestry related studies in British Columbia, for example by Rollerson and Sondheim (1985), Howes (1987), and Rollerson (1992). In the forest industry, background data consists of landslide occurrence during

[12] The first sentence or two of each hazard class criteria describe general conditions, and the following sentences describe conditions specific to individual map areas.

the critical 5 to 15-year time period following logging. The predicted spatial probability of occurrence relates to the same time period and can therefore be converted into a temporal probability of occurrence.

The choice of relevant terrain attributes and their use in establishing the multi-parameter classification is done by judgment or by trial and error, by testing different combinations of parameters. The selection of terrain attributes can be guided by a parallel relative univariate analysis of each separate terrain attribute. Rollerson and Sondheim (1985) tried different classifications based on slope, slope morphology, surface material, aspect, and the occurrence of natural landslides, and found that different classifications were needed for clearcut and road related landslides. Howes (1987) defined 15 multi-parameter classes based on landform, drainage, soil depth, slope angle and morphology and the presence of gully erosion. (Resources Inventory Committee 1996).

Probabilistic multivariate analysis uses objective multiple regression methods to establish a correlation between probability of occurrence and a group of terrain attributes. The method can be applied on a site-specific basis (e.g., Pack 1995), or on an overlay polygon basis, (e.g., Carrara 1983).

A simple version of probabilistic multivariate analysis is the matrix approach suggested by DeGraff and Romesburg (1984). Using overlays of maps delineated by terrain attribute polygons, they defined a separate class for each combination of independent terrain attributes. For example, using three terrain attributes, such as bedrock, slope and drainage, with four classes in each, the resulting matrix had $4 \times 4 \times 4 = 4^3 = 64$ possible classes. While conceptually simple, the large number of combination classes, which can result even with a few terrain attributes, requires a detailed database of landslide occurrences to achieve statistically significant correlation.

More formal multiple regression and discriminant statistical analyses, using as many as 25 terrain attributes, have been conducted by Carrara (1983, Carrara et al. 1991) with the help of a GIS. Van Westen (1993) tested similar procedures on a carefully mapped study area and found that no significant correlations resulted due to insufficient quality of the input data. He found that both relative and probabilistic univariate analyses produced satisfactory results with the same data.

The main disadvantage of the probabilistic multi-variate analysis is that it excludes the experience and judgement of the mapper in producing correlations. Thus, the results are totally dependent on the quality of the data (Resources Inventory Committee 1996).

The advantage of the CHAID analysis used in this study over some more conventional multivariate analyses is that the geologist can visually inspect the decision trees produced by the analysis and intervene manually to prune branches of the tree that do not make sense geologically. For example, small sample sizes in the terminal nodes of some CHAID trees can result in the identification of statistically significant, but special or anomalous relationships that are not geologically sensible. In these situations, the geologist should intervene and prune a node or branch. Because of the need to assess the geologic validity of the results, only a geologist undertakes these analyses.

Appendix B

Freshwater Creek Watershed Analysis

Surface Erosion Assessment

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EXECUTIVE SUMMARY

The Surface Erosion Module evaluated the effects of roads, timber harvesting, and other land uses on surface erosion in the Freshwater Creek Watershed. The following conclusions were reached in answer to the critical questions for the module.

Sensitivity of soils to erosion: Soils in the eastern part of the watershed underlain by Franciscan rocks have a moderate erosion potential, and soils in the western half of the basin underlain by the Wildcat Group have a higher erosion potential.

Background sediment yield: Sediment input from soil creep was evaluated, and averaged 2,700 tons/yr (90 tons/sq mi/yr). Sediment input from natural fires is low due to the infrequent occurrence of natural fire in redwood stands.

Timber harvest: Surface erosion from timber harvest was evaluated, and averaged 225 tons/year over the past 10 years (7 tons/sq mi/yr). Input from timber harvest is higher following years with more harvest and lower when less harvest occurs. High densities of bladed skid trails in tractor yarded units and erodible soils yielded the highest erosion rates. Little surface erosion occurs on cable-yarded or helicopter yarded units. Broadcast burning, particularly hot burns or burns combined with mechanical site preparation, results in some surface erosion on steeper slopes. Use of spot herbicide applications did not noticeably increase surface erosion. Input of sediment from harvest units drops rapidly within 2-3 years following harvest.

Other land uses: Surface erosion from home building and the Freshwater stables was evaluated and yielded small amounts of erosion (1-4 tons/year). At present, there is little dispersed grazing in forest lands or use by recreational vehicles, so little erosion is associated with these land uses.

Road erosion: Surface erosion from roads was evaluated, and averaged 6,200 tons/yr under current road use conditions (200 tons/sq mi/yr). The majority (65%) of the road sediment is produced from the many miles of native surfaced roads in the watershed. Gravel-surfaced mainline roads produce another 25% of the road-related surface erosion. Approximately 24 miles (12%) of roads in the watershed deliver directly to streams, and an estimated 80 additional miles (38%) are within 200 ft of a stream and deliver a portion of their sediment to streams. The SEDMODL program was found to over-estimate the length of road directly delivering to streams by about 85% compared to the PWA road inventory. Keeping this over-estimate in mind, SEDMODL is an effective tool to predict surface erosion from roads in areas where a complete road inventory is not made.

An estimate of road gully erosion and stream crossing washouts was made based on the PWA field inventory of PALCO roads. An estimated total of 8,550 tons of sediment was delivered to streams over the most recent decade covered by the inventory (1988-1997). This is a small amount compared to road surface erosion.

Surface erosion from all sources delivers primarily silt and clay-sized particles to streams in the watershed, with about 70% of sediment silt- and clay-sized, 25% sand-sized, and the remainder fine gravel. This is due to the fact that most of the soils in the watershed have a very high silt and clay content, and surface erosion generally does not have enough energy to move particles larger than sand size. The silt and clay contribute to turbidity and suspended concentrations in streams in the watershed.

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1.0 INTRODUCTION

Surface erosion is the detachment of soil particles by water, wind, or raveling. In the majority of forested basins, a thick layer of duff protects the soil from surface erosion, and most rainfall and snowmelt infiltrates into the soil. However, if the duff layer is removed to expose bare mineral soil, or the soil is compacted to concentrate runoff, surface erosion can occur. Most sediments delivered to streams from surface erosion are small particles (sand, silt, clay). The goal of the Freshwater Creek Surface Erosion Assessment is to provide assessment and prescription team members with an understanding of the following issues:

- Which areas of the watershed are sensitive to surface erosion?
- What types of activities occur in the basin that could cause surface erosion?
- How much sediment is delivered to streams[1] from surface erosion resulting from each land management activity (in comparison with background inputs of sediment) and is it enough to negatively affect aquatic habitat or water quality?

1.1 SURFACE EROSION CRITICAL QUESTIONS

The following critical questions were used to guide the analysis to produce the information necessary for the Watershed Analysis Team to understand surface erosion processes in the Freshwater Watershed.

1.1.1 Hillslope Erosion

- How erodible are the soils or geological formations in the watershed when disturbed?
- What activities in the watershed could contribute to surface erosion on hillslopes (e.g., tractor or cable yarding, construction of layouts, broadcast burning, mechanical site preparation, treatment of competing vegetation during revegetation, wildfire, mining, agriculture, recreational vehicle use)?

[1] A stream channel is defined as any drainage depression containing a defined bed and banks, extending continuously below the drainage site. The flow regime can be ephemeral, intermittent, or perennial. This definition includes Class I, II, and III streams.

- How much and what grain size of sediment is delivered to streams from surface erosion associated with each activity on hillslopes? What land management practices and mechanisms allow delivery?

- Which areas of the watershed have greater potential for surface erosion if ground-disturbing activities take place?

1.1.2 Road Erosion

- Which portions of the road network contribute sediment to streams in the watershed?

- How much and what grain size of sediment is delivered from road surface erosion (and gullying)?

- What road attributes trigger surface erosion (e.g., traffic rates, surfacing, road widths, cutslope or fillslope erosion, gully erosion)?

1.1.3 Effects on Aquatic Habitat and Water Quality

- How much and what grain size of sediment would be delivered to streams if the watershed was not managed (i.e., background sediment input)?

- What amounts and types of sediment are contributed from forest practices?

- What is the potential effect of sediment on aquatic habitat and water quality? (Note: this is determined in conjunction with the Channel and Fisheries analysts during Synthesis and is not directly addressed in the Surface Erosion Assessment.)

1.2 BASIN CHARACTERISTICS INFLUENCING SURFACE EROSION

There are several inherent characteristics in any watershed that influence the susceptibility of the basin to surface erosion. These include the topography, soils/geology, climate, and vegetation in the watershed. In addition, the current and historic land ownership and land use patterns in the watershed influence the amount of ground disturbance and resulting surface erosion that takes place.

1.2.1 Topography

Soils on steeper slopes are more susceptible to erosion when disturbed than the same soil on gentler ground. Slopes in the Freshwater Watershed are generally moderate (less than 35% slope gradient). Steep slopes (over 65% slope gradient) are found along portions of the inner gorge areas of Freshwater Creek and the major tributaries, including Cloney Gulch, Graham Gulch, the upper mainstem, the South Fork, and Little Freshwater Creek. Other steep slopes are found in headwall areas underlain by the Wildcat Formation in the South Fork and Little Freshwater drainages. Very gently sloping ground is found along the lower, alluvial portions of the mainstem valley.

1.2.2 Geology/Soils

The texture (grain size) and consolidation of soil influence how easily the soil particles are eroded. Large gravel and cobble-sized particles are more difficult to erode via surface erosion processes, and are left behind as a protective lag deposit on eroding surfaces. Sand and silt-sized particles are very easy to erode; soils with a high sand/silt fraction are generally very erodible. Clay-sized particles, while very small and easily carried once in suspension, are actually more difficult to erode because clay soils are usually consolidated, and electrostatic charges between the small clay particles hold them together.

Soil texture is largely controlled by the underlying geology. The Freshwater Creek Watershed is dominated by rocks of the Wildcat Group and Franciscan Central Belt metasedimentary rocks, with smaller amounts of the underlying Yager Formation exposed in some stream channels, as well as Quaternary alluvium in the lower watershed. A detailed description of the geologic formations and history of the watershed is included in the Mass Wasting Assessment (Appendix A); important for surface erosion processes is how these formations influence soil texture and erodibility.

The Wildcat Group underlies the western half of the watershed (Map A-9 in the Mass Wasting Assessment) and is composed of slightly indurated (i.e., not consolidated) mudstone, siltstone, claystone, fine-grained sandstone, and minor conglomerate. Because the sediments are primarily silt- and sand-sized and are geologically young sediments (not indurated into hard rock), they are quite erodible when exposed.

The Yager Formation underlies the Wildcat Group and is exposed in places in stream bottoms where the river has cut down through the Wildcat sediments. The Yager Formation includes indurated mudstones, shales, and siltstones that weather to soft clayey materials, and harder graywackes and conglomerates that remain as boulders along streams.

Rocks of the Franciscan Central Belt underlie the eastern half of the watershed and include pervasively sheared metasedimentary rocks consisting of a matrix of fine sediments with included blocks of harder metamorphic rocks. These rocks weather to sand, silt, and clay with a higher fraction of larger rocks, which slightly reduces their erosion potential when compared to Wildcat sediments.

The alluvium filling the lower Freshwater valley includes Quaternary river terrace deposits and Holocene alluvial deposits of unconsolidated sand, gravel, silt, and clay. These sediments are erodible if exposed on steep cuts, but are generally less erodible because of the gentle slopes in the lower valley.

Soils in the Freshwater Creek Watershed have been mapped by the Natural Resource Conservation Service (NRCS, formerly the Soil Conservation Service). The most recent mapping of soils was in the 1970s; the NRCS is in the process of updating soil maps of Humboldt County. Map B-1 shows the most recent (1970s) map of soils in Freshwater Creek.

Soils are roughly correlated with underlying geology, with Larabee soils developed in areas of Wildcat Formation in the western half of the basin and Hugo, Atwell, Melbourne, and small areas of other soils on Franciscan rocks in the eastern portions of the basin. Bottomland and Farmland soils are developed on the Quaternary alluvium in the lower mainstem. Table 1-1 shows the properties of soils in the basin pertinent to surface erosion – the soil depth, texture, drainage, permeability, and erosion hazard based on the NRCS database.

All the methods used to estimate the delivery of sediment from the erosion source area to a stream are based on the assumption that sediment is carried to the stream by overland flow. If the water carrying the sediment infiltrates into the soil, it is assumed that the sediment carried in the flow is deposited and does not reach a stream. During adaptation of the Surface Erosion Module methods for PALCO lands (PALCO 2000), several commenters raised questions about the delivery of sediment through underground soil pipes rather than via overland flow. Soil pipes are present in at least some soils in the Freshwater Creek Watershed. The Pacific Watershed Associates (PWA) field crew reported seeing water flowing out of soil pipes in some road cutbanks during their field surveys.

Table 1-1: Properties of soils in the Freshwater Creek Watershed.

Soil series name	Percent total basin area	Depth range (in.)	Parent Material	Texture of surface/ subsurface	Drainage	Permeability	Erosion Hazard (Low, Moderate, High, Extreme)
Atwell	13%	36-72	Sheared sedimentary rock	Loam/ gravelly clay loam	* Mod. well or somewhat poor	* Mod. slow surface; very slow below	M to H
Boomer	2%	26-60	metamorphosed basic igneous rock	Gravelly loam/ gravelly clay loam	* Well	* Mod. slow	L
Empire	0.2%	40-70	Soft sedimentary rock	Loam/ clay loam	* Well to mod. well	* Mod. rapid to slow	M to H
Hely	0.2%	40-70	Soft sedimentary rock	Loam/ fine sandy loam	* Well	* Rapid to mod. rapid	H
Hugo	22%	30-60	Sandstone & shale	Gravelly loam/ stony clay loam	* Well	* Mod. rapid	M to E
Hugo Var.	0.2%	30-60	Metamorphosed sedimentary rock	Gravelly loam/ gravelly clay loam	* Well	* Mod. rapid	M
Josephine	2%	30-60	Sandstone and shale	Loam/ clay loam	* Moderate	* Moderate	M
Kinman	1%	40-72	Sandstone and shale	Clay loam/ clay	* Mod. well or somewhat poor	* Slow	M
Larabee	44%	40-70	Soft sedimentary rock	Loam/ clay loam	* Moderate	* Moderate	M
Laughlin	0.1%	16-36	Sandstone and shale	Loam/ loam	* Well	* Mod.	M to H
Melbourne	5%	30-60	Sandstone and shale	Loam/ clay loam	* Well	* Moderate	M
Tyson	0.3%	18-48	Sandstone and shale	Gravelly loam/ very gravelly loam	* Well	* Mod.	M
Wilder	0.04%	26-50	Sandstone	Sandy loam/ gravelly sandy loam	* Mod. well to well	* Mod. rapid	H
Yorkville	2%	30-60	Metamorphosed rock	Clay loam/ clay	* Mod. well to well	* Slow to very slow	M to H
** Bottom Land	2%	64-70+	Sedimentary alluvium	Loam/ Silt loam	Mod. well to imperf.	Mod. rapid to slow	L
** Farmland	4%	64-70+	Sedimentary alluvium	Loam/ Silt loam	Mod. well to imperf.	Mod. rapid to slow	L
** Terraces	0.4%	64-70+	Sedimentary alluvium	Loam/ Silt loam	Mod. well to imperf.	Mod. rapid to slow	L to M
*** x7 (power line)	2%	*** Varies	*** Varies	*** Varies	*** Varies	*** Varies	-

Notes:
*Information on soil drainage and permeability characteristics for these soils was obtained from the USDA NRCS Official Soil Series Descriptions database (http://www.statlab.iastate.edu/soils/osd/).

**Mapping units Bottomland, Farmland, and Terraces contain areas mapped by McLaughlin and Harradine (1965) as primarily Loleta and Russ soil series. Estimates of soil characteristics are based on these two series.

***Mapping unit x7 contains areas classified by McLaughlin and Harradine (1965) as residential, business, and industrial areas. In the Freshwater, this soil is mapped along the transmission line corridor. Soil characteristics can be inferred from adjacent map units.

During field visits for the Surface Erosion Module, two types of underground passageways were observed. The first type occurred in some swales that on the surface had no channel features, but contained a hidden channel totally covered with fallen tree limbs/slash and leaf litter. The majority of these covered swales were mapped as Class III channels on watershed maps, and so any sediment delivered to them would be considered delivered to the stream system in the present assessment.

The second type of underground passageways observed fit the classic definition of soil pipes—large macropores within the soil profile. It is likely that some of the sediment delivered to soil pipes in the watershed eventually is routed to the stream system. Researchers in the area report increased sediment output from some soil pipes following timber harvest and no increased sediment output from other soil pipes (Ziemer 1992). There is little if any quantifiable information available on the delivery of sediment to streams from soil pipes. Since the process takes place underground, there was little opportunity for observing this process. Therefore, for the present assessment, delivery of sediment through soil pipes was not quantified.

1.2.3 Climate

The Freshwater Creek Watershed receives an average of 40-75 in. of rain per year, with lower amounts of rain in the lower mainstem and increasing precipitation at higher elevations. The majority of the precipitation falls as rain, with snow uncommon in most of the basin. Most of the precipitation occurs between October and May, with occasional intense storms during the winter months. The weighted mean annual precipitation over the entire basin is 60 in./year. The two-year one-hour rainfall is 0.5 in. Details of basin climate and historic rainfall records are described in the Hydrologic Change Assessment (Appendix C).

1.2.4 Land Ownership and Use

Approximately three quarters of the Freshwater Creek Watershed is owned by PALCO and managed for commercial timber production. Several areas in the upper, eastern portions of the watershed are owned by small, private landowners and used for residences, ranching, and timberlands. The majority of the lower mainstem valley is residential and/or pastureland and owned by small private landowners. Ownership is shown on Map B-7.

1.2.5 Types of Ground-disturbing Activities

Ground-disturbing activities in the Freshwater Watershed include road construction and use, timber harvest operations, grazing, recreational vehicle use, and development on residential lots.

The following potential sources of sediment were identified by the Freshwater Watershed Analysis Team at the beginning of the analysis. Underlined sources are considered in this Surface Erosion Assessment; the other sources are considered in either the Mass Wasting or Stream Channel Assessment.

Background input:

- soil creep
- mass wasting from undisturbed areas
- stream bank erosion
- natural fire

Timber harvest erosion (associated with clearcuts or partial cuts; constructing layouts for tree felling; tractor/skidder trails; cable yarding; mechanical site preparation or burning; or treatment of competing vegetation during revegetation with herbicides, hand thinning, or other methods):

- surface erosion
- mass wasting
- management-related streambank erosion

Road and landing erosion:

- mass wasting
- surface erosion
- gullying
- culvert washouts

Other uses:

- grazing in forested areas
- tilled fields (mostly lower basin)
- pastures (headwaters area, lower basin)
- home building activities/urbanization
- recreational vehicle use
- mining (gravel mining in streams)
- rock pits

1.2.6 Sub-basins Used in the Assessment

In consultation with the Hydrology and Stream Channel analysts, eight sub-basins were selected within the Freshwater Watershed to localize the study of watershed processes. These sub-basins correspond to the major tributaries and include Upper Freshwater, South Fork, Little Freshwater, Graham Gulch, Cloney Gulch, McCready Gulch, School Forest, and Lower Freshwater. Within these sub-basins, 49 smaller Hydrologic Analysis Units (HAUs) were delineated by the hydrology analyst to analyze effects at an even smaller spatial scale. A map showing where these sub-basins and HAUs is located is included in the Hydrologic Change Assessment (Appendix C, Figure 1-4). Sub-basins are delineated on maps in the surface erosion report.

2.0 BACKGROUND SEDIMENT YIELD

An estimate of the background sediment input rate, the amount of sediment that would be expected to be supplied to channels if there were no land management activities in the basin, is important to allow the Watershed Analysis Team to compare background and management inputs. In most forested basins, tree throw, animal burrowing, and soil creep move sediment slowly downhill and feed mechanisms such as streambank erosion that deliver it to the channel. Other mechanisms, including mass wasting and surface erosion following wildfires, can also deliver sediment to streams in undisturbed basins. In the Freshwater Watershed, we considered background erosion components of soil creep (inclusive of tree throw and burrowing), wildfires, streambank erosion, and mass wasting. The estimates of soil creep and surface erosion from wildfires are discussed in this Surface Erosion Assessment; streambank erosion is developed in the Stream Channel Assessment and further considered in this Surface Erosion Assessment, and mass wasting is discussed in the Mass Wasting Assessment. All background sources are compiled and discussed in the sediment budget discussion in the Stream Channel Assessment.

2.1 METHODS

2.1.1 Soil Creep

Soil creep was calculated using the following formula (WDNR 1997):

Annual Sediment Yield from Soil Creep = Length of Stream Channel x 2 banks x Soil Depth x Average Creep Rate x Soil Bulk Density

A creep rate of 0.04 in./yr (1 mm/year) was used for slopes less than 30%; a rate of 0.08 in./year (2 mm/year) was used for steeper slopes (WDNR 1997). These rates are similar to creep rates of 0.04-0.1 in/yr (1-2.5 mm/yr) measured in nearby Redwood Creek (Swanston et al. 1984). Soil creep rates may be higher on areas of large, deep-seated landslides (Map A-3 in the Mass Wasting report). Swanston et al. found displacement rates of 0.12-0.52 in/yr (3-131 mm/yr) in areas of Redwood Creek underlain by active earthflows. In the Freshwater basin, only one active earthflow was found that delivered to a stream. Sediment input from that earthflow was quantified separately in the mass wasting and stream channel reports. Soil depths used were those reported by the NRCS for each soil type (Table 1-1). A bulk density value of 1.2 tons/cubic yard was used based on bulk density measurements on Wildcat and Franciscan geologies (pers. comm., Tom Koler).

The length of stream channel from the GIS database (Class I, II, and III streams) was overlaid with the hillslope gradient coverage and soil coverage to produce a table of stream length by soil by hillslope gradient by sub-basin. The above formula and rates were applied to this table and summed to produce soil creep by sub-basin. These calculations are shown in Data Worksheet B2-1.

2.1.2 Wildfires

In many areas of the western United States, wildfires are a natural component of the ecosystem and a mechanism for disturbance. Intense fires can burn vegetation and duff layers that protect the underlying mineral soil from erosion, and in some cases produce hydrophobic soil conditions that reduce infiltration and increase runoff and erosion. Less intense fires do not burn all vegetation or the duff layer, and usually result in little surface erosion. Revegetation following natural fires is often rapid, especially in riparian areas where adequate moisture exists, and in areas that are not intensely burned.

Many researchers have investigated wildfire recurrence and ecology in coastal California redwood and Douglas-fir ecosystems (Agee 1993, Finney 1991, Finney and Martin 1989, Stuart 1987, Viers 1980 and 1982). The cool, humid climate and generally moist conditions of lower elevation redwood forests do not provide a good medium for wildfire initiation or propagation. As a result, fire recurrence intervals in undisturbed redwood forests are considered to be on the order of 25-50 years for low intensity fires (Viers 1980 and Stuart 1987), and 500-600 years for high intensity, stand-replacing fires (Viers 1980). In higher elevation Douglas-fir ecosystems, low intensity fires are more frequent, and stand replacing fires have a recurrence interval of 130-750 years (Agee 1993).

Because of the low recurrence interval of high intensity fires in undisturbed ecosystems represented in the Freshwater Watershed and the rapid revegetation that takes place following disturbance due to the moist climate, we did not feel that surface erosion from wildfires was a large component of the background sediment input rates in the watershed. This is consistent with the opinion of fire ecology researchers in the area (pers. comm., Steve Underwood, National Park Service). Therefore, no estimate of sediment input associated with wildfires was made.

2.1.3 Separating Erosion Estimates into Grain Size Components

Information on the grain size distribution of Wildcat and Franciscan rocks in the Freshwater basin was provided by Tom Koler (pers. comm., 2000) based on 122 samples taken in the area. Table 2-1 shows the average grain size distribution and bulk density for each geology. This information was used to divide the calculated erosion rates from all erosion processes into grain size components.

Table 2-1: Grain size distribution and bulk density of basin sediments by geology.

Geology	Percent Gravel (>4.75 mm)	Percent Med/Coarse Sand (2-4.75 mm)	Percent Fine Sand (0.075-2 mm)	Percent Silt and Clay (<0.075 mm)	Bulk Density (tons/cu yd)
Wildcat	2.4	4.4	15.5	77.6	1.23
Franciscan	11.5	10.2	20.5	57.8	1.2

2.2 ANALYSIS AND RESULTS

The method to estimate soil creep developed by the WDNR incorporates sediment input to streams from several different input mechanisms, including streambank erosion and small streambank landslides. In the Freshwater Creek basin, a separate estimate of streambank erosion and slides was made for the period 1942-1997 based on an inventory of approximately 16 miles of Class I stream channels on PALCO land (Map 9 in PWA 1999). Half of the inventoried sediment input from streambank erosion and small streambank slides was assumed to be attributed to background erosion (the other half was assumed to be related to management activities). Table 2-2 shows a comparison of calculated soil creep and average annual streambank/small slides input from the inventoried stream reaches.

Table 2-2: Comparison of calculated soil creep and inventoried streambank erosion/slides on Class I channels.

Sub-basin	Estimated soil creep (tons/mi of stream/yr)	Streambank erosion/slides (tons/mi of stream/yr)
Cloney	9	17
Graham Gulch	11	28
Little Freshwater	8	11
Lower Freshwater	--[1]	--
McCready Gulch	8	6
School Forest	--	--
South Fork	8	49
Upper Freshwater	8	25
Total Watershed	8	25

[1]Streambank surveys did not include Lower Freshwater or School Forest sub-basins.

Estimated soil creep from the inventoried Class I channels averaged 8 tons/mile of stream channel/year. Inventoried bank erosion and slides attributed to background inputs on the same channels averaged 25 tons/mile of stream channel/year, and ranged from 6 tons/mi/yr in McCready Gulch to 49 tons/mi/yr in the South Fork sub-basin. Since the soil creep calculation incorporates streambank erosion and slides, the Analysis Team felt it was important not to double-count this background sediment source. Therefore, the estimated input from soil creep along Class I channels was subtracted from the final soil creep figures, and the inventoried streambank erosion/slide rates were extrapolated to cover all Class I channels in the inventoried sub-basins. In the Lower Freshwater and School Forest sub-basins, where no streambank erosion inventories were conducted, the soil creep estimate was used for Class I channels. Soil creep estimates were used for all Class II and III channels.

The calculated average annual sediment input from soil creep is shown in Table 2-3. An average of about 2,700 tons/yr is calculated to be supplied to the entire watershed from the processes that are included in soil creep. The majority of this sediment (1,900 tons/yr) is silt- and clay-sized as a result of the very fine-grained soils in the area. Only a small amount (about 160 tons/yr) is gravel sized; low amounts of coarse-grained sediment are supplied to streams in the watershed under undisturbed conditions due to the low amounts of gravel in the underlying geologic formations. Sediment inputs from other background sources (mass wasting, streambank erosion/slides) are estimated in the Mass Wasting and Stream Channel Modules and compiled in the sediment budget section of the Stream Channel Assessment.

Table 2-3: Average annual input from soil creep (tons/yr).

Sub-basin	Gravel (>4.75 mm)	Med/Coarse Sand (2-4.75 mm)	Fine Sand (0.075-2 mm)	Silt/Clay (<0.075 mm)	Total (tons/yr)	Tons/ sq mi/yr
Cloney	30	30	70	220	350	70
Graham Gulch	20	20	40	160	240	100
Little Freshwater	20	30	100	490	640	140
Lower Freshwater	10	10	30	140	190	60
McCready Gulch	10	10	20	110	150	80
School Forest	0	0	10	40	50	80
South Fork	10	20	60	260	350	110
Upper Freshwater	60	60	140	480	740	70
Total Watershed	160	180	470	1,900	2,710	90

2.3 CONFIDENCE DISCUSSION

A true measure of background sediment yield is difficult to determine in a managed basin. Soil creep estimates are often used as one component of background sediment yield (WDNR 1997, Reid and Dunne 1996). Soil creep is based on length of streams, average creep rates, and average soil depths. Confidence is good that the length of streams in the GIS database represents actual stream lengths on the ground in most parts of the watershed since the stream layer has been field checked in many areas as part of timber harvest planning. Confidence in average soil depths is good – soil depths based on regional mapping and profiling are similar to those measured as part of PALCO soil testing in the watershed (pers. comm., Tom Koler). Confidence in soil creep rates is low to moderate. Soil creep is extremely hard to measure accurately since the rates are so low. Comparison between soil creep estimates and bank erosion/slide estimates indicates that soil creep estimates may be low in some sub-basins. However, uncertainties in soil creep rates will only have a minor influence on the overall sediment budget since the rates are so low (Reid and Dunne 1996).

3.0 HILLSLOPE SURFACE EROSION

The hillslope portion of the Surface Erosion Assessment concentrates on the non-road related causes of surface erosion. Ground-disturbing activities analyzed for the Freshwater Creek Watershed include timber harvest activities, agricultural practices, home building, and use by recreational vehicles. The module identifies areas of the watershed that are sensitive to ground-disturbing activities, estimates how much sediment is produced from different actions, and determines what circumstances result in erosion and delivery of sediment to streams.

3.1 METHODS

3.1.1 Surface Erosion Potential Map

Different parts of the Freshwater Creek Watershed have different inherent rates of surface erosion potential as a result of variations in soil and slope characteristics. A map of surface erosion potential in the Freshwater Watershed based on the California State Board of Forestry Procedure for Estimating Surface Soil Erosion Hazard Rating (Technical Rule Addendum Number 1; CDF 1981) was prepared. This procedure uses a scoring system based on soil characteristics, hillslope gradient, vegetative cover, and precipitation to rate soil erosion hazard. For the Freshwater Watershed, each soil type was assigned a numeric value based on soil texture, depth to bedrock, and percent coarse fragments (Item I in the CDF procedure). The slope factor (Item II) was based on the slope factors in the GIS slope coverage in 10% slope breaks (i.e., 10% slope was given a rating of 2; 10-20% slope had a 5 rating, etc.). The protective vegetative cover remaining after disturbance (Item III) was assumed to be bare soil and set to the maximum value of 15, and a 2-year, 1-hour rainfall intensity value of 0.5 in. (corresponding to a numerical rating of 6 for Item IV) was used for the watershed. The assumption of bare soil conditions for Item III was used to display the erosion hazard of watershed areas when completely disturbed, representative of a bladed skid trail or road cut in the first year or two after disturbance. Most of the management activities in the basin such as partial cuts or unburned clearcuts do not remove all vegetation and do not result in bare soil conditions, so the erosion hazard rating from these activities would be less than displayed on the map.

Disturbed areas of large, deep-seated landslides may have a higher surface erosion potential than calculated using the CDF rating system. However, the generally hummocky topography in these areas may reduce the delivery of eroded sediments by trapping it in microtopographic features. No quantification of these effects was made because no literature was found documenting differing erosion rates. Deep-seated landslides are displayed on Map A-3 in the Mass Wasting Module.

Disturbed areas of recent landslide activity will have a higher surface erosion potential for several years until the area revegetates and stabilizes. An estimate of surface erosion associated with landslides has been made as part of the Mass Wasting Module.

Soil erodibility ratings only refer to the susceptibility of soil to erosion when disturbed. To determine if eroded soil in a specific location has the potential to reach a waterway, a separate examination of delivery potential must be made.

3.1.2 Timber Harvest Activities

Timber harvest activities that disturb and/or compact the soil have the potential to result in surface erosion. Activities include constructing layouts for falling timber; tractor, cable, or helicopter yarding; broadcast or pile burning; and mechanical site preparation. The degree of canopy removal, the regrowth of vegetation, removal/disturbance of ground cover and duff, and the degree of compaction can affect the amount of erosion.

3.1.2.1 Aerial Photograph and Field Inventory

To determine the extent and types of surface erosion processes occurring in the Freshwater basin, observations were made of timber harvest units both on aerial photographs and on the ground. The objectives of the observations were:

(1) to observe the type and extent of surface erosion processes;

(2) to observe how quickly disturbed areas are revegetated;

(3) to observe delivery to streams (the effects of buffers at trapping sediment); and

(4) to observe erosion on units with different management, soil/geology, and slope gradient (Table 3-1).

While it is not generally possible to directly measure the amount of sheet erosion that has occurred on a unit, observations of soil pedestals were made, along with measurements of gullies to give some on-the-ground verification of erosion rates that were calculated with the Water Erosion Prediction Project (WEPP) model (Section 3.2.3.3).

Table 3-1: Variables considered while selecting harvest units for field visits in the Freshwater.

Geology	Major Soil Types	Slope	Harvest Type	Yarding Method	Site Prep Activity	Year Harvested
Wildcat	Larabee	Flat (<5%)	Clearcut	Tractor	None	Current year
Franciscan	Atwell	Gentle (5-20%)	Partial Cut	Cable	Broadcast burn	1-2 years old
	Hugo					
	Melbourne	Moderate (20-40%)		Helicopter	Pile burn	5 years old
		Steep (40-60%)			Herbicide	10 years old
		Very Steep (>60%)				

Aerial Photographs

Recent (1997) aerial photographs were perused to look at differences in overall ground disturbance between different types of timber harvest practices. Cable yarding corridors and skid trails were traced onto Mylar overlays for 18 tractor yarded and 8 cable yarded units to quantify ground disturbance. They were then digitized into a GIS coverage, and the total length of yarding pathways in each unit was summed. This number was divided by total harvest unit area to obtain skid trail or yarding corridor density (miles/square mile). The total length of yarding pathways was also multiplied by average pathway width and then divided by total harvest unit area to obtain the average percent of a unit disturbed by each type of harvest practice.

Field Observations

The Surface Erosion Analyst and resource agency and public representatives conducted field visits to harvest units in the Freshwater basin on September 28, 29, and 30, 1999. The surface Erosion Analyst also visited units on November 11, 1999. Eleven harvest unit areas, several consisting of several different harvest units grouped together, were visited that were harvested between 1991 and 1999. Table 3-2 summarizes the units visited and observations made in the units. Most field observations were made in units harvested in the past four years. There was relatively little harvest in the watershed in 1993, 1994, or 1995 so units of this age were difficult to sample. Copies of the field forms/notes are included in Attachment B-1.

In addition, field observations of percent cover within harvest units and on skid trails were made in July 2000 to determine appropriate cover values for the WEPP model runs on harvest units. These observations included all types of ground cover (canopy, brush, litter, forbs, rocks, and woody debris) and are included as Attachment B-2.

Table 3-2: Summary of field observations in harvest units.

Harvest unit designation	Year of harvest	Geology	Harvest type	Skidding method	Site prep?	Hillslope gradient	Percent vegetative cover	
							In-unit	Skid trail
20588	1996	Wildcat	Clearcut	tractor	no burn	30-50%	95	5
20589	1996	Wildcat	Clearcut	tractor	herbicide	30-50%	75	5
20254	1997	alluvium	Clearcut	tractor	herbicide	0-45%	50	10
22711/ 20735	1997/8	Wildcat	Clearcut	cable	broadcast burn	30-60%	5-30%	n/a
20606	1997	Franciscan	Clearcut	tractor	herbicide	30-40%	85	10
22640	1997/98	Wildcat	Clearcut/ partial	tractor/cable	pile burned	30-60%	10	5
21833	1997	Franciscan	Clearcut	tractor	no burn	40-60%	99	
21832	1997	Franciscan	Clearcut	cable	no burn	40-60%	80	n/a
20620	1998	Wildcat	Clearcut	tractor	herbicide	30-40%	60	100
572	1991	Franciscan	Clearcut	tractor	herbicide	30-40%	100	100
9-29, 1 (new unit, not on map)	1999	Franciscan	Partial	tractor	no burn	25%	n/a	0

3.1.2.2 Estimating Sediment Production from Timber Harvest

The Water Erosion Prediction Project (WEPP) model was used to estimate surface erosion associated with timber harvest units. The WEPP model was developed by a federal inter-agency team as a physically based soil erosion model that provides an estimate of erosion and sediment delivery through a buffer based on site-specific soil, ground cover, and topographic conditions and the local climate. The WEPP model uses simulated daily precipitation over a 30-year period that accounts for variations in precipitation to determine if there is runoff and any resulting erosion or transport of sediment from a site. The Disturbed WEPP model, an interface to the WEPP model set up to analyze surface erosion from timber harvest, skid trails, fire, and grazing land uses, was used to predict surface erosion from these activities in the Freshwater Watershed.

At present, the Disturbed WEPP model is not set up to be used on a watershed basis but must be run for portions of individual harvest units. For the Freshwater Watershed Analysis, erosion from all units harvested in the past 10 years was estimated based on a series of Disturbed WEPP runs for varying silviculture, slope, and stream buffer widths (i.e., Watercourse and Lake Protection Zone, or WLPZ). Three different sets of Disturbed WEPP runs were made to provide a range of erosion/delivery values based on a range of reasonable input values. The different input variables used in the three model runs are presented in tables.

Table 3-3 compares the climate, soil, hillslope gradient, and vegetation file parameters used for the three runs. The "Initial WEPP run" was made using the default soil parameters contained within the WEPP model that are closest to the soil properties measured in the Freshwater Creek Watershed. Similarly, the Orick Prairie Creek climate station was chosen for the Initial WEPP run because it has a mean annual precipitation of 62.73 in. (close to the mean in the Freshwater basin) and a similar distribution of precipitation throughout the year. The Eureka WBO climate station is closest in physical location to the watershed, but it was not used for the Initial WEPP run because the mean annual precipitation is 37.29 in., much lower than the mean precipitation in the Freshwater basin. Runs using the Eureka WBO climate showed the WEPP model is very sensitive to precipitation; the precipitation at Orick was 70% higher than at Eureka, and resulted in a 300-400% increase in delivered sediment.

Table 3-3: Comparison of factors used for Disturbed WEPP runs.

Factor	Initial WEPP run	Modified WEPP run	Skid trails and burns modeled separately
Climate Station[1]	Orick Prairie Creek Park (mean annual precip. of 62.73 in.)	Eureka WBO (mean annual precip. of 37.9 in.) modified to give a mean annual precip. of 61 in.	Orick Prairie Creek Park (mean annual precip. of 62.73 in.)
Soil Texture	Clay loam[2]	Modified clay loam[3]	Clay loam
Hillslope and Buffer Gradient	5, 10, 20, 30, 40, 50, 60, 70 percent planar slope – same for all three runs		
Lower element (buffer) treatment	standard 20-year old forest, 100% cover	modified 20-year old forest, 100% cover[4]	standard 20-year old forest, 100% cover

[1] See climate descriptions in Attachment B-3
[2] See soil descriptions in Attachment B-4
[3] Standard clay loam soil was modified based on the grain size distribution from soil samples taken in the basin (Table 2-1) and soil depths and initial saturation levels measured in the watershed. See soil descriptions in Attachment B-4
[4] Standard vegetation files were modified to reflect tree characteristics of redwood forests; maximum canopy height was increased to 40 meters, the leaf area index was increased to 20, and the fraction of canopy remaining after senescence was set to 99%.

The "Modified WEPP run" was made using climate, soil, and vegetation files that were modified from the default values available in the standard model. These modifications were possible because a PALCO hydrologist (Bill Conroy) had previously traveled to the USFS Intermountain Research Station in Idaho to receive training in use of WEPP from Bill Elliot, one of the developers of the WEPP model. Bill Conroy obtained the PC-based version of the WEPP code and instructions on how to modify the default climate, soil, and vegetation files. Modifications to the standard soil files were made based on measurements of soil characteristics in the basin. The Eureka WBO climate station was modified to increase daily rainfall intensities to result in a mean annual precipitation of 61 in. (temperature values were not changed). The vegetation files were modified to represent tree heights and litter in a redwood forest.

Table 3-4 shows the treatment and cover values that were used for the Initial and Modified WEPP runs to represent vegetation and cover conditions at 1, 2, 5, and 20 years following harvest. The cover conditions were selected based on field observations of total cover in recent and older harvest units in the Freshwater Creek Watershed (Attachment B-2). It was assumed for simplicity in these runs that all clearcut units were burned in the fall following harvest. Tractor yarded units have reduced cover compared to cable or helicopter yarded units based on observations that 15% of tractor yarded units are skid trails, and cover on skid trails in year 1 is 10% and in year 2 is 25%. For example, a 2-year old cable yarded selection has 95% cover. If the same unit is tractor yarded, 15% of the unit has 25% cover and 85% of the unit has 95% cover, the net cover is 85% (25% x 0.15 + 95% x 0.85 = 85% cover). Actual cover values input into the WEPP model for the runs were approximately 10% higher than those in Table 3-4 because the WEPP model grows trees and produces leaf litter and biomass and internally determines annual ground cover values it uses for computations of erosion. These internal cover values are generally lower than the user input cover value. As described in the model documentation, the "Calibrate Cover" procedure was used iteratively to determine the correct input cover value to produce the actual cover value desired (e.g., for the Orick climate using a 5-year-old forest treatment, an input cover value of 80% is needed to get a calibrated cover value of 70.14%).

Table 3-4: WEPP treatments used for Upper Element (harvest unit) for the Initial and Modified WEPP runs.

Harvest Method	Year 1	Year 2	Year 5	Year 20
Clearcut, tractor yarded (fall burn)	5-year old forest[1], 70% cover[2]	5-year old forest, 75% cover	5-year old forest, 98% cover	20-year old forest, 100% cover
Clearcut, cable or heli yarded (fall burn)	5-year old forest, 85% cover	5-year old forest, 90% cover	5-year old forest, 100% cover	20-year old forest, 100% cover
Selection, thin, seedtree, shelterwood tractor yarded	5-year old forest, 75% cover	5-year old forest, 85% cover	5-year old forest, 98% cover	20-year old forest, 100% cover
Selection, thin, seedtree, shelterwood cable or heli yarded	5-year old forest, 90% cover	5-year old forest, 95% cover	5-year old forest, 100% cover	20-year old forest, 100% cover
Overstory removal, tractor yarded	5-year old forest, 80% cover	5-year old forest, 85% cover	5-year old forest, 98% cover	20-year old forest, 100% cover
Overstory removal, cable or heli yarded	5-year old forest, 95% cover	5-year old forest, 98% cover	5-year old forest, 100% cover	20-year old forest, 100% cover
Undisturbed areas	---	---	---	20-year old forest, 100% cover

[1] "5-year old forest" is the WEPP designation for a recently harvested area and does not imply that the area was harvested exactly 5 years ago. The specific cover values input into the model are used to represent tree regeneration under the "5-year old forest" designation for age 1, 2, and 5 year old stands in the present model runs, as described in the Disturbed WEPP model documentation (Elliot et al. 2000).

[2] "Cover" includes residual overstory, understory, logging slash, annual grasses and forbs, coarse woody debris, litter, and duff; essentially, any vegetative matter (live or dead) that protects the ground surface from raindrop impact.

The third set of WEPP runs, the "Skid trails and burns modeled separately," was made modeling skid trails as separate hillslope elements, and modeling broadcast burns as low intensity fire in year 1. These runs were done to determine if modeling skid trails separately and using the low intensity fire treatment resulted in differences in the estimate of delivered sediment. Table 3-5 shows the differences in treatments and cover types that were used for these runs. The year 5 and year 20 values for all harvest types and the year 1 and 2 values for cable or helicopter yarded partial cuts were the same as the two previous runs.

Table 3-5: Different WEPP treatments used for Upper Element (harvest unit) for the runs with skid trails and burns modeled separately.

Harvest Method	Year 1	Year 2
Clearcut, tractor yarded (fall burn)	15% of area: Skid trail 10% cover 85% of area: 30 % of units – low intensity fire, 85% cover 70% of units – 5-year forest 90% cover	15% of area: Skid trail 25% cover 85% of area: 5-year forest, 90% cover
Clearcut, cable or heli yarded (fall burn)	30 % of units – low intensity fire, 85% cover 70% of units – 5-year forest 90% cover	same as Table 3-4
Selection, thin, seedtree, shelterwood tractor yarded	15% of area: Skid trail 10% cover 85% of area: 5-year old forest, 90% cover	15% of area: Skid trail 25% cover 85% of area: 5-year forest, 95% cover
Selection, etc. ,cable or heli yarded	same as Table 3-4	same as Table 3-4
Overstory removal, tractor yarded	15% of area: Skid trail 10% cover 85% of area: 5-year old forest, 95% cover	15% of area: Skid trail 25% cover 85% of area: 5-year forest, 98% cover
Overstory removal, cable or heli yarded	same as Table 3-4	same as Table 3-4

For harvest units that were tractor yarded, 15% of the area was modeled as a 100-ft long skid trail delivering to a buffer. The 100-ft length was based on field observations of the approximate distance between water bars on skid trails. The gradient of the skid trail was set at the hillslope gradient up to a 20% slope. For a 30% hillslope, the skid trail was set at 20% (10% lower gradient); for hillslopes of 40% and higher, the skid trail gradient was set to 30%. This is based on field observations that most skid trails do not go straight up and down slopes on steep hillsides, but cut across the hillslope. Harvest units that were clearcut were further subdivided into broadcast burned (low intensity fire treatment) and unburned (5-year forest treatment). In the Freshwater Creek Watershed, approximately 60% of the clearcut units are scheduled to be broadcast burned, but only half of the scheduled units are actually burned due to moisture content limitations. It was assumed that 30% of all clearcut units were burned and 70% were unburned, and a blended rate of the two predicted erosion rates was used for clearcut units.

In all three model runs, the upper element (harvest unit) and lower element (buffer) widths were made based on a total modeled distance of 200 ft, with buffer widths based on the standard CDF WLPZ widths shown in Table 3-6. For example, a harvest unit on a 20% slope near a Class II stream would have an upper (harvest) unit length of 150 ft and a lower (buffer) unit length of 50 ft. These modeled buffer widths are much narrower than those currently required by PALCO's HCP, but are the buffer widths used for recent harvest prior to implementation of the HCP. Thus, the WEPP model estimates of surface erosion represent estimates for previous harvest but probably overestimate erosion that would occur under future conditions when wider buffers are used.

Table 3-6: Stream buffers used to model past surface erosion from harvest units (based on CDF Forest Practice Rule WLPZ widths).

Slope Gradient (%)	Class I stream buffer (ft)	Class II stream buffer (ft)	Class III stream buffer (ft)
< 30%	75	50	25
30% - 50%	100	75	50
> 50%	150	100	50

The result of each WEPP run is sediment delivery at the bottom of the hillslope (delivery through buffer) in tons/acre/year. For the Freshwater Watershed Analysis, sediment delivery through time was analyzed for each timber harvest unit from the year harvested (year 1) through the time when the WEPP model predicts that sediment delivery is equal to its version of "background" erosion (a 20-year old forest with 100% cover). As noted in Tables 3-4 and 3-5, WEPP model runs were made for conditions 1, 2, 5, and 20 years following harvest. These results were interpolated to predict sediment delivery for each year over a 20-year time span. The erosion rate that WEPP predicted as the "background" rate was also subtracted from each year's rate since the intent of the harvest analysis is to separate out the effects of timber harvest from background erosion, which is calculated separately (see Section 2.0). An example of how the WEPP runs were used to predict sediment delivery from a clearcut, tractor-yarded unit on a 30% slope with a Class I stream buffer is shown in Figure 3-1. A similar analysis was done for each of the 324 different management/slope/stream buffer combinations analyzed.

Table 3-7 shows the predicted total sediment delivery to streams from harvest units over the 20-year "life" of the unit (in tons/acre of harvest unit) from the three different WEPP runs.

Figure 3-1: Example WEPP data used to estimate timber harvest erosion.

Estimated sediment delivered to streams (tons/acre of harvest unit/yr)				
Years after Harvest	1	2	5	20
WEPP model output	1.21	1.05	0.61	0.61
Adjusted to remove "background" rate	0.65	0.49	0.05	0.05

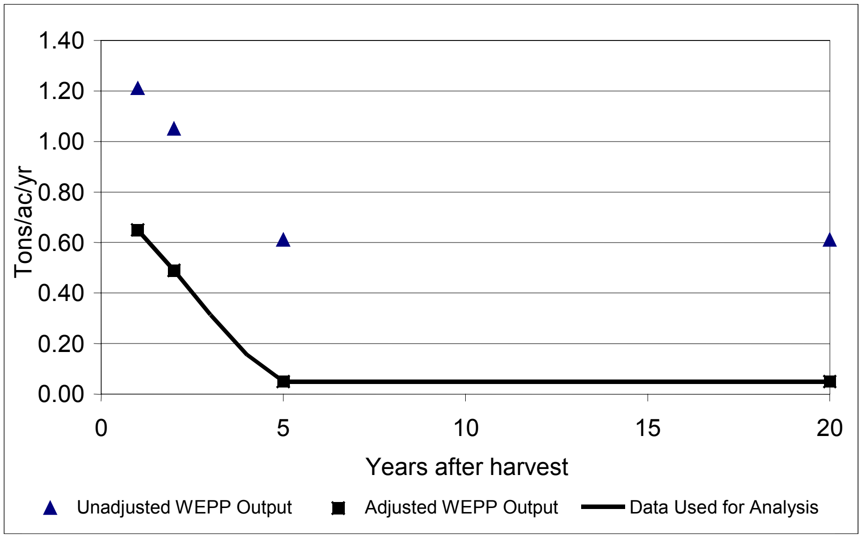

Table 3-7: Sample WEPP-predicted sediment delivered from harvest units (tons/acre of harvest unit over 20 years).

Stream class/ Buffer width	Silvi-culture	Yarding	Initial WEPP run				Modified WEPP run				Skid trails and burns modeled separately			
			10%	20%	30%	40%	10%	20%	30%	40%	10%	20%	30%	40%
Class I 75-100 ft	Clearcut	Tractor	0.07	0.32	0.61	0.84	0.12	0.27	0.18	0.39	0.26	1.09	1.28	2.89
		Cable/Heli	0.00	0.11	0.31	0.43	0.10	0.21	0.09	0.25	0.10	0.40	0.61	0.83
	Selection	Tractor	0.02	0.19	0.42	0.58	0.11	0.24	0.13	0.30	0.17	0.83	1.01	2.52
		Cable/Heli	0.00	0.05	0.23	0.31	0.09	0.20	0.07	0.21	0.00	0.05	0.23	0.31
	Overstory	Tractor	0.01	0.16	0.37	0.52	0.11	0.23	0.12	0.29	0.03	0.75	0.99	2.45
		Cable/Heli	0.00	0.01	0.20	0.22	0.09	0.17	0.05	0.19	0.00	0.01	0.20	0.22
Class II 50-75 ft	Clearcut	Tractor	0.08	0.69	0.89	1.58	0.14	0.47	0.52	0.85	0.34	1.52	1.58	3.91
		Cable/Heli	0.01	0.34	0.44	0.93	0.11	0.38	0.39	0.65	0.15	0.76	0.90	1.55
	Selection	Tractor	0.04	0.48	0.62	1.19	0.13	0.42	0.44	0.73	0.21	1.14	1.16	3.34
		Cable/Heli	0.00	0.26	0.31	0.76	0.11	0.36	0.36	0.61	0.00	0.26	0.31	0.76
	Overstory	Tractor	0.04	0.43	0.56	1.10	0.12	0.40	0.42	0.70	0.21	1.11	1.09	3.22
		Cable/Heli	0.00	0.21	0.22	0.63	0.10	0.35	0.34	0.58	0.00	0.21	0.22	0.63
Class III 25-50 ft	Clearcut	Tractor	0.12	1.11	1.60	2.41	0.16	0.57	0.79	1.19	0.44	2.13	2.47	5.17
		Cable/Heli	0.01	0.61	0.92	1.50	0.12	0.46	0.61	0.94	0.20	1.19	1.59	2.39
	Selection	Tractor	0.05	0.80	1.19	1.84	0.14	0.51	0.68	1.04	0.27	1.61	1.74	4.36
		Cable/Heli	0.00	0.50	0.73	1.22	0.12	0.43	0.58	0.88	0.00	0.50	0.73	1.22
	Overstory	Tractor	0.04	0.73	1.10	1.72	0.14	0.49	0.66	1.01	0.27	1.53	1.65	4.20
		Cable/Heli	0.00	0.42	0.62	1.04	0.11	0.41	0.55	0.84	0.00	0.42	0.62	1.04

Note that these numbers are not solely erosion rates and are not in tons/year, but are total tons delivered to a stream from an acre of harvest unit. The rates in Table 3-7 show expected patterns of higher delivered sediment from higher gradient areas, and higher rates from harvest practices with greater disturbance (i.e., tractor yarded or burned areas). Less sediment is delivered from harvest areas with wider stream buffers.

Overall, the Modified WEPP runs predict about half as much sediment delivered than the Initial WEPP runs. In general, the deeper soils in the Modified runs result in less runoff and, therefore, less erosion. However, the Modified runs vary considerably, with some estimates higher than the Initial run, and some 3-4 times lower. The runs with skid trails and burns modeled separately show about 2 to 3 times as much erosion as the Initial WEPP runs for burned or tractor yarded units.

The WEPP output tables were used in combination with a GIS analysis of the acres of timber harvest in PALCO's database between 1989-1999 to calculate the total amount of sediment delivered to streams. The GIS database was queried to determine the number of acres of each type of harvest practice within 200 ft of a stream, as well as acres farther than 200 ft from a stream. All of the sediment predicted from the WEPP model runs from areas of units within 200 ft of a stream was assumed to be delivered to streams (the WEPP model runs already took into account the effects of the WLPZ buffers). The 200-ft distance was selected to be consistent with the delivery distance assumptions used in the road analysis (Section 4.2.3.2) and research on delivery distance of sediments (Ketcheson and Megahan 1996, Brake et al. 1997). For harvest areas over 200 ft away from a stream, it was assumed that 1% of the total sediment predicted from the WEPP runs was delivered to streams (Figure 3-2). This assumption is based on personal judgement that in some timber harvest units, small-scale topography or management practices such as log skidding may provide pathways for delivery of sediment from over 200 ft away from a stream. These situations are likely very minor and not quantifiable at a watershed scale, so a factor of 1% was chosen to take these situations into account.

The acres of timber harvest from the GIS database, along with the stream class for each unit, were used in combination with the lookup tables of predicted tons/acre/yr of sediment delivery from the WEPP model results to predict total annual sediment supplied to streams for the period 1989-2010 from timber harvest that occurred between 1989 and 1999. These calculations are shown in Data Worksheets B3-1, B3-2, and B3-3.

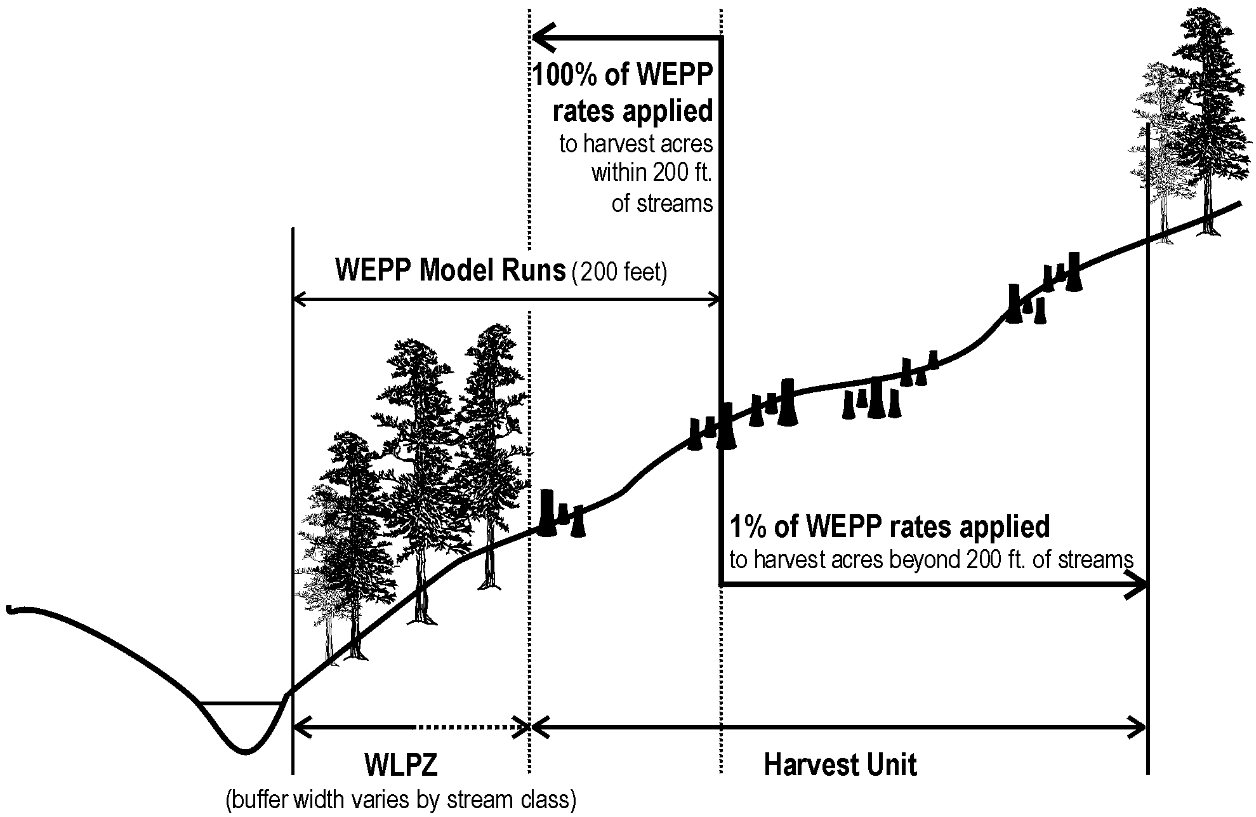

Figure 3-2: Relationship of WLPZ buffers and 200-ft delivery distance used in application of WEPP model to timber harvest erosion.

Comparison Between Harvest Erosion Estimate Method and PWA Sediment Source Investigation Methods

Pacific Watershed Associates prepared a Sediment Source Investigation for Freshwater Creek in 1999 (PWA 1999). Part of their analysis included a preliminary estimate of surface erosion related to timber harvest activities. Surface erosion was not the main objective of their report, with the understanding that a more detailed estimate would be prepared as part of the current Watershed Analysis activities. Their analysis was completed primarily from aerial photo interpretation and several simplifying assumptions and conservative estimates of ground disturbance, delivery, and erosion rates appropriate for the level of detail for that section of their analysis.

The PWA analysis was based on an average surface lowering rate of 0.2 in./yr, taken from the high end of erosion pin measurements on road cutbanks (from Madej, pers. comm..) and other areas of bare soil (Marron et al. 1995). This rate was applied over a 5-year period, to yield an erosion rate of 161 tons/acre (32 tons/acre/year for 5 years). The erosion rate was applied to all areas of bare soil within each type of harvest unit and modified by percent delivery, with percent bare soil and delivery percent set by harvest and yarding method as follows: **tractor clearcut** – 70% bare soil, 15% delivery, net 17 tons/acre delivered; **tractor partial cut** – 40% bare soil, 10% delivery, net 6.5 tons/acre delivered; **cable clearcut** – 80% bare soil, 15% delivery, net 19 tons/acre delivered; and **cable partial cut** – 20% bare soil, 5% delivery, net 1.6 tons/acre delivered. The resulting delivered erosion rates were applied to all acres of timber harvest within the watershed regardless of how close to or far from a stream they were located. The net result of the PWA analysis was much higher delivered sediment rates from harvest surface erosion than the present analysis, which took into account specific information about each harvest unit, including hillslope, distance of portions of the unit from a stream, and field measurements of percent bare soil and ground cover.

3.1.3 Other Land Management Activities

Other land management activities in the Freshwater Watershed that were considered for the Surface Erosion Assessment included agricultural practices (grazing in forested areas and pastures), recreational vehicle use, and homesites. Based on conversations with PALCO land managers, there is little if any current grazing in forested areas on PALCO lands (pers. comm., Rich Bettis, 12/1/99) so that source was not considered further.

Based on aerial photograph and field observations, the dispersed grazing on grasslands in the upper portions of the basin did not appear to be a major source of surface erosion and was not considered further. Conversations with the head of the Far West Motorcycle Club (pers. comm., Dale at Leon's Muffler, 4/18/00) indicated that while the club maintains an agreement with PALCO for riding on their lands, they have not ridden much, if at all, in the Freshwater basin in the past 10 years and likely will not in the near future. This erosion source was not considered further.

Homesites in the lower basin and upper watershed areas have been developed over the past century. During the clearing, construction, and revegetation/landscaping of lots and houses, surface erosion can occur. To get an idea of the magnitude of surface erosion associated with home building, the WEPP model was run with the following assumptions: Eureka WBO rainfall, silt loam soil, 1-acre average home site, 5% hillslope gradient, 200-ft average hillslope length, short grass cover, with cover percent 10% in year 1, 50% in year 2, and 100% in year 3 and following. Summing the results of the WEPP run (5 tons/acre Year 1, 0.5 tons/acre Year 2, 0.1 tons/acre Year 3) yields 5.6 tons eroded for each homesite (an average of 0.03 in. of ground lowering over the acre). Assuming that an average of 10% of the total sediment from all homesites is delivered to streams, the net result is 0.6 ton delivered per homesite. This rate was applied to the number of new homesites noted on aerial photos during each photograph period to obtain an average input rate from home building in the watershed.

One additional source of sediment that was noted in the lower watershed was turbid runoff from the concentrated grazing in some pastures at the Freshwater Valley Stables. Field and aerial photograph observations indicate that the stables operate concentrated grazing on approximately 10 acres of land. Ground cover varies considerably between pastures, from 10-100% depending upon use. The hillslope gradient averages 10% and the average hillslope length is 250 ft. These variables were used in the Disturbed WEPP model to obtain average annual erosion rates. Assuming 10% of the acreage has a ground cover of 10% (5.8 ton/acre/yr), another 10% of the pasturelands has a ground cover of 100% (0.1 ton/acre/yr), and the remaining 80% has 50% groundcover (0.7 ton/acre/yr), the net result is 0.7 ton/acre/year. Based on field observations, the pastureland drains to the road ditch along the Freshwater-Kneeland Road. Some of the ditch water is carried under the road in a culvert where it disappears into a hole in the ground that could not be traced. The remainder of the ditch delivers to a small stream. Assuming that 50% of the runoff from the pastures reaches a stream, a total of 3.5 tons/year is predicted to be delivered from the 10 acres of horse pasture.

3.2 ANALYSIS AND RESULTS

3.2.1 Timber Harvest History

Logging in the Freshwater Creek Watershed began in the 1860s, probably with steam donkey and/or oxen yarding in the School Forest sub-basin of the lower watershed (Map B-2). Steam donkey and railroad logging spread up the drainage in the 1870s, 1880s, and 1890s to include McCready Creek (1870s), lower Cloney Gulch (1880s and 1890s), Falls Gulch (1880s), Graham Gulch (1880s and 1890s), and lower Little Freshwater Creek (1870s and 1890s). A small amount of terrain in the upper end of the mainstem, below Kneeland Road, was also harvested in the late 1800s. This period of earliest logging in Freshwater Creek ended at the turn of the century.

Railroad logging operations recommenced in the 1920s along the mainstem of Freshwater Creek, within Little Freshwater Creek, and in the downstream reaches and ridge top areas of the South Fork. By the end of the 1930s, the remainder of Little Freshwater Creek, the South Fork, and most of the mainstem had been clearcut harvested. Between 1940 and 1954, the small amount of remaining old-growth in the watershed (located mostly in the upper Cloney and Falls Gulch areas) had been harvested. This marked what can be considered the end of first cycle logging in the Freshwater Creek Watershed. This logging cycle was characterized by clearcut harvest, burning, and generally high impact activities that led to both elevated disturbance levels and higher surface erosion rates. Figure 3-3 shows the rate of harvest by decade during first cycle logging.

Map B-2 shows the extent of railroad logging routes that had been developed in the Freshwater Creek Watershed. A transition in logging technology, from steam donkey cable yarding and railroad hauling to tractor yarding and truck hauling, took place in Freshwater Creek in the 1950s and 1960s. At the end of the first cycle logging, in the 1940s, tractors had been introduced and had been used in isolated areas to build spur roads and to perform a minor amount of yarding of harvested areas. By the 1960s, tractor yarding and truck hauling had completely replaced the older methods.

Map B-3 and Figure 3-4 describe the second cycle logging history (second-growth logging) in the Freshwater Creek Watershed, as derived from analysis of historic aerial photography and Timber Harvest Plans (THP) records for the period from about 1955 through 1997.

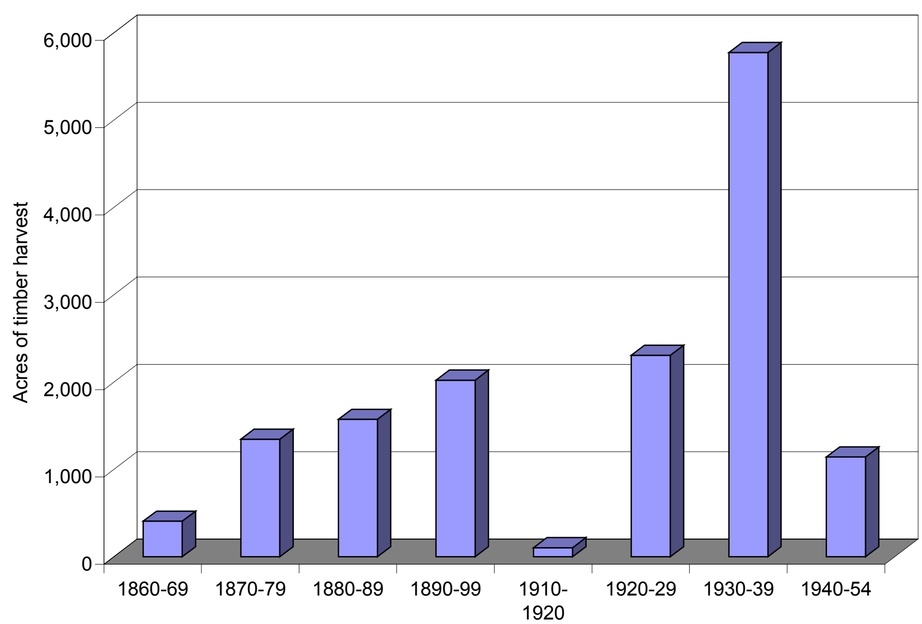

Figure 3-3: Acres harvested during first-cycle timber harvest, 1860-1954.

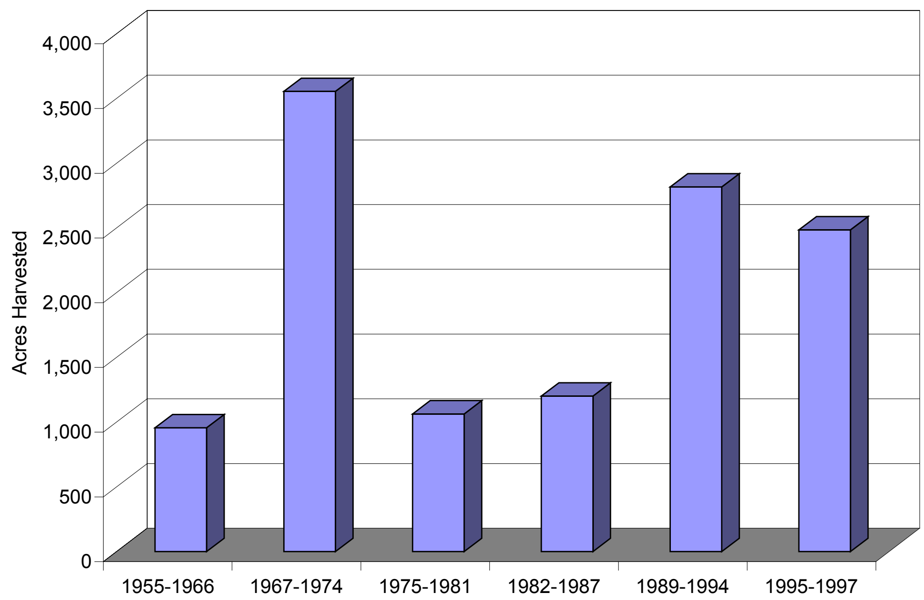

Figure 3-4: Acres harvested during second-cycle timber harvest, 1955-1997.

By the 1960s, McCready Gulch, the School Forest area, and lower Cloney Gulch had developed second-growth forests from 80 to 100 years old. Road construction and partial cut tractor logging (thinning) dominated forest operations in the watershed from 1966 through 1994. Between 1966 and 1974, the first truck roads were built into the lower basin, and widespread tractor logging was being employed to commercially thin portions of the advanced second-growth forest. Logging practices during this period continued to result in high disturbance and high surface erosion levels. Beginning in 1973, revisions to California's Forest Practice Rules resulted in improved logging practices, as well as a general trend of reduced disturbance, wider stream buffers, and less sediment delivered per acre of harvest than during previous decades. During second cycle logging, partial cutting (both tractor and cable yarded) dominated, particularly during the most recent photo period, from 1994 to 1997. Clearcutting, divided evenly between tractor and cable yarding, accounted for the remaining acres harvested (Table 3-8).

Harvesting rates have fluctuated for both first and second cycle logging periods in the Freshwater Creek Watershed. Early logging, prior to the late 1950s, was almost exclusively by clearcutting and cable yarding. Virtually the entire watershed was logged (clearcut) by the 1950s, with overall harvesting and clearcutting rates for this period peaking in the 1930s at nearly 600 acres/year (Figure 3-3). With the exhaustion of old-growth timber, harvesting rates declined in the 1940s and 1950s and then picked up again in the late 1960s as lower basin second growth forests were commercially thinned.

Table 3-8: Harvesting methods during second cycle logging (acres).

Year	Clearcut		Partial Cut		Total
	Tractor yarded	Cable yarded	Tractor yarded	Cable yarded	
1955-1966	190	-	-	767	956
1967-1974	68	0	3,436	51	3,555
1975-1981	34	138	891	-	1,063
1982-1987	134	408	633	26	1,201
1988-1994	291	441	1,685	401	2,817
1995-1997	323	377	522	1,263	2,485
Total period	1,039	1,364	7,166	2,508	12,077

Clearcut harvesting rates have again systematically increased to an average of just under 400 acres per year for the most recent period (1995-1997), while overall harvesting rates (clearcutting plus partial cutting) have risen to an average of over 1,200 acres per year in the same period (Table 3-8).

3.2.2 Soil Erosion Potential Map

The Potential Erosion Hazard Rating Map of the Freshwater Watershed (Map B-4) was produced using the guidelines in CDF Technical Rule Addendum No. 1 (1981). The hazard ratings shown on the map are based on bare soil conditions and represent the erosion hazard at a specific point assuming all vegetative cover is removed and bare soil is exposed, representative of conditions of a newly bladed skid road, haul road or landing, or a construction site around a residence or other building. Other land management practices that retain some or all of the vegetative cover, such as full-suspension cable or helicopter yarding, partial cuts, and dispersed grazing in pastures, would have a correspondingly lower erosion hazard rating. Disturbed areas of large, deep-seated landslides may have a higher surface erosion potential than shown on the map. Deep-seated landslides are shown on Map A-3 in the Mass Wasting Module.

The erosion hazard rating map only rates the potential for soil detachment; it does not represent the potential for eroded sediment to be delivered to a stream. Delivery potential at a specific site is a function of the hillslope gradient, distance, and number of obstructions that trap sediment between the erosion site and a stream (Ketcheson and Megahan 1996). Therefore, while a site may have a high erosion hazard rating, it may have characteristics that give it a low delivery potential.

3.2.3 Surface Erosion from Timber Harvest

3.2.3.1 Ground Disturbance Associated with Timber Harvest

The amount of ground disturbance associated with timber harvest varies depending on the type of yarding method used and what, if any, site preparation techniques are used following harvest. The discussion of surface erosion from timber harvest units considers portions of a unit that are used for skid trails or yarding corridors separately from in-unit ground disturbance, referring to areas of a harvest unit not associated with skidding/yarding. Yarding methods used in the Freshwater include tractor skidding, cable yarding, and helicopter yarding. In-unit activities include clearcutting, partial cutting (all non-clearcut harvesting) and site preparation (broadcast or pile burning, brush raking, and herbicide use).

Skid Trails/Yarding Corridors

Field and aerial photograph observations in the Freshwater Watershed confirm research in other areas (Megahan 1980, Clayton 1990) that has found tractor yarding disturbs more ground than cable skyline yarding (Table 3-9). The skid trail/cable corridor density and percent of area disturbed as presented in Table 3-9 are based on measurements from the 1997 aerial photographs and refer only to disturbance resulting from the yarding method. Based on field and aerial photo evidence, approximately 10-15% of the area in tractor units have bare soil exposed associated with the tractor yarding (90-100% of skid trail is bare soil). Approximately 1% of the area in cable yarded units (10% of the yarding corridor) had bare soil exposed, primarily near landings where logs were not fully suspended due to the topography and bumped the edges of landings.

Table 3-9: Disturbance and bare soil associated with yarding in the Freshwater Creek Watershed.

Harvest/yarding method		Skid trail or cable corridor density (mi/sq mi)	Percent of total harvest unit disturbed for skidding	Percent bare ground in harvest unit from yarding method
Clearcut	tractor yarded	65	15%	15%
	cable yarded	50	11%	1%
Partial cut	tractor yarded	46	10%	10%
	cable yarded	34	8%	1%

Helicopter yarding has been used in the Freshwater Creek Watershed only since 1998 for harvest of approximately 200 acres, so no helicopter units were observed on the 1997 aerial photos. Observations of one recent clearcut helicopter unit adjacent to the Freshwater-Kneeland road showed very little, if any, bare soil exposed.

In-unit Harvest Practices

In-unit harvest practices include the harvesting itself as well as post-harvesting site preparation to enhance the re-stocking of timber. Harvest methods employed in the Freshwater Creek Watershed include clearcutting, where all trees are removed but shrubs and herbaceous vegetation is left, and partial cutting, where only a portion of the merchantable trees are removed. There are several types of partial cutting methods employed in the Freshwater. Selection, thin, seedtree, and shelterwood harvesting remove more trees than overstory removal, which is considered separately in the WEPP modeling.

Following harvest, a forester determines if any site preparation techniques will be used to encourage the regrowth of trees (Table 3-10). A percentage of the clearcut units are burned to kill unwanted vegetation and dispose of slash. Broadcast burning involves burning the entire unit with slash distributed as it falls. Based on field observations, broadcast burning results in fires with spotty intensity (areas of low, moderate, and high intensity), variable vegetation remaining, and little ground disturbance. Percent in-unit bare soil is variable depending upon the intensity of the fire but is generally less than 15%. Pile burning involves machine raking slash and debris into piles and then burning the unit. Pile burning results in hot, intense fires near the piles and, based on field observations, little vegetation or slash cover remaining within the unit and much more ground disturbance due to the machine raking. Burning is either conducted in the spring or fall when moisture conditions are optimal. Spring burns have a summer growing season during which herbaceous material and root sprouts can develop to provide some protection from erosion before the winter rainy season.

Table 3-10: Harvest methods and site preparation methods used in the Freshwater Creek Watershed.

Harvest Method	Burning	Herbicide possible?
Clearcut	Broadcast burn or Pile burn or None	Yes
Partial cut (selection, thin, seedtree, shelterwood, overstory removal)	None	Yes

Herbicides are used within selected units in the Freshwater Creek Watershed to kill unwanted vegetation. Herbicides are hand-applied, often only to selected species, after a few growing seasons. Field observations of units where herbicides had been applied showed only the selected brush was killed, and little net reduction in soil protection resulted because understory herbaceous material remained.

3.2.3.2 Comparison of Timber Harvest Erosion Prediction Methods

Unlike mass wasting or bank erosion, where an evacuated volume of eroded material can be measured on the ground, the volume of past surface erosion is extremely difficult to measure in the field. Surface erosion rates on the ground vary greatly both spatially and from year to year, so an intensive, research level field measurement program would be needed to determine site-specific erosion rates with high certainty. This type of research effort is beyond the scope of a watershed analysis. No direct measurements of surface erosion rates were made in the Freshwater Creek Watershed, but incidental observations of the evidence of surface erosion were made during the field survey. In addition, surface erosion was modeled several different ways, and information on surface erosion rates from nearby watersheds was collected. The different estimates of surface erosion rates were compared to indicate the range of surface erosion rates from timber harvest.

Measured Surface Erosion Rates in Redwood Creek

Surface erosion rates on slopes underlain by sandstone or schist were measured using erosion pins in the Redwood Creek watershed during 1975-78 (Marron et al. 1995). The sandstone unit is a pervasively sheared, unmetamorphosed sandstone with interbeds of mudstone and conglomerate that weathers to gravelly sandy clay loams of the Hugo and Melbourne soil series. The schist is a fine-grained quartz-mica schist that weathers to gravelly clay loams or clays belonging to the Masterson, Orick, and Sites series. Rainfall during the measurement period averaged 58 in./yr. Slopes on study sites were between 15 and 35%. The rates measured were highly variable, complicated by deposition of organic matter on the uphill side of the pins. Mean erosion rates on forested slopes (sandstone and schist) and cable- and tractor-yarded sandstone slopes were the same, 0.3 mm/yr (2 tons/acre/yr). The mean erosion rate on cable-yarded schist slopes was 1.1 mm/yr (7 tons/ac/yr), and on tractor-yarded schist slopes was 4.6 mm/yr (30 tons/acre/yr).

Estimated Erosion Rates Based on Field Observations in the Freshwater Watershed

Several indicators of surface erosion rates were observed in harvest units during field work. While these observations do not represent rigorous, controlled measurements of surface erosion rates, they do indicate the magnitude of erosion rates and provide a reality check on rates estimated using the WEPP model. The observations were made in the fall of 1999, following the large storms the previous few winters, and represent erosion under extremely high precipitation conditions; they are therefore greater than expected average annual rates (such as the WEPP model predicts).

Field observations of cable and helicopter yarded units showed little evidence of surface erosion since little bare ground was exposed unless a unit was burned. Based on these observations, erosion rates in un-burned, cable, or helicopter units should be very low.

In a one-year old unit that had been clearcut, cable yarded, and broadcast burned, ¼-½ in. high soil pedestals were observed on intensely burned areas of the unit. Less intensely burned areas did not have soil pedestals. The unit had a 30-60% slope gradient. Sediment eroded from part of the unit was captured on an old road bed downhill of the unit. Approximately 40 cubic ft was deposited, produced from a 0.367 acre area, yielding approximately 5 tons/acre/yr, or an average ground lowering of 0.03 in. (0.8 mm). It is not known what portion of the total sediment eroded from the burned unit was captured on the road bed, so the 5 tons/acre/yr should be considered a minimum estimate of erosion and delivery with no buffer following a winter with high rainfall.

Field estimates of rill and gully dimensions on skid trails in the Freshwater Creek Watershed during the present study averaged 4-6 tons/acre of skid trail/yr during the first 1-3 years after harvest on skid trails on 30-40% slopes. This only represents rill and gully erosion, not interrill erosion. Another observation on skid trails on 30-40% slopes in clearcut units underlain by Wildcat was that the top 6 in. of "fluffy" churned up soil and organic matter seen on fresh skid trails was absent on 4-5 year old skid trails. Assuming that 6 in. of soil was eroded from these skid trails over 5 years, and a bulk density of 0.6 tons/cu yd (half the 1.2 tons/cu yd measured on Wildcat) to account for the "fluffy" soil, this would yield an average of 81 tons/acre of skid trail/yr. This should be considered a maximum rate. These rates were observed on unvegetated skid trails the first few years following harvest. Rates decrease as skid trails stabilize and revegetate; 10-year old skid trails were well-vegetated, stable, and showed little, if any, erosion.

Comparison with Modeled Erosion and Delivery Rates

The Disturbed WEPP model was run with no buffers to estimate surface erosion for a variety of hillslope gradients and treatments. Table 3-11 shows a comparison of the erosion rates predicted from the three different WEPP model runs with the field-observed erosion rates discussed above. The WEPP rates in the table are for the first year following harvest, expressed in tons/acre of harvest unit/year.

Rates measured by Marron et al. (1995) indicate soils developed on schist are much more erodible than those derived from sandstone parent material. Soils in the Freshwater are derived from sandstone, siltstone, and sheared metasedimentary rocks. Soils derived from sandstone and metasedimentary rocks in the Freshwater are probably comparable to the sandstone soils of

Marron et al. (1995). Finer-grained Freshwater soils are probably more erodible than the sandstone but not as erodible as the schist soils of Marron.

Table 3-11: Comparison of measured/observed and WEPP predictions of erosion rates (all rates in tons/acre/year).

Measured/observed		Initial WEPP run (year 1)	Modified WEPP run (year 1)	Skid trails and burns modeled separately (year 1)
Redwood Creek measured rates (Marron et al. 1995)				
Cable yarded		Clearcut, cable yarded, 15-35% slope, no buffer		
Sandstone	2			
Schist	7	0.3-0.8	0.2-0.5	0.7-1.8
Tractor yarded		Clearcut, tractor yarded, 15-35% slope, no buffer		
Sandstone	2			
Schist	30	0.5-1.4	0.2-0.6	2.2-5.0
Field observations in Freshwater after winter with very high rainfall		Clearcut, cable yarded, broadcast burn, 30-60% slope, no buffer		
Cable-yarded, broadcast burn, 30-60% slope	5	mean annual: 1.2-2.3 30-yr: 3.7-6.9	mean annual: 0.6-1.6 30-yr: 3.5	mean annual: 4.9-8.3 30-year: 13.8-22.8
skid trails, 30-40% slope, rill erosion	4-6	Skid trails, 30-40% slope, no buffer		
Skid trails, maximizing assumptions	81	(not modeled separately)	(not modeled separately)	Mean annual: 24 30-year: 52

Marron et al. (1995) measured 2 tons/acre/yr of erosion on cable-yarded sandstone units and 7 tons/acre/yr on schist units. The WEPP model (Initial run) predicts 0.3-0.8 ton/acre/yr of erosion. On tractor yarded slopes, Marron et al. (1995) measured 2 tons/acre/yr of erosion on sandstone units and 30 tons/acre/yr on schist; the WEPP model predicts 0.5-1.4 tons/acre/yr.

The Modified WEPP runs predict about half as much delivered sediment as the Initial run; the runs with skid trails and burns modeled separately predict about 2-3 as much as the Initial run.

The field observations of approximate erosion amounts in the Freshwater Creek Watershed were made following a few winters with very high rainfall. The WEPP model can predict erosion from years with higher rainfall, expressed as recurrence intervals of the annual rainfall (similar to recurrence intervals of flood events in the hydrologic record, but based on total annual rainfall). The 30-year recurrence year's delivered sediment was used for comparison with field-observed rate. The total annual rainfall during 1998 was the second highest in the 51-year rainfall period at the Eureka rainfall gage, suggesting that the comparison would be appropriate. On the cable-yarded, broadcast burned unit, a very approximate measurement of 5 tons/acre/yr was observed; the Initial run of the WEPP model predicts 3.7-4.9 tons/acre/yr delivered. On skid trails, 4-6 tons/acre/yr of from rill erosion were observed, with a maximizing observation of up to 81 tons/acre/yr if 6 in. of soil was lost from the entire skid trail. The WEPP model run of a skid trail modeled separately could be compared to these observations. It predicted 52 tons/acre/yr delivered to streams under the 30-year recurrence rainfall year.

Surface erosion varies considerably both spatially and through time depending upon site-specific topography, cover, and soil conditions, as well as the intensity and duration of rainfall events. Based on the comparison of measured and observed rates of surface erosion with different runs of the WEPP model, it appears the model predicts surface erosion rates reasonably well. The Initial WEPP runs are somewhat lower than the rates measured in Redwood Creek, but very similar to approximate rates observed in Freshwater Creek. The Modified WEPP run appears to produce low estimates, and the modeling of skid trails and burns separately produces somewhat higher rates. All model runs produced similar differences between treatments, with tractor yarding and burning of units producing more erosion than cable or helicopter yarding and site preparation techniques that do not disturb the ground. The differences between treatments are more pronounced at higher slopes (over about 30%), as observed in the field.

As with any model or even measurements of erosion rates, the numerical values should be treated as estimates and are most useful for showing differences between different harvest methods and treatments.

3.2.3.3 WEPP Model Predictions of Surface Erosion and Delivery from Recent Harvest

An analysis of erosion associated with recent (1989-1999) harvest units based on WEPP modeling was completed using information on harvest type, yarding method, harvest unit slope, distance from stream, and stream buffer width. This analysis provides an estimate of surface erosion associated with the acres and types of recent harvest under CDF Forest Practice Rules. Current and future timber harvest practices on PALCO lands will be governed by the HCP, which includes wider buffer widths than the CDF buffers. The buffers instituted under the HCP are expected to result in lower delivery rates than those noted here.

The acres of timber harvest on PALCO lands from 1989-1999 are shown in Table 3-12. Harvest was concentrated in Cloney and Graham Gulch, Little Freshwater, and the Upper Mainstem sub-basins through 1994, with little harvest anywhere in the watershed in 1995. Beginning in 1996, harvest was concentrated in Little Freshwater, the South Fork, Cloney Gulch, and the Upper Mainstem.

Total annual predicted sediment delivered to streams from surface erosion associated with the 1989-1999 harvest units based on the Initial WEPP run is shown in Table 3-13. This amount includes erosion from previous years' harvest, so the 1990 harvest includes erosion associated with units harvested in 1990 as well as revegetating units harvested in 1989. Note, however, that it does not include erosion from any harvest prior to 1989, so total erosion predicted in the first few years is lower than later in the period.

Table 3-12: Acres of recent (1989-1999) timber harvest on PALCO lands in Freshwater Creek.

Subbasin	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	Total
Cloney Gulch	119		218	204					307	928		1,776
Graham Gulch		15	118	81	265	310			23	156	76	1,045
Little Freshwater		113	126	39	16	296		377	644	499		2,109
Mainstem	11				114			2	39	44		211
McCready Gulch	1							0	98	197	75	370
School Forest								10		51		61
South Fork	46	189	1	109		0		435	350	324	28	1,482
Upper Mainstem		226	133	15	36	17	17	58	125	367	345	1,338
Grand Total	177	543	595	448	431	624	17	882	1,586	2,567	524	8,393

Table 3-13: Total predicted sediment delivered to streams from timber harvest surface erosion resulting from 1989-1999 harvest (tons) based on Initial WEPP run.

Sub-basin	1989[1]	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Cloney Gulch	12	9	30	34	19	12	7	5	51	153	93
Graham Gulch	0	2	15	22	67	107	61	38	24	44	56
Little Freshwater	0	20	29	28	21	42	26	50	86	105	70
Mainstem	1	1	1	0	11	8	5	3	8	15	11
McCready Gulch	0	0	0	0	0	0	0	0	15	35	27
School Forest	0	0	0	0	0	0	0	0	0	8	6
South Fork	6	23	17	17	9	6	6	41	74	85	56
Upper Mainstem	0	29	39	27	28	16	12	27	41	77	82
TOTAL	19	84	131	129	155	191	117	164	299	521	401

[1]Erosion in 1989 and 1990 does not reflect cumulative erosion from harvest in years prior to 1989, so is lower than estimates for 1991-1999.

The amount of predicted sediment delivery from harvest surface erosion is based not only on acres harvested, but harvest and yarding method, hillslope gradient, and buffer width, so there is not a 1:1 correlation between acres harvested and resulting sediment delivery.

Figure 3-5 shows a comparison of predicted sediment input to streams from harvest surface erosion based on the three different WEPP model runs. The Initial WEPP run predicts about twice as much erosion as the run using soil and vegetation files modified to reflect conditions in the Freshwater Watershed (Modified WEPP run). The WEPP run with skid trails and burned units modeled separately shows higher rates for the first 1-2 years following harvest activities, but rates drop to similar levels within 3 years of harvest.

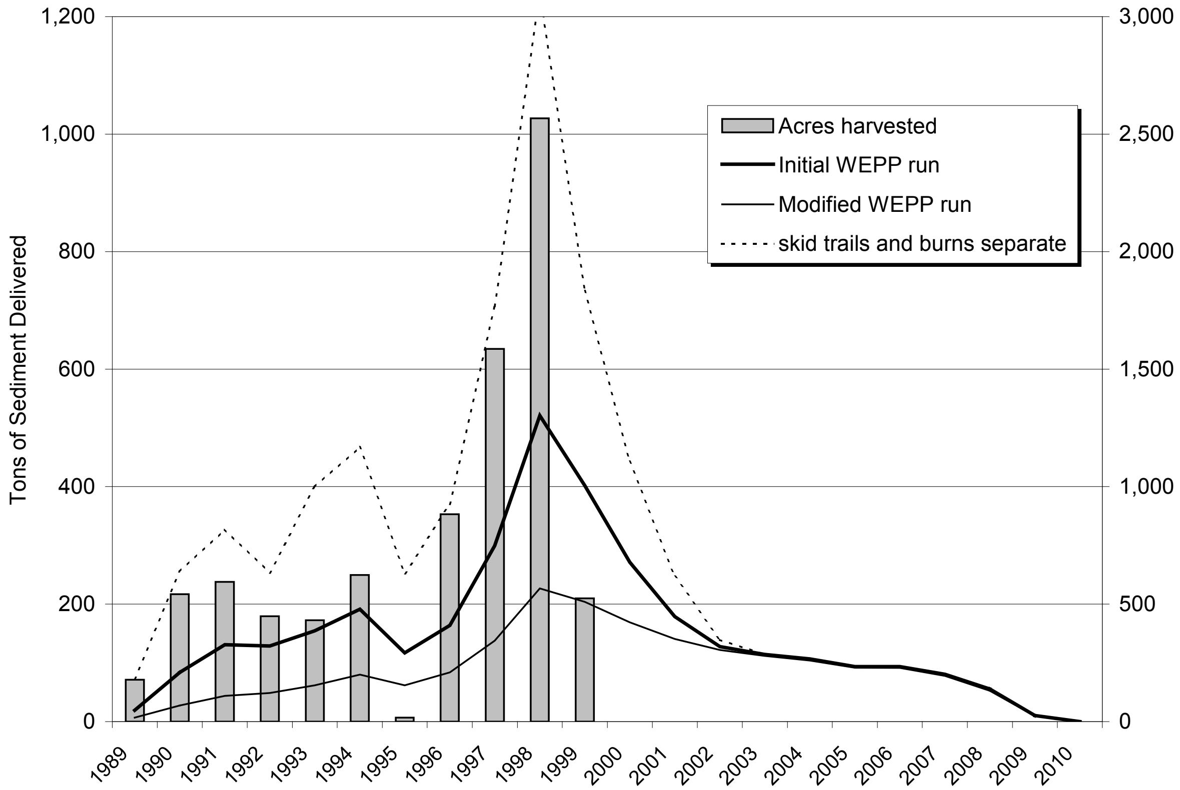

Figure 3-5: Recent (1989-1999) timber harvest (acres) and resulting surface erosion (tons).

Based on the Initial WEPP run, surface erosion/delivery associated with timber harvest in the early 1990s held steady at about 100-200 tons/year. The Modified and separate skid trails/burns runs predicted 30-50 tons/yr and 200-400 tons/yr, respectively, during the early 1990s. Sediment delivery increased in 1997 as harvest rates increased and will remains at these levels for several years as a result of harvest in 1997-1998. The Initial WEPP run estimates were used for further analysis because they represent a mid-range of predicted values. While there is a large range of estimated sediment delivery between the three model runs, the total input from harvest surface erosion is small relative to other sediment sources no matter which set of out put values is selected (see sediment budget discussion in the stream channel and cumulative effects reports).

The Initial WEPP model run was also used to predict future erosion from the recent harvest units, displayed in Table 3-14 and Figure 3-5. These forward-looking estimates do not include any harvest after 1999. Surface erosion from timber harvest units drops to low levels 3-5 years after harvest as the units revegetate and stabilize.

Table 3-14: Future predicted sediment delivered to streams from 1989-1999 timber harvest (surface erosion, in tons). Rates assume no additional harvest in the watershed after 1999.

Sub-basin	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Cloney Gulch	61	34	19	17	17	17	17	17	13	0	0
Graham Gulch	40	31	22	19	14	7	7	7	6	3	0
Little Freshwater	52	39	31	30	29	24	24	19	10	0	0
Mainstem	7	4	2	2	1	1	1	1	1	0	0
McCready Gulch	17	8	4	4	4	4	4	4	3	0	0
School Forest	4	2	1	1	1	1	1	1	1	0	0
South Fork	40	29	27	23	23	23	23	16	9	1	0
Upper Mainstem	50	32	21	18	17	16	16	15	13	7	0
TOTAL	271	179	127	114	107	93	93	80	55	10	0

Sources of Harvest-Related Sediment

In addition to information about how much sediment is produced from all harvest units, it is helpful to determine how much sediment is delivered from the different harvest methods so that the prescription team can determine the most effective ways to reduce sediment delivery if needed.

Estimates of the amount of sediment delivered to streams over the entire 20 years (1989-2008) associated with different harvest practices and yarding methods in units cut between 1989-1999 are shown in Table 3-15. Also shown are total acres harvested for each method and the average sediment delivered in tons/acre of harvest unit.

About 70% of the harvest in the Freshwater Creek Watershed during the 1989-1999 period has been partial cuts, split evenly between tractor and cable yarding, although there has been a shift to more cable yarding since 1996. The remaining 30% of the areas have been clearcut, again split fairly evenly between tractor and cable yarding but shifting to more cable yarding in recent years. A small amount of the harvest units have been helicopter yarded, all in 1998 and 1999. Approximately 0.5 ton/acre of harvest unit has been delivered to streams in the watershed from the last 10 years' harvest. The fact that there is little variation in the average delivered sediment rate between different harvest practices is because during this 10-year period, PALCO has generally done tractor yarding on lower gradient hillslopes and farther away from streams compared to cable or helicopter yarding. Delivery from tractor yarded units of a given slope is about equal to delivery from cable or helicopter units on a 10-15% steeper slope. Approximately 50% of the tractor yarded acres are within 200 ft of a stream, while 80% of the cable yarded acres are within 200 ft of a stream. While there is more ground disturbance and erosion in tractor yarded units, the combination of lower gradient and greater distance from a stream reduces the delivery, so the net sediment reaching a stream expressed in tons/acres harvested has been similar between the harvest and yarding methods.

Table 3-15: Estimates of total sediment delivered by harvest practice and yarding method from 1989-1999 harvest (based on Initial WEPP runs).

	Helicopter	Tractor	Cable	Total
Total delivered sediment (tons)				
partial	80	1,650	1,310	3,040
clearcut	30	770	760	1,560
total	110	2,420	2,070	4,600
Acres harvested				
partial	130	3,000	2,930	6,060
clearcut	100	1,070	1,160	2,330
total	230	4,070	4,090	8,390
Average tons/acre of harvest unit				
partial	0.6	0.6	0.4	0.5
clearcut	0.3	0.7	0.7	0.7
total	0.5	0.6	0.5	0.5

Grain Size of Delivered Sediment

About 70% of the sediment input from timber harvest surface erosion is silt and clay, and another 25% is sand-sized (Table 3-16). Only a small amount is coarser than sand; generally, surface erosion does not have enough energy to transport large particles, but occasional deeper rills and gullies can move small gravel.

The average annual input rates in Table 3-16 are annualized rates based on sediment input for the most recent 10-year period (1990-1999). On an average annual basis for the past 10 years, timber harvest has contributed about 7 tons/sq mi of watershed/yr.

Table 3-16: Average annual input from timber harvest, 1990-1999, by grain size (tons/yr).

Sub-basin	Gravel (>4.75mm)	Med/Coarse Sand (2-4.75 mm)	Fine Sand (0.075-2 mm)	Silt/Clay (<0.075 mm)	Total (tons/yr)	Tons/ sq mi/yr
Cloney	4	4	8	25	40	9
Graham Gulch	4	4	8	30	45	17
Little Freshwater	1	2	8	35	50	10
Lower Freshwater	>1	>1	1	5	6	2
McCready Gulch	>1	>1	1	5	7	3
School Forest	>1	>1	>1	1	1	2
South Fork	2	2	6	25	35	11
Upper Freshwater	4	4	8	25	40	4
Total Watershed	15	16	40	150	225	7

3.2.3.4 WEPP Predictions of Harvest Erosion and Delivery from Older Harvest

Due to the concerns raised about the cumulative effects of sediment from past land management activities in relation to channel capacity in the lower watershed, an historic sediment budget was prepared (see Channel Assessment, Appendix E). An estimate of surface erosion associated with older timber harvest (1954-1988) was made for the sediment budget based on available information on acres harvested in each aerial photo period and types of historic harvest (Table 3-8). Sediment delivery rates were adjusted for each photo period to account for less stringent environmental measures, lack of stream buffers, and types of timber skidding/yarding methods employed during that time. It was assumed that 50% of the sediment from the entire harvested area was delivered to streams to account for the lack of stream buffers, yarding up stream channels, and lack of erosion control measures and water bars on skid trails that resulted in more of the area of a harvest unit being hydrologically connected to the stream network. The following rates of delivered sediment were used based on tons/acre from WEPP runs on an average 30% hillside slope and the harvest methods shown in Table 3-8: pre-1954, 2.4 tons/acre assuming all units were tractor clearcut; 1954-1966, 2.1 tons/acre assuming 20% tractor clearcut and 80% tractor partial cut; 1967-1974, 1.8 tons/acre assuming all units tractor partial cut; and 1975-1987, 0.6 ton/acre assuming 75% tractor partial cut, 8% tractor clearcut, 17% cable clearcut, no yarding up stream channels, and implementation of stream buffers. Calculated sediment delivered during each period is shown in Table 3-17.

Table 3-17: Estimates of total sediment delivered from second cycle timber harvest, 1942-1987 (in total tons over photo period).

	Aerial photo period			
Sub-basin	**1942-1954**	**1955-1966**	**1967-1974**	**1975-1987**
Cloney	680	130	2,670	120
Graham Gulch	290	0	1,700	0
Little Freshwater	760	10	0	320
Lower Freshwater	10	340	480	140
McCready Gulch	0	240	800	640
School Forest	0	0	70	200
South Fork	0	210	0	60
Upper Freshwater	2,220	1,470	530	290
Total Watershed	3,960	2,400	6,250	1,770
Number of years in period	13	12	8	13

3.2.3.5 Effects of Possible Strategies to Reduce Harvest Erosion/Delivery

Harvest practices that cause the most ground disturbance result in more surface erosion than practices that preserve the ground cover and duff layer protecting soil from erosion. In the Freshwater, the erodible soils, the high density of bladed skid trails on tractor yarded units (50-65 mi/sq mi), machine raking, and the use of fire for site preparation are the situations that result in higher rates of surface erosion. The following initial information is provided for the prescription team to assess the effects of measures to reduce harvest-related surface erosion, if needed. Additional data and tables showing the effects of any prescriptions being considered will be made available to the prescription team as needed.

Limit Use of Bladed Skid Trail on Slopes Over 30%

Erosion increases rapidly with slope on skid trails over about 20-30% gradient. Reducing skid trail density by using designated skid trails will reduce erosion. For example, on a 30% slope, reducing skid trail density from 15% to 10% results in a 30% reduction in delivered sediment; reducing skid trail density to 5% results in a 65% reduction in delivered sediment. Limiting bladed skid trails, where practical, will also reduce the amount of disturbed ground. Field observations found that waterbars on skid trails are not always effective in Wildcat areas; rills and gullies form that can be deep enough to erode through the waterbars, so particular care should be taken in these areas.

Effects of Buffers

Vegetated buffers between ground-disturbing activities and a stream filter out sediment as water infiltrates into the soil and water velocities decrease, causing particles to deposit on the forest floor. The majority of research on buffer effectiveness has been in areas of sandier soils and relates to filtering of forest road runoff. These studies have shown that buffer effectiveness is a function of hillside slope, buffer width, and the number of obstructions on the ground to slow water velocities and trap sediment. Most studies show buffer widths of 30-150 ft capture most sediment (Trimble and Sartz 1957, Haupt 1959, Haupt and Kidd 1965, Burroughs and King 1989, Ketcheson and Megahan 1996, Brake et al. 1997). The fine-grained sediment (silt and clay) found in Freshwater soils do not drop out as quickly as coarser-grained sand or gravel particles, but some filtering does take place. Deposits of sediment on low gradient areas downslope of eroding harvest units were observed in the field.

The WEPP model was used to predict the relative effectiveness of buffer strips at filtering fine-grained soils (clay loam). As an example, the model was run for a 100-ft long skid trail on varying hillslopes (Figure 3-6). WEPP predicts that sediment delivery drops quickly with buffer widths up to about 100 ft, then decreases more slowly with wider buffers. A 25-ft buffer reduces delivered sediment to 65% of the eroded amount; a 50-ft buffer reduces delivery to 50%, and a 100-ft buffer reduces delivery to 35%. WEPP predicts that there is a diminishing rate of return for wider buffers – a 200-ft buffer reduces delivery to 20% and a 300-ft buffer reduces delivery to 15%. Note that these WEPP model runs suggest that the maximum 200-ft sediment delivery distance assumed in the module methods based on the work of many researchers may underestimate sediment travel distances for the fine-grained soils in the Freshwater Watershed. The net numerical difference in the analysis from this assumption (the assumed 1% delivery in areas farther than 200 ft from a stream instead of up to 20% delivery predicted in the WEPP model) is relatively small and well within the ±50% range given for the WEPP model results (Elliot et al. 2000). This aspect of uncertainty is reflected in the confidence discussion and monitoring recommendations.

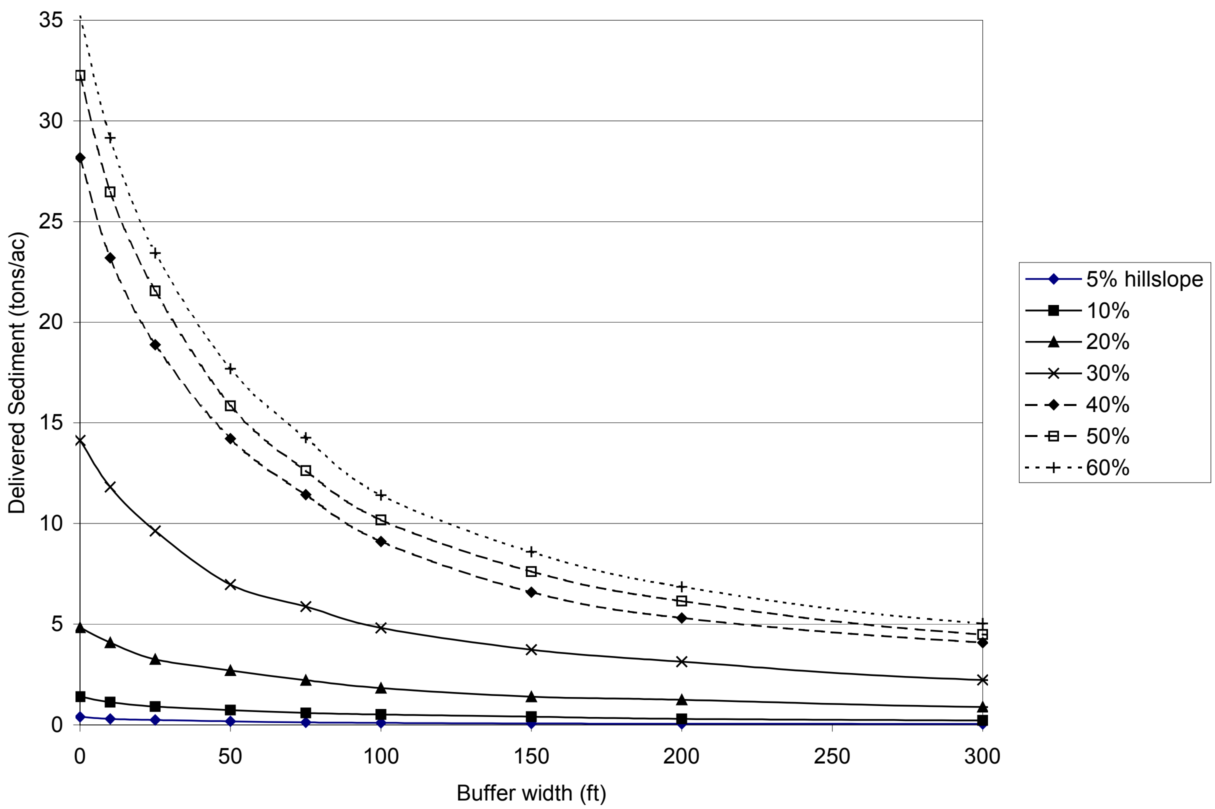

Figure 3-6: WEPP prediction of effect of buffer at filtering sediment from skid trail.

3.2.4 Surface Erosion from Other Land Management Activities

Surface erosion associated with other (non-timber) land management activities in the watershed was also considered. As described in Section 3.1.3, it was decided that there was so little erosion associated with dispersed grazing in the upper watershed or recreational vehicle use that these sources were not quantified.

Surface erosion associated with homesite development was quantified, based on WEPP predictions of 0.6 ton/homesite and the number of homesites constructed during each aerial photo period, an average of 1-3 tons/year is added from this source (Table 3-18). This is minor compared to other sediment sources and was not considered further. However, measures to limit erosion of sediment into streams should be considered during future home building or land clearing activities near streams. Surface erosion from concentrated grazing in pastures at the Freshwater Valley Stables was also quantified. Turbid runoff from some pastures was seen following a rainstorm during field work. Based on a WEPP analysis of the slope, soils, and vegetative cover, it was estimated that an average of 3.5 tons/yr is delivered to Freshwater Creek from the stables.

Table 3-18: Estimates of sediment delivered from home building.

Aerial photo year	Number of new homes	Average homes/year	Average sediment input (tons/yr)
1954	98	2	1
1966	49	4	2
1974	21	3	2
1987	75	6	3
1994	43	6	3
1997	18	6	3
Total	304	-	-

3.3 SUMMARY OF HILLSLOPE EROSION

Surface erosion from timber harvest in the Freshwater Creek Watershed has varied through time as timber harvest practices have changed and the intensity of harvest has fluctuated. Average annual rates of sediment delivered to streams from timber harvest have ranged from a low of about 100-150 tons/year from the mid 1970s to early 1990s to highs of 400-500 tons/year in the early 1970s and late 1990s. Sediment from a particular unit decreases as the unit revegetates and reaches low levels 4-5 years following harvest.

Tractor skidding and post-logging burning of clearcut units involving hot burns or mechanical site preparation are the two largest producers of surface erosion associated with harvest units. An evaluation of past tractor skidding operations shows that 10-15% of a unit is disturbed by skid trails, resulting in bare ground. Erosion from skid trails and burned areas increases with slope; care should be taken when using tractor skidding on slopes over about 30% and when burning slopes over about 50%. Cooler broadcast burns, particularly in cable-yarded units where there is little other ground disturbance, result in less erosion. Cable and helicopter yarding result in little ground disturbance and therefore little chance of surface erosion.

Surface erosion associated with other (non-timber) land management practices in the basin is minor in comparison with timber-related sources.

3.4 CONFIDENCE DISCUSSION

Confidence in the assessment of surface erosion associated with timber harvest units is moderate.

Based on field observations, confidence is high that tractor yarding results in much more surface erosion than cable skyline or helicopter yarding. Confidence is also high that burning units (particularly pile burning) results in moderate surface erosion, depending upon how intense the burn was and whether it was a fall or spring burn. Confidence is high that spot herbicide applications do little to increase surface erosion. Confidence is moderate in the assessment of delivery of eroded sediments to streams through buffers. The fine-grained soils in the watershed do not settle out quickly and are more difficult to filter than sandier soils.

Confidence in the quantification of surface erosion rates is moderate. The WEPP model is a fairly intricate model to apply, and several limitations with the current application were discovered. As with any model, the results should be used as an estimate of the magnitude of erosion in comparison with other sources. The WEPP model documentation states that the accuracy of predicted erosion rates are, at best, ±50% (Elliot et al. 2000).

4.0 ROAD EROSION

Unlike surface erosion from exposed hillslopes where revegetation usually occurs within a few years, road surfaces can continue to erode as long as the road is used. The road cutslopes and fillslopes tend to revegetate, reducing erosion from those sources over time. However, the tread and ditch provide fine-grained sediments as long as they continue to be disturbed by traffic and road grading activities. The focus of this part of the assessment is to identify portions of the road network that deliver sediment to streams and therefore could affect aquatic habitat or water quality. This assessment develops an understanding of the overall effects of the road system on sediment yield by roughly quantifying the amount of sediment delivered to streams from roads for comparison with estimated sediment input rates for background and other land management activities.

4.1 METHODS

The Freshwater Watershed is the first in a series of watershed analyses that will be conducted on PALCO lands. As part of adapting the WDNR watershed analysis methods to northern California, several variations on the WDNR methods (WDNR 1997) to calculate road erosion were proposed for the Freshwater basin to compare the different methods. Based on the results, a single approach will be selected for future watersheds.

Four different types of analyses or field surveys exist to help calculate road surface erosion in the Freshwater basin (Table 4-1). Each has its own uses and drawbacks. An ideal approach for estimating road surface erosion would be one that calculates erosion from a road segment, determines the amount of the eroded sediment that reaches a stream, and stores the results in a GIS database so the effects can be displayed and summed spatially. The erosion and delivery calculations would be based on site-specific measurements of erosion and delivery in the watershed. Unfortunately, road erosion can be difficult to measure and vary widely with weather, road, and traffic conditions at a single site, so several years of data collection is needed to obtain good relationships between site conditions and erosion. This type of data collection and analysis is a research-level effort and beyond the scope of a watershed analysis. Because site-specific erosion data were not available for the Freshwater assessment, results from the different methods to estimate erosion were compared with field observations of erosion and delivery and information from road managers to evaluate the most effective method to calculate road surface erosion.

Table 4-1: Comparison of road surface erosion analysis methods/field data.

Method	Description	Estimates Erosion	Delineates Segments Delivering	Uses; Pros/Cons
PWA Road Survey	Spatially delineates (maps) length of road ditch that delivers to streams on PALCO ownership		X	Provides map of length of road delivering sediment to streams. Freshwater survey did not include complete information on road surface and cutslope condition, so cannot be used to estimate erosion directly. Useful to check SEDMODL predictions of delivering segment lengths. Only covers PALCO ownership.
"Standard" WDNR Method	Estimates sediment delivered to streams from empirical relationships based on road conditions measured in field	X		Does not delineate delivering segments, but bases delivery on average percent of road network connected to streams.
SEDMODL	GIS-based model that estimates sediment delivery to streams from empirical relationships based on road conditions. Spatially delineates (maps) road segments that deliver sediment.	X	X	Once set up, easy to run over large areas (GIS based). Tends to over-estimate length of road delivering. Erosion estimates based on empirical relationships (similar to WDNR method).
WEPP: Road Model	Process-based model that estimates erosion from a road segment and delivery through a stream buffer with given characteristics	X		Estimates erosion for a single road segment. To apply to a watershed, it requires multiple runs, either one for each road segment that has been measured in the field or enough (hundreds) to produce a lookup table relating field measured road segment characteristics to erosion amount. Models filtering effects of buffers. Does not account for traffic effects.

As part of their sediment source study, PWA surveyed all roads on PALCO ownership in the Freshwater basin. During this survey, PWA collected information on the location and length of road ditch that drained to streams on PALCO's roads. They did not collect information on the road surfacing, use, width, or cutslope condition, so the data cannot be used directly to calculate road erosion, but information on ditch connectivity can be compared to lengths of road delivering to streams predicted by SEDMODL.

The standard WDNR approach for estimating surface erosion is based on a series of empirical relationships that increase or decrease the amount of erosion from a road segment depending on the condition of that road segment. A major disadvantage of this method is that it does not delineate road segments that are delivering, but assigns an average delivery percentage to road classes or types.

The SEDMODL program is a GIS-based model that delineates road segments delivering sediment to streams and then calculates erosion and delivery from each segment based on empirical relationships similar to those used in the WDNR methodology. The model tends to over-estimate the length of segments that deliver to streams because it is based on 10-meter Digital Elevation Model (DEM) data that are not sensitive to small-scale changes in topography that can be seen in the field, and the present version does not account for cross drains or outsloped roads that reduce the length of road directly delivering to a stream.

The WEPP model is a physically based model that was developed by an inter-agency team to estimate erosion over a wide range of climate, soil, slope, and vegetation conditions. At the present time, the WEPP model is set up to calculate road erosion and delivery through a buffer from a single road segment. Road characteristics, length delivering, and buffer characteristics must be input by the user. The model does not currently have the ability to select road segments in GIS. The model calculates erosion and delivery based on equations that predict runoff and resulting erosion or deposition of soil each day for 30 years of computer-generated climate. The model does not take into account differences in traffic levels on roads. In its present configuration, it is useful to provide another estimate of erosion and delivery rates from specific road segments for comparison with those computed by SEDMODL or the WDNR procedure.

Specific information on each of the different methods is provided in Appendix B of the Methods to Complete Watershed Analysis on Pacific Lumber Company Lands (PALCO 2000). Information on the rates or relationships as they were applied to the Freshwater Watershed are provided below.

4.1.1 Field Measurements of Road Characteristics

Three different field surveys of road characteristics were made in the Freshwater Watershed. PWA completed a survey of roads in 1997 as part of their Sediment Source Investigation (PWA 1999). Much of their inventory concentrated on culvert conditions, mass wasting problems, and eroding cutslopes/fillslopes. However, they did collect information on the length of ditch that drained to streams at stream crossings, culverts, and drainage dips on all roads on PALCO's ownership. This information was linked to a drainage point on a map and entered into a GIS layer so that the data were available spatially. The PWA inventory also collected information on road gullies and culvert washouts that are summarized in this Surface Erosion Assessment.

PALCO staff made field measurements of road dimensions during the Spring of 1999. Road dimensions were measured for different types of road in the watershed (highway, mainline, secondary, spur, and decommissioned). A representative sample of each type was measured. Sampling locations were randomly chosen by overlaying a point grid on a map of the road system. At each sample location, the following measurements were made: hillslope position; distance to stream; road type; traffic level; tread (width, slope, age and surface material); inside ditch width; cutslope (length, cover percent, and slope); and fillslope (length, cover percent and slope).

During field sampling for the hillslope portion of the assessment, Harza Engineering Company staff did some spot checking of road characteristics as a QA/QC check on the previous field measurements. Information on road dimensions as well as delivering length was checked.

4.1.2 "Standard" WDNR Road Erosion Estimates

In the standard WDNR method, road erosion is calculated using a set of empirical relationships:

Total Segment Erosion = (Tread + Cutslope/Ditch + Fillslope) × Road Area × Delivery Factor

Tread = 40% × Basic Erosion Rate × Surfacing Factor × Traffic/Precip Factor

Cutslope/Ditch = 40% × Basic Erosion Rate × Cover Factor

Fillslope = 20% × Basic Erosion Rate × Cover Factor

Table 4-2 shows the basic erosion rates that were used for the different geologic types found in Freshwater.

Table 4-2: Basic erosion rates for WDNR road erosion (erosion rates in tons/acre/year of road prism).

Geology	Basic Erosion Rate (tons/acre/yr)
Franciscan melange	60[1]
Alluvium (Holocene)	15
Yager Formation (Tertiary-Cretaceous)	60
Wildcat Group Undifferentiated (Pleistocene-Miocene)	60

[1] Basic erosion rates for Franciscan melange and Yager Formation are suggested as 30 tons/acre/yr in the methods document (PALCO 2000). However, based on field observations and grain size sampling of these geologies in the Freshwater Creek watershed, it was determined they were similar to the Wildcat Group and warranted a higher erosion rate. While the Franciscan and Yager are likely not quite as erodible as the Wildcat, the same rate was used for all three units for consistency with the hillslope erosion analysis where no distinction was made in erosion rates.

Table 4-3 shows the average road prism widths and cover percentages measured in the field, along with factors that were used in the computation of road erosion rates based on the WDNR method.

Table 4-3: WDNR road erosion factors used for Freshwater Creek.

Road Type	Number of samples	Road prism width (ft)	Cutslope cover (avg. %)	Cutslope cover factor	Fillslope cover (avg. %)	Fillslope cover factor	Surfacing factor	Traffic/ ppt factor
Paved road	11	57	60	0.31	80	0.18	0.03	50
Gravel mainline	14	48	60	0.31	70	0.25	0.2	50
Gravel secondary	19	40	40	0.44	40	0.44	0.2	10
Native spur	13	33	50	0.37	50	0.37	1	1
Abandoned	8	21	50	0.37	70	0.25	1	0.05

For the delivery factor in the WDNR method assessment, it was assumed that all roads were insloped, so all portions of the road prism in a delivering segment drained to the stream. The length of road delivering to streams was based on 13% of total road length based on PWA's road inventory (PWA 1999). The PWA survey did not collect information on indirect delivery rates. For the WDNR analysis, a delivery factor of 1 (100%) was used for all lengths delivering and 0 (0%) for all other lengths since field measurements of indirect delivery lengths were not available. The WDNR calculations of road erosion are included in Data Worksheet B4-1.

4.1.3 SEDMODL

The SEDMODL program is a GIS-based model that determines portions of the road network that drain directly or indirectly to streams and calculates average annual sediment input from each of these segments. It is a cost-effective tool that could be used either in place of intensive field surveys of the road network, or in portions of the watershed where intensive surveys are not conducted (e.g., non-PALCO land).

In preparation for running the SEDMODL program, the road GIS database was checked against recent (1997) aerial photographs to make sure the database included all roads. Roads not in the database but observed on the photographs were digitized and added to produce a complete road coverage. The new road segments were all on non-PALCO land and included logging roads, local roads, agricultural roads, and long driveways.

The SEDMODL program calculates road surface erosion using the following formulas:

Total Sediment Delivered from each Road Segment (in tons/year) = Tread + Cutslope

Tread = Geologic Erosion Rate × Tread Surfacing Factor × Traffic Factor × Segment Length × Road Width × Road Slope Factor × Precipitation Factor × Delivery Factor

Cutslope = Geologic Erosion Rate × Cutslope Cover Factor × Segment Length × Cutslope Height × Delivery Factor

The local precipitation and geology GIS coverages available in PALCO's GIS were used in the model to obtain the precipitation factors and the geologic erosion rate. Geologic erosion rates were based on those in Table 4-2 (above). The model generates the segment length, road slope factor, cutslope height, and delivery factor based on the local topography from the 10-meter DEM coverage in GIS.

The user-input parameters used for the SEDMODL run are shown in Table 4-4. These factors are based on observations or measurements of the various road characteristics on PALCO lands during the field surveys and extrapolation of these factors to non-PALCO roads. A cutslope cover of 70% was used for all road types since the present version of the model only allows one value for all roads.

Table 4-4: Road erosion factors used for SEDMODL run in Freshwater Creek.

Road Type	Road width (tread + ditch in ft)[1]	Tread Surfacing	Tread Surfacing factor	Traffic Use	Traffic Factor
Paved road	26	Asphalt	0.03	Primary	10
Gravel mainline	21	Gravel	0.2	Primary	10
Gravel secondary	20	Gravel	0.2	Secondary	2
Native spur	16	Native	1	Spur	1
Abandoned	16	Grass native	0.5	Abandoned	0.1
Grassed farm road	12	Grass native	0.5	Spur	1
Gravel driveway	12	Gravel	0.2	Spur	1

[1] Note that this measurement includes only tread plus ditch portions of road prism, in contrast to the previous table which includes cutslope and fillslope portions of road prism. SEDMODL accounts for the cutslope and fillslope separately.

The SEDMODL program usually over-estimates the length of direct delivery segments. For the final road erosion analysis, the road erosion estimates from SEDMODL were adjusted to reduce the direct delivery lengths based on the PWA survey results (described in Section 4.2.3). The SEDMODL road erosion calculations are included in Data Worksheet B4-2.

4.1.4 WEPP: Road Model

The WEPP: Road model available through the USFS internet user interface was used to compute road erosion from various road configurations for comparison with other erosion estimates (http://forest.moscowfsl.wsu.edu/cgi-bin/fswepp/wr/wepproad.pl). A variety of road characteristics were run for comparison with those that were generated using the SEDMODL program (Table 4-5). The Orick Prairie Creek Park climate station was chosen from the available climate stations as the closest station with similar mean annual precipitation and climate characteristics to the Freshwater (Attachment B-3). Several different road gradients were modeled for each road type. Buffer widths of 100 and 200 ft were used for comparison with the SEDMODL assumptions of buffer effectiveness (the sediment leaving the road value was used for comparison with direct delivery values from SEDMODL). Four different types of roads were modeled with different road configurations, following the guidelines in the WEPP: Road Technical Documentation. Mainline roads were modeled as insloped with a bare ditch, assuming that regular road maintenance would disturb the ditch. Secondary roads were modeled as insloped with a vegetated or rocked ditch, assuming that maintenance would not be as frequent and the ditch would have time to stabilize. Spur roads were modeled as outsloped and rutted, assuming that they are primarily native surfaced and traffic produces wheel indentations that direct surface flow down the indentations rather than off the road surface. Abandoned roads were modeled as outsloped and unrutted, assuming that there is no traffic on these roads (they are blocked and revegetating). Rates from the WEPP output for abandoned roads were multiplied by a traffic factor of 0.1, the same factor used for the SEDMODL runs, since the WEPP model assumes traffic on all roads (pers. comm., Bill Elliot).

Table 4-5: Road and climate characteristics used for WEPP: Road runs.

Factor	Variables used for all road types			
Climate Station	Orick Prairie Creek Park (mean annual precipitation 62.73 in.)			
Soil Texture	Clay loam			
Road Gradient	2%, 5%, 7%, 10%			
Buffer Gradient	30%			
Buffer Length	0 ft (sediment leaving road), 100 ft, 200 ft			
	Variables that varied by road type			
	Mainline	Secondary	Spur	Abandoned
Road Design	Insloped, bare ditch	Insloped, vegetated or rocked ditch	Outsloped, rutted	Outsloped, unrutted
Road Length[1]	125 ft	100 ft	100 ft	100 ft
Road Width[2]	21 ft	20 ft	16 ft	16 ft
Road surface	Gravel	Gravel	Native	Native

[1] The road length in WEPP: Road was based on the average connected road ditch length at a stream crossing from the PWA survey for each road type.
[2] In WEPP: Road, the road width includes the tread and ditch.

4.1.5 Comparison Between Road Surface Erosion Estimate Method and PWA Sediment Source Investigation Methods

Pacific Watershed Associates prepared a Sediment Source Investigation for Freshwater Creek in 1999 (PWA 1999). Part of their analysis included a preliminary estimate of road surface erosion. Surface erosion was not the main objective of their report, with the understanding that a more detailed estimate would be prepared as part of the current Watershed Analysis activities. Their analysis was based on several simplifying assumptions regarding road attributes and use patterns appropriate for the level of detail for that section of their analysis.

The PWA analysis was based on an average surface lowering rate of 0.14 ft/decade (27 tons/acre/yr) and an average road width of 20 ft for all roads. This rate was applied to the total length of connected roads on PALCO ownership in the watershed based on their total road inventory of PALCO roads. No rates were applied for indirect delivery segments. The net result of the PWA analysis was much lower delivered sediment rates from road surface erosion than the present analysis, which took into account specific information about each road segment and included non-PALCO roads as well as indirect delivery from road segments within 200 ft of a stream.

4.2 ANALYSIS AND RESULTS

4.2.1 Road Building History

The road building history of the Freshwater Creek Watershed started with railroad lines constructed between 1860 and 1940 to remove timber from the basin. Several of these routes were converted to conventional truck roads in later years. In addition to timber haul routes, roads to access residential developments in the lower watershed and northern and eastern ridgelines have been developed. The following description of the road building history of the basin is taken from PWA (1999), and has been updated to include the entire watershed, covering non-PALCO lands (47 miles of roads) as well as the PALCO land (170 miles of road) covered in PWA's report.

The first routes built in the Freshwater Creek Watershed were railroads used to haul logs out of the basin. Old railroad grades can be found throughout the watershed (Map B-3) and include ridge routes, some mid-slope routes, routes which paralleled or occupied major stream channels in the valley bottoms, and inclines that were used to connect upslope logging areas with valley bottom rail lines. Most (but not all) large stream channel crossings along the rail lines employed trestles rather than fills, so impacts of direct sedimentation at large crossings were minimized.

Although excavation was minimized in most areas, railroad grade construction often employed extensive sidecasting and the filling of small streams with logs, organic debris, and soil.

Railroad construction in the Freshwater occurred during two phases. The early phase lasted from the 1860s through about 1900. This construction accompanied early harvesting in the lower watershed in the School Forest, McCready, Cloney, Graham, and lower Freshwater Creek areas. The latter three watersheds had rail lines constructed directly up or alongside the main stream channels. After a 20-year lull in activities, a second period from about 1920 through 1940 saw renewed harvesting and railroad construction in the upper watershed. During this period, virtually all the remaining old-growth forests on PALCO lands in the Freshwater Creek Watershed were harvested. Harvesting during both periods of railroad logging consisted of clearcutting and cable yarding. Historical accounts suggest that harvest areas were broadcast burned both before and following clearcutting. Just under 40 miles of railroad line had been constructed on PALCO property in the Freshwater Creek Watershed by the end of the 1940s.

Map B-5 and Figure 4-1 depict the general road construction history for the Freshwater Creek Watershed, as derived from an analysis of aerial photography. Construction of logging roads paralleled the advent and use of tractor for yarding, because the same machines were used for both activities. By the mid-1940s, it appears that tractors were being used in isolated portions of the watershed to yard concentrations of logs to the railroad lines.

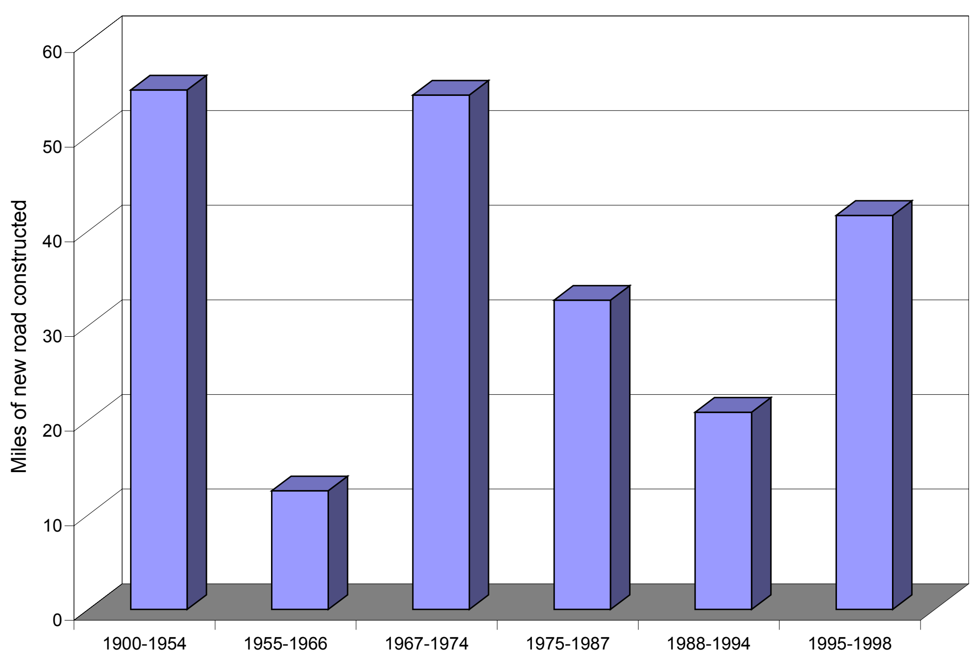

Figure 4-1: Miles of new road construction by aerial photo period.

Some large skid trails are apparent in both the 1947 and 1954 aerial photography, but large scale tractor yarding had not yet commenced in the watershed. In addition to the 32 miles of logging roads constructed prior to 1954, approximately 22 miles of roads to access residential areas were built prior to the 1954 photos. The rate of residential road building has held steady at an average of about 0.5 mile/year throughout most of the photo record.

Compared to many other north coast watersheds, harvesting and road building activity in Freshwater Creek remained at low levels even through the 1966 photo period, largely because of the limited availability of merchantable large trees (nearly all the old-growth had been harvested during first cycle logging). Between 1966 and 1974, approximately 54 miles of roads were built, for an average construction rate of 6.8 miles/yr. Some of the main truck roads in the watershed were built, along the old railroad grades. These early roads took advantage of the previous excavations and low or moderate grades of the rail routes. Other roads were built in middle hillslope positions of Graham, Cloney, and lower McCready Gulch to support tractor yarding of second-growth stands, and these were often abandoned shortly after their use. Between 1975 and 1987, an additional 33 miles were constructed in upper McCready Gulch, in lower Little Freshwater Creek, and in the upper parts of the mainstem, all areas first logged in the middle and late 1800s.

Roads built from 1988-1994 include many short ridge spur roads in Little Freshwater Creek and around the headwaters of Graham Gulch and Cloney Gulch built off the old ridge-top railroad grades. An additional 42 miles of road were constructed between 1995 and 1998. Unlike many of the roads constructed prior to 1987 that followed stream courses, many of the new roads built in the 1990s largely consist of main line ridge roads and short spurs built on tributary ridges to provide access for cable yarding. Since ridgetop roads are farther away from streams and do not have stream crossings, they have fewer opportunities for sediment inputs to streams than mid-slope or valley bottom roads.

As with the adjacent Elk River Watershed, Freshwater Creek is typical of a number of coastal basins where early logging removed the old-growth forest, but truck roads were not constructed over much of the area until second-growth forests were entered. For this reason, logging road construction has continued and even accelerated in recent years, as these areas are accessed for harvesting. The need for ridge-top and midslope roads for second-growth harvesting and cable yarding explains the relatively high rates of recent road construction. Most of the 35 miles of new logging road constructed between 1994 and 1997 in Freshwater Creek occurred along ridges in the western half of Little Freshwater Creek and on ridges in the South Fork. In addition, a number of old 1974 midslope roads in Cloney Gulch and McCready Gulch, which had been abandoned for over 20 years, were also rebuilt.

4.2.2 Current Status of Roads in the Watershed

At the time of this Watershed Analysis (1999-2000), there are a total of 208 miles of active road in the Freshwater Watershed, and 8.9 miles of roads decommissioned under HCP guidelines (Table 4-6 and Map B-6). This figure includes roads on PALCO and non-PALCO lands.

Table 4-6: Current roads in the Freshwater Creek Watershed.

Subbasin	Paved road	Gravel mainline	Gravel secondary	Native spur	Abandoned	Driveways & farm roads	Total	Road density (mi/sq mi)	Decommissioned under HCP
Cloney	1.8	3.6	0.8	28.5	7.7	-	**42.3**	9.0	-
Graham Gulch	4.6	0.4	4.4	12.4	2.3	-	**24.0**	9.5	-
Little Freshwater	-	11.8	3.4	16.2	2.9	0.1	**34.3**	7.3	-
Lower Freshwater	6.4	0.0	0.8	6.1	0.2	12.5	**26.0**	8.4	-
McCready Gulch	0.9	0.1	1.3	15.6	2.4	0.4	**20.6**	10.3	0.7
School Forest	1.1	0.4	0.1	3.1	-	0.1	**4.8**	7.9	-
South Fork	-	5.2	3.4	5.7	0.3	-	**14.7**	4.7	1.5
Upper Freshwater	1.8	3.4	9.5	21.0	2.4	3.4	**41.5**	4.1	6.7
Total Watershed	16.5	24.8	23.6	108.5	18.1	16.5	**208.1**	6.8	8.9

There are 16.5 miles of main paved (asphalt) roads, including the Freshwater-Kneeland Road that bisects the basin and then follows the eastern ridgeline and portions of the Greenwood Heights Road that skirts the northern boundary of the watershed. Gravel road segments include 25 miles of gravel mainline and 24 miles of gravel secondary roads that are distributed throughout the basin and are used primarily to access timberlands. There are 109 miles of native-surfaced roads, mostly spur roads in timberlands that are used to access specific timber harvest parcels, but are not used year-round or for through traffic. Approximately 18 miles of road have been abandoned in the watershed and currently receive no traffic. An additional 16.5 miles of agricultural roads, and long driveways are located primarily on land owned by small private landowners.

Overall road density in the watershed is 6.8 miles of road/square mile of land. Road densities are highest in Cloney, McCready, and Graham gulches, which include primarily timber roads.

High densities in Lower Freshwater are influenced by local roads/driveways as well as timber roads, while School Forest and Little Freshwater include mostly timber roads.

In addition to different road densities, the position of roads is different in the sub-basins, reflecting when the roads were constructed and the type of logging systems employed. Most of the logging road system in Cloney, Graham, and McCready gulches and the School Forest sub-basin was constructed in the 1970s and early 1980s to serve tractor-yarding operations. The road system in these sub-basins includes a network of closely spaced stream-side, mid-slope, and ridge-top roads (Map B-6). In contrast, the majority of the roads in the South Fork and Little Freshwater sub-basins are ridge-top roads constructed in the 1990s to serve cable yarded units.

4.2.3 Comparison of Road Surface Erosion Estimates

Calculating the amount of road surface erosion delivered to streams in the watershed requires both determining which portions of the road network drain to streams and estimating the amount of sediment produced from those road segments.

4.2.3.1 Selection of Delivering Segments

Two of the road erosion methods used in the Freshwater Watershed divide the road network into segments that deliver to streams (Table 4-1).

SEDMODL divides the road network into four categories to calculate the road delivery factor: (1) those that drain directly to streams; (2) those that are within 100 ft of a stream; (3) those within 200 ft of a stream; and (4) those that are farther than 200 ft from a stream. Placement of each road segment into one of these categories is based on the road, stream, and topography layers in the GIS database. SEDMODL was run on the entire Freshwater Watershed.

The PWA road survey covered all roads on PALCO lands and delineated the length of ditch at each drainage structure (stream crossings as well as cross-drains) that drained to a stream. These ditch lengths were digitized to produce a GIS coverage. The PWA survey did not cover any roads on non-PALCO lands (approximately 22% of the roads in the watershed), and did not assess indirect delivery of road sediment though forested buffers to streams.

A comparison of the connected ditch lengths from the PWA survey with the direct delivery segments from the SEDMODL run (PALCO roads only) is shown in Table 4-7 and Map B-7.

The SEDMODL program overestimates the length of road delivering directly to streams by approximately 85% compared to the PWA field survey results. The overestimates are primarily due to two conditions that SEDMODL does not account for: (1) the installation of cross-drains that divert ditch water onto the forest floor and shorten the length of ditch connected to a stream (information on cross drain locations is not provided to SEDMODL); and (2) outsloped roads that do not have ditches (SEDMODL assumes all roads are insloped with a ditch).

Table 4-7: Comparison of PWA survey and SEDMODL prediction of road lengths directly delivering to streams (PALCO roads only).

Sub-Basin	PWA field survey of direct delivery (miles)	SEDMODL prediction of direct delivery (miles)	Difference (miles)	Percent SEDMODL overestimates
Cloney	4.7	9.2	4.6	98%
Graham Gulch	2.2	6.2	4.0	182%
Little Freshwater	1.8	4.6	2.9	163%
Lower Freshwater	1.1	1.4	0.3	27%
McCready Gulch	3.6	6.2	2.6	73%
School Forest	0.6	0.8	0.2	40%
South Fork	1.4	1.7	0.3	22%
Upper Freshwater	4.4	6.3	1.9	44%
Total watershed	19.7	36.5	16.8	85%
Predicted percent of road network delivering	13%	19%		

The SEDMODL program also predicts indirect delivery of road sediment from portions of the road network that do not directly drain to a stream, but are within 100 and 200 ft of a stream. The PWA survey did not include indirect delivery.

4.2.3.2 Erosion Rates

Three tools were used to estimate surface erosion and delivery from roads: the empirical relationships between road condition and erosion in the WDNR and SEDMODL methods, and the physically based WEPP: Road model. The relationships originally developed in the WDNR method and SEDMODL were based on road erosion measurements in Washington, Oregon, Idaho, and the southeastern United States that relate measured road erosion and delivery to road traffic, surfacing, and slope, underlying geologic type, and local rainfall. WEPP is a physically based model that uses climate, soil, topography, road slope, surfacing, and condition to predict if runoff and erosion occur. Direct measurements of road erosion rates by researchers in northern California were not available for comparison with the regional rates used in the models.

The three methods also predict delivery of sediment through vegetated buffers, with the WDNR and SEDMODL using relationships based on distance from a stream and the WEPP: Road model calculating sediment delivery based on buffer width, condition, and slope.

Erosion Rates from Segments that Deliver Directly to Streams

Erosion rates calculated by the WEPP and SEDMODL programs were compared for mainline, secondary, spur, and abandoned road segments with similar attributes. These are the rates that would be used for roads that deliver directly to streams, with no buffer between the ditch and the stream (i.e., road/stream crossings). Road gradients of 2%, 5%, 7%, and 10% were modeled. Both models predict similar erosion rates for secondary, spur, and abandoned roads on roads with gradients up to about 10% (Figure 4-2). On steep roads with a 10% gradient, SEDMODL predicts more sediment delivered than WEPP due to the fact that the SEDMODL program uses a slope factor of 2.5 for roads with a 10% and higher gradient. The SEDMODL program uses a single factor for a range of slope values; since the 10% gradient is just at the cutoff for the higher slope factor, it maximizes the difference between the two methods.

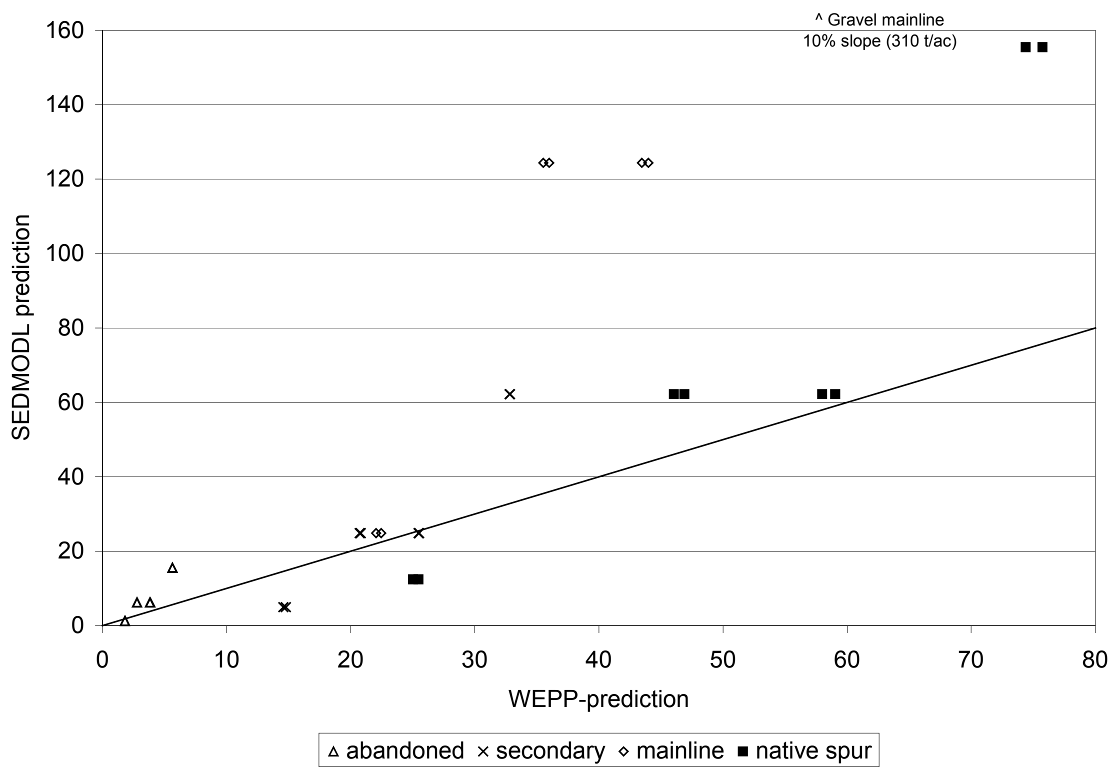

Figure 4-2: Comparison of WEPP: Road and SEDMODL rates of sediment delivered from a road segment that drains directly to a stream (tons/acre). Line indicates 1:1 ratio between predictions.

The SEDMODL results for mainline roads are 2 to 6 times higher than the WEPP model predictions. The SEDMODL program uses a traffic factor of 10 for mainline roads in the Freshwater Watershed; the WEPP program does not have an explicit traffic factor but includes some level of log truck traffic. Road research has shown that heavier use by log truck traffic results in higher erosion rates (Foltz 1996, Kochenderfer and Helvey 1987, Reid 1981, Reid and Dunne 1984, Sullivan and Duncan 1980). Therefore, the SEDMODL rates seem reasonable for heavily used mainline roads.

No direct measurements of road surface erosion were found from area roads; however, the rate of road surface lowering was compared to rates that gravel is added to roads. Roads that receive summer use are generally rocked at a rate of about 3 in. every 5 years (average 0.6 in./year); roads that are also used by logging trucks in the winter get about 6 in. of gravel/year (pers. comm., Ray Miller, PALCO). SEDMODL predicts 1.15 in. of road surface lowering on mainline roads, 0.3 in. on secondary roads, and 0.6 in. on native surfaced spur roads. Under the HCP, log truck traffic is not allowed during wet weather (when there is enough rain to generate overland flow off the road). SEDMODL predictions are within the range of summer use road gravelling rates. One other incidental observation was made on a secondary road in the Freshwater basin during field work. At the end of the summer period, ¼ - ½ in. of dust had collected on the road surface from truck use over the summer. Considering the dust has a lower density than the dense road surface, this is in the range of predicted erosion rates for secondary roads and provides increased confidence in the estimates.

Erosion Rates from Segments that do not Deliver Directly

Sediment delivery rates were also compared for roads that do not deliver directly to a stream, but drain to the forest floor close to a stream. The SEDMODL program uses two delivery classes: roads within 100 ft of a stream are assumed to deliver 35% of the sediment eroded from them, and roads between 101 and 200 ft are assumed to deliver 10% of the sediment. The WEPP program was run for buffer widths of 100 and 200 ft. Figure 4-3 shows a comparison of the two models. WEPP predictions of delivered sediment rates from roads 100 ft from a stream compare quite well with the SEDMODL predictions, with WEPP predicting about 1.5 times more sediment delivered than SEDMODL.

However, at 200 ft, WEPP predicts 2 to 7 times as much sediment is delivered as SEDMODL predicts. One of the reasons for this is that the WEPP model predicts erosion within the buffer, essentially modeling a gully forming downslope of a road culvert and resulting in more erosion with longer buffer lengths (Figure 4-4). While gullies do form downslope of some culverts, this phenomenon generally occurs on steep slopes with long lengths of road between culverts, and would not be expected downslope of short (e.g., 100 ft) road lengths or on gentle (e.g., 25% gradient) buffer slopes. The SEDMODL rates of delivery were used for the present analysis.

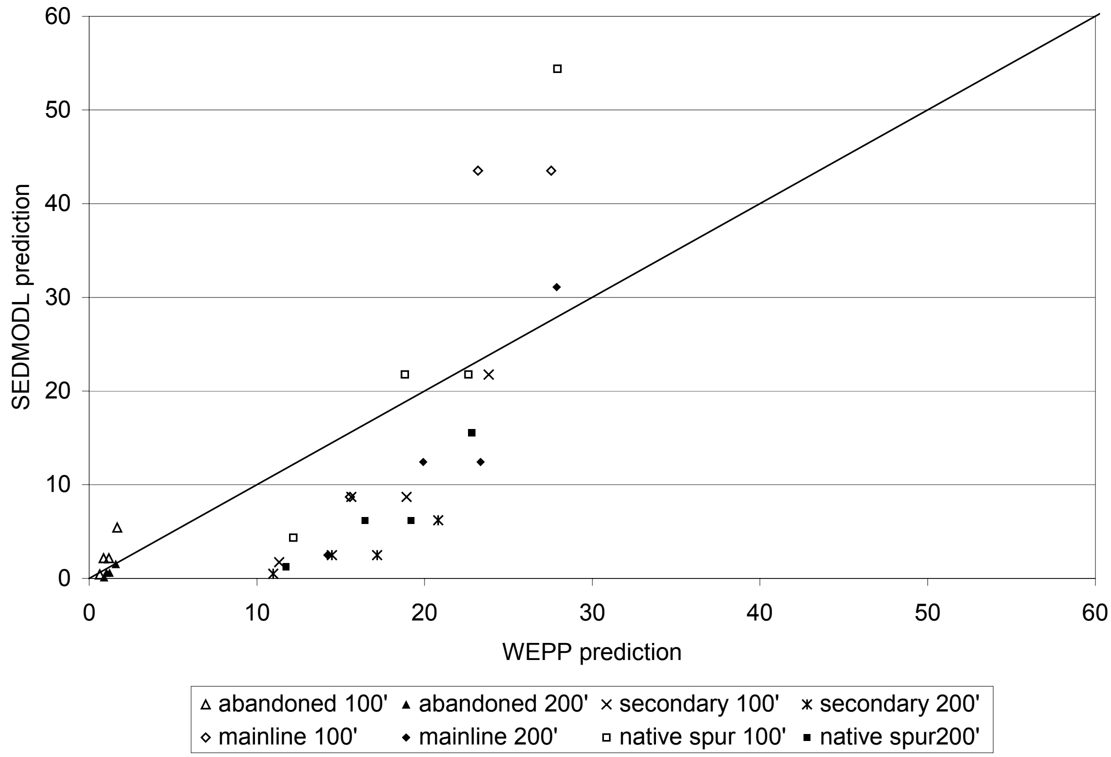

Figure 4-3: Comparison of WEPP: Road and SEDMODL rates of sediment delivered from a road segment 100 and 200 ft from a stream (tons/acre). Line indicates 1:1 ratio between predictions.

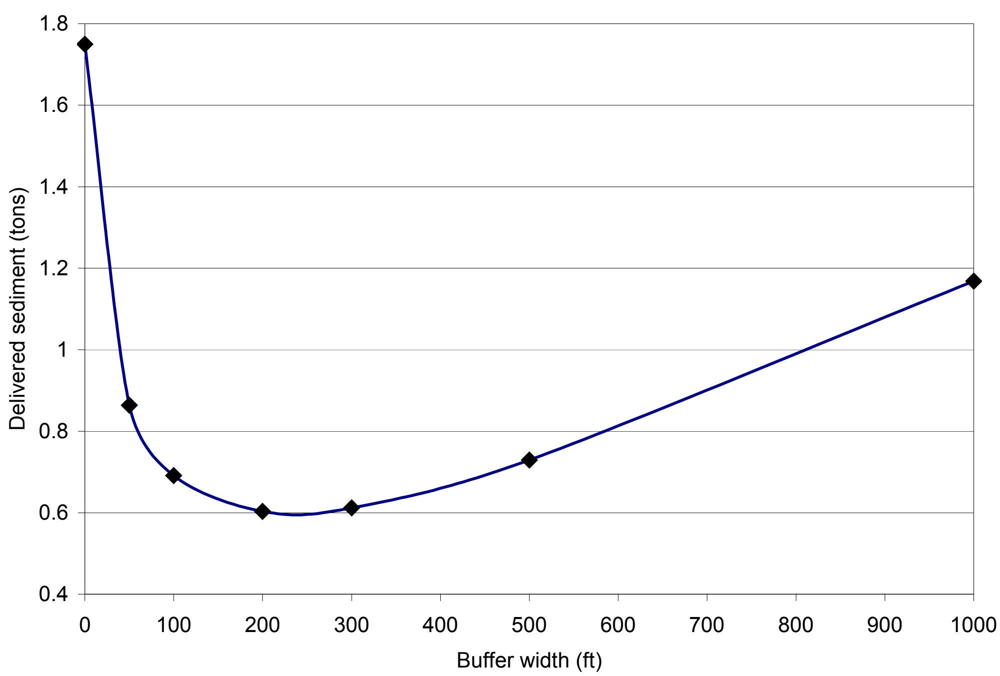

Figure 4-4: WEPP prediction of road buffer effectiveness (100 ft of native surfaced road, 25% buffer slope).

Estimate of Net Sediment Production

For comparison, an estimate of sediment delivery from all roads in the watershed was made using two methods: the WDNR method (Table 4-8); and the SEDMODL model (Table 4-9). The WDNR estimate assumes that 13% of the roads deliver directly to streams (PWA 1999); no indirect delivery ratios were assessed in the field so they are not included in the WDNR estimate.

Table 4-8: Estimate of road surface erosion using WDNR method (average tons/year).

Sub-basin	Asphalt	Gravel Mainline	Gravel Secondary	Native	Abandoned	Driveways & Farm Roads	Sub-basin Total
Cloney	70	680	30	550	30	-	1,360
Graham Gulch	190	70	180	240	10	-	690
Little Freshwater	-	2,220	140	310	10	-	2,680
Lower Freshwater	220	-	30	100	-	50	400
McCready Gulch	40	20	50	300	10	-	420
School Forest	40	70	-	60	-	-	170
South Fork	-	990	140	110	-	-	1,240
Upper Freshwater	80	640	380	410	10	20	1,540
Total Watershed	640	4,690	950	2,080	70	70	8,500

Table 4-9: Estimate of road surface erosion using SEDMODL (average tons/year).

Sub-basin	Asphalt	Gravel Mainline	Gravel Secondary	Native	Abandoned	Driveways & Farm Roads	Sub-basin Total
Cloney	-	420	10	1,410	80	-	1,920
Graham Gulch	50	10	140	760	30	-	990
Little Freshwater	-	1,110	70	550	20	-	1,750
Lower Freshwater	20	-	40	250	-	50	360
McCready Gulch	10	10	20	1,030	40	-	1,110
School Forest	-	10	-	120	-	-	130
South Fork	-	320	80	270	-	-	670
Upper Freshwater	-	140	350	1,000	10	40	1,540
Total Watershed	80	2,020	710	5,390	180	90	8,470

The estimates from the SEDMODL program include both direct delivery (SEDMODL predicts 19% of the road surface delivers) as well as indirect delivery (another 28% of the road surfaces are within 200 ft of a stream). Note that the SEDMODL estimate of erosion from native surfaced roads is much higher than the WDNR estimate. This is because SEDMODL predicts that 21% of the native surfaced roads deliver directly to streams; the WDNR estimate assumed 13% delivered.

For the final estimate of road surface erosion, the SEDMODL results were used and adjusted based on the direct delivery lengths from the PWA road survey. This allows information on spatial distribution of eroding segments (i.e., which road segments are delivering the most sediment to streams) to be provided to the prescriptions team.

4.2.4 Estimate of Surface Erosion and Delivery from Roads

After comparison of the different methods to calculate road surface erosion, the SEDMODL method was selected to calculate road erosion over the entire watershed. However, the original calculations discussed in the previous section were modified to account for the over-estimate of direct delivery lengths compared to field surveys. The SEDMODL output was adjusted to reduce the length of direct delivery segments in each sub-basin based on the ratio of predicted to measured lengths from the PWA field surveys (Table 4-7 above). Twenty-five percent of the sediment from the lengths of direct delivery road that were removed from the direct delivery category was added into the indirect delivery category since these segments are all close to streams. The 25% factor was based on the assumption that some of the subtracted road segments were within 100 ft of the stream (35% factor in SEDMODL) and some were within 200 ft of a stream (10% factor in SEDMODL).

Table 4-10 and Map B-8 show the estimate of average annual road surface erosion based on the current (1999) road configuration in the Freshwater Creek Watershed, divided into sediment from roads that drain directly to streams (23.5 miles over the entire watershed) and delivery from roads within 100 and 200 ft of a stream (37 and 44 miles, respectively).

The highest relative sediment input rates (in tons/square mile of watershed/yr) are in McCready, Cloney, and Graham gulches and the Little Freshwater sub-basins. Recall that these sub-basins have high road densities. The three gulches also have high densities of native surfaced roads with many stream crossings and connected ditch lines, and most of the sediment in these sub-basins comes from the native surfaced roads (Table 4-11). In Little Freshwater, most of the roads are ridgetop roads with fewer stream crossings, and most of the sediment comes from the mainline road that follows the western side of the sub-basin.

Table 4-10: Current (1999) sediment input from road surface erosion (average tons/year).

Sub-basin	Direct delivery	Roads within 100 ft of a stream	Roads within 200 ft of a stream	Total road Input (tons/yr)	Tons/sq mi of sub basin/yr
Cloney	830	350	120	1,310	280
Graham Gulch	290	260	50	600	240
Little Freshwater	470	470	250	1,190	250
Lower Freshwater	230	60	20	310	100
McCready Gulch	560	190	60	800	400
School Forest	80	20	10	110	180
South Fork	310	170	130	610	190
Upper Freshwater	830	270	170	1,280	130
Total Watershed	3,600	1,790	810	6,210	200

Table 4-11: Percent of total sediment input contributed by road type in each sub-basin.

Sub-Basin	Paved roads	Gravel mainline	Gravel secondary	Native spur	Abandoned roads	Driveways & farm roads
Cloney	-	22%	-	74%	4%	-
Graham Gulch	5%	1%	14%	77%	3%	-
Little Freshwater	-	63%	4%	31%	1%	-
Lower Freshwater	6%	-	10%	71%	-	13%
McCready Gulch	1%	1%	1%	93%	4%	-
School Forest	1%	6%	-	93%	-	-
South Fork	-	48%	12%	40%	-	-
Upper Freshwater	-	9%	23%	65%	1%	3%
Total Watershed	1%	24%	8%	64%	2%	1%

The School Forest sub-basin has a high road density of mostly native surfaced roads but fewer stream crossings; therefore, less sediment is delivered to streams per unit area. Both the South Fork and Upper Mainstem sub-basins have lower road densities. Mainline roads in the South Fork, secondary roads in the Upper Mainstem, and native-surfaced roads in both basins supply sediment. The Lower Mainstem includes primarily residential and agricultural areas, with mostly paved roads and driveways that have much lower erosion rates than gravel or native surfaced logging roads, so the overall sediment supply from roads is less.

4.2.4.1 Grain Size of Delivered Sediment

About 70% of the sediment input from road surface erosion is silt and clay, and another 25% is sand-sized, mostly fine sand smaller than 2 mm (Table 4-12). Only a small amount is coarser than sand; generally surface erosion does not have enough energy to transport large particles, but erosion from road ditches during intense storms can move small gravel. On an average annual basis, road surface erosion has contributed about 200 tons/sq mi of watershed/yr.

Table 4-12: Average annual input from road surface erosion by grain size (tons/yr).

Sub-basin	Gravel (>4.75 mm)	Med/Coarse Sand (2-4.75 mm)	Fine Sand (0.075-2 mm)	Silt/Clay (<0.075 mm)	Total (tons/yr)	Tons/ sq mi/yr
Cloney	120	110	250	820	1,300	280
Graham Gulch	50	50	110	390	600	240
Little Freshwater	30	50	190	920	1,190	250
Lower Freshwater	10	10	50	240	310	100
McCready Gulch	30	40	130	610	810	400
School Forest	<5	<5	20	90	110	180
South Fork	30	40	100	440	610	190
Upper Freshwater	130	120	250	770	1,270	130
Total Watershed	400	420	1,100	4,280	6,200	200

4.2.4.2 Predictions of Historic Road Erosion and Delivery

Due to the concerns raised about the cumulative effects of sediment from past timber harvest and roads in relation to channel capacity in the lower watershed, an estimate of surface erosion associated with roads during the period 1942-1987 was made based on the miles of road in the watershed during each aerial photo period. Calculated sediment delivered during each period is shown in Table 4-13. This information is used for the sediment budget discussion in the Stream Channel Assessment (Appendix E).

Table 4-13: Estimates of sediment delivered from road surface erosion, 1942-1987 (in total tons over photo period).

	Aerial photo period			
Sub-basin	1942-1954	1955-1966	1967-1974	1975-1987
Cloney	1,400	1,700	7,400	11,100
Graham Gulch	2,200	2,200	4,200	6,200
Little Freshwater	4,500	4,200	2,800	9,100
Lower Freshwater	2,100	2,700	2,400	4,000
McCready Gulch	800	1,200	4,300	10,200
School Forest	300	300	500	1,500
South Fork	1,600	2,100	1,300	2,200
Upper Freshwater	5,400	6,900	5,900	12,600
Total Watershed	18,300	21,300	28,800	56,900
Number of years in period	13	12	8	13

4.2.4.3 Road Gullies and Stream Crossing Washouts

PWA conducted a field inventory of all roads on PALCO lands to identify sediment production and delivery from roads. Their inventory and assessment included: stream crossing washouts, gullies, surface erosion, cutbank failures, and road-related debris slides. The following sections summarize the stream crossing washout and road gully erosion discussion in their report (PWA 1999). The reader is referred to the full PWA report for details. Note that the PWA survey covered only PALCO roads – 76% of the roads in the watershed – and estimates of gully erosion or washouts were not made for non-PALCO roads. The majority of non-PALCO roads occur in the lower watershed and are likely not as susceptible to gullies or washouts as the forest roads that are on steeper terrain.

Sites of past road stream crossing washouts and gullies were identified in the field and from aerial photograph investigations. In addition, stream crossings with a future diversion/gully potential were identified. Stream crossing washouts included locations where the fill in an abandoned stream crossing was eroded and included Humboldt log crossings. Gullies were identified as locations where a gully had formed in the road ditch, tread, fillslope, and/or hillslope downslope from a road. The estimated amount of sediment from washouts and road gullies is summarized in Table 4-14.

Table 4-14: Estimates of sediment delivered from road washouts[1] and road gullies on PALCO roads (in tons over photo period).

	Aerial photo period				
Sub-basin	1942-1954	1955-1966	1967-1974	1975-1987	1988-1997
Cloney	0	2,080	2,890	700	1,890
Graham Gulch	0	0	2,020	1,070	830
Little Freshwater	0	0	0	310	640
Lower Freshwater	0	0	40	270	240
McCready Gulch	0	100	1,400	740	720
School Forest	0	0	170	40	260
South Fork	5,640	2,530	30	30	1,330
Upper Freshwater	170	970	200	460	2,640
Total Watershed	5,810	5,680	6,750	3,620	8,550
Number of years in period	13	12	8	13	10

[1] Sediment yield from stream crossing sites is probably underestimated (perhaps significantly) because road maintenance and road reconstruction work in the areas of past failures often conceals evidence of past erosion.

Stream crossing washouts were identified where road crossings have either slowly or catastrophically failed. These are primarily abandoned road crossings, and most are old Humboldt log crossings that fail progressively over a relatively long period of time as the logs decay. The amount of erosion from this source is probably underestimated by 10-50% because road reconstruction and maintenance masks the evidence of washouts. However, the road inventory was conducted prior to road reconstruction and documented the original condition of most crossings. Road gullies were primarily caused by blocked/plugged stream crossing culverts that caused the stream to be diverted down a section of roadway before crossing the road and returning to the streambank. In total, 56 stream were identified on PALCO ownership that had been diverted in the past. These diversions created rills and gullies in the road prism and down hillslopes. Most of the diversions produced less than 60 tons of material, but a few large diversion were documented in Cloney and Graham Gulch. Past and potential future diversion sites are shown on Map B-8.

4.3 EFFECTS OF POSSIBLE STRATEGIES TO REDUCE ROAD EROSION

There are several different strategies for reducing surface erosion from roads and reducing the delivery to streams. Many of these strategies are already being implemented on PALCO lands as part of the HCP. These road improvements will reduce the effect of roads on the fine sediment and turbidity load of streams across the ownership. The following general information on the effectiveness of different techniques is provided. A more detailed analysis of the effects of HCP stormproofing will be provided to the Prescriptions Team for use in their process.

On established roads, surface erosion rates are primarily controlled by: road surfacing; traffic on roads; and the area of the road surface, ditch, and cutslope that drain to a stream. In the Freshwater Creek Watershed, the majority of road erosion comes from native-surfaced spur roads (64%) and gravel-surfaced mainline roads (24%). Methods for reducing road-related surface erosion and subsequent delivery are summarized below.

- Surfacing: Research has shown that placing durable gravel on a native surfaced road can reduce erosion by 80% (Burroughs and King 1989). Good quality gravel is not always easy to obtain in the Freshwater Creek area, but even poor quality gravel can reduce erosion rates (Foltz and Truebe 1995). Surfacing only lengths of road that deliver sediment to a stream would reduce sediment delivery cost-effectively.

- Reducing length delivering: Adding drainage structures (driveable dips or cross drains) near stream crossings to direct ditch and tread runoff onto the forest floor can reduce delivery of sediment if properly constructed. Research in other areas (Ketcheson and Megahan 1996) and the WEPP model both show that sediment delivery drops rapidly with 50 to 100 ft of vegetation between a culvert outfall and the stream as long as runoff is dispersed and the hillslope is gentle enough that a gully does not form.

Maintaining outsloped roads where feasible near stream crossings is another method to reduce the length of road delivering. Outsloped roads are sometimes difficult to maintain and can pose safety hazards for drivers. However, in locations where they are feasible, they act to disperse water onto a hillside where runoff can infiltrate and sediment can easily drop out rather than collecting it and concentrating it like ditches and culverts do.

- Reducing traffic: Both reducing traffic and limiting road use during wet weather can reduce erosion by minimizing the breakdown of the road surface. PALCO roads are already gated, which limits road use to company traffic and eliminates recreational use that can sometimes be a concern. Use of roads is limited to essential, light vehicles when the roads are wet which also reduces erosion.

- Reduced tire pressure: Research on the Olympic Peninsula in Washington and in the Oregon Cascades has shown that reduced tire pressures in logging trucks increases the contact area of each tire and reduces erosion (Foltz and Burroughs 1991; Foltz 1992). Constant reduced pressure resulted in a 40% reduction in sediment; a central tire inflation system where the driver could reduce the pressure even further when needed, resulted in an 80% reduction.

- Sediment traps: Sediment traps in the ditch line or at culvert outfalls are another possible sediment reduction strategy. Because they require high maintenance, they are not useful in many settings but could be an option in areas where few other opportunities exist.

- Decommissioning roads no longer needed: PALCO has begun decommissioning roads as part of their road plan under the HCP. Removing stream crossings, ripping the road surface, re-contouring the road prism to fit the hillslope, and revegetating the area result in a few years of higher sediment input but a long-term reduction in sediment as the road stabilizes and is no longer a sediment source.

- New roads: Minimize the construction of new roads. Where new roads are necessary to access an area, construction of roads along routes that minimize stream crossings and use of drainage structures and surfacing at crossings will minimize sediment input to streams.

4.4 CONFIDENCE DISCUSSION

Confidence is excellent in the location of road segments that deliver sediment to streams on PALCO roads since a 100% field survey was conducted. Confidence is good in the conclusion that road surface erosion is a fairly major source of fine sediment to streams in the Freshwater Creek Watershed.

Confidence is moderate in the erosion rates predicted using the SEDMODL and WEPP programs. Actual road erosion varies widely between years and road segments based on site-specific road, use, and weather conditions.

5.0 SUMMARY

5.1 SURFACE EROSION FROM ROADS AND TIMBER HARVEST

The Surface Erosion Assessment evaluated portions of the background sediment yield as well as the effects of roads, timber harvesting, and other land uses on surface erosion in the Freshwater Creek Watershed. The following conclusions were reached in answer to the critical questions for the module (Section 1.1):

- **Sensitivity of soils to erosion**: An erosion hazard map of the watershed was prepared based on CDF guidelines which rate erosion hazard from soil texture, depth, hillslope gradient, precipitation intensity, and ground cover conditions. With all protective vegetation removed, soils in the eastern part of the watershed underlain by Franciscan rocks have a moderate erosion potential, and soils in the western half of the basin underlain by the Wildcat Group have a high erosion potential (Map B-4). Areas with the steepest slopes (over about 60%) on Wildcat soils have an extreme erosion hazard.

- **Background sediment yield**: Sediment input from soil creep was evaluated, and averaged 2,700 tons/yr (90 tons/sq mi/yr; Table 2-3). Sediment input from natural fires is low due to the infrequent occurrence of natural fire in redwood stands.

- **Timber harvest**: Surface erosion delivered to streams from timber harvest was evaluated, and averaged 225 tons/year over the past 10 years (7 tons/sq mi/yr; Table 3-16). Input from timber harvest is higher following years with more harvest and lower when less harvest occurs. High densities of bladed skid trails in tractor yarded units and erodible soils yielded the highest erosion rates. Little surface erosion occurs on cable-yarded or helicopter yarded units. Broadcast burning, particularly hot burns or burns combined with mechanical site preparation, results in some surface erosion on steeper slopes. Use of spot herbicide applications did not noticeably increase surface erosion. Input of sediment from harvest units drops rapidly within 2-3 years following harvest.

- **Other land uses**: Surface erosion delivered to streams from home building and the Freshwater Valley Stables was evaluated and yielded small amounts of erosion (1-4 tons/year). At present, there is little dispersed grazing in forest lands or use by recreational vehicles, so little erosion is associated with these land uses.

- **Road erosion**: Surface erosion delivered to streams from roads was evaluated, and averaged 6,200 tons/yr under current road use conditions (200 tons/sq mi/yr; Table 4-12).

The majority (65%) of the road sediment is produced from the many miles of native surfaced roads in the watershed. Gravel-surfaced mainline roads produce another 25% of the road-related surface erosion. Approximately 24 miles (12%) of roads in the watershed deliver directly to streams, and an estimated 80 additional miles (38%) are within 200 ft of a stream and deliver a portion of their sediment to streams. The SEDMODL program was found to over-estimate the length of road directly delivering to streams by about 85% compared to the PWA road inventory. Keeping this over-estimate in mind, SEDMODL is an effective tool to predict surface erosion from roads in areas where a complete road inventory is not made.

An estimate of road gully erosion and stream crossing washouts was made based on the PWA field inventory of PALCO roads. An estimated total of 8,550 tons of sediment was delivered to streams over the most recent decade covered by the inventory (1988-1997). This is a small amount compared to road surface erosion.

Surface erosion from all sources delivers primarily silt and clay-sized particles to streams in the watershed, with about 70% of sediment silt- and clay-sized, 25% sand-sized, and the remainder fine gravel. This is due to the fact that most of the soils in the watershed have a very high silt and clay content, and surface erosion generally does not have enough energy to move particles larger than sand size. The silt and clay contribute to turbidity and suspended concentrations in streams in the watershed.

Inputs from surface erosion and other sediment sources are compiled in the sediment budget section of the Stream Channel Assessment (Appendix E). The effects of sediment inputs on the channel, fish, and amphibian resources in the watershed are discussed in the cumulative effects section of the Main Report.

5.2 MONITORING RECOMMENDATIONS

Monitoring recommendations in Watershed Analysis are generally made for two purposes: (1) validation monitoring to increase confidence in critical conclusions (recommended to provide additional information regarding a watershed process that was investigated and found to be an important process, but had a high degree of uncertainty associated with the conclusions); or (2) effectiveness monitoring to determine if prescriptions are effective at minimizing the effects of land use practices on critical watershed resources.

In the Freshwater Creek Watershed Analysis, confidence was moderate in the numerical estimates of erosion from harvest units and roads. Three estimates of harvest-related erosion were made, with up to a 5-fold difference between the lowest and highest estimates. However, even the estimate with maximizing assumptions resulted in erosion amounts that are small in comparison to other sources (including estimated background input). Therefore, monitoring of harvest-related erosion is not recommended for this watershed analysis.

Roads are the primary source of sediment to Freshwater Creek, and road surface erosion is predicted to be one of the largest sources of management-related sediment in most sub-basins (see the sediment budget discussion in the Stream Channel Assessment, Appendix E). The different methods used to estimate road surface erosion were in fairly good agreement, and the total amount of estimated fine sediment input from all sources was very close to the amount measured at the community's Freshwater gage site (again, see sediment budget discussion in the Stream Channel Assessment). Therefore, while measurements of road surface erosion from different use roads would be helpful to increase our confidence that basic erosion rates and relationships between traffic use and erosion measured in other parts of the country are applicable to the Freshwater Watershed and other watersheds in PALCO's analysis program, they are not absolutely necessary.

One area where a high degree of uncertainty exists that could have a large effect on the road surface erosion estimates is in the estimates of indirect delivery ratios. The road analysis in this module predicts that 38% of the road network that doesn't deliver directly is within 200 ft of a stream and delivers a portion of its sediment. In the Freshwater, this indirect delivery accounts for half of the total road surface erosion delivered to streams. Much of the road-related research on the effectiveness of vegetation at trapping road runoff and sediment that is used as the basis for assumptions in watershed analysis has been conducted on sandy soils in the Idaho batholith (Ketcheson and Megahan 1996). A study done on finer-grained soils in the Oregon Coast Range has shown much shorter travel distances (Brake et al. 1997), but there are several questions about whether that study accurately accounted for fine particles. It is not the place or intent of watershed analysis to do research-level studies on watershed processes. However, it would be very helpful to make a number of observations of how far sediment is carried across the forest floor in storm runoff at selected ditch relief culverts. This would not only increase confidence in the estimates of indirect delivery from roads, but be helpful for determining how effective the current program of upgrading, improving, and disconnecting road drainage from streams is at reducing the delivery of road surface erosion.

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6.2 PERSONAL COMMUNICATIONS

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Dale, Far West Motorcycle Club, Eureka, CA; phone conversation with K. Dubé, Harza Engineering Company, 4/18/00.

Elliot, Bill, Project Leader, Soil and Water Engineering, USFS Rocky Mountain Research Station; phone conversation with K. Dubé, Harza Engineering Company, 8/11/00.

Koler, Tom, geologist, PALCO, Scotia, CA; phone conversation with K. Dubé, Harza Engineering Company, 5/17/00.

Miller, Ray, road manager, PALCO, Scotia, CA; phone conversation with K. Dubé, Harza Engineering Company, 5/10/00.

Underwood, Steve, ecologist, National Park Service, Crescent City, CA; phone conversation with K. Dubé, Harza Engineering Company, 4/18/00.

Ziemer, Bob, hydrologist, Redwood Sciences Lab, Arcata, CA; phone conversation with K. Dubé, Harza Engineering Company, 11/22/99.

Appendix C

Freshwater Creek Watershed Analysis

Hydrologic Change Assessment

Prepared for:

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Scotia, CA

Prepared by:

Ed Salminen
Watershed Professionals Network (WPN)

December 2003

EXECUTIVE SUMMARY

The effect of land management practices on peak flows having recurrence intervals of from 0.25 to 15 years was analyzed for 49 Hydrologic Analysis Units (HAUs) in the Freshwater Watershed. Estimated relative increases in peak flows due to harvest-related changes in canopy interception/evapotranspiration loss were found to be greatest in the high-frequency, low-magnitude events, and to decrease with increasing event size. Among the 49 HAUs within the Freshwater Watershed, the estimated percent increase in the peak flow having a recurrence interval of 0.25 years ranges from 1 to 27%, with a median value of 13% for average antecedent wetness conditions. Based on these modeling results, the peak flow that formerly occurred on average every 0.25 years (i.e., 4 times per year) is now estimated to occur from 0.25 (i.e., no change) to 0.22 years among the 49 HAUs. The estimated percent increase in the peak flow having a recurrence interval of 2 years ranges from 0 to 23% (median value of 11%) for average antecedent wetness conditions. Based on these modeling results, the peak flow that formerly occurred on average once every two years is now estimated to occur from once every 2.0 (i.e., no change) to once every 1.7 years among the 49 HAUs. Peak flows from the annual series (i.e., those peak flows having a recurrence interval of 2 to 15 years in this analysis) are of a magnitude large enough to cause overbank flooding, the severity of the flooding generally increasing with increasing peak flow recurrence interval. Within the "flood-prone" portions of the watershed (i.e., those areas along lower Freshwater Creek that are prone to flooding of private, non-PALCO property), the estimated percent increase in the peak flow having a recurrence interval of 2 years ranges from 9 to 11% for average antecedent wetness conditions. Based on these modeling results, the peak flow that formerly occurred on average once every two years is now estimated to occur from once every 1.9 to once every 1.8 years among the flood-prone HAUs. The estimated percent increase in the peak flow having a recurrence interval of 15 years ranges from 0 to 4% (median value of 2%) for average antecedent wetness conditions. Based on these modeling results, the peak flow that formerly occurred on average once every 15 years is now estimated to occur from once every 15.0 (i.e., no change) to once every 11.3 years among the 49 HAUs. The estimated percent increase in the peak flow having a recurrence interval of 15 years is 2% within the flood-prone HAUs for average antecedent wetness conditions. Based on these modeling results, the peak flow that formerly occurred on average once every 15 years is now estimated to occur from once every 13.5 to once every 13.0 years among the flood-prone HAUs.

Estimates of the effects of compacted areas (i.e., roads, skid trails, residential development, etc.) on peak flows were modeled for events having a recurrence interval of 2, 5, and 10 years. Results from the compacted-area modeling were constant over the range of recurrence intervals. The estimated percent increase in peak flows having a recurrence interval of 2, 5, and 10 years ranged from 0 to 4% (median value of 2%) among all 49 HAUs within the Freshwater Watershed. The estimated percent change in peak flows within the flood-prone HAUs for peak flows having a recurrence interval of 2, 5, and 10 years ranged from 1% to 2%.

Estimates of the effects of connectivity of the road drainage and stream systems were modeled for three HAUs in the Freshwater Watershed. The percent increase in the effective drainage network (i.e., length of connected ditches/length of stream, expressed as a percentage) ranged from 0% (i.e., no connected ditches) in 12 of the 49 HAUs to 23%, with a median value of 6%. The limited extent to which the road system is connected to the stream system in the Freshwater Watershed has resulted in a relatively small increase in the effective drainage density. The three HAUs selected for modeling had among the highest percent increases in effective drainage network. Modeling was limited to peak flow events having recurrence intervals of 2, 5, and 10 years. Model results for the HAU with the greatest percent increase in the effective drainage network showed a 1% increase in peak flows having recurrence intervals of 2-, 5-, and 10-years. Modeling results for the second HAU showed a 3% decrease in peak flows having recurrence intervals of 2, 5, and 10 years. Modeling results for the third HAU showed a 2% increase in peak flows having recurrence intervals of 2 and 5 years, and a 1% increase in peak flows having a recurrence interval of 10 years. Based on this modeling, it appears that road drainage connectivity generally results in a slightly earlier rise to peak as compared to the historical condition. The value of the instantaneous peak flow, however, may be slightly higher or slightly lower than the historical condition, depending on whether the arrangement of connected road ditches serves to synchronize or desynchronize overall storm runoff.

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1.0 INTRODUCTION

The fundamental hydrologic change question addressed in the Pacific Lumber (PALCO) Watershed Analysis Methodology (PALCO 2000) is:

1. **How much do land use activities in the watersheds alter naturally occurring peak flows?**

The following procedural questions are intended to assist in answering this fundamental question:

1. What is the history of floods and associated storm events in the watershed?
2. What are the peak-flow-generating processes active in the watershed?
3. What are the current forest canopy conditions in the Hydrologic Analysis Units (HAUs) within the watershed?
4. What were the historical forest canopy conditions in the HAUs within the watershed?
5. What are future forest canopy conditions likely to be in the HAUs within the watershed over the next 10 years?
6. To what extent have peak flows been changed in the HAUs within the watershed as a result of forest canopy changes?
7. To what extent are peak flows likely to be changed in the HAUs within the watershed as a result of anticipated forest canopy changes over the next 10 years?
8. To what extent is the current road system hydrologically connected to the stream channel system within the watershed?
9. To what extent is the road system likely to be hydrologically connected to the stream channel system within the watershed in 10 years' time?
10. To what extent have peak flows been changed as a result of roads being hydrologically connected to streams under current conditions?
11. To what extent are peak flows likely to change in the next 10 years as a result of roads being hydrologically connected to streams?

12. To what extent are soils compacted in the watershed at the current time?

13. To what extent are soils likely to be compacted in the watershed in 10 years' time?

14. To what extent have peak flows been changed as a result of soil compaction under current conditions?

15. To what extent are peak flows likely to change in the next 10 years as a result of soil compaction?

The objective of the Hydrologic Change Assessment is to answer these critical questions as they relate to the analysis area. The significance of any estimated changes in peak flows are assessed in the Channels Module (Appendix E).

1.1 WATERSHED OVERVIEW

The analysis area consists of three contiguous CALWATER Planning Watersheds (Figure 1-1). The analysis area drains to Freshwater Slough, an arm of Humboldt Bay, in Humboldt County, California. The downstream (northwesterly) end of the analysis area is approximately three miles east of the city of Eureka. The entire analysis area encompasses 30.8 mi^2. Elevations within the analysis area range from sea level at the mouth of the watershed to approximately 2,850 ft along Barry Ridge, located in the southwest corner of the analysis area. Slopes in the Freshwater Watershed are generally moderate (less than 35% slope gradient). Slopes over 65% gradient are found along portions of the inner gorge areas of Freshwater Creek and the major tributaries, and in headwall areas underlain by the Wildcat Formation in the South Fork and Little Freshwater drainages. Very gently sloping ground is found along the lower, alluvial portions of the mainstem valley. Ownership within the analysis area is approximately 78% PALCO and 22% small holdings (Figure 1-1).

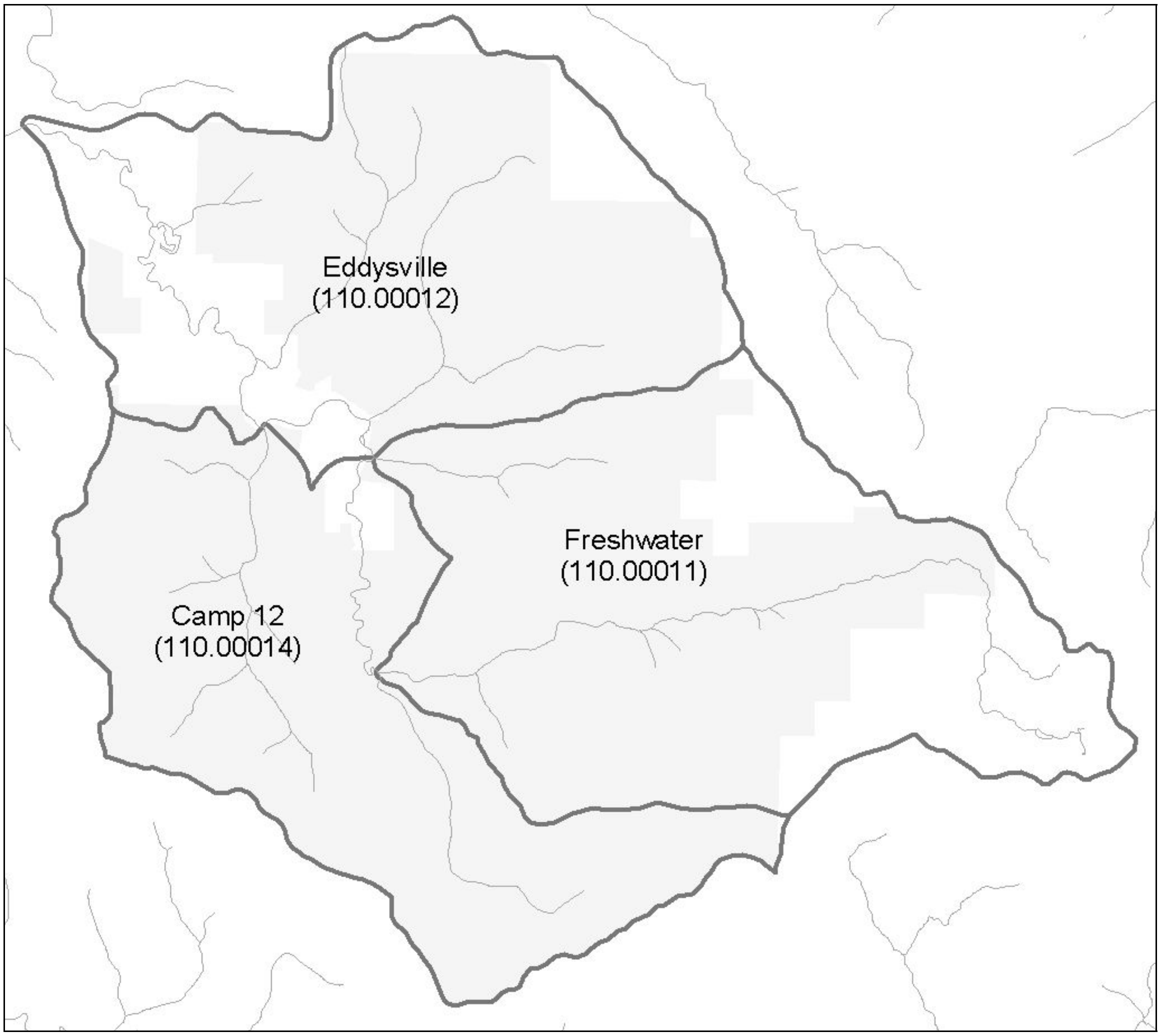

Figure 1-1: Freshwater Watershed Analysis area showing CALWATER Planning Watersheds, Class I streams, and PALCO ownership (gray-shaded area).

Major land uses in the watershed are forest (91% of the watershed area), agricultural/ residential (8%), and power line right-of-way (1%) (Figure 1-2). The primary paved public roads in the watershed include Old Arcata Road, which passes through the watershed near the mouth; Greenwood Heights Drive, which follows the ridgeline on the north side of the watershed; and the Freshwater-Kneeland Road, which travels up the Freshwater valley from the mouth, intersecting Greenwood Heights Drive by way of Graham Gulch.

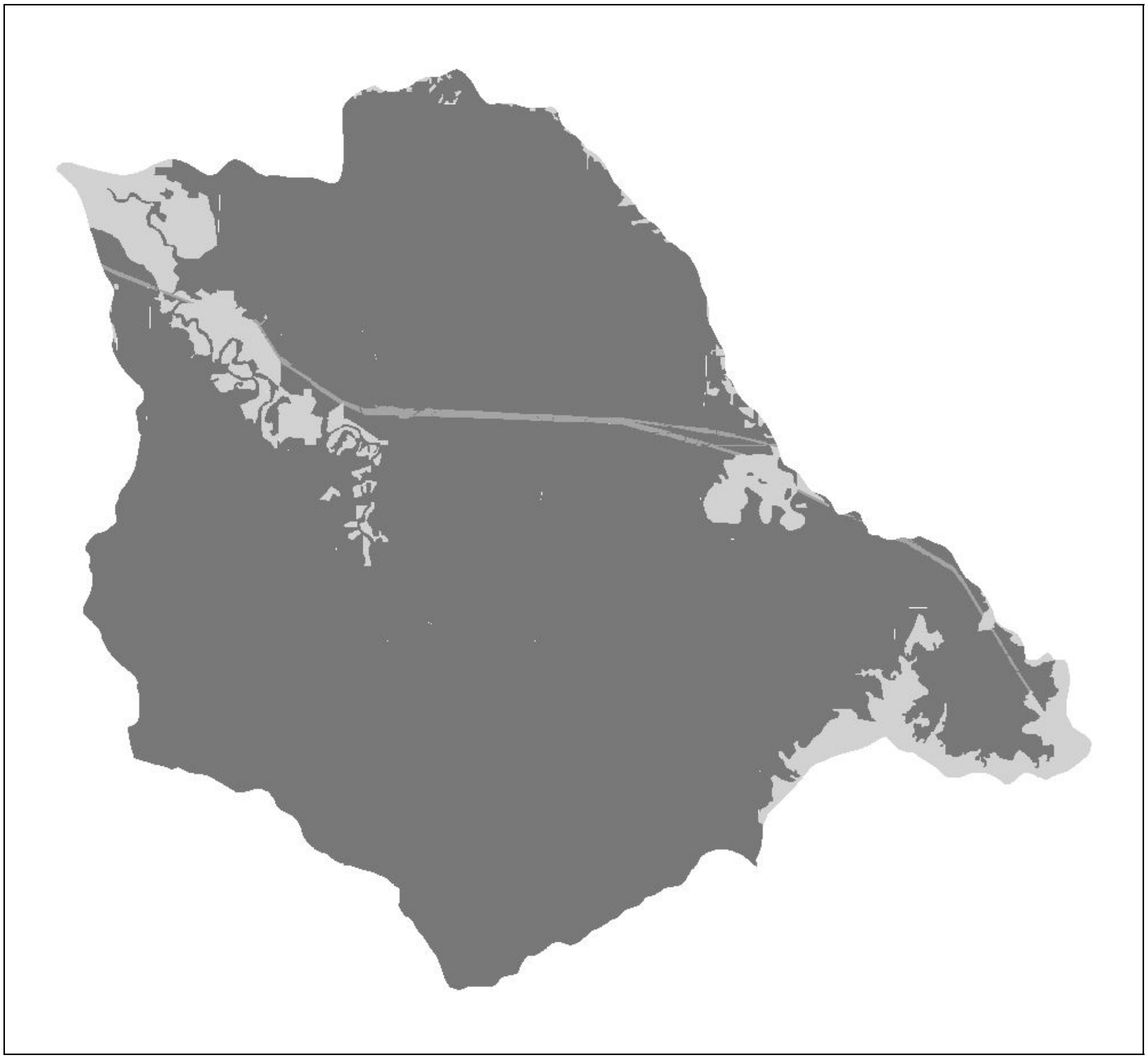

Figure 1-2: Major land use groups in the Freshwater Watershed include forest lands (shown in black), agricultural/residential areas (shown in light gray), and power line right-of-way (shown in gray).

Soils information for the Freshwater Watershed was provided in digital format from PALCO (Figure 1-3). Source information for this GIS coverage was from the Soil-Vegetation Project, a cooperative effort conducted by the USDA Forest Service – Pacific Southwest Forest and Range Experiment Station, in the early 1960s (USDA Forest Service 1961). Information on characteristics of the soil series found in the watershed was taken primarily from McLaughlin and Harradine (1965). Additional information on soil characteristics was obtained from the Natural Resources Conservation Service (NRCS) Official Soil Series Descriptions database. Figure 1-3 shows the 18 soil mapping units within the Freshwater Watershed, and Table 1-1 lists those soils characteristics most relevant to watershed hydrology. Hydrologic soil groupings have not been determined to date for the soils found in the Freshwater Watershed (pers. comm., W. Reed, NRCS, 5/2/200).

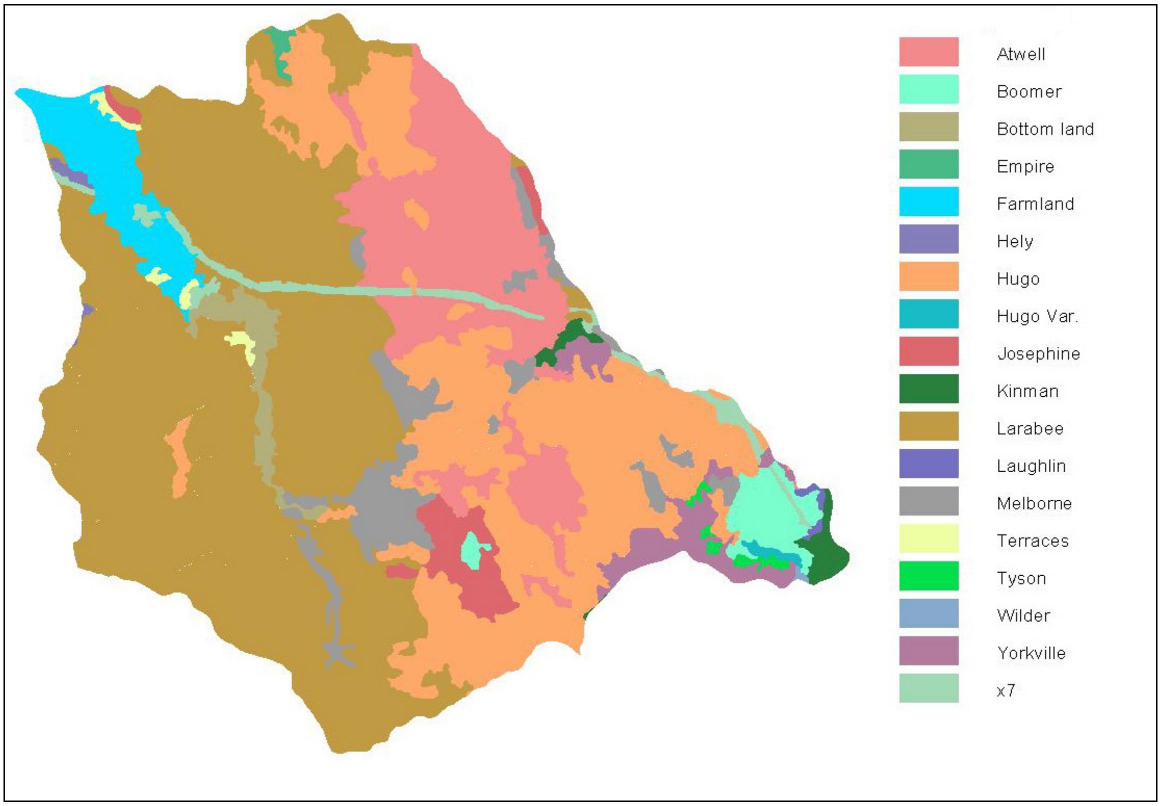

Figure 1-3: Soil groups found in the Freshwater Watershed. Refer to Table 1-1 for relevant characteristics (Source: PALCO GIS Department).

The major disturbances in the analysis area are floods (discussed further below), and mass wasting (discussed in the Mass Wasting Module Report, Appendix A). The cool, humid climate and generally moist conditions of lower elevation redwood forests does not provide a good medium for wildfire initiation or propagation. As a result, fire recurrence intervals in undisturbed redwood forests are considered to be on the order of 25-50 years for low intensity fires (Viers 1980; Stuart 1987), and 500-600 years for high intensity, stand-replacing fires (Viers 1980).

Table 1-1: Characteristics of soils found in the Freshwater Watershed.

Soil series name	% basin area	Depth range (in.)	Parent Material	Texture of surface/ subsurface	Drainage	Permeability
Atwell	13%	36-72	Sheared sedimentary rock	Loam/gravelly clay loam	* Mod. well or somewhat poor	* Mod. slow surface; very slow below
Boomer	2%	26-60	metamorphosed basic igneous rock	Gravelly loam/ gravelly clay loam	* Well	* Mod. slow
Empire	0.2%	40-70	Soft sedimentary rock	Loam/clay loam	* Well to mod. well	* Mod. rapid to slow
Hely	0.2%	40-70	Soft sedimentary rock	Loam/fine sandy loam	* Well	* Rapid to mod. rapid
Hugo	22%	30-60	Sandstone & shale	Gravelly loam/ stony clay loam	* Well	* Mod. rapid
Hugo Var.	0.2%	30-60	Metamorphosed sedimentary rock	Gravelly loam/ gravelly clay loam	* Well	* Mod. rapid
Josephine	2%	30-60	Sandstone and shale	Loam/clay loam	* Moderate	* Moderate
Kinman	1%	40-72	Sandstone and shale	Clay loam/clay	* Mod. well or somewhat poor	* Slow
Larabee	44%	40-70	Soft sedimentary rock	Loam/clay loam	* Moderate	* Moderate
Laughlin	0.1%	16-36	Sandstone and shale	Loam/loam	* Well	* Moderate
Melbourne	5%	30-60	Sandstone and shale	Loam/clay loam	* Well	* Moderate
Tyson	0.3%	18-48	Sandstone and shale	Gravelly loam/ very gravelly loam	* Well	* Moderate
Wilder	0.04%	26-50	Sandstone	Sandy loam/ gravelly sandy loam	* Mod. well to well	* Mod. rapid
Yorkville	2%	30-60	Metamorphosed rock	Clay loam/clay	* Mod. well to well	* Slow to very slow
** Bottom Land	2%	64-70+	Sedimentary alluvium	Loam/Silt loam	Mod. well to imperf.	Mod. rapid to slow
** Farmland	4%	64-70+	Sedimentary alluvium	Loam/Silt loam	Mod. well to imperf.	Mod. rapid to slow
** Terraces	0.4%	64-70+	Sedimentary alluvium	Loam/Silt loam	Mod. well to imperf.	Mod. rapid to slow
*** x7	2%	*** Varies	*** Varies	*** Varies	*** Varies	*** Varies

Source: McLaughlin and Harradine (1965) except where noted.
Notes:
* Information on soil drainage and permeability characteristics for these soils was obtained from the USDA NRCS Official Soil Series Descriptions database (http://www.statlab.iastate.edu/soils/osd/).
** Mapping units Bottomland, Farmland, and Terraces contain areas mapped by McLaughlin and Harradine (1965) as primarily Loleta and Russ soil series. Estimates of soil characteristics are based on these two series.
*** Mapping unit x7 contains areas classified by McLaughlin and Harradine (1965) as residential, business, and industrial areas. Soil characteristics can probably be inferred from adjacent map units.

1.2 HYDROLOGIC ANALYSIS UNITS

Forty-nine Hydrologic Analysis Units (HAUs) were defined for the Freshwater Watershed (Figure 1-4; Table 1-2) following the methodology outlined in the Watershed Analysis Methodology (PALCO 2000, pages 32-34). The only deviations from the PALCO methodology were that HAUs were not defined for the Class I tributary entering Freshwater Creek within HAU FC01, nor for the two small Class I tributaries entering the mainstem of Freshwater Creek within HAU FC06 (Figure 1-4). A separate HAU was not delineated for the tributary in FC01 because this entire HAU is non-PALCO ownership (see Figure 1-1 above; the downstream boundary of FC01 was placed at a point at which there was no upstream influence of PALCO lands). The tributaries within FC06 were originally classified as Class II streams. Reclassification of these streams as Class I occurred during the analysis process. Most of the other module analyses (e.g., Mass Wasting, Surface Erosion) are conducted at the scale of the eight sub-basins that comprise the watershed (Figure 1-4). Application of the PALCO methodology resulted in more HAUs than sub-basins However, all HAUs nest within sub-basins and are coded to reflect the sub-basin within which they reside (e.g., all of the HAUs within the Cloney Gulch sub-basin begin with "CL").

Reference is made throughout this report to both HAUs exclusive of upstream drainage area, and HAUs including upstream drainage area. HAUs exclusive of upstream drainage area refer to the individual polygons shown in Figure 1-4. The sum of all 49 HAUs exclusive of upstream drainage area equals the entire analysis area (i.e., 30.8 mi^2). HAUs including upstream drainage area refer to the HAU polygon itself and the sum of all upstream contributing area (e.g., HAU CL5 would include the sum of the area in HAUs CL1 – CL5, 4.7 mi^2; Figure 1-4, Table 1-2).

HAUs (exclusive of upstream drainage area) range in size from 0.01 mi^2 (0.03% of watershed area) to 3.86 mi^2 (12.5% of area), with a median value of 0.5 mi^2 (1.6% of area). HAUs, including upstream drainage area range in size from 0.13 mi^2 (0.43% of watershed area) to 30.7 mi^2 (i.e., the entire watershed).

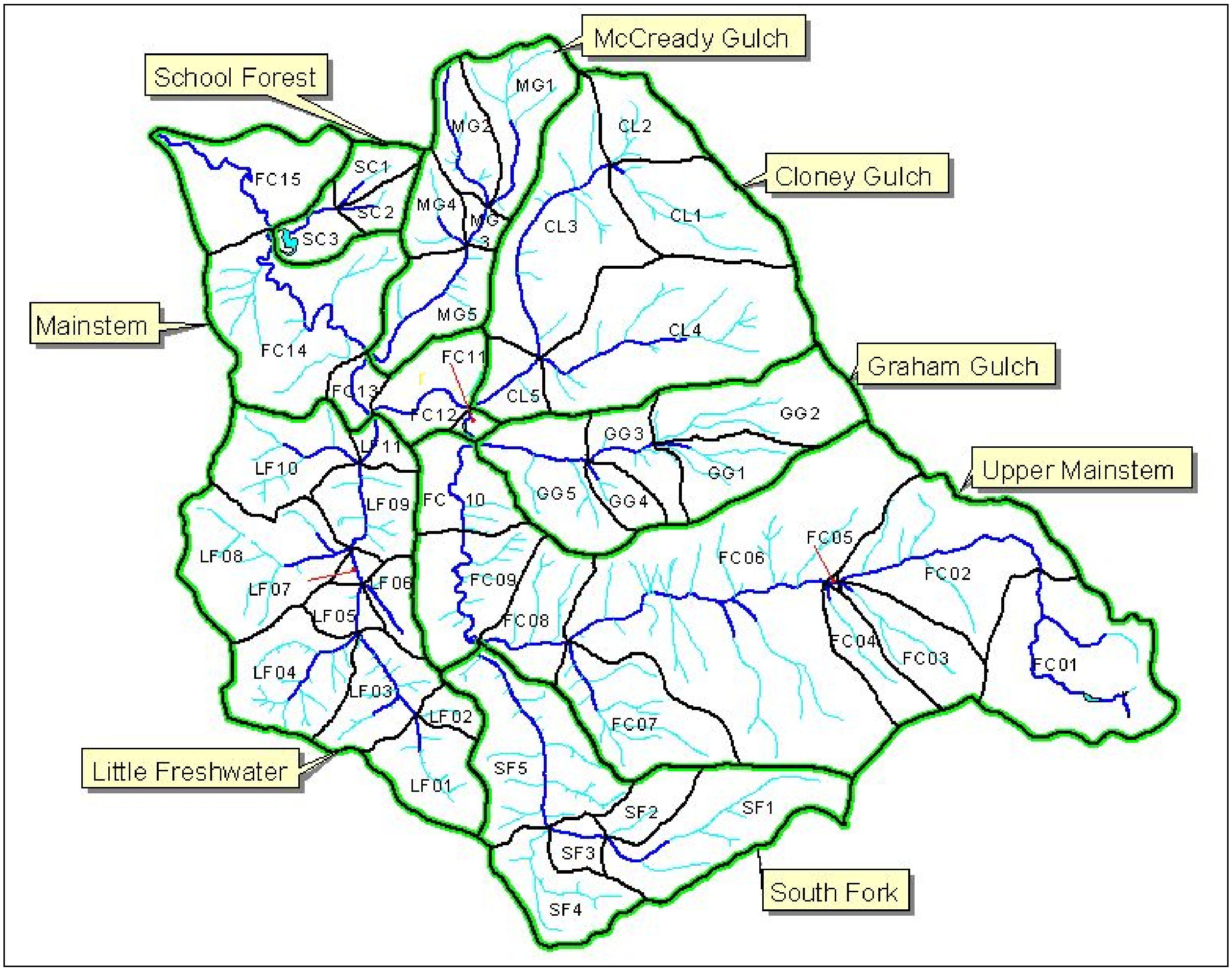

Figure 1-4: Freshwater Watershed showing sub-basins (Green outlines) and HAUs (black outlines). Class I streams shown in dark blue, Class II streams in light blue.

Table 1-2: Hydrologic Analysis Units (HAUs) in the Freshwater Watershed.

Sub-basin Name	Exclusive of upstream drainage area			Including upstream drainage area		
	HAU	Mi^2	% of watershed	HAUs in contributing area	Mi^2	% of watershed
South Fork	SF1	1.00	3.24%	SF1	1.00	3.24%
	SF2	0.27	0.86%	SF2	0.27	0.86%
	SF3	0.16	0.53%	SF1 - SF3	1.43	4.63%
	SF4	0.56	1.81%	SF4	0.56	1.81%
	SF5	1.15	3.72%	SF1 - SF5	3.13	10.17%
Little Freshwater	LF01	0.53	1.71%	LF01	0.53	1.71%
	LF02	0.13	0.43%	LF02	0.13	0.43%
	LF03	0.52	1.68%	LF01 - LF03	1.18	3.83%
	LF04	0.72	2.35%	LF04	0.72	2.35%
	LF05	0.18	0.59%	LF01 - LF05	2.08	6.77%
	LF06	0.22	0.70%	LF06	0.22	0.70%
	LF07	0.07	0.23%	LF01 - LF07	2.37	7.70%
	LF08	1.01	3.29%	LF08	1.01	3.29%
	LF09	0.47	1.54%	LF01 - LF09	3.85	12.53%
	LF10	0.68	2.21%	LF10	0.68	2.21%
	LF11	0.14	0.47%	LF01 - LF11	4.68	15.20%
Graham Gulch	GG1	0.43	1.41%	GG1	0.43	1.41%
	GG2	0.80	2.60%	GG2	0.80	2.60%
	GG3	0.37	1.20%	GG1 - GG3	1.60	5.20%
	GG4	0.19	0.62%	GG4	0.19	0.62%
	GG5	0.73	2.37%	GG1 - GG5	2.52	8.19%
Cloney Gulch	CL1	0.80	2.60%	CL1	0.80	2.60%
	CL2	0.42	1.36%	CL2	0.42	1.36%
	CL3	1.41	4.57%	CL1 - CL3	2.62	8.53%
	CL4	1.81	5.87%	CL4	1.81	5.87%
	CL5	0.27	0.89%	CL1 - CL5	4.70	15.29%
McCready Gulch	MG1	0.64	2.09%	MG1	0.64	2.09%
	MG2	0.39	1.27%	MG2	0.39	1.27%
	MG3	0.11	0.34%	MG1 - MG3	1.14	3.71%
	MG4	0.28	0.92%	MG4	0.28	0.92%
	MG5	0.58	1.89%	MG1 - MG5	2.01	6.52%
School Forest	SC1	0.20	0.65%	SC1	0.20	0.65%
	SC2	0.17	0.55%	SC2	0.17	0.55%
	SC3	0.24	0.77%	SC1 - SC3	0.60	1.97%
Upper Mainstem	FC01	1.40	4.56%	FC01	1.40	4.56%
	FC02	1.30	4.24%	FC01; FC02	2.71	8.80%
	FC03	0.50	1.63%	FC03	0.50	1.63%
	FC04	0.33	1.07%	FC04	0.33	1.07%
	FC05	0.01	0.03%	FC01 - FC05	3.55	11.53%
	FC06	3.86	12.54%	FC01 - FC06	7.40	24.07%
	FC07	0.85	2.76%	FC07	0.85	2.76%
	FC08	0.52	1.70%	FC01 - FC08	8.78	28.53%
	FC09	0.74	2.39%	FC01 - FC09; SF1 - SF5	12.64	41.10%
	FC10	0.50	1.62%	FC01 - FC10; SF1 - SF5	13.14	42.72%
Mainstem	FC11	0.06	0.19%	FC01 - FC11; SF1 - SF5; GG1 - GG5	15.72	51.09%
	FC12	0.50	1.62%	FC01 - FC12; SF1 - SF5; GG1 - GG5; CL1 - CL5	20.92	68.00%
	FC13	0.17	0.56%	FC01 - FC13; SF1 - SF5; GG1 - GG5; CL1 - CL5; LF01 - LF11	25.77	83.77%
	FC14	1.48	4.81%	FC01 - FC14; SF1 - SF5; GG1 - GG5; CL1 - CL5; LF01 - LF11; MG1 - MG5	29.25	95.11%
	FC15	0.90	2.93%	FC01 - FC15; SF1 - SF5; GG1 - GG5; CL1 - CL5; LF01 - LF11; MG1 - MG5; SC1 - SC3	30.76	100.00%
Total		**30.76**	**100%**			

1.3 CLIMATE

The analysis area experiences climatic conditions typical of coastal northern California. The northern California coast has a completely maritime climate, marked by high levels of humidity throughout the year (NOAA 2000). The rainy season runs from approximately October through April, during which time approximately 90% of the annual precipitation occurs (Table 1-3, Figures 1-5 and 1-6). The dry season lasts from May through September. During the dry season, morning low clouds and fog are common, often clearing by early afternoon and returning by evening. Mean monthly and annual precipitation estimates for the Freshwater Watershed were calculated using PRISM precipitation maps, and are representative of the climatological period 1961-90 (PRISM is an analytical model that uses point data and a digital elevation model [DEM] to generate spatial estimates of annual and monthly precipitation. Descriptions of the PRISM data can be found online at http://www.ocs.orst.edu/prism/prism_new.html). Estimated mean annual precipitation for the analysis area is 60 in. Mean monthly precipitation estimates for the entire watershed range from 0.25 in. for the month of July to 11 in. for the month of December (Figure 1-6). Precipitation amounts vary within the watershed and roughly correlated with elevation. For example, estimated mean annual precipitation in HAU FC15 (exclusive of upstream areas) is only 46 in., as compared with 73 in. for HAU FC01. Monthly precipitation amounts follow similar patterns

Air temperatures in the north coast area are moderate, and the annual fluctuation is one of the smallest in the conterminous United States (NOAA 2000). Seasonal air temperature variation is small due to the proximity to the Pacific Ocean. The prevailing northwest winds cross cold up-welling waters usually present along the along the Humboldt County coast. The record high temperature in Eureka is only 85^{o}F, and the record low only 20^{o}F. Mean minimum temperature in Eureka for the month of January is 41^{o}F (Figure 1-7), and the coldest low temperatures in a typical winter are in the mid 30s. Mean maximum temperatures in Eureka for the month of September is 63^{o}F (Figure 1-7), while the highest temperatures are typically in the mid 70s. Inland locations (e.g., Grizzly Creek Redwoods State Park; Table 1-3, Figure 1-5) experience wider seasonal variation in air temperatures (Figure 1-7).

Table 1-3: Weather stations and climatic data used in this assessment.

Station (ID#)	Latitude/ Longitude	Elevation (ft)	Data used; available period of record (may be missing values)
Bridgeville 4 NNW (1080)	N 40° 32' W 123° 49'	2,100	Daily precipitation: 6/1/54 – 5/31/00 Daily snowfall: 6/1/54 – 5/31/00 Daily snowdepth: 6/1/54 – 5/31/00
Eureka * (2910)	N 40° 48' W 124° 10'	20	Hourly precipitation: 7/1/48 – 4/29/00 Daily precipitation: 7/1/48 - 5/31/00 Daily snowfall: 6/1/42 - 5/31/00 Daily snowdepth: 12/1/41 - 5/31/00 Daily min. & max. air temperatures: 7/1/48 - 5/31/00
Grizzly Ck State Park (3647)	N 40° 29' W 123° 55'	410	Daily precipitation: 12/1/79 – 5/31/00 Daily snowfall: 12/1/79 - 5/31/00 Daily snowdepth: 12/1/79 - 5/31/00 Daily min. & max. air temperatures: 12/1/79 - 5/31/00
Klamath (4577)	N 41° 31' W 124° 02'	25	Hourly precipitation: 7/1/48 - 12/31/97
Kneeland 2 (4586)	N 40° 40' W 123° 55'	2,661	Hourly precipitation: 7/1/48 – 5/31/52
Kneeland 9 S (4588)	N 40° 37' W 123° 57'	2,133	Hourly precipitation: 5/1/52 – 6/30/54
Kneeland 10 SSE (4587)	N 40° 38' W 123° 54'	2,356	Hourly precipitation: 6/1/54 – 4/29/00
Freshwater Ck	N 40° 45' W 124° 3'	50	15-min. precipitation: 2/24/99-4/2/00

Notes:

* Eureka (located in downtown Eureka until October 1994 when it was moved to Woodley Island)

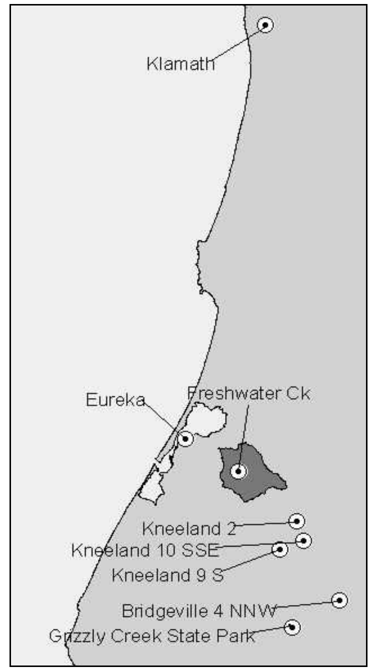

Figure 1-5: Climate stations in the vicinity of the Freshwater Watershed used in this assessment.

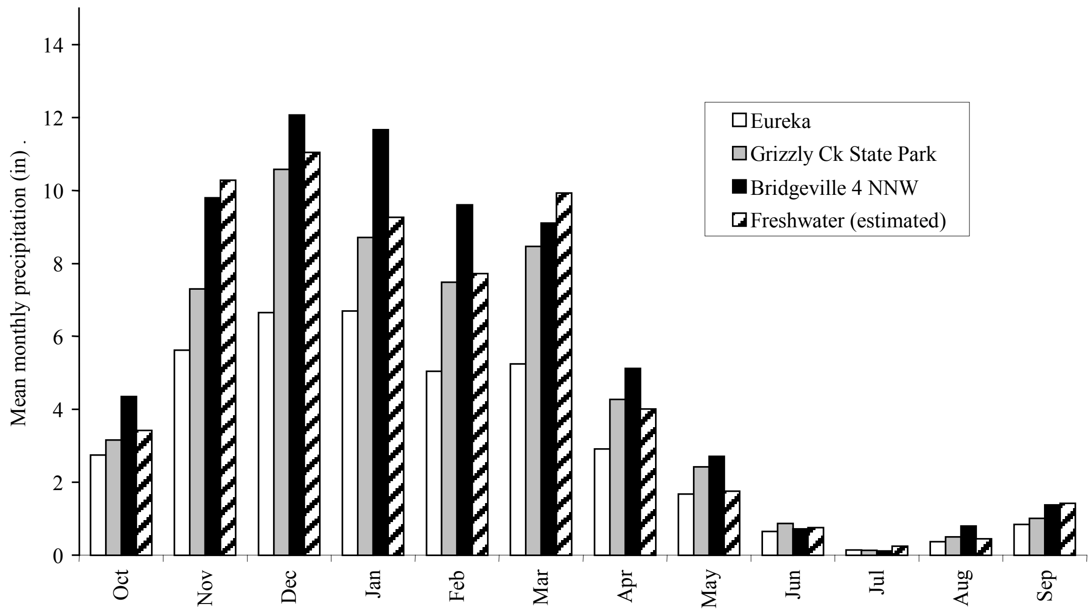

Figure 1-6: Mean monthly values for observed precipitation at several climate stations in the vicinity of the analysis area (refer to Table 1-3, Figure 1-5 for locations), and estimated values (PRISM) for the Freshwater Watershed.

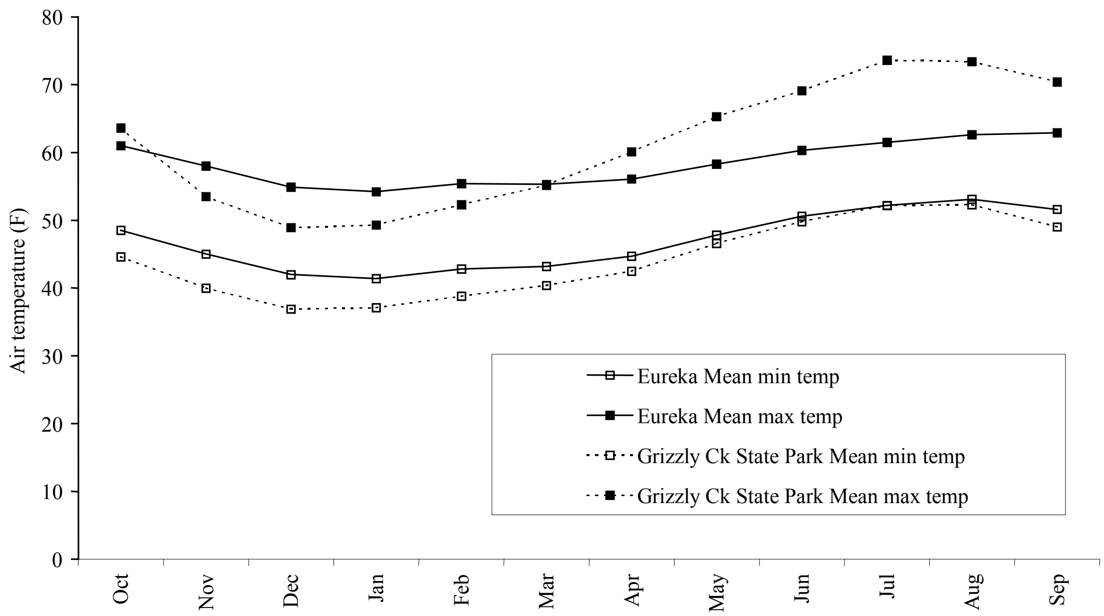

Figure 1-7: Mean minimum and maximum monthly air temperatures at stations near the analysis area (refer to Table 1-3, Figure 1-5 for locations).

A search for snowpack information turned up no information at any stations even remotely close to the analysis area. The Western Regional Climate Center lists no SNOTEL stations in the north coast area in their station inventories (http://wrcc.sage.dri.edu/). The NRCS lists no snow course sites on their web site (ftp.wcc.nrcs.usda.gov/data/snow/snow_course/listca.txt). A search of the California Data Exchange (CDEC) website (http://cdec.water.ca.gov/) revealed no climate stations in Humboldt County with Snowpack or snow course information.

Daily snowfall records are available for several stations in the vicinity of the analysis area (Table 1-3, Figure 1-5). Figure 1-8 shows mean monthly snowfall at the Eureka, Grizzly Creek Redwoods State Park, and Bridgeville 4 NNW stations.

Mean annual snowfall at the Eureka station over the period of record was 0.35 in., and ranged from 0 in. (in 37 out of 54 years or record) to 3.5 in. (in 1989). Monthly snowfall values range from a minimum of 0 in. (recorded at least once in every month of the year), to a maximum of 3.5 in. recorded in February 1989. No snowfall has ever been recorded over the period of record in the months of April through October.

Mean annual snowfall at the Grizzly Creek Redwoods State Park station over the period of record was 1.72 in., and ranged from 0 in. (in 13 out of 19 years or record) to 10.0 in. (in 1990). Monthly snowfall values range from a minimum of 0 in. (recorded at least once in every month of the year), to a maximum of 7.5 in. recorded in February 1989. No snowfall has ever been recorded over the period of record in the months of April through November.

Mean annual snowfall at the Bridgeville 4 NNW station over the period of record was 24.08 in., and ranged from 1.40 in. to 78.5 in. (in 1964). Monthly snowfall values range from a minimum of 0 in. (recorded at least once in every month of the year), to a maximum of 45.0 in. recorded in December 1988. No snowfall has ever been recorded over the period of record in the months of June through October.

Although no snowfall records are available from within the Freshwater Watershed, we may infer based on the proximity and elevation range of the above stations that conditions in Freshwater would fall within the range of values given above.

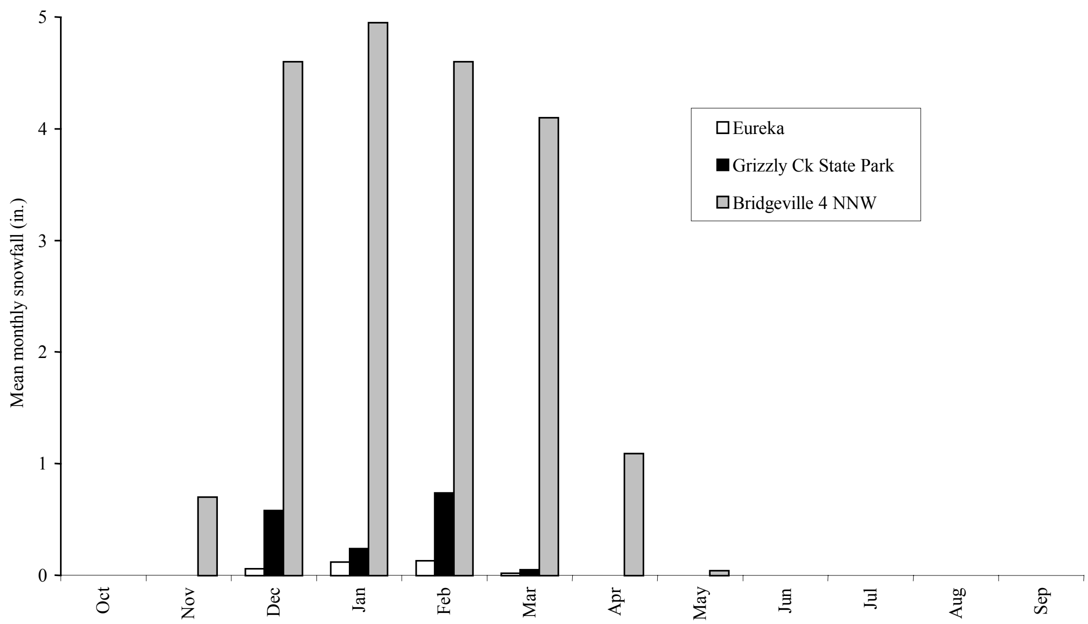

Figure 1-8: Mean monthly values for snowfall at stations near the analysis area (refer to Table 1-3, Figure 1-5 for locations).

1.4 SEASONAL RUNOFF PATTERNS

Mean daily stream flow records are available for three U.S. Geologic Survey (USGS) gages in the vicinity of the analysis area and were calculated from 15-minute streamflow data available from two short-term gages located within the watershed (Table 1-4, Figure 1-9). Mean daily streamflow at the Little River gage ranges from 0.04 to 194 cfs/mi^2, with an average value of 3.5 cfs/mi^2. Mean daily streamflow at the Elk River gage ranges from 0.01 to 63 cfs/mi^2, with an average value of 1.9 cfs/mi^2. Mean daily streamflow at the Jacoby Creek gage ranges from 0.12 to 94 cfs/mi^2, with an average value of 2.5 cfs/mi^2.

Mean daily streamflow records for the Freshwater Creek gage are for a very short time period (01/13/99 – 04/02/00); consequently, two overlapping annual periods were used to calculate mean daily flow parameters. For the time period 01/13/99 – 01/12/00, mean daily streamflow ranged from 0.02 to 32 cfs/mi^2, with an average value of 2.5 cfs/mi^2. For the time period 04/01/99 – 04/02/00, mean daily streamflow ranged from 0.02 to 33cfs/mi^2, with an average value of 2.1 cfs/mi^2.

Table 1-4: Stream gages used in this assessment.

Station Name (USGS #)	Drainage area (mi^2)	Daily values period of record	Peak flow period of record
Little River (11481200)	40.5	10/01/1955 - 05/10/2000	WY1953-WY1998
Elk River (11479700)	44.2	10/01/1957 - 09/30/1967	WY1957-WY1967
Jacoby Creek (11480000)	5.8	04/01/1955 - 09/30/1964	WY1954-WY1974
* Freshwater Ck (N/A)	13.1	01/13/99 – 04/02/00	
* McCready Gulch (N/A)	1.9	12/08/98 - 03/31/99	

Notes:

* The Freshwater Creek station is operated by Salmon Forever in conjunction with the USFS Redwood Sciences Laboratory. The McCready Gulch station is operated by Humboldt State University. Data for both locations is available in 15' time increments.

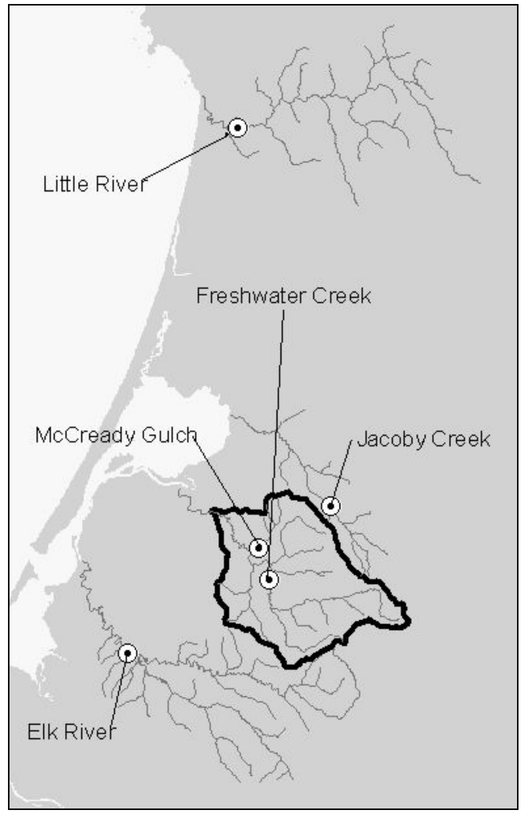

Figure 1-9: Stream gages in the vicinity of the Freshwater Watershed used in this assessment.

Mean daily streamflow at both the Freshwater Creek and McCready Gulch stations showed reasonably good correlations with the Little River gage:

$$Q_{\text{mean daily Freshwater}} = 0.3305 * Q_{\text{mean daily L. River}}^{0.9159} \quad (n = 446;\ r^2 = 0.88)$$

$$Q_{\text{mean daily McCready}} = 0.007 * Q_{\text{mean daily L. River}}^{1.1723} \quad (n = 109;\ r^2 = 0.79)$$

These results suggest that the Little River gage may provide a reasonable long-term approximation of conditions within the Freshwater Watershed.

Mean monthly discharge values (expressed as discharge per unit area) were calculated for the five gages located in the vicinity of the analysis area (Figure 1-10). Monthly values for the Freshwater Creek gage appear to track best with the Jacoby Creek gage, although all sites show a similar pattern in seasonal flow.

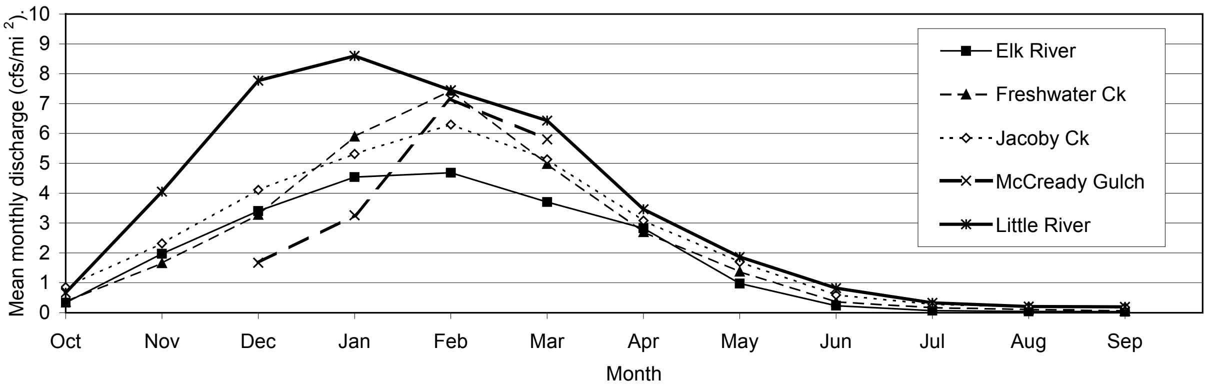

Figure 1-10: Mean monthly discharge at several stream gages in the vicinity of the analysis area (refer to Table 1-4, Figure 1-9 for locations).

September has the lowest mean monthly flow at all locations (Figure 1-10). Mean monthly streamflow for the month of September was plotted over the period of record for the Little River gage (Figure 1-11). The period of the 1970s through the mid 1980s displayed relatively higher September streamflows, while the past ten-year period has been closer to the long-term average. The years of this assessment (1999-2000) were somewhat below the long-term average.

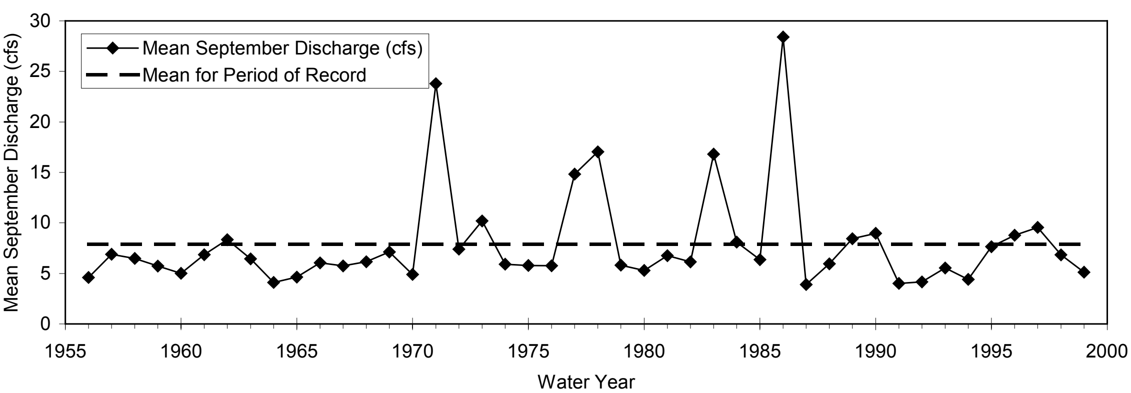

Figure 1-11: Mean September discharge for the Little River gage over the period of record.

1.5 FLOOD HISTORY

Section 4.2 of the PALCO methodology (PALCO 2000) provides techniques for evaluating the flood history of a watershed. The primary reasons for investigating flood history are to:

- Provide context for the Stream Channel, Riparian, and Mass Wasting analysts to interpret historical disturbances;
- Evaluate linkages between historic flooding and climatic conditions that will provide context for interpreting changes in flood peaks assessed in the following sections; and
- Evaluate which processes (e.g., rain, rain-on-snow [ROS]) are the dominant producers of peak flows in the watershed.

Two approaches to evaluating flood history in a watershed are presented in Section 4.2 of the PALCO Watershed Analysis Methodology (PALCO 2000): estimating flood history from historic stream gage records, and using an antecedent precipitation index (API) model to develop a synthetic hydrograph for the watershed. The following two sections describe how each approach was implemented in the Freshwater Watershed; the combined summary for each approach is given in Section 1.5.3. The evaluation of peak flow processes is given in Section 1.5.4.

1.5.1 Flood History from Historic Gage Records

The longest available gage record in the vicinity of the Freshwater Watershed is from the Little River gage (Table 1-4, Figure 1-9). Two approaches were taken to evaluate the appropriateness of using the Little River flood history for the Freshwater Watershed: A comparison was made of the relevant basin parameters for the two watersheds, and anecdotal information on floods that are reported to have occurred in the Freshwater Watershed was compared to the peak flow record from the Little River gage.

The Little River Watershed is located due north of Freshwater, and the distance between watershed centroids is approximately 18½ miles (Table 1-4, Figure 1-9). The Little River Watershed is approximately 25% larger than the Freshwater Watershed, and average watershed elevation is slightly higher; however, overall the two watersheds compare reasonably well (Table 1-5).

Table 1-5: Watershed parameters for the Freshwater Watershed and contributing watershed area of the Little River stream gage.

Parameter	Freshwater	Little River
Basin area (sq. miles)	30.8	40.5
Average elevation (ft)	910	1,097
Average basin slope (%)	30%	26%
Max. flow path, including overland and streamflow (miles)	14	16
Slope along max. flow path (%)	3.8%	3.9%
Distance from point in stream closest to centroid to outlet (miles)	5.9	6.5
Percentage of area facing south	46%	50%
Distance to furthest point along basin perimeter (miles)	8.9	9.9
Basin length divided by basin area (miles/miles^2)	2.6	2.4
Perimeter of basin (miles)	35.0	48.5

Anecdotal information on flooding in the Freshwater Watershed was collected from four sources, as summarized in Table 1-6. Conroy (1999) gives the dates of six flood events that occurred between 1974 and 1983. These six events caused flooding of private property in the Freshwater valley, and were photographed by the Humboldt County Department of Public Works (DPW). Kurt and Gale Hippen are residents at the Horseshoe Bend Ranch, located along Freshwater Creek near the downstream end of HAU FC14 (see Figure 1-4). The Hippens provided anecdotal information on flooding at Horseshoe Bend Ranch for the period 9/86 to 3/99 (pers. comm., Hippen, 7/20/99). The Hippens rated each flood event as either a "field flood," indicating a flood that was overbank and in their fields, or as a larger event where water was under their house. Alan Cook, another Freshwater valley resident, provided information on events during 1998-99 that flooded the Howard Heights Road, located along Freshwater Creek near the upstream end of HAU FC14 (pers. comm., A. Cook, 10/11/99). The final source of flood information for Freshwater Creek is the stream gage, which is located near the downstream end of HAU FC10 (Figures 1-4 and 1-9, Table 1-4). The two largest events from the period of record are included in Table 1-6.

The results from Table 1-6 suggest that over half of the flood events (26 out of 45) reported to have occurred in the Freshwater valley had no corresponding event at the Little River gage. However, it is important to keep in mind that the USGS only reports peak flows from the partial

Table 1-6: Comparison of floods reported to have occurred in the Freshwater valley, and corresponding peak flows recorded at the Little River gage.

Flooding reported in Freshwater valley		Corresponding peak at L. River gage				
Flood date	**Notes and source of information**	**Peak Type ***	**Water Year**	**Peak date**	**Disch. (cfs)**	**Peak rank****
1/16/74	Flood photographed by Humboldt County DPW (Conroy 1999)	Partial	1974	1/16/74	3170	87
3/30/74	Flood photographed by Humboldt County DPW (Conroy 1999)	Partial	1974	3/29/74	4590	44
3/18/75	Flood photographed by Humboldt County DPW (Conroy 1999)	Annual	1975	3/18/75	9830	1
12/1/82	Flood photographed by Humboldt County DPW (Conroy 1999)	None recorded				
1/27/83	Flood photographed by Humboldt County DPW (Conroy 1999)	None recorded				
12/10/83	Flood photographed by Humboldt County DPW (Conroy 1999)	Partial	1984	12/11/83	4260	52
12/6/86	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
6/15/87	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
11/22/88	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	Partial	1989	11/22/88	4570	45
1/10/89	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	Annual	1989	1/10/89	4800	38
1/7/90	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	Annual	1990	1/7/90	2740	97
12/10/92	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	Annual	1993	12/10/92	3100	89
1/22/93	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
2/19/93	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
2/17/94	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
1/7/95	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	Annual	1995	1/9/95	4350	50
1/9/95	Water under the house at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
1/10/95	Water under the house at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
3/9/95	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
12/29/95	Water under the house at Hippens (pers. comm., Hippen, 7/20/99)	Partial	1996	12/30/95	7800	12
1/23/96	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
1/27/96	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
2/8/96	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
2/16/96	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
3/5/96	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
12/4/96	Water under the house at Hippens (pers. comm., Hippen, 7/20/99)	Partial	1997	12/4/96	5900	29
12/8-9/96	Water under the house at Hippens (pers. comm., Hippen, 7/20/99)	Partial	1997	12/8/96	6100	27
12/27/96	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
1/1/97	Water under the house at Hippens (pers. comm., Hippen, 7/20/99)	Annual	1997	1/1/97	9150	5
1/12/98	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
1/17/98	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	Partial	1998	1/16/98	3380	79
1/26/98	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
2/8/98	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
2/19/98	Field flood (Hippen, 7/20/99); Howard Hts. Rd (Cook, 10/11/99)	None recorded				
2/21/98	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	Annual	1998	2/21/98	4090	58
3/23/98	Field flood (Hippen, 7/20/99); Howard Hts. Rd (Cook, 10/11/99)	None recorded				
11/21/98	House flood (Hippen, 7/20/99); Howard Hts. Rd (Cook, 10/11/99)	Annual	1999	11/21/98	9470***	4
12/2/98	Field flood (Hippen, 7/20/99); Howard Hts. Rd (Cook, 10/11/99)	Partial	1999	12/2/98	3770***	65
2/6/99	Field flood (Hippen, 7/20/99); Howard Hts. Rd (Cook, 10/11/99)	None recorded				
2/7/99	Field flood (Hippen, 7/20/99); Howard Hts. Rd (Cook, 10/11/99)	None recorded				
2/9/99	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
3/24/99	Water crossed Howard Heights Road (Alan Cook, 10/11/99)	None recorded				
3/25/99	Fields flood at Hippens (pers. comm., Hippen, 7/20/99)	None recorded				
1/11/00	Largest flood event in POR for Freshwater Ck gage (902 cfs)	Partial	2000	1/11/00	3890*	62
1/14/00	Second largest event in POR for Freshwater Ck gage (890 cfs)	Annual	2000	1/14/00	4330*	51

Notes:
* Annual = largest event in that water year, partial = peak flow above threshold value of 3,000 cfs
** Relative size ranking out of the 103 events that occurred over the period of record.
*** Provisional value, subject to change. Provided by the USGS, 8/4/00

duration series that are larger then the threshold value of 3,000 cfs. Therefore, some of the flood events reported in the Freshwater valley may have had a corresponding peak at the Little River gage that was not reported. It may be most appropriate to look at the "large" magnitude events reported in the Freshwater valley in determining the appropriateness of using the Little River gage record to estimate flood history for the watershed.

Although we do not know the magnitudes of most of the floods reported to have occurred in the Freshwater valley, we can qualitatively evaluate them using the anecdotal source information. The six events reported by Conroy (1999) were apparently large enough to cause concern to the Humboldt County DPW, and can probably be classed as "large" events. Similarly, the events reported by Hippens (pers. comm., 7/20/99) to have caused flooding under their home may also be appropriately classed as "large" events. Of these 13 "large" events, nine had corresponding peak flows at the Little River gage (Table 1-6). These nine events were ranked as the 1st, 4th, 5th, 12th, 27th, 29th, 44th, 52nd, and 87th largest peak flows out of the 103 peaks on record at the Little River gage.

In summary, the peak flow history of the Little River gage may provide us with some insight on the flood history in the Freshwater Watershed; however, there appear to be large events that occur in Freshwater with no corresponding peak at the Little River gage. Consequently, any extrapolation of flood history should be used with caution.

1.5.2 Flood History from Synthetic Hydrographs

An attempt was made to develop a synthetic hydrograph following the approach outlined by Beschta (1990; see PALCO 2000, page 22). Three attempts were made, using rainfall records from the Eureka, Kneeland, and Freshwater rain gages (Table 1-3, Figure 1-5). An estimate of the temporal decay coefficient "C" was first made by regressing discharge at the Freshwater Creek stream gage[1] (Table 1-4, Figure 1-9) at time "t" (Q_t) against discharge at time "t-1" (Q_{t-1}) for 15 rain-free time periods. This resulted in the following relationship:

$$Q_t = 0.9603 * Q_{t-1} + 1.0797; \quad r^2 = 0.9981 \qquad \text{(Equation \#1)}$$

The slope of the line represents the temporal decay coefficient "C" (i.e., C = 0.9603 for a one-hour time step).

[1] Discharge data for the Freshwater gage is available in 15-minute increments. It was necessary to convert these data to a one-hour increment to be compatible with the Eureka and Kneeland precipitation records, which use a one-hour time step. Discharge for each one-hour time step was taken as the maximum discharge reported within each one-hour period.

An antecedent precipitation index (API) value was calculated for each time step for each of the three rainfall records (i.e., Eureka, Kneeland, and Freshwater), using the following relationship:

$$API_t = (API_{t-1} * C) + P \qquad \text{(Equation \#2)}$$

Where C is the temporal decay coefficient calculated above, and P is the input of precipitation (P) for the given time step. API_t was then regressed against observed discharge values at the Freshwater Creek stream gage to derive a relationship with discharge at time t (Q_t) of the form:

$$Q_t = (S * API_{t+I})^2 \qquad \text{(Equation \#3)}$$

where S and I represent the slope and intercept of the regression equation, respectively. Results using the three rainfall records are presented in Table 1-7.

Table 1-7: Equations developed for predicting streamflow at the Freshwater Creek gage using precipitation records from the Freshwater, Eureka, and Kneeland 10 SSE rainfall records.

Precipitation record used	S	I	C	Lag time	r^2	N	Equation #[1]
Freshwater	13.9404	2.8994	0.9899	02:45	0.718	38,367	**(4)**
Eureka	13.2128	3.1105	0.9603	03:00	0.609	10,673	**(5)**
Kneeland	8.1850	3.6014	0.9603	02:00	0.437	4,366	**(6)**

[1] Equation #s 4, 5, and 6 take the form $Q_t = (S*((API_{t-1} *C)+P)+I)^2$

Values for the slope (S) and intercept (I) from equation #3 are shown in Table 1-7, along with the decay coefficient (C) used in equation #2. The decay coefficient C was adjusted for a 15-minute time step when using the Freshwater precipitation record. Adjustment of C was made using the following relationship (Beschta 1990):

$$C = C'^{(\Delta t/\Delta t')} \qquad \text{(Equation \#7)}$$

Where: C = decay coefficient for a 15' time step, C' = decay coefficient for a 60' time step; Δt = 0.15 hours; and $\Delta t'$ = 1.0 hours. Precipitation values were lagged to account for distance of the precipitation gage from the watershed. Lag times used ranged from –2 to +4 hours (in 1-hour increments) for the Eureka and Kneeland stations, and from –1 to +2 hours 45 minutes (in 15-minute increments) for the Freshwater station. Table 1-7 lists the lag time that provided the best results (i.e., highest r^2 value). Slope (S) and Intercept (I) values were all significant at $p<0.0001$. Finally, the number of observations (n) used to develop these equations are shown in Table 1-7. The reason for the relatively small number of observations from the Kneeland station is that data were missing for six time periods during the period of record, for the Freshwater Creek stream gage. The hourly precipitation records from the three Kneeland weather stations (Table 1-3, Figure 1-5) are generally of poor quality. Over the period of record, the Kneeland gages are missing 14% of the hourly precipitation observations; most of these during storm periods. By comparison, the Eureka gage is missing 2% of the hourly observations (almost all of the missing data are in one year).

Results presented in Table 1-7 suggest, not surprisingly, that the precipitation record from within the Freshwater Watershed is most closely correlated with the short-term streamflow record available at the Freshwater Creek stream gage. Unfortunately, this precipitation record is too short to be used for developing a synthetic hydrograph. The Kneeland precipitation records have the poorest correlation (Table 1-7) with the Freshwater Creek streamflow record (as well as significant gaps in the data). This poor correlation is not surprising given that the gage is located approximately 10 miles southeast of the centroid of the Freshwater Watershed, in the Eel River basin (in comparison, the Eureka precipitation gage is located approximately 8½ miles WNW of the watershed). Consequently, the Kneeland precipitation records were not used for developing a synthetic hydrograph.

The Eureka precipitation record provides the best data source with which to develop a long-term synthetic hydrograph for the Freshwater Watershed, despite the unexplained variation in equation #5 above. The Eureka hourly rainfall record had missing values for 15 separate 11-hour periods and one 1-hour period in water year (WY) 1948-51, all of water year 1995, the months of May and October 1996, the month of April 1997, a 7-hour period on 9/1/96, and a 22-hour period on 12/4 – 12/5/96. However, accumulated daily precipitation totals were available for these missing periods. Hourly values for these missing periods were estimated by distributing this daily amount over the 24-hour period using the hourly distribution record from the Klamath station (Table 1-3, Figure 1-5).

1.5.3 Summary of Flood History

Neither the flood history from adjacent gage records, nor the synthetic hydrograph developed using the API methodology, provide a perfect representation of flood history in the Freshwater Watershed. However, these two sources of information probably provide us our best estimate of what that history may have been. Figure 1-12 illustrates the historic peak flows (expressed as cfs/mi^2) for the Little River, Elk River, and Jacoby Creek USGS stream gages (left axis); and the estimated discharge at the Freshwater gage developed using equation # 5 (Table 1-7) from the Eureka hourly precipitation record. Also shown in Figure 1-12 are the coverage periods for aerial photography.

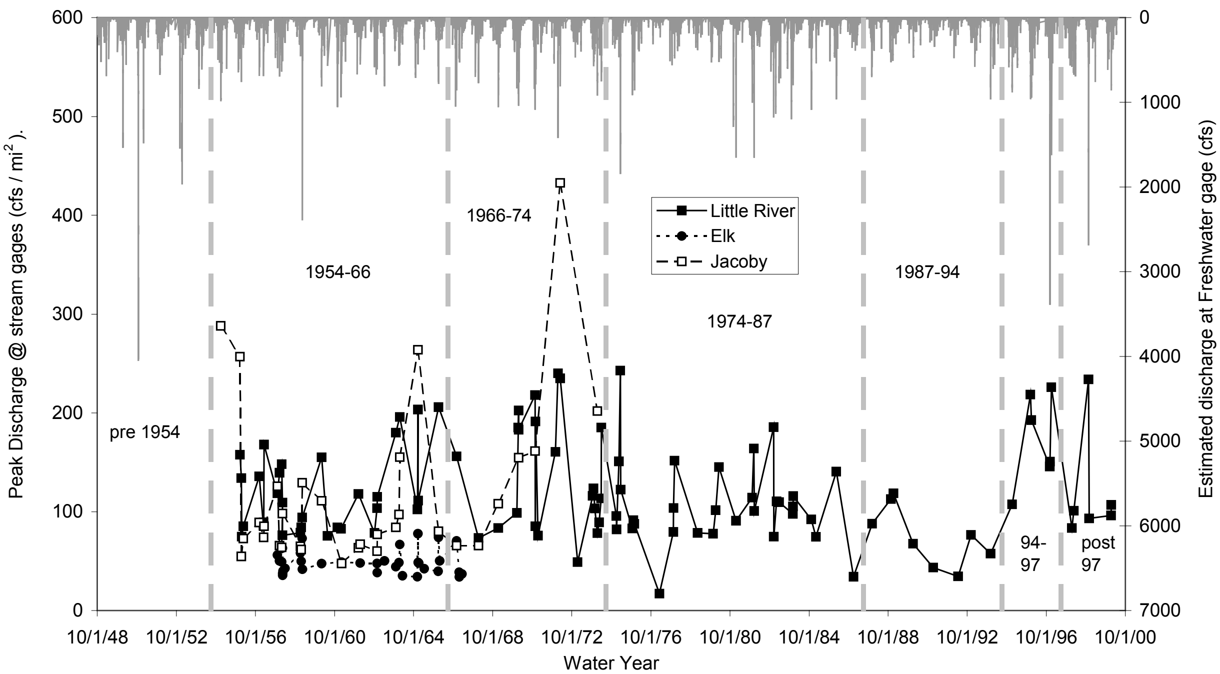

Figure 1-12: Flood history in the vicinity of the analysis area. Historic peak flows (expressed as cfs/mi^2) for the Little River, Elk River, and Jacoby Creek USGS stream gages (left axis), and estimated discharge at the Freshwater gage developed using equation # 5 (Table 1-7) and the Eureka hourly precipitation record. Aerial photo coverage periods are shown as vertical dashed lines.

Taking the data presented in Figure 1-12 as our best estimate of the peak flow history in the Freshwater Watershed, and comparing among aerial photo coverage periods, it appears that the period from 1987-94 was a period of relatively small peak flow magnitudes. The 1994-97 and post-1997 periods experienced peak flow magnitudes at or above pre-1987 levels for the watershed.

1.5.4 Peak-Flow Generating Processes

An analysis of which peak-flow generating processes (i.e., rain-on-snow, rainfall only) are likely to be active in the Freshwater Watershed was undertaken to decide if it would be necessary to implement the rain-on-snow methodology discussed in Section 4.3.2 of the PALCO methodology (PALCO 2000). All 103 peakflow records (both annual and partial-duration series) for the Little River stream gage were examined to estimate the active processes. Peak-flow type was estimated for each event as rain-on-snow (ROS), rain only (RAIN), or unknown (UNK). Classification was made by examining climate records from the Eureka, Grizzly Creek Redwoods State Park, and Bridgeville 4 NNW climate stations (Table 1-3, Figure 1-5) for the day of the observed peak flow, and for the two days preceding the day of the peak.

No snow depth was reported at the Eureka station on any of the peak flow related dates (no missing values). If no depth of snow was reported at the Bridgeville 4 NNW station (the highest elevation station) for any day within the three-day period, then the peak flow was classified as RAIN (89 of the 103 peak flows). If snow depth values were missing from the Bridgeville 4 NNW station, but no depth of snow was reported at the Grizzly Creek Redwoods State Park station, then the peak flow was also classified as RAIN (3 of the 103 peak flows).

Snow depth values were not available at either the Bridgeville 4 NNW or the Grizzly Creek State Park stations for the peak flow related dates for five events (although no snow depth was reported at the Eureka station on any of the peak flow related dates). These five peak flows were classified as UNK.

The six remaining peak flow events had some depth of snow reported at the Bridgeville 4 NNW and/or the Grizzly Creek Redwoods State Park stations for at least one of the three days on or preceding the date of the peak flow. One of the six events had no data available at the Bridgeville 4 NNW station for the three peak flow related dates; 1 in. of snow depth reported at the Grizzly Creek Redwoods State Park station two days prior to the peak flow event; and 0 in. of snow reported for both the day prior to the peak and the day of the peak. Of the remaining five peaks, no data were available at the Grizzly Creek Redwoods State Park station for the peak flow related dates, and a maximum of 4 in. snow depth was reported at the Bridgeville 4 NNW station.

Based on the results given above, 89% (92 of 103) of the historic peak flow events at the Little River gage appear to be rain-only peak flow events, 5% (5 of 103) are unknown as to the peak flow generating process, and the remaining 6% (6 of 103) may have some contribution to peak flows from rain-on-snow (at least in the higher elevation areas of the watershed). However, given the minor amount of snow depth present during these storms, it is unlikely that the contribution of rain-on-snow to the peak flow magnitude is significant. Consequently, the rain-on-snow methodology included in the PALCO methodology was not implemented in this analysis.

2.0 RELATIVE CHANGES IN PEAK FLOWS DUE TO CANOPY INTERCEPTION / EVAPOTRANSPIRATION LOSS

The purpose of this portion of the Hydrologic Change Assessment is to evaluate relative (i.e., percent) changes in peak flows changes due to the reduction in canopy interception and evapotranspiration associated with forest harvesting. Relative peak flow increases were estimated using an equation developed at the Caspar Creek Experimental Watersheds (Lewis et al. in press), and are a function of the amount logged (c), time since logging (t), antecedent watershed wetness (w), and storm size[2]. Section 2.1 describes the GIS data layers necessary for this analysis, Section 2.2 describes the approach used to manipulate the GIS layers to arrive at the data used for the analysis, and Section 2.3 describes the data analysis itself. Results of the assessment are presented in Section 2.4. One deviation from the PALCO methodology was that no analysis was performed on the peak flow changes associated with possible (or likely) future harvesting. It was decided at a pre-Synthesis meeting with the SRT in May 2000 that it would be more useful to evaluate future conditions iteratively during the prescription phase of the Watershed Analysis.

2.1 GIS DATA REQUIREMENTS

GIS data layers needed to perform the analysis were supplied primarily by PALCO; however, data were also provided by California Department of Forestry (CDF) and some additional sources (described below). The following is a description of the GIS data layers used in the analysis.

<u>Harvest History, PALCO Lands:</u> PALCO supplied a polygon coverage of harvest history on their lands. Year of harvest was available for each polygon back to 1986. This coverage included information on harvest year (year that the timber harvest was completed), silvicultural prescription (i.e., clearcut, partial cut, shelterwood removal, no-cut areas within harvest units, etc.), and silvicultural system (i.e., tractor, yarder, helicopter, etc.).

<u>Post-Harvest Residual Canopy Coverage, PALCO Lands:</u> PALCO supplied a polygon coverage of the post-harvest residual canopy coverage on their lands. Residual canopy closure values were available in this coverage by the following canopy closure classes: 0-05%, 05-25%, 25-50%, 50-75%, and 75-100% residual canopy closure.

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[2] The reader may wish to refer to Section 4.3.1 of the PALCO methodology (PALCO 2000) for information on the methods used to complete this section. In particular, the reader may wish to review Section 4.3.1.1 of the PALCO methodology, which provides background information on the equations used to assess peak flow changes associated with timber harvest.

Timber Harvest Plan (THP) Coverages, All Lands: CDF supplied polygon coverages (one coverage for each year) of THPs filed in the watershed back to 1990. These coverages were provided on 10/5/99. These coverages included information on year that the THP was filed (not necessarily the same as year that the unit was harvested), THP number, landowner, silvicultural prescription, and silvicultural system. No information was included in these coverages on post-harvest residual canopy coverage. Hardcopy files for the non-PALCO THPs were inspected at the CDF Fortuna office on 10/12/99. The THP coverages were adjusted (where appropriate) to reflect the actual year of harvest. In some situations, the area actually harvested did not correspond to the area mapped in the THP coverage. Harvest boundaries were altered to reflect what was actually harvested. Post-harvest residual canopy cover information was added to the GIS coverages based on notes in the CDF records (if available), or estimated based on silvicultural prescription. Post-harvest residual canopy cover information was recorded using the same classes that were used for the PALCO data (i.e., 0-05%, 05-25%, 25-50%, 50-75%, and 75-100%).

Roads Coverage, All Lands: A line coverage of roads in the analysis area was compiled by the Surface Erosion analyst from a variety of sources. Sources of road information for the Freshwater Watershed included PALCO, CDF, and inventories conducted by Pacific Watershed Associates (PWA 1999). Additional information on road surfacing and road widths was compiled by the Surface Erosion analyst and included in the GIS coverage (see Surface Erosion Report, Appendix B, for additional information).

Historical Vegetation Coverage, All Lands: An estimate of historic (or pre-settlement) forest canopy coverage for the watershed is needed to provide a baseline against which current canopy conditions are compared (see Section 4.3.1.2.1 of the PALCO manual). A polygon coverage was developed by scanning and rectifying the 1:1,000,000 scale potential natural vegetation of California map included in Barbour and Major (1988), and digitizing boundaries between vegetation types. Four separate potential natural vegetation types fall within the Freshwater Watershed.

HAUs, All Lands: Hydrologic Analysis Units (see Figure 1-4, Table 1-2) were delineated on 1:24,000 scale USGS 7.5" quad maps, and digitized to create a polygon coverage.

Ownership, All Lands: PALCO supplied a polygon coverage of ownership (PALCO and non-PL) within the watershed.

Soil Types, All Lands: PALCO supplied a polygon coverage of soil types (see Figure 1-3) within the watershed.

Digital Orthophoto, All Lands: PALCO supplied a digital orthophoto of the Freshwater Watershed. This was useful for mapping the non-forest land uses in the watershed (agricultural, residential, power line ROW, etc.), and as a backdrop for digitizing any non-PALCO forest stand information interpreted from stereo aerial photo pairs.

2.2 GIS DATA MANIPULATION

The data layers listed above were manipulated to produce a final polygon coverage of the watershed having polygons that were unique with respect to the following attributes:

- **Current Land Use**: The current land use associated with each polygon was recorded. Categories used in the Freshwater Watershed were "agricultural/residential" (Ag/Res), "forest," "power line," and "road" (Note: roads were further broken out by road surfacing [gravel, native, and paved]; however, this information was not used in this portion of the assessment, but was used in Section 3.0 and 4.0 below). Note that current land use in the context used here refers to the apparent land use visible from aerial photographs, not the land use recognized by local planning agencies. For example, a private landowner may own 5 acres of land, 1 acre of which is occupied by a home and surrounding lawn and the remainder of which has trees on the property. Only 1 acre would be classified as Ag/Res, and the remaining 4 acres would be classified as forest, even though the local planning agency may classify all 5 acres as residential.

- **Harvest Year**: Year of last harvest. Areas last harvested prior to 1986 were coded as "<1986", regardless of the year of last harvest. Non-forest areas (i.e., roads, power line ROW, agricultural/residential areas) were coded "n/a."

- **Residual Canopy Closure**: Post-harvest residual canopy closure was recorded for each forested polygon (i.e., < 5%, 5-25%, 25-50%, 50-75%, 75-100%). Polygons last harvested prior to 1986 were coded "n/a", as were non-forest areas (i.e., roads, power line ROW, agricultural/ residential areas).

- **Historical Condition**: This refers to the historical (or pre-settlement) canopy condition of the polygon. Each polygon was recorded as being either historically "forested" or "non-forested."

- **HAU**: Each polygon was coded by the hydrologic analysis unit that it was located within.

- **Road Surfacing**: Road polygons were coded as to their surface condition (i.e., paved, gravel, or native-surfaced). Non-road polygons were coded as "n/a." (Note: this information was not used in this portion of the analysis, but was used in Section 3.0 and 4.0 below).

- **Harvest System**: The harvest system (i.e., tractor, yarder, helicopter) associated with the most recent past harvest was recorded for all forested polygons whose harvest year was 1986-1999. Areas harvested prior to 1986 and areas of non-forest land use were coded as "n/a." (Note: this information was not used in this portion of the analysis, but was used in Section 3.0 and 4.0 below).

- **Land Owner**: The land owner associated with each polygon was recorded as either "PL" for lands owned by Pacific Lumber, or "non-PL" for all other lands. (Note: this information was not used in this portion of the analysis, but was used in Section 3.0 and 4.0 below).

The following describes step-by-step the processing of the data layers listed in Section 2.1 above that was followed to arrive at the final polygon coverage used in this assessment:

Step 1. <u>Intersected the "Harvest History" and "Post-harvest residual canopy coverage" coverages for PALCO lands</u>: This resulted in a single preliminary polygon coverage that has polygons that are unique with respect to year of last harvest and post-harvest residual canopy coverage for PALCO lands.

Step 2. <u>Combined the CDF THP coverages into a single polygon coverage</u>: THP data from CDF were provided as separate polygon coverages for each year (1990-1999). These coverages were combined into a single coverage.

Step 3. <u>Erased the portions of the CDF THP coverage that overlapped PALCO lands</u>: The harvest history / canopy coverage information supplied by PALCO was assumed to be more accurate than the information provided in the CDF THP coverages, because the CDF info was based on what is proposed rather than what is actually completed (Note: a portion of the harvest units on PALCO lands were cross-checked against aerial photographs and CDF GIS layers to evaluate the accuracy PALCO's coverages). Consequently, the polygons resulting from Step 2 that are on PALCO lands were erased. In addition, obvious edge matching problems were corrected (i.e., some THPs in the CDF coverages that list PALCO as the landowner overlapped onto non-PALCO property and vice versa; harvest unit boundaries were adjusted to match up with property boundaries).

Step 4. <u>Edited the combined CDF THP coverage</u>: Harvest year values were adjusted to reflect the year that the THP was actually harvested, and post-harvest residual canopy cover information was added (as described above), based on the review of hardcopy files for the non-PALCO THPs at the CDF Fortuna office on 10/12/99. Additionally, harvest unit boundaries were altered if necessary to reflect the areas actually harvested.

Step 5. Combined harvest/canopy coverage for PALCO lands with combined CDF THP coverage: The resulting coverages from Steps 1 and 4 above were combined into a single polygon coverage with no overlapping polygons.

Step 6. Added additional polygons interpreted from aerial photographs: The resulting polygon coverage from Step 5 covered all of the PALCO lands, and most of the non-PALCO lands, in the Freshwater Watershed. However, there were several areas of non-PALCO lands within the watershed that were not accounted for. Some of these areas were forested areas that had been harvested prior to 1986, other areas were harvested sometime between 1986 and 1990 (recall that CDF's THP coverage only extends back to 1990), and others were areas of non-forest land use. Stereo aerial photographs (from 1987, 1994, and 1997) were used to identify forested areas harvested between 1986 and 1990, forested areas harvested prior to 1986, and areas of non-forest land use. These areas were digitized into the resulting coverage from Step 5 using the digital orthophoto as a backdrop to guide the digitizing. Areas of non-forest land use were assigned a current land use code ("Ag/Res" or "power line"; areas of "road" land use are added in a following step). If more than one land use was present, the polygon was identified based on its "dominant" land use. For example, where power lines were present on forest lands "Power line" was identified as the dominant land use because vegetation maintenance of the ROW was considered to be more significant hydrologically than forest management activities. Conversely, there were areas in the Freshwater valley where the power lines crossed residential lands. In these areas "Ag/Res" was listed as the dominant (more hydrologically significant) land use.

Step 7. Converted road coverage from line to polygon coverage: The effect of roads addressed in this section of the assessment (i.e., in assessing relative changes in peak flows due to canopy interception/evapotranspiration loss) is their influence on maintaining permanent openings in what would otherwise be a forested canopy. Consequently, it is necessary to convert the line coverage of roads provided by the Surface Erosion analyst into a polygon coverage. The following average road tread widths, provided by the Surface Erosion analyst, were used to convert the line coverage to a polygon coverage:

Paved roads:	Average width = 30 ft
Gravel-surfaced roads:	Average width = 20 ft

Native-surfaced roads: Average width = 16 ft

Tread width was used instead of road-prism width because the adjacent forest canopy tends to overhang the road, resulting in a canopy opening approximately the same width as the road tread. Road polygons were assigned a "Road" land use code.

Step 8. Erased road area from preliminary polygon area: The area occupied by the road polygons in Step 8 was erased from the resulting coverage from Step 6.

Step 9. Merged road polygons with preliminary polygons: The resulting polygons from Steps 7 and 8 were merged into a single polygon coverage.

Step 10. Assigned historical condition value to each polygon: Section 4.3.1.2.1 of the PALCO methodology (PALCO 2000) discusses the need to estimate, within a given watershed, what the distribution of historic (or pre-settlement) forest canopy coverage was, and to use this as a "baseline" against which current canopy conditions are compared to provide input for the modeling. Two sources of information were used to estimate the historic condition (i.e., either "forested" or "non-forested") of each polygon from the resulting coverage from Step 9.

The potential natural vegetation mapping units described in Barbour and Major (1988) were used as the initial estimate of historic conditions in the Freshwater Watershed (Figure 2-1). Eighty-nine percent of the watershed area falls within the Redwood Forest type (87%) or Mixed Evergreen Forest type (2%). These mapping units were described as having been historically fully-forested. The remaining watershed area (located in the Freshwater valley) falls within the Coastal Saltmarsh (1%) and Coastal Prairie-Scrub Mosaic (10%) types, mapping units described as having been historically non-forested. Initially, it was considered to use the mapping units from Barbour and Major (1988) "as is" to assign an historic condition to the polygons that resulted from Step 9. However, given the poor resolution of units mapped at a scale of 1:1,000,000 (and the likelihood of inclusions of other types which cannot be practically mapped at this scale), it seemed most appropriate to assign an historical condition of "non-forested" to only the Ag/Res lands, and road areas within Ag/Res lands, located within the Freshwater valley (including the small area of Ag/Res lands at the southeast end of the valley that extend into the Redwood Forest type; see Figure 2-1). These areas are located on the valley floor, and more closely meet the descriptions of soil and topography associated with the Coastal Saltmarsh and Coastal Prairie-Scrub Mosaic mapping units. Consequently, the remaining areas within the Coastal Saltmarsh and

Coastal Prairie-Scrub Mosaic mapping units (the areas that are currently forested within the Freshwater valley) were assigned an historical condition of "forested."

The second source of information used to estimate historic conditions was the estimated suitability of the soils groups (Figure 1-3) for timber production. McLaughlin and Harradine (1965) identified three of the soil groups (Laughlin, Kinman, and Yorkville; Figure 1-3) located within the Freshwater Watershed as being "unsuited" for timber production. These soil groups have almost a one-to-one correspondence with the remaining Ag/Res lands in the watershed (Figure 2-1; Ag/Res lands located outside of the Freshwater valley). Consequently, all remaining Ag/Res lands in the watershed, and road areas within Ag/Res lands, were also assigned a historical condition of "non-forested."

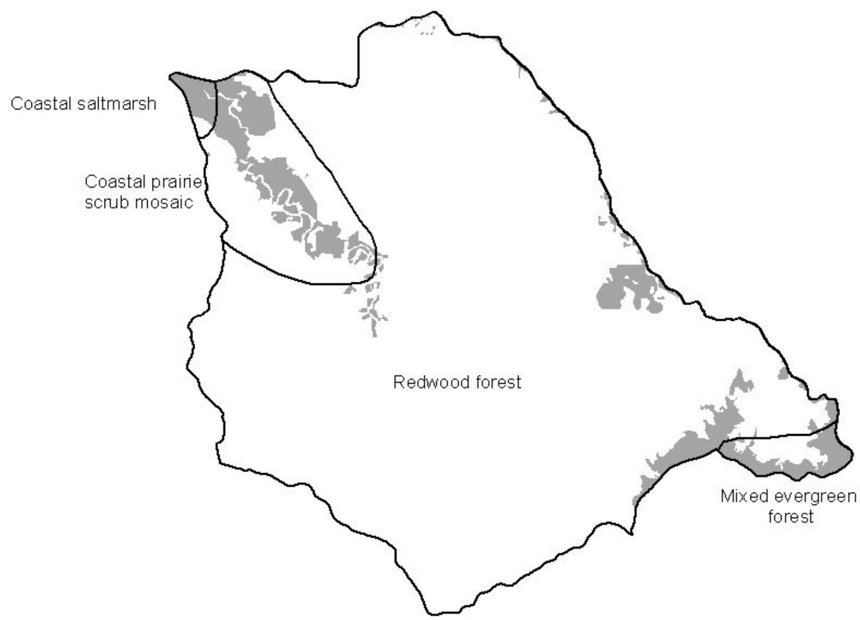

Figure 2-1: Location of potential natural vegetation types as mapped by Barbour and Major (1988) (outlined in black), and agricultural/residential lands (shown in gray).

Step 11. Intersected the preliminary polygon coverage with the HAU coverage: The resulting polygons from Step 10 were intersected with the HAU coverage. The resulting polygon coverage (the "final polygon coverage") had all of the attribute information needed for the analysis described in the following section.

2.3 DATA ANALYSIS

Polygon attribute information from the "final polygon coverage" produced in Step 11 above was imported into an Excel spreadsheet for data analysis. Acreage was first summarized within each HAU (exclusive of upstream drainage area) by harvest year/canopy closure class for forested areas; and by Agricultural/Residential, Power line - historically forested, Power line - historically non-forested, Road - historically forested, and Road - historically non-forested categories for areas of non-forest land use (Attachment C-1).

Acreage was next summed for each HAU including upstream areas that drain to a given HAU. For example, HAUs GG1 and GG2 are located upstream of HAU GG3 (Table 1-2, Figure 1-4). Acreage was summarized for all three HAUs to account for peak flow changes for the HAU and all upstream areas.

Percent change in peak flow was calculated for each of the acreage categories (i.e., harvest year/ canopy closure class for forested areas; Ag/Res, Power line-historically forested, Power line-historically non-forested, Road-historically forested, and Road-historically non-forested for areas of non-forest land use) in each HAU (including upstream area) using equation #1 from the PALCO methodology (Section 4.3.1.1.1, page 27, PALCO 2000). Use of equation #1 from the PALCO methodology requires values for the variables "c" (= 1-R; where R = residual canopy coverage following harvest) and "t" (= years since harvest; range is from 1 to 14). Information on post-harvest residual canopy cover for forested areas is available only in the categories shown in Table 2-1. Consequently, values for the variable "c" used in equation #1 of the PALCO methodology (PALCO 2000, page 27) were taken as mid-point values (Table 2-1). The values for "t" for forested areas are the number of years since harvesting (the values for forest areas harvested in 1986 or before are set to 14; a value of 14 yields no predicted change in equation #1).

Agricultural/residential lands in the watershed were assigned a "c" value of 0 and a "t" value of 14 years (i.e., these areas have no contribution to peak flow changes using the Caspar Creek equation). The reason for selecting these values was that agricultural/residential areas are estimated to have been historically non-forested or sparsely forested (see discussion in Section 2.2, Step 10 above). Even to the extent this assumption is not correct, the effect is to minimize the impacts of land use on non-PALCO lands. The assessment of peak flow changes from PALCO lands is unaffected. Power lines and roads that fall within areas that are assumed to have been historically non-forested were also assigned "c" values of 0, and "t" values of 14 years as well.

Table 2-1: Values of "c" and "t" used in equation 1[1].

Land use	Residual post-harvest canopy cover category	"C" value used in equation 1	"t" value used in equation 1
Forest	< 5%	0.97	1-14
	5-25%	0.85	1-14
	25-50%	0.63	1-14
	50-75%	0.37	1-14
	75-100%	0.12	1-14
Agricultural/residential		0	14
Power line-historically forested		0.85	5
Power line-historically non-forested		0	14
Road-historically forested		0.97	1
Road-historically non-forested		0	14

[1] Equation 1 from PALCO (2000).

Power lines that occupy areas estimated to have been historically forested were assigned a "c" value of 0.85, and a "t" value of 5 years. The reasoning for using a "c" value of 0.85 was that power line clearing typically does not remove all tree vegetation (e.g., where power lines cross deep creek draws, trees are normally retained). A "t" value of 5 years was used because power line clearing was assumed to occur on approximately a 10-year cycle; consequently the mid-point value was used. Roads that occupy areas estimated to have been historically forested were assigned a "c" value of 0.97 and a "t" value of 1 year; the same as recent clearcuts.

Peak flow increases were modeled using equation #1 for each category (i.e., harvest year/ canopy closure class for forested areas; Ag/Res, Power line-historically forested, Power line-historically non-forested, Road-historically forested, and Road-historically non-forested for areas of non-forest land use) in each HAU (including upstream area) and multiplied by the acreage for each category. Results were summed and divided by the total HAU acreage (including upstream area) to arrive at an area-weighted estimated peak flow increase for the HAU.

2.4 RESULTS

Table 2-2 presents the relative increases in peak flows modeled for the partial-duration series events by HAU, and Table 2-3 gives the results for the annual series events. Results are provided for the minimum, average, and maximum antecedent wetness conditions (see Section 4.3.1.1.3 of the PALCO methodology for further details on antecedent wetness). Although minimum and maximum antecedent wetness levels help define the potential range of responses, average wetness values likely provide the best overall estimate of potential peak flow increases.

Table 2-2: Relative increases in peak flows for partial-duration series events by HAU.

Sub-basin Name	HAU	$Q_{0.25}$			$Q_{0.5}$			Q_1		
		Min Wet.	Avg Wet	Max Wet	Min Wet.	Avg Wet	Max Wet	Min Wet.	Avg Wet	Max Wet
South Fork	SF1	37%	13%	6%	35%	11%	4%	33%	10%	3%
	SF2	2%	1%	0%	2%	0%	0%	1%	0%	0%
	SF3	34%	12%	5%	32%	10%	4%	30%	9%	3%
	SF4	68%	22%	10%	63%	19%	7%	60%	17%	6%
	SF5	55%	18%	8%	51%	16%	6%	49%	14%	5%
Little Fresh-water	LF01	65%	22%	10%	61%	19%	7%	58%	17%	6%
	LF02	48%	17%	8%	45%	14%	6%	43%	13%	4%
	LF03	52%	17%	8%	48%	15%	6%	46%	13%	4%
	LF04	80%	27%	12%	74%	23%	9%	71%	20%	7%
	LF05	63%	21%	10%	59%	18%	7%	56%	16%	5%
	LF06	64%	21%	10%	60%	18%	7%	57%	16%	5%
	LF07	63%	21%	10%	59%	18%	7%	56%	16%	5%
	LF08	71%	24%	11%	66%	20%	8%	63%	18%	6%
	LF09	63%	21%	9%	59%	18%	7%	56%	16%	5%
	LF10	24%	8%	3%	22%	7%	3%	21%	6%	2%
	LF11	56%	18%	8%	52%	16%	6%	49%	14%	5%
Graham Gulch	GG1	33%	12%	5%	31%	10%	4%	30%	9%	3%
	GG2	38%	13%	6%	35%	11%	4%	33%	10%	3%
	GG3	42%	14%	6%	39%	12%	5%	37%	11%	3%
	GG4	50%	17%	8%	47%	14%	6%	44%	13%	4%
	GG5	45%	15%	7%	42%	13%	5%	40%	11%	4%
Cloney Gulch	CL1	54%	18%	8%	50%	15%	6%	48%	13%	4%
	CL2	48%	15%	7%	45%	13%	5%	42%	11%	4%
	CL3	55%	18%	8%	51%	15%	6%	49%	13%	4%
	CL4	47%	16%	7%	44%	13%	5%	41%	12%	4%
	CL5	53%	17%	8%	49%	15%	6%	47%	13%	4%
McCready Gulch	MG1	45%	14%	6%	42%	12%	4%	39%	10%	3%
	MG2	49%	15%	7%	45%	13%	5%	43%	11%	4%
	MG3	44%	14%	6%	41%	12%	4%	39%	10%	3%
	MG4	41%	12%	6%	38%	11%	4%	35%	9%	3%
	MG5	43%	13%	6%	40%	11%	4%	38%	10%	3%
School Forest	SC1	27%	8%	4%	25%	7%	3%	23%	6%	2%
	SC2	47%	15%	6%	43%	12%	5%	41%	11%	4%
	SC3	23%	7%	3%	22%	6%	2%	21%	6%	2%
Upper Mainstem	FC01	8%	3%	1%	8%	2%	1%	7%	2%	1%
	FC02	17%	5%	2%	16%	5%	2%	15%	4%	1%
	FC03	12%	4%	2%	11%	3%	1%	11%	3%	1%
	FC04	15%	5%	2%	14%	4%	2%	13%	4%	1%
	FC05	16%	5%	2%	15%	4%	2%	14%	4%	1%
	FC06	20%	7%	3%	19%	6%	2%	18%	5%	2%
	FC07	5%	2%	1%	4%	1%	1%	4%	1%	0%
	FC08	20%	7%	3%	19%	6%	2%	18%	5%	2%
	FC09	31%	10%	5%	29%	9%	3%	28%	8%	3%
	FC10	31%	10%	5%	29%	9%	3%	27%	8%	3%
Mainstem	FC11	33%	11%	5%	31%	9%	4%	29%	8%	3%
	FC12	37%	12%	6%	35%	10%	4%	33%	9%	3%
	FC13	40%	13%	6%	38%	11%	4%	36%	10%	3%
	FC14	39%	13%	6%	37%	11%	4%	35%	10%	3%
	FC15	38%	12%	6%	36%	11%	4%	34%	10%	3%

Note: HAUs include upstream contributing area.

Table 2-3: Relative increases in peak flows for annual series events by HAU.

Sub-basin Name	HAU	Q_2			Q_5			Q_{10}			Q_{15}		
		Min Wet.	Avg Wet	Max Wet	Min Wet.	Avg Wet	Max Wet	Min Wet.	Avg Wet	Max Wet	Min Wet.	Avg Wet	Max Wet
South Fork	SF1	20%	11%	8%	11%	7%	6%	6%	4%	3%	3%	2%	1%
	SF2	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	SF3	18%	10%	8%	10%	7%	5%	5%	4%	3%	2%	2%	1%
	SF4	36%	19%	15%	20%	13%	10%	10%	7%	5%	5%	4%	2%

Table 2-3: Relative increases in peak flows for annual series events by HAU.

Sub-basin Name	HAU	Q_2			Q_5			Q_{10}			Q_{15}		
		Min Wet.	Avg Wet	Max Wet	Min Wet.	Avg Wet	Max Wet	Min Wet.	Avg Wet	Max Wet	Min Wet.	Avg Wet	Max Wet
	SF5	30%	16%	12%	16%	11%	8%	8%	6%	4%	4%	3%	2%
Little Freshwater	LF01	36%	19%	15%	19%	13%	10%	10%	7%	5%	5%	4%	2%
	LF02	27%	14%	11%	15%	10%	7%	7%	6%	4%	4%	3%	1%
	LF03	28%	15%	11%	15%	10%	7%	8%	6%	4%	4%	3%	2%
	LF04	43%	23%	17%	23%	15%	11%	12%	9%	6%	5%	4%	2%
	LF05	34%	18%	14%	19%	12%	9%	9%	7%	5%	4%	4%	2%
	LF06	34%	18%	14%	19%	12%	9%	9%	7%	5%	4%	4%	2%
	LF07	34%	18%	14%	19%	12%	9%	9%	7%	5%	4%	4%	2%
	LF08	38%	20%	15%	21%	13%	10%	10%	8%	5%	5%	4%	2%
	LF09	34%	18%	14%	18%	12%	9%	9%	7%	5%	4%	4%	2%
	LF10	13%	7%	5%	7%	4%	3%	3%	2%	2%	2%	1%	1%
	LF11	30%	16%	12%	16%	11%	8%	8%	6%	4%	4%	3%	2%
Graham Gulch	GG1	19%	10%	8%	10%	7%	5%	5%	4%	3%	2%	2%	1%
	GG2	21%	11%	8%	11%	7%	5%	6%	4%	3%	3%	2%	1%
	GG3	23%	12%	9%	12%	8%	6%	6%	5%	3%	3%	2%	1%
	GG4	27%	14%	11%	15%	10%	7%	7%	5%	4%	3%	3%	1%
	GG5	24%	13%	10%	13%	9%	6%	7%	5%	3%	3%	3%	1%
Cloney Gulch	CL1	29%	15%	11%	15%	10%	7%	8%	6%	4%	4%	3%	2%
	CL2	25%	13%	10%	13%	8%	6%	6%	5%	3%	3%	2%	1%
	CL3	29%	15%	11%	15%	10%	7%	8%	6%	4%	4%	3%	2%
	CL4	25%	13%	10%	14%	9%	7%	7%	5%	3%	3%	3%	1%
	CL5	28%	15%	11%	15%	10%	7%	7%	6%	4%	3%	3%	1%
McCready Gulch	MG1	23%	12%	9%	12%	8%	6%	6%	4%	3%	3%	2%	1%
	MG2	25%	13%	10%	13%	8%	6%	6%	5%	3%	3%	2%	1%
	MG3	23%	11%	9%	12%	8%	6%	6%	4%	3%	3%	2%	1%
	MG4	21%	11%	8%	11%	7%	5%	5%	4%	3%	2%	2%	1%
	MG5	22%	11%	9%	12%	8%	6%	6%	4%	3%	3%	2%	1%
School Forest	SC1	14%	7%	5%	7%	5%	3%	4%	3%	2%	2%	1%	1%
	SC2	24%	12%	9%	13%	8%	6%	6%	5%	3%	3%	2%	1%
	SC3	12%	6%	5%	6%	4%	3%	3%	2%	2%	1%	1%	1%
Upper Mainstem	FC01	5%	2%	2%	2%	2%	1%	1%	1%	1%	1%	0%	0%
	FC02	9%	5%	4%	5%	3%	2%	2%	2%	1%	1%	1%	0%
	FC03	7%	3%	3%	4%	2%	2%	2%	1%	1%	1%	1%	0%
	FC04	8%	4%	3%	4%	3%	2%	2%	2%	1%	1%	1%	0%
	FC05	8%	4%	3%	5%	3%	2%	2%	2%	1%	1%	1%	0%
	FC06	11%	6%	4%	6%	4%	3%	3%	2%	1%	1%	1%	1%
	FC07	2%	1%	1%	1%	1%	1%	1%	1%	0%	0%	0%	0%
	FC08	11%	6%	4%	6%	4%	3%	3%	2%	1%	1%	1%	1%
	FC09	17%	9%	7%	9%	6%	4%	4%	3%	2%	2%	2%	1%
	FC10	17%	9%	7%	9%	6%	4%	4%	3%	2%	2%	2%	1%
Mainstem	FC11	18%	9%	7%	10%	6%	5%	5%	4%	2%	2%	2%	1%
	FC12	20%	10%	8%	11%	7%	5%	5%	4%	3%	3%	2%	1%
	FC13	22%	11%	9%	12%	8%	6%	6%	4%	3%	3%	2%	1%
	FC14	21%	11%	8%	11%	7%	5%	6%	4%	3%	3%	2%	1%
	FC15	20%	11%	8%	11%	7%	5%	5%	4%	3%	3%	2%	1%

Note: HAUs include upstream contributing area.

Estimated relative increases in peak flows are greatest in the high-frequency, low-magnitude events, and decrease with increasing event size. The estimated percent increase in the peak flow having a recurrence interval of 0.25 years ($Q_{0.25}$; i.e., the peak flow that occurs on average four times per year) ranges from 1% (for HAU SF2) to 27% (for HAU LF04), with a median value of 13% for average antecedent wetness conditions (Table 2-2). The estimated percent increase in the $Q_{0.25}$ peak flow under minimum antecedent wetness conditions ranges from 2% (HAU SF2) to 80% (HAU LF04), with a median value of 42%. The estimated percent increase in the $Q_{0.25}$

peak flow under maximum antecedent wetness conditions ranges from 0% (HAU SF2) to 12% (HAU LF04), with a median value of 6%.

The estimated percent increase in the peak flow having a recurrence interval of 0.5 years ($Q_{0.5}$) ranges from 0% (for HAU SF2) to 23% (for HAU LF04), with a median value of 11% for average antecedent wetness conditions (Table 2-2). The estimated percent increase in the $Q_{0.5}$ peak flow under minimum antecedent wetness conditions ranges from 2% (HAU SF2) to 74% (HAU LF04), with a median value of 39%. The estimated percent increase in the $Q_{0.5}$ peak flow under maximum antecedent wetness conditions ranges from 0% (HAU SF2) to 9% (HAU LF04), with a median value of 4%.

The estimated percent increase in the peak flow having a recurrence interval of 1 year (Q_1) ranges from 0% (for HAU SF2) to 20% (for HAU LF04), with a median value of 10% for average antecedent wetness conditions (Table 2-2). The estimated percent increase in the Q_1 peak flow under minimum antecedent wetness conditions ranges from 1% (HAU SF2) to 71% (HAU LF04), with a median value of 37%. The estimated percent increase in the Q_1 peak flow under maximum antecedent wetness conditions ranges from 0% (HAU SF2) to 7% (HAU LF04), with a median value of 3%.

The estimated percent increase in the peak flow having a recurrence interval of 2 years (Q_2) ranges from 0% (for HAU SF2) to 23% (for HAU LF04), with a median value of 11% for average antecedent wetness conditions (Table 2-3). The estimated percent increase in the Q_2 peak flow under minimum antecedent wetness conditions ranges from 1% (HAU SF2) to 43% (HAU LF04), with a median value of 22%. The estimated percent increase in the Q_2 peak flow under maximum antecedent wetness conditions ranges from 0% (HAU SF2) to 17% (HAU LF04), with a median value of 9%. Hydrologic analysis units FC10 through FC15 (Figure 1-4, Table 1-2) drain to those portions of Freshwater Creek that are prone to flooding of private, non-PALCO property (referred to hereafter as the “flood-prone HAUs”). Peak flows from the annual series (Table 2-3; peak flows having a recurrence interval of 2 or more years) are of a magnitude large enough to cause overbank flooding, the severity of the flooding generally increasing with increasing peak flow recurrence interval. Within the flood-prone HAUs, the estimated percent increase in the Q_2 peak flow is 9% for FC10 and FC11, 10% in FC12, and 11% in FC13-FC15 for average antecedent wetness conditions (Table 2-3). Within the flood-prone HAUs, the estimated percent increase in the Q_2 peak flow under minimum antecedent wetness conditions ranges from 17% (HAU FC10) to 22% (HAU FC13), with a median value of 20%. The estimated percent increase in the Q_2 peak flow under maximum antecedent wetness conditions within the flood-prone HAUs is 7% for FC10 and FC11, 8% in FC12 and FC14-FC15, and 9% in FC13. The reason that increases are greater for HAU FC13 (relative to FC14 and FC15) is that within HAU FC13, the Little Freshwater sub-basin represents a higher proportion of the HAU area, and peak flow increases are relatively greater from the Little Freshwater sub-basin.

The estimated percent increase in the peak flow having a recurrence interval of 5 years (Q_5) ranges from 0% (for HAU SF2) to 15% (for HAU LF04), with a median value of 8% for average antecedent wetness conditions (Table 2-3). The estimated percent increase in the Q_5 peak flow under minimum antecedent wetness conditions ranges from 0% (HAU SF2) to 23% (HAU LF04), with a median value of 12%. The estimated percent increase in the Q_5 peak flow under maximum antecedent wetness conditions ranges from 0% (HAU SF2) to 11% (HAU LF04), with a median value of 6%. Within the flood-prone HAUs, the estimated percent increase in the Q_5 peak flow is 6% for FC10 and FC11, 7% for FC12 and FC14-FC15, and 8% for FC13 for average antecedent wetness conditions (Table 2-3). Within the flood-prone HAUs, the estimated percent increase in the Q_5 peak flow under minimum antecedent wetness conditions is 9% for FC10, 10% for FC11, 11% for FC12 and FC14-FC15, and 12% for FC13. The estimated percent increase in the Q_5 peak flow under maximum antecedent wetness conditions within the flood-prone HAUs is 4% for FC10, 5% for FC11-FC12 and FC14-FC15, and 6% for FC13.

The estimated percent increase in the peak flow having a recurrence interval of 10 years (Q_{10}) ranges from 0% (for HAU SF2) to 9% (for HAU LF04), with a median value of 4% for average antecedent wetness conditions (Table 2-3). The estimated percent increase in the Q_{10} peak flow under minimum antecedent wetness conditions ranges from 0% (HAU SF2) to 12% (HAU LF04), with a median value of 6%. The estimated percent increase in the Q_{10} peak flow under maximum antecedent wetness conditions ranges from 0% (HAU SF2) to 6% (HAU LF04), with a median value of 3%. Within the flood-prone HAUs, the estimated percent increase in the Q_{10} peak flow is 3% for FC10, and 4% for FC11-FC15 for average antecedent wetness conditions (Table 2-3). Within the flood-prone HAUs the estimated percent increase in the Q_{10} peak flow under minimum antecedent wetness conditions is 4% for FC10, 5% for FC11-FC12 and FC15, and 6% for FC13 and FC14. The estimated percent increase in the Q_{10} peak flow under maximum antecedent wetness conditions within the flood-prone HAUs is 2% for FC10 and FC11, and 3% for FC12-FC15.

The estimated percent increase in the peak flow having a recurrence interval of 15 years (Q_{15}) ranges from 0% (for HAU SF2) to 4% (e.g., for HAU LF04), with a median value of 2% for average antecedent wetness conditions (Table 2-3). The estimated percent increase in the Q_{15} peak flow under minimum antecedent wetness conditions ranges from 0% (HAU SF2) to 5% (e.g., for HAU LF04), with a median value of 3%. The estimated percent increase in the Q_{15} peak flow under maximum antecedent wetness conditions ranges from 0% (HAU SF2) to 2% (e.g., for HAU LF04), with a median value of 1%. Within the flood-prone HAUs, the estimated percent increase in the Q_{15} peak flow is 2% for FC10-FC15 for average antecedent wetness conditions; 2% for FC10 and FC11, and 3% for FC12-FC15 under minimum antecedent wetness conditions; and 1% for FC10-FC15 under maximum antecedent wetness conditions (Table 2-3).

3.0 RELATIVE CHANGES IN PEAK FLOWS DUE TO COMPACTED AREAS

The purpose of this portion of the assessment is to evaluate relative (i.e., percent) changes in peak flows due to soil compaction associated with land management activities. Section 3.1 below provides an overview of the approach used for this analysis, and Sections 3.2, 3.3, and 3.4 describe how the primary modeling parameters were developed. Results are presented in Section 3.5. One deviation from the PALCO methodology was that no analysis was performed on the peak flow changes associated with possible (or likely) future soil compaction. It was decided at a pre-Synthesis meeting with the SRT in May 2000 that it would be more useful to evaluate future conditions iteratively during the prescription phase of the analysis.

3.1 OVERVIEW OF APPROACH

The effects of soil compaction on peak flows were modeled using the Rational Method. The Rational Method is the most widely used uncalibrated equation for estimating peak flows in small watersheds (McCuen 1989). The Rational Method takes the form of the following equation:

$$Q_{tr} = CIA \qquad \text{(Equation \#8)}$$

Where $\mathbf{Q_{tr}}$ is peak discharge (in cfs) for a given recurrence interval; **C** is the runoff coefficient for the watershed (dimensionless); **I** is rainfall intensity (in./hour) for the return period (for a duration equal to the time of concentration for the watershed); and **A** is the drainage area of the watershed (in acres).

The approach taken was to first estimate values of **C** for each HAU (exclusive of upstream drainage area) under both current and historic conditions. Rainfall intensity (**I**) was obtained from an intensity-duration-frequency (IDF) curve for the given recurrence interval (frequency) of the event, and for a duration equal to the time of concentration ($\mathbf{T_c}$) of each HAU (note: values of **I** and **A** were held constant between the two modeling scenarios). Instantaneous peak flow values were then calculated for each HAU (exclusive of upstream drainage area) under both modeling scenarios (i.e., current and historic conditions). Storm hydrographs were then estimated from instantaneous peak flow values using a unit hydrograph approach. Storm hydrographs were then routed downstream to estimate instantaneous peak flow values for HAUs including upstream drainage area (e.g., storm hydrographs from HAUs CL1 and CL2 were routed downstream and combined with the hydrograph from HAU CL3 (exclusive of upstream area) to produce a combined hydrograph at the mouth of HAU CL3). Relative changes in peak flows due to soil compaction were then calculated for each HAU including upstream drainage area by comparing the results for historic and current conditions:

Relative change (%) in Q_{tr} = $[(Q_{tr: current} - Q_{tr: historic}) / Q_{tr: historic}) * 100]$ (Equation #9)

Calculation of **C** values for each HAU was carried out using polygon attribute information from the "final polygon coverage" (from Section 2.2 above), the soils coverage for the watershed (Figure 1-3, Table 1-1), and a slope class coverage for the watershed (supplied by PALCO). All other data analysis was performed using the Watershed Modeling System (WMS), Version 6.0, a commercially available hydrologic modeling software package developed by the Brigham Young University Environmental Modeling Research Laboratory (BYU 1999).

Several assumptions and limitations are inherent in the use of the Rational Method (McCuen 1989; CALTRANS 1995; BYU 1999). Use of the Rational Method is limited to areas no larger than approximately 1 mi^2 in size, unless the overall watershed is subdivided into smaller units, and the resulting hydrographs are then routed to downstream areas (this size limitation has been overcome in this analysis by calculating peak flow increases for HAUs exclusive of upstream drainage area, and then routing the resulting hydrographs downstream). Peak discharge is assumed to have the same frequency of occurrence as rainfall. Rainfall intensity (**I**) is assumed constant over the storm duration and is uniformly distributed over the watershed. Instantaneous peak flow values are assumed to occur when runoff reaches the outlet from all areas of the HAU (this is equivalent to the time of concentration). Published values for the runoff coefficient **C** are limited for forested areas (the Rational Method is most widely applied in urban and rural watersheds). Although the Rational Method is extensively used for estimating peak flows in small rural drainages and for urban drainage design, results are considered to be an approximation (BYU 1999).

3.2 CALCULATION OF RUNOFF COEFFICIENT

The California Department of Transportation (CALTRANS) has developed an approach for estimating **C** values for undeveloped (i.e., non-urban) areas through consideration of four site characteristics: relief, soil infiltration, vegetation cover, and surface storage (CALTRANS 1995). Values suggested by CALTRANS for these four site characteristics are given in Table 3-1. An overall **C** value for a given site is estimated by summing the appropriate value for each of the four characteristics given in Table 3-1. For example, a site with average slopes of 5%, clay soils, good grassland area, and normal surface storage would have an overall **C** value of: 0.14 + 0.08 + 0.04 + 0.06 = 0.32.

Table 3-1: Runoff coefficients for undeveloped areas (from CALTRANS 1995).

Modifier	Partial C values and description of conditions			
Relief	**.28 - .35** Steep, rugged terrain with average slopes above 30%	**.20 - .28** Hilly, with average slopes of 10 to 30%	**.14 - .20** Rolling, with average slopes of 5 to 10%	**.08 - .14** Relatively flat land, with average slopes of 0 to 5%
Soil Infiltration	**.12 - .16** No effective soil cover, either rock or thin soil mantle of negligible infiltration capacity	**.08 - .12** Slow to take up water, clay or shallow loam soils of low infiltration capacity, imperfectly or poorly drained	**.06 - .08** Normal; well drained light or medium textured soils, sandy loams, silt and silt loams	**.04 - .06** High; deep sand or other soil that takes up water readily, very light well drained soils
Vegetation Interception	**.12 - .16** No effective plant cover, bare or very sparse cover	**.08 - .12** Poor to fair; clean cultivation crops, or poor natural cover, less than 20% of drainage area over good cover	**.06 - .08** Fair to good; about 50% of area in good grassland or wood-land, not more than 50% of area in cultivated crops	**.04 - .06** Good to excellent; about 90% of drainage area in good grassland, woodland or equivalent cover
Surface Storage	**.10 - .12** Negligible surface depression few and shallow; drainageways steep and small, no marshes	**.08 - .10** Low; well defined system of small drainageways; no ponds or marshes	**.06 - .08** Normal; considerable surface depression storage; lakes and pond marshes	**.04 - .06** High; surface storage, high; drainage system not sharply defined; large flood plain storage or large number of ponds or marshes

Soil types in the watershed were assigned to one of three soil infiltration categories based on surface/subsurface texture, drainage, and porosity (Table 1-1). Soil types classified as having "Slow" infiltration (Kinman and Yorkville) were assigned a partial **C** values of 0.10. Soil types classified as having "Slow-Normal" infiltration (Atwell, Boomer, Empire, Josephine, Larabee, Bottom Land, Farmland, and Terraces) were assigned a partial **C** values of 0.08. Soil types classified as having "Normal" infiltration (Hely, Hugo, Hugo variant, Laughlin, Melbourne, Tyson, Wilder) were assigned a partial **C** values of 0.07. Soil polygons classified as "x7" (Figure 1-3, Table 1-1) were assigned the same infiltration class as adjacent soil types.

A slope class coverage was provided for the analysis by PALCO. Slope information provided PALCO was for 300 ft x 300 ft squares, with the mean slope for each square recorded by 5% slope increments[3]. Polygons from this coverage were aggregated into four slope categories: 0-5%, 5-10%, 10-30%, and >30% (Figure 3-1). Partial **C** values were assigned to each polygon using mid-point values from Table 3-1 (i.e., $\mathbf{C}_{0\text{-}5\%}$ = 0.11 , $\mathbf{C}_{5\text{-}10\%}$ = 0.17, $\mathbf{C}_{10\text{-}30\%}$ = 0.24, and $\mathbf{C}_{>30\%}$ = 0.315).

[3] Calculation of mean slope by 300 ft x 300 ft polygons tends to smooth out some of the steeper-slope areas that may be found within a given polygon.

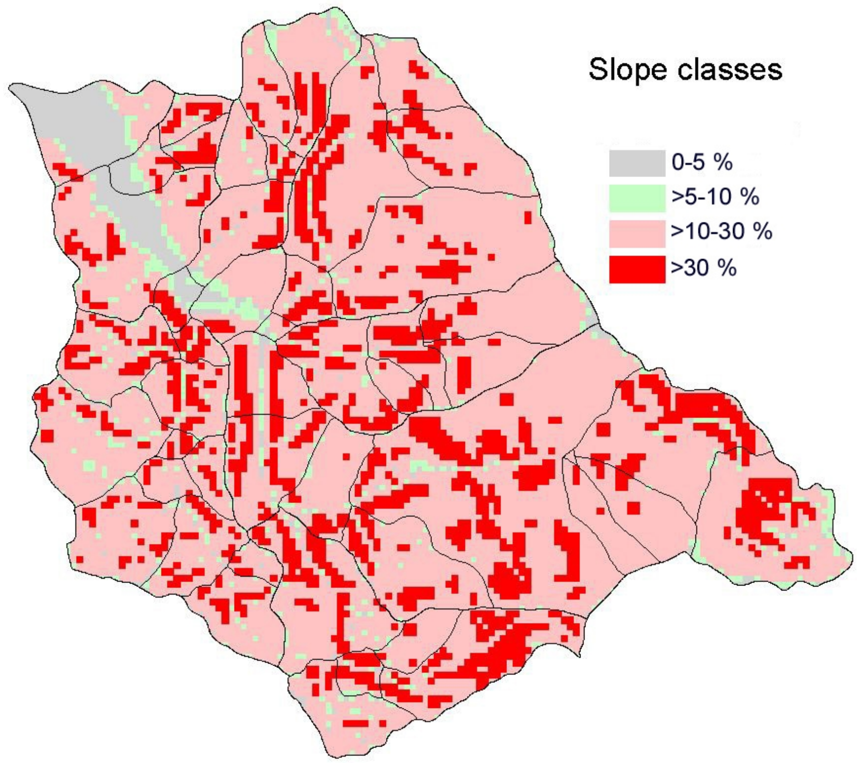

Figure 3-1: Slope class map, Freshwater Watershed.

An historical surface storage coverage was created using the slope class map (Figure 3-1), and the stream coverage for the watershed (provided by PALCO GIS). Polygons having an average slope of 0-5% that intersected streams were assumed to have a "Normal-High" surface storage (Table 3-1), and were assigned a partial **C** value of 0.06. The reasoning for this was that these polygons are assumed to represent floodplain areas with many opportunities for surface storage. Most of these polygons are located along Freshwater Creek in the lower Freshwater valley. All other slope polygons were assumed to have "Low" surface storage, and were assigned a partial **C** value of 0.09 (Table 3-1).

This final polygon coverage from Section 2.2 was intersected with soil infiltration, slope, and surface storage coverages described above to create a new coverage having polygons that are unique with respect to: (1) current land use (i.e., agricultural/residential, forest, power line, or road); (2) harvest year (for forested areas); (3) harvest system (i.e., tractor, yarder, helicopter); (4) soil type; (5) slope class; (6) surface storage; and (7) HAU. Historical **C** values were calculated for each polygon by summing up the partial C values for each component. A partial C value of 0.05 was used to represent the historical contribution of vegetation (Table 3-1; all areas of the watershed were assumed to have had >90% area in good woodland, grassland, or equivalent cover).

$$C_{poly} = C_{slope} + C_{infiltration} + C_{storage} + C_{vegetation} \qquad \text{(Equation \#10)}$$

Current **C** values were also calculated for each polygon using equation #10. The values for $\mathbf{C_{slope}}$ were assumed to be the same currently as for the historical condition (i.e., no change in slope due to land management activities). The values for $\mathbf{C_{infiltration}}$ for polygons of "Power line" land use were also assumed to be the same currently as for the historical condition (i.e., no change in soil infiltration due to power line land uses). The values for $\mathbf{C_{infiltration}}$ for polygons of "Agriculture/Residential" land use were arrived at by adding a value of 0.02 to values of $\mathbf{C_{infiltration}}$ for the historical condition. The assumption behind this adjustment is that Agricultural/Residential activities decrease soil infiltration by one infiltration class (e.g., from "Slow-Normal" to "Slow").

The values for $\mathbf{C_{infiltration}}$ for those polygons of "Forest" land use where the last timber harvest occurred prior to 1986, or harvesting occurred from 1986-1999 but the harvest system was "Helicopter" or "Cable yarding," were also assumed to be the same currently as for the historical condition (i.e., no change in soil infiltration if no harvest in the past 14 years or harvest was done with helicopter or cable yarding). This assumption probably misses some areas where changes in infiltration still persist due to harvesting that occurred prior to 1986; however, any error is probably small given that the majority (56%) of the "Forest" land in the watershed has had some harvest in the past 14 years, and some recovery has probably occurred in those areas harvested prior to 1986. The Surface Erosion analyst recommended including areas of cable yarding in this category based on field observations indicating very little soil compaction associated with cable yarding (see Surface Erosion Assessment, Appendix B, for more information). Current values for $\mathbf{C_{infiltration}}$ for those polygons of "Forest" land use where "Tractor" harvesting has occurred from 1986-1999 were calculated using the following equation (Note: this category also includes polygons where the harvest method was listed as "Unknown" or "Tractor/Yarder"):

$$C_{infiltration\text{-}current} = (0.85 * C_{infiltration\text{-}historic}) + (0.15 * 0.16) \qquad \text{(Equation \#11)}$$

Field observations by the Surface Erosion analyst indicate that approximately 15% of the area of tractor-yarded harvest units is disturbed due to harvest operations. Consequently, Equation #11 assigns the historic value of $\mathbf{C_{infiltration}}$ to 85% of the polygon, and the minimum $\mathbf{C_{infiltration}}$ value (0.16; Table 3-1) to the remaining 15% of the polygon. The effects of compaction were assumed not to decay over the 14-year period for which harvest data are available (compacted areas remain impervious to water infiltration for up to decades until vegetation becomes established and roots begin to penetrate and break up the compacted soil [Froehlich 1979; Vanderheyden 1980; Froehlich et al. 1985]). Current values of $\mathbf{C_{infiltration}}$ used for polygons of "Road" land use were also the minimum $\mathbf{C_{infiltration}}$ values (0.16) given in Table 3-1.

The values for $\mathbf{C_{storage}}$ for polygons of "Power line" and "Agriculture/Residential" land uses were assumed to be the same currently as for the historical condition (i.e., no change in surface storage due to power line or "Agriculture/Residential" land uses). The values for $\mathbf{C_{storage}}$ for those polygons of "Forest" land use where the last timber harvest occurred prior to 1986, or harvesting occurred from 1986-1999 but the harvest system was "Helicopter" or "Cable yarding," were also assumed to be the same currently as for the historical condition (i.e., no change in surface storage if no harvest in the past 14 years or harvest was done with helicopter or cable yarding).

Current values for $\mathbf{C_{storage}}$ for those polygons of "Forest" land use where "Tractor" harvesting has occurred from 1986-1999 were calculated using the following equation (Note: this category also includes polygons where the harvest method was listed as "Unknown" or "Tractor/Yarder"):

$$C_{storage\text{-}current} = (0.85 * C_{storage\text{-}historic}) + (0.15 * 0.12) \qquad \text{(Equation \#12)}$$

As stated above, field observations by the Surface Erosion analyst indicate that approximately 15% of the area of tractor-yarded harvest units is disturbed due to harvest operations. Consequently, equation #12 assigns the historic value of $\mathbf{C_{storage}}$ to 85% of the polygon, and the minimum $\mathbf{C_{storage}}$ value (0.12; Table 3-1) to the remaining 15% of the polygon. Current values of $\mathbf{C_{storage}}$ used for polygons of "Road" land use were also the minimum $\mathbf{C_{storage}}$ values (0.12) given in Table 3-1.

Current values for $\mathbf{C_{vegetation}}$ were assumed to be the same currently as for the historical condition. The reason for this counter-intuitive assumption is that the effects of canopy interception/evapotranspiration loss have already been accounted for in Section 2.0 of this report.

Area-weighted composite **C** values were calculated for each HAU (exclusive of upstream area) for both the historic ($\mathbf{C_{HAU\text{-}Historic}}$) and current ($\mathbf{C_{HAU\text{-}Current}}$) conditions using equation #13:

$$C_{HAU} = (C_{poly1} * A_{poly1} + C_{poly2} * A_{poly2} + \ldots C_{poly\ n} * A_{poly\ n}) / (A_{poly1} + A_{poly2} + \ldots A_{poly\ n}) \qquad \text{(Equation \#13)}$$

Where $\mathbf{A_{poly\ n}}$ is the area of a given polygon. Results for both the historic and current conditions are presented in Table 3-2.

Table 3-2: Composite C values for HAUs (exclusive of upstream area) for historic and current conditions.

Sub-basin Name	HAU	Historic	Current
South Fork	SF1	0.4793	0.4866
	SF2	0.4569	0.4579
	SF3	0.4789	0.4812
	SF4	0.4516	0.4563
	SF5	0.4656	0.4683
Little Freshwater	LF01	0.4618	0.4652
	LF02	0.4570	0.4605
	LF03	0.4633	0.4661
	LF04	0.4611	0.4669
	LF05	0.4556	0.4582
	LF06	0.4635	0.4664
	LF07	0.4777	0.4798
	LF08	0.4555	0.4611
	LF09	0.4707	0.4823
	LF10	0.4667	0.4732
	LF11	0.4828	0.4952
Graham Gulch	GG1	0.4611	0.4770
	GG2	0.4608	0.4753
	GG3	0.4718	0.4845
	GG4	0.4650	0.4821
	GG5	0.4740	0.4833
Cloney Gulch	CL1	0.4656	0.4769
	CL2	0.4521	0.4619
	CL3	0.4672	0.4770
	CL4	0.4661	0.4800
	CL5	0.4719	0.4898

Sub-basin Name	HAU	Historic	Current
McCready Gulch	MG1	0.4475	0.4536
	MG2	0.4578	0.4620
	MG3	0.4738	0.4799
	MG4	0.4507	0.4584
	MG5	0.4594	0.4680
School Forest	SC1	0.4728	0.4830
	SC2	0.4797	0.4941
	SC3	0.3990	0.4120
Upper Mainstem	FC01	0.4651	0.4763
	FC02	0.4677	0.4751
	FC03	0.4638	0.4774
	FC04	0.4615	0.4714
	FC05	0.4505	0.4592
	FC06	0.4681	0.4753
	FC07	0.4673	0.4697
	FC08	0.4594	0.4641
	FC09	0.4708	0.4802
	FC10	0.4669	0.4813
Mainstem	FC11	0.4256	0.4423
	FC12	0.4275	0.4419
	FC13	0.4143	0.4252
	FC14	0.4259	0.4381
	FC15	0.3575	0.3771

3.3 CALCULATING RAINFALL INTENSITY

Rainfall intensity (**I**) was obtained for each HAU from an intensity-duration-frequency (IDF) curve for the given recurrence interval (frequency) of the event, and for a duration equal to the time of concentration ($\mathbf{T_c}$) of each HAU. Time of concentration is defined as the time required for storm runoff to travel from the most remote point within the HAU to the outlet of the HAU.

An assumption of the Rational Method is that the peak flow occurs when all areas of the HAU are contributing to the outlet; consequently, the duration used in determining rainfall intensity (I) from the IDF curve is equal to the time of concentration. Time of concentration is the cumulative sum of flow along three components of the longest flow pathway in the HAU: sheet flow, shallow concentrated flow, and open channel flow. The most widely used equations for defining time of concentration along these three pathways, and the ones used in this modeling exercise, are from the NRCS Technical Release 55 (TR55) (NRCS 1986):

Sheet flow	$T_t = (0.007(nL)^{0.8}) / ((P_{2y,24h})^{0.5}\ S^{0.4})$	(Equation #14)
Shallow concentrated flow	$T_t = L/58084.2S^{0.5}$	(Equation #15)
Open channel flow	$T_t = (nL) / (5349.6\ R^{2/3}\ S^{1/2})$	(Equation #16)

Where:

Where:	T_t	=	Travel time (hours)
	n	=	Manning's roughness coefficient
	L	=	Flow path length (ft)
	$P_{2y,24h}$	=	2-year, 24-hour rainfall (in.)
	S	=	Slope (ft/ft)
	R	=	Hydraulic radius (ft)

As stated above, a data analysis was performed using the Watershed Modeling System (WMS), Version 6.0 (BYU 1999). The WMS model automatically determines the longest flow path in each HAU based on HAU geometry, stream location, and channel and upland slope (determined from digital elevation model [DEM] data). The open channel portion of the longest flow path coincided with the stream channel segment imported into WMS from the PALCO hydrology coverage. The sheet flow portion of the longest flow path (located at the upslope end of the flow path) was set to be approximately 300 ft in length, the maximum distance recommended by the NRCS (1986). The remainder of the longest flow path (in between the open channel and sheet flow portions) was the shallow concentrated flow path.

Values of L (flow path length) and S (slope) in equations #14, #15, and #16 were computed within WMS from DEM data. The Manning's roughness coefficient used for the sheet flow pathway was 0.8 for all HAUs. This is the value suggested by the NRCS (1986) for forested areas with dense underbrush. The Manning's roughness coefficient used for all open channel flow pathways was 0.05, a value suggested by the Channel Module analyst.

Values for $P_{2y,24h}$ were computed for each HAU by first geo-referencing images of the 2-year, 24-hour rainfall from the NOAA Atlas (Miller et al. 1973), and then digitizing isopluvial boundaries to polygon boundaries. Values of the 2-year, 24-hour rainfall for a given polygon were taken as the average value of the boundary isopluvials. Isopluvial polygons were clipped to HAU boundaries, and an area-weighted average $P_{2y,24h}$ value was calculated for each HAU. Values of $P_{2y,24h}$ ranged from 3.50 in. for the HAU located close to the watershed outlet (FC14 and FC15) to 4.75 in. for FC01, located in the headwaters.

Hydraulic radius (the ratio of channel cross-sectional area to wetted perimeter) can be approximated as the average channel depth (Knighton 1984). Sixty-four observations of bankfull channel depth from the Freshwater Watershed, collected as part of the Channel Module, were used to estimate depth as a function of drainage area (A, in acres):

$$Depth\ (ft) = 0.2831A^{0.279} \qquad [r^2 = 0.74] \qquad \text{(Equation \#17)}$$

Values of depth ranged from 0.5 ft in headwater HAUs (LF02, SC2, GG4, SC1) to 4.4 ft at the watershed outlet (FC14, FC15). Estimated bankfull depth values from equation #17 were used to approximate hydraulic radius vales in equation #16.

The WMS model includes a sub-routine to create IDF curves for the 2, 5, 10, 25, 50, and 100-year peak flow events based on user input of values of the 2-year, 6-hour ($P_{2y,6h}$); 2-year, 24-hour ($P_{2y,24h}$); 100-year, 6-hour ($P_{100y,6h}$); and 100-year, 24-hour ($P_{100y,24h}$) precipitation values. Values were computed for each HAU as described above for the $P_{2y,24h}$ event, using images from the NOAA Atlas (Miller et al. 1973). Values of $P_{2y,6h}$ ranged from 1.80 to 2.10 in. among HAUs, with a watershed-wide area-weighted value of 1.96 in. Values of $P_{2y,24h}$ ranged from 3.50 to 4.75 in. among HAUs (as described above), with a watershed-wide area-weighted value of 4.03 in. Values of $P_{100y,6h}$ ranged from 3.50 to 3.75 in. among HAUs, with a watershed-wide area-weighted value of 3.73 in. Values of $P_{100y,24h}$ ranged from 7.0 to 10.0 in. among HAUs, with a watershed-wide area-weighted value of 8.26 in. To simplify modeling input, the watershed-wide area-weighted values were used for all HAUs.

Values of rainfall intensity (**I**) were held constant between modeling scenarios. Management activities have the potential to change the Manning's roughness coefficient used for the sheet flow pathways in equation #14; however, given that all sheet flow pathways were located in forested areas, and that surface conditions are likely to be the same both pre and post harvesting (i.e., dense underbrush), it seemed reasonable to leave this value unchanged. Management activities also have the potential to change the Manning's roughness coefficient used for open channel flow in equation #16 by either fining or coarsening bed material, or through reduction of large roughness elements (i.e., coarse woody debris). However, analysis performed in the Riparian Module indicates that most stream segments in the watershed have high levels of in-stream woody debris, and it is difficult to discern any clear trend in either bed-fining or coarsening across the watershed. Although precipitation intensity patterns are subject to temporal variation, they are not affected (in any practical sense) by management activities. Values of HAU area (**A**) were also held constant between the two modeling scenarios.

3.4 CHANNEL ROUTING

As stated in Section 3.1, instantaneous peak flow values were calculated for each HAU (exclusive of upstream drainage area) using the Rational Method; storm hydrographs were then estimated from instantaneous peak flow values using a unit hydrograph approach, and these storm hydrographs were then routed downstream to estimate instantaneous peak flow values for HAUs including upstream drainage area.

The WMS modeling package contains five different unit hydrographs that can be selected to generate a storm hydrograph from the instantaneous peak flow value. Of these five, the Universal Hydrograph (Figure 3-2) appeared to most closely approximate the shape of peak flows observed at the Freshwater and McCready Gulch stream gages (Table 1-4, Figure 1-9). Assumptions of the Universal Hydrograph are that the time base is equal to 11 times the time of concentration (t_c), the instantaneous peak flow (Q_p) occurs at 3 times t_c, and the ordinate values (Q/Q_p) at time t/t_c are as shown in Figure 3-2 (BYU 1999).

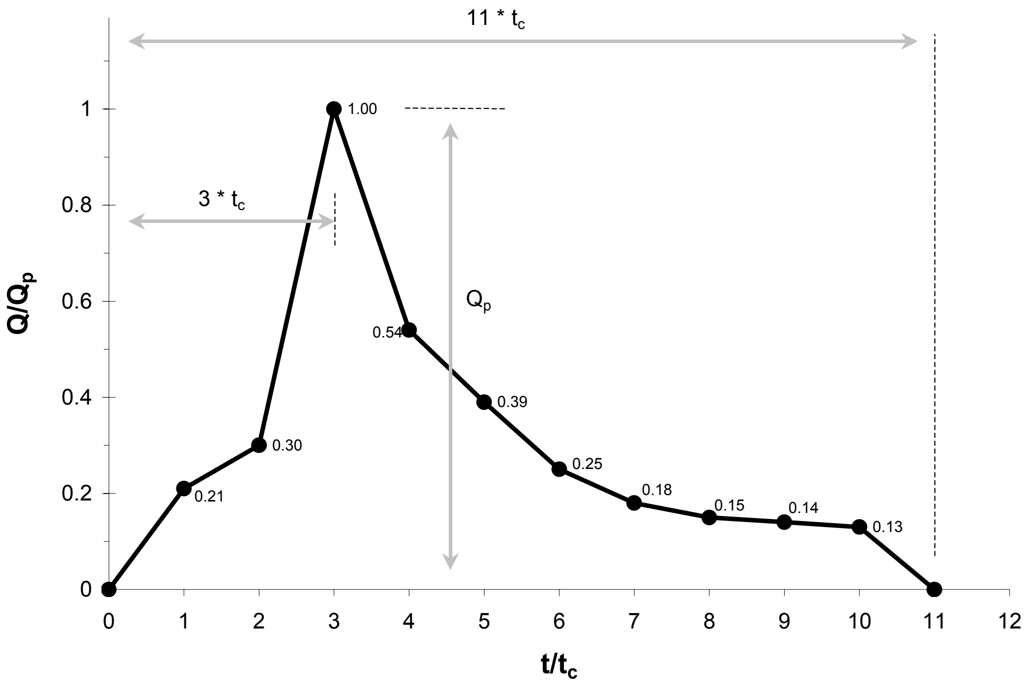

Figure 3-2: Characteristics of the Universal unit hydrograph (BYU 1999).

Storm hydrographs produced for each HAU exclusive of upstream drainage area were next routed downstream to estimate instantaneous peak flow values for HAUs including upstream drainage area. The lag time for when a given upstream hydrograph "arrives" at some downstream point of interest is a function of the connecting channel, and was computed within the WMS modeling package using equation #16. As was done for the t_c pathways, the values of L (channel length) and S (slope) were computed within WMS from DEM data; the Manning's roughness coefficient used for all open channel routing reaches was 0.05; and estimated bankfull depth values from equation #17 were used to approximate hydraulic radius values.

3.5 RESULTS

Relative changes in peak flows due to soil compaction were calculated for each HAU (including upstream drainage area) by comparing the results for historic and current conditions using equation #9. Results are given in Table 3-3.

Table 3-3: Modeled relative increases in peak flows by HAU (including upstream contributing area) due to soil compaction.

Sub-basin Name	HAU	Q_2	Q_5	Q_{10}
South Fork	SF1	2%	2%	2%
	SF2	0%	0%	0%
	SF3	1%	1%	1%
	SF4	1%	1%	1%
	SF5	1%	1%	1%
Little Freshwater	LF01	1%	1%	1%
	LF02	1%	1%	1%
	LF03	1%	1%	1%
	LF04	1%	1%	1%
	LF05	1%	1%	1%
	LF06	1%	1%	1%
	LF07	1%	1%	1%
	LF08	1%	1%	1%
	LF09	1%	1%	1%
	LF10	1%	1%	1%
	LF11	1%	1%	1%
Graham Gulch	GG1	3%	3%	3%
	GG2	3%	3%	3%
	GG3	3%	3%	3%
	GG4	4%	4%	4%
	GG5	3%	3%	3%
Cloney Gulch	CL1	2%	2%	2%
	CL2	2%	2%	2%
	CL3	2%	2%	2%
	CL4	3%	3%	3%
	CL5	3%	3%	3%
McCready Gulch	MG1	1%	1%	1%
	MG2	1%	1%	1%
	MG3	1%	1%	1%
	MG4	2%	2%	2%
	MG5	1%	1%	1%
School Forest	SC1	2%	2%	2%
	SC2	3%	3%	3%
	SC3	3%	3%	3%
Upper Mainstem	FC01	2%	2%	2%
	FC02	2%	2%	2%
	FC03	3%	3%	3%
	FC04	2%	2%	2%
	FC05	2%	2%	2%
	FC06	2%	2%	2%
	FC07	1%	1%	1%
	FC08	2%	2%	2%
	FC09	1%	1%	1%
	FC10	1%	1%	1%
Mainstem	FC11	2%	2%	2%
	FC12	2%	2%	2%
	FC13	2%	2%	2%
	FC14	2%	2%	2%
	FC15	2%	2%	2%

Results given in Table 3-3 are limited to the peak flows having a recurrence interval of 2 years (Q_2), 5 years (Q_5) and 10 years (Q_{10}). No precipitation frequency values are available from the NOAA Atlas (Miller et al. 1973) for the $Q_{0.25,}$ $Q_{0.5}$, Q_1, or Q_{15} events; consequently, the sub-routine within the WMS model used to create IDF curves is unable to generate values for these events.

Unlike the modeled results from Section 2.0 for relative changes due to canopy interception/ evapotranspiration loss (which show greatest relative increases in peak flows in the higher-frequency, lower-magnitude events), the results shown in Table 3-3 are constant over the range of recurrence intervals. The estimated percent increase in the Q_2, Q_5, and Q_{10} peak flow events ranges from 0% (for HAU SF2) to 4% (for HAU GG4) with a median value of 2% (Table 3-3). Within the flood-prone HAUs (i.e., HAUs FC10-FC15), the estimated percent increase in the Q_2, Q_5, and Q_{10} peak flow events are 1% for FC10 and 2% for HAUs FC11-FC15 (Table 3-3).

4.0 RELATIVE CHANGES DUE TO ROAD DRAINAGE

The purpose of this portion of the assessment is to evaluate relative (i.e., percent) changes in peak flows due to the connectivity of the road drainage and stream systems. The extent to which road drainage ditches are connected to the stream system in the Freshwater Watershed is summarized in Section 4.1 below. An overview of the modeling approach used in this assessment is provided in Section 4.2. Section 4.3 provides details on delineation of sub-HAUs within the three HAUs chosen for analysis, and Section 4.4 describes how model parameters were developed. Results are presented in Section 4.5. One deviation from the PALCO methodology was that no analysis was performed on the peak flow changes associated with possible (or likely) future road drainage connectivity. It was decided at a pre-Synthesis meeting with the SRT in May, 2000, that it would be more useful to evaluate future conditions iteratively during the prescription phase of the analysis.

4.1 SUMMARY OF ROAD DRAINAGE CONNECTIVITY

Information on the connectivity of the road drainage and stream systems was collected for PALCO lands within the Freshwater Watershed by Pacific Watershed Associates (PWA 1999). In total, 814 road ditches[4] with combined length of 19.7 miles were reported by PWA to have a surface water connection to the stream network. A GIS point coverage showing the locations where connected ditches intersect the stream network was provided by PWA for this analysis. The point coverage supplied by PWA was converted to a line coverage by following along the road for the distance reported by PWA. In some situations, a stream connection was reported by PWA, but no stream was shown on the stream coverage. In these situations, a stream was added to the stream coverage layer from the point of the ditch connection to the closest downstream mapped stream segment. Road drainage ditches connected to streams are summarized by HAU in Table 4-1 and shown in Figure 4-1.

The percent increase in the effective drainage network (i.e., length of connected ditches/length of stream; expressed as a percentage) ranges from 0% (i.e., no connected ditches) in 12 of the 49 HAUs (SF2, SF3, SF4, LF02, LF06, LF07, LF11, FC01, FC05, FC10, FC11, FC13); to 23% in HAU MG4; with a median value of 6% (Table 4-1).

[4] PWA reported a total of 551 separate road ditches in the Freshwater Watershed, many of which contributed from both sides of the stream channel (i.e., entering the stream from both the left and right banks). For the purposes of this report, a given ditch that connected from both sides was treated as two separate ditches.

Drainage pirating, or the capture of runoff from one HAU and transport to an adjacent HAU, is estimated to be occurring at nine locations on PALCO lands in the Freshwater Watershed (Figure 4-2, Table 4-2). Areas of drainage pirating range from an estimated 0.01 to 8.1 acres.

Table 4-1: Summary of connected road ditches by HAU (exclusive of upstream drainage area).

Sub-basin Name	HAU	Total # of connected ditches	Total length of connected ditches (miles)	Total length of streams (miles)	% increase in effective drainage network
South Fork	SF1	24	1.13	8.09	14%
	SF2	-	-	2.08	0%
	SF3	-	-	2.05	0%
	SF4	-	-	6.42	0%
	SF5	8	0.22	15.06	1%
Little Freshwater	LF01	3	0.13	6.84	2%
	LF02	-	-	1.56	0%
	LF03	2	0.01	6.67	0%
	LF04	24	0.70	9.52	7%
	LF05	2	0.01	2.99	0%
	LF06	-	-	2.40	0%
	LF07	-	-	1.39	0%
	LF08	21	0.50	13.96	4%
	LF09	14	0.20	4.35	5%
	LF10	12	0.19	5.72	3%
	LF11	-	-	0.95	0%
Graham Gulch	GG1	26	0.40	4.29	9%
	GG2	16	0.29	5.26	6%
	GG3	33	0.46	4.75	10%
	GG4	12	0.18	1.52	12%
	GG5	42	0.95	8.52	11%
Cloney Gulch	CL1	20	0.39	5.16	8%
	CL2	15	0.38	2.60	15%
	CL3	82	2.06	12.55	16%
	CL4	63	1.55	15.01	10%
	CL5	11	0.18	2.36	8%
McCready Gulch	MG1	29	0.52	4.59	11%
	MG2	25	0.41	3.18	13%
	MG3	8	0.10	1.18	9%
	MG4	37	0.67	2.98	23%
	MG5	57	1.78	8.02	22%
School Forest	SC1	6	0.06	1.22	5%
	SC2	6	0.09	1.52	6%
	SC3	8	0.22	1.46	15%
Upper Mainstem	FC01	-	-	9.26	0%
	FC02	44	0.98	10.92	9%
	FC03	9	0.39	3.41	12%
	FC04	7	0.37	2.45	15%
	FC05	-	-	0.11	0%
	FC06	71	2.38	31.13	8%
	FC07	3	0.07	8.90	1%
	FC08	7	0.12	5.80	2%
	FC09	43	1.14	9.90	12%
	FC10	-	-	5.45	0%
Mainstem	FC11	-	-	0.33	0%
	FC12	7	0.22	3.76	6%
	FC13	-	-	1.10	0%
	FC14	12	0.20	11.84	2%
	FC15	5	0.06	4.39	1%
Total		**814**	**19.70**	**284.95**	

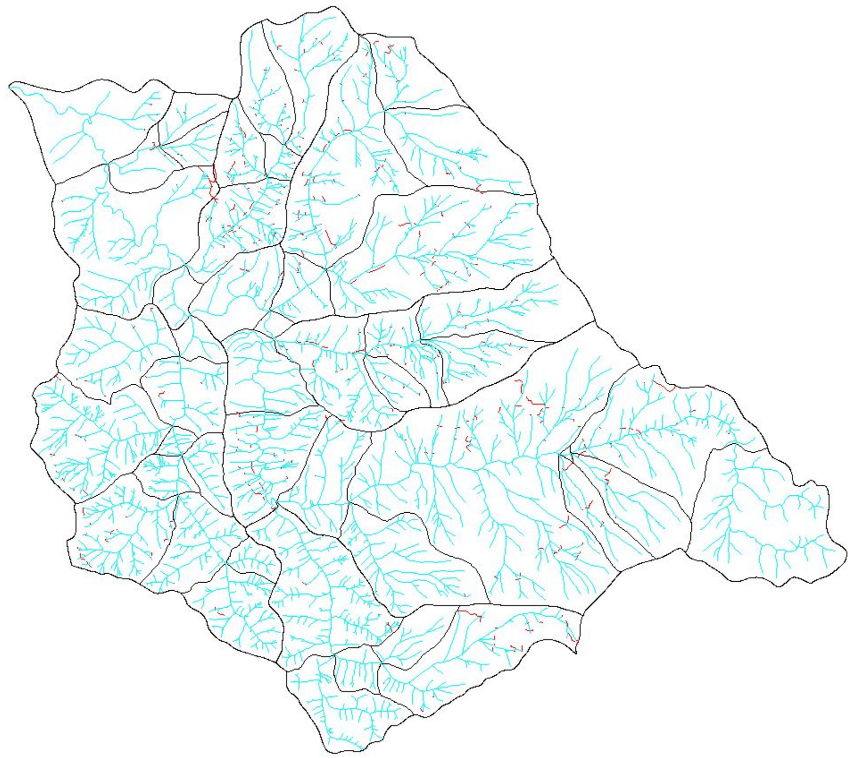

Figure 4-1: Road ditches (red lines) connected to the stream network (blue lines). HAU boundaries are shown in black.

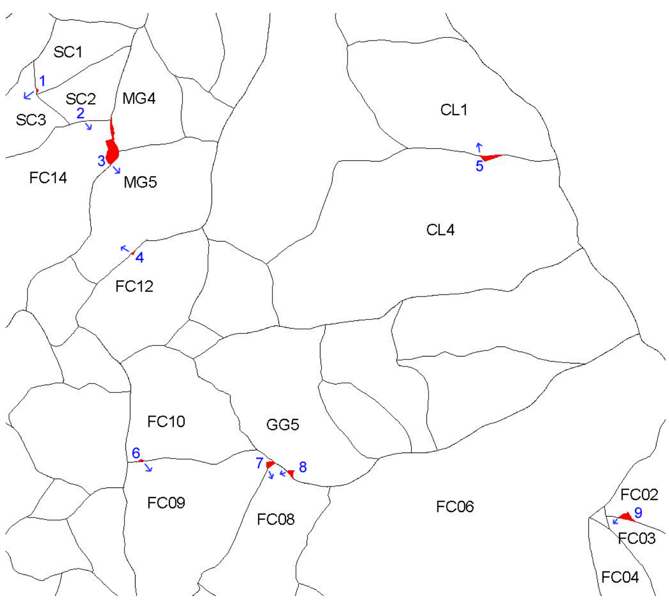

Figure 4-2: Areas where road ditches transport drainage to adjacent HAUs.

Table 4-2: Attributes of areas where road ditches transport drainage to adjacent HAUs.

Map #	Area Pirated (acres)	Pirated from	Pirated to
1	0.2	SC1	SC2
2	0.01	SC2	FC14
3	8.1	MG4 and FC14	MG5
4	0.2	FC12	MG5
5	1.8	CL4	CL1
6	0.3	FC10	FC09
7	1.0	FC09	FC08
8	0.8	GG5	FC08
9	1.8	FC02	FC03

4.2 OVERVIEW OF MODELING APPROACH

The effects of the connectivity of the road drainage and stream systems on peak flows were also modeled using the Rational Method (equation #8 above), although using a slightly different approach. Each HAU was divided into sub-HAUs based on the current locations of connected road drainage ditches. Road ditches connected to the stream system were modeled as additional stream segments in the current condition scenario (note that this approach is likely to be conservative with respect to road ditch effects, as ditches are unlikely to intercept all flow from the upslope contributing area). Runoff coefficient (**C**) values were estimated for each sub-HAU (exclusive of upstream drainage area) under both current and historic conditions. Rainfall intensity (**I**) was obtained from an intensity-duration-frequency (IDF) curve for the given recurrence interval (frequency) of the event, and for a duration equal to the time of concentration ($\mathbf{T_c}$) of each sub-HAU (note: values of **I** and **A** were not constant between the modeling scenarios). Instantaneous peak flow values were calculated for each sub-HAU (exclusive of upstream drainage area) under both modeling scenarios (i.e., current and historic conditions), and storm hydrographs developed using a unit hydrograph approach. Storm hydrographs were then routed downstream to estimate instantaneous peak flow values at the mouth of the HAU. Relative changes in peak flows due to road drainage connectivity were then calculated for the HAU by comparing the results for historic and current conditions.

The modeling involved with this section of the assessment was too time-intensive to be performed for the entire watershed. Thus, the three HAUs with the highest percent increase in the effective drainage network that have no upstream contributing drainage area outside of the HAU were selected for modeling. HAUs with upstream contributing area outside of the HAU are further complicated by the need to model runoff within the entire contributing area. HAUs MG4, FC04, and CL2 were the three HAUs selected for modeling (Table 4-1).

4.3 SUB-HAU DELINEATION

Each of the three modeled HAUs was divided into sub-HAUs based on the current locations of connected road drainage ditches (e.g., Figure 4-3, HAU MG4). The intersection of each connected road drainage ditch with a stream channel was defined as the outlet of a sub-HAU. For the historic condition (i.e., with no road ditches), the same sub-HAU outlet locations were used, although the contributing area to the sub-HAU outlet was usually smaller (e.g., Figure 4-4, HAU MG4). This approach resulted in the delineation of 25 sub-HAUs within HAU MG4, 5 sub-HAUs within FC04 (Figures 4-5 and 4-6), and 9 sub-HAUs within CL2 (Figures 4-7 and 4-8).

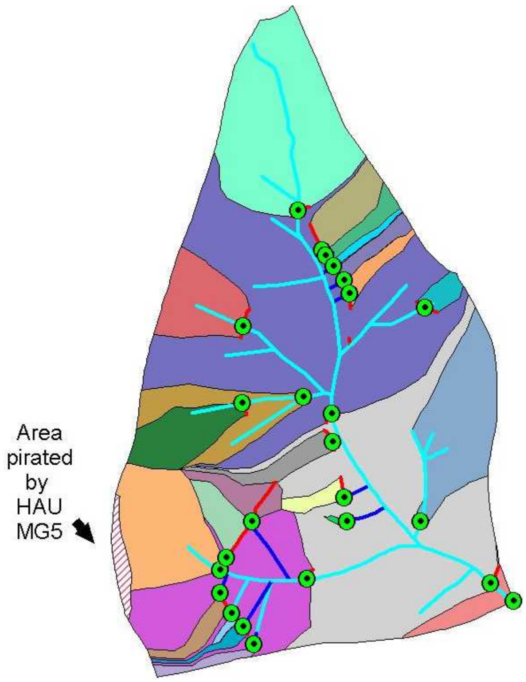

Figure 4-3: HAU MG4 subdivided into 25 sub-HAUs representing __current conditions__. Light blue lines indicate locations of mapped Class I-III streams, dark blue lines indicate locations of interpolated streams, and red lines indicate locations of road ditches connected to streams. Green circles indicate sub-HAU outlets. Cross-hatching indicates area pirated by HAU MG5.

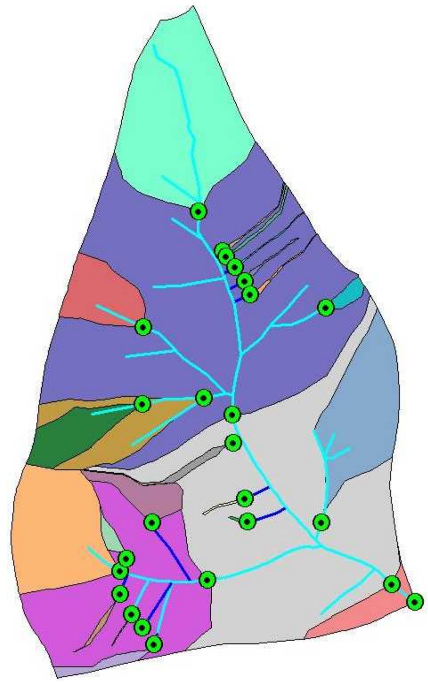

Figure 4-4: HAU MG4 subdivided into 25 sub-HAUs representing the __historic (unroaded) condition__. Light blue lines indicate locations of mapped Class I-III streams, dark blue lines indicate locations of interpolated streams. Green circles indicate sub-HAU outlets.

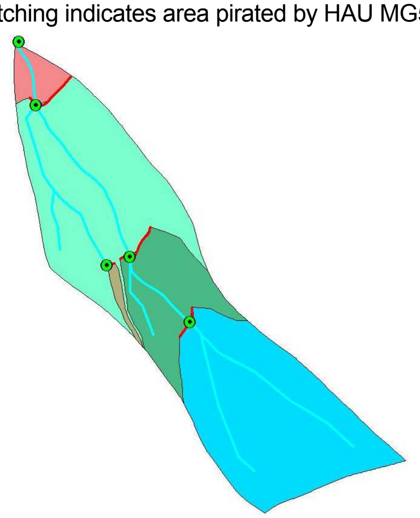

Figure 4-5: HAU FC04 subdivided into 5 sub-HAUs representing __current conditions__. Light blue lines indicate locations of mapped Class I-III streams, dark blue lines indicate locations of interpolated streams, and red lines indicate locations of road ditches connected to streams. Green circles indicate sub-HAU outlets. Cross-hatching indicates area pirated by HAU MG5.

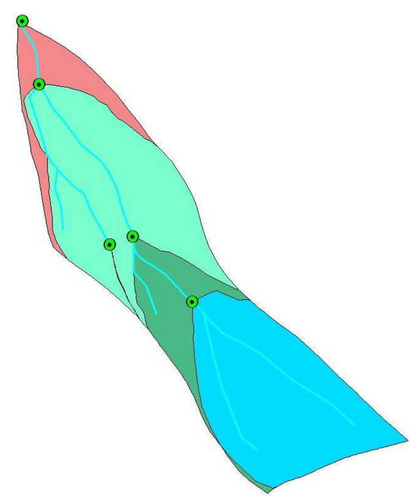

Figure 4-6: HAU FC04 subdivided into 5 sub-HAUs representing the __historic (unroaded) condition__. Light blue lines indicate locations of mapped Class I-III streams, dark blue lines indicate locations of interpolated streams. Green circles indicate sub-HAU outlets.

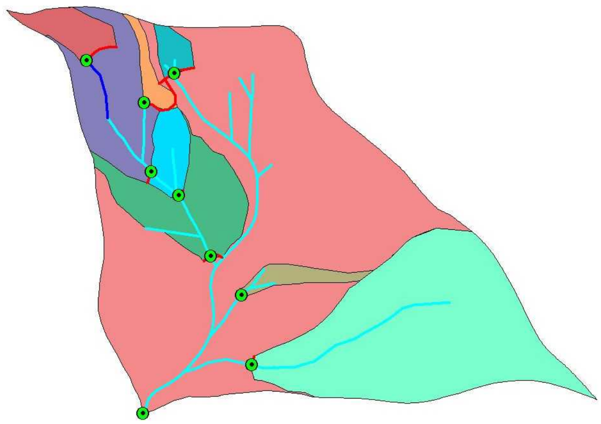

Figure 4-7: HAU CL2 subdivided into 9 sub-HAUs representing current conditions. Light blue lines indicate locations of mapped Class I-III streams, dark blue lines indicate locations of interpolated streams, and red lines indicate locations of road ditches connected to streams. Green circles indicate sub-HAU outlets. Cross-hatching indicates area pirated by HAU MG5.

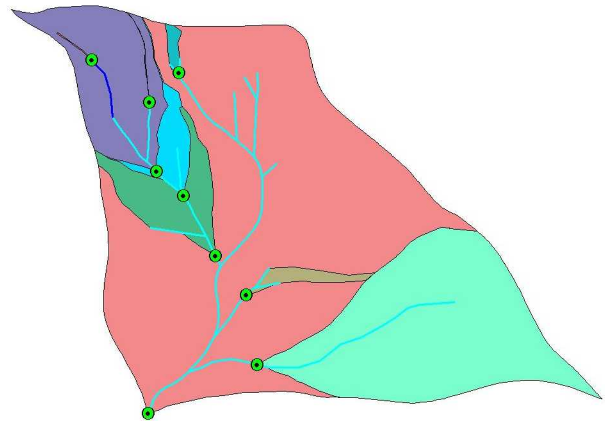

Figure 4-8: HAU CL2 subdivided into 9 sub-HAUs representing the historic (unroaded) condition. Light blue lines indicate locations of mapped Class I-III streams, dark blue lines indicate locations of interpolated streams. Green circles indicate sub-HAU outlets.

4.4 MODEL PARAMETERS

Area-weighted composite **C** values were calculated for each sub-HAU (exclusive of upstream area) for both the historic and current conditions using the approach described in Section 3.2. The polygon coverage from Section 3.2 (having polygons that are unique with respect to current land use, harvest year, harvest system, soil type, slope class, and surface storage) was intersected with polygon coverages of each sub-HAU (i.e., Figures 4-3 through 4-8). Area-weighted composite **C** values were calculated for each sub-HAU for both the historic and current conditions using equation #13. A summary of the **C** values used in the road drainage modeling is given in Table 4-3.

Rainfall intensity (**I**) was calculated for each sub-HAU/modeling scenario within the WMS model (BYU 1999), using the techniques described in Section 3.3 above. Rainfall intensity (**I**) was obtained for each sub-HAU/modeling scenario from an intensity-duration-frequency (IDF) curve for the given recurrence interval (frequency) of the event, and for a duration equal to the time of concentration ($\mathbf{T_c}$) of each sub-HAU. Time of concentration was calculated by summing the travel time for the sheet flow, shallow concentrated flow, and open channel flow pathways using equations #14, #15, and #16, respectively. Note that, unlike in Section 3.0, $\mathbf{T_c}$ varies for a given sub-HAU between modeling scenarios. This is because in the road-drainage modeling the geometry of the sub-HAU changes between modeling scenarios (i.e., the drainage area is different due to the road-ditch pathways). Consequently, values of **I** are also different between modeling scenarios.

Table 4-3: Summary of runoff coefficient (C) values used in road drainage modeling.

HAU	Number of sub-HAUs	Historic			Current		
		Min	Max	Median	Min	Max	Median
MG4	25	0.3389	0.5100	0.4596	0.3788	0.5079	0.4627
FC04	5	0.4508	0.4665	0.4588	0.4523	0.4791	0.4659
CL2	9	0.4100	0.4604	0.4494	0.4292	0.4741	0.4627

The WMS model automatically determines the longest flow path in each sub-HAU based on sub-HAU geometry, open-channel location (including both streams and connected ditches in the current conditions scenario), and channel and upland slope (determined from DEM data). The open channel portion of the longest flow path coincided with the stream channel/connected ditch segment imported into WMS from the stream/ditch coverage (Figure 4-1). The sheet flow portion of the longest flow path (located at the upslope end of the flow path) was set to be approximately 300 ft in length, the maximum distance recommended by the NRCS (1986). The remainder of the longest flow path (in between the open channel and sheet flow portions) was the shallow concentrated flow path.

Values of L (flow path length) and S (slope) in equations #14, #15, and #16 were computed within WMS from DEM data. The Manning's roughness coefficient used for the sheet flow pathways was 0.8 for all HAUs. This is the value suggested by the NRCS (1986) for forested areas with dense underbrush. The Manning's roughness coefficient used for all open channel flow pathways (both stream channel and ditches) was 0.05.

Area-weighted 2-year 24-hour Precipitation ($P_{2y,24h}$) values, calculated for each HAU in Section 3.3, were used for each sub-HAU in equation # 14. Values of $P_{2y,24h}$ were 3.75 in. for all sub-HAUs within HAU MG4, 4.5 in. for all sub-HAUs within HAU FC04, and 4.25 in. for all sub-HAUs within HAU CL2.

Hydraulic radius for each stream pathway was approximated in equation #16 using the depth-drainage area relationship in equation #17. A hydraulic radius value of 0.6 ft was used for all connected ditch pathways.

Intensity-duration-frequency (IDF) curves were calculated within the WMS model based on user input of values of the 2-year, 6-hour ($P_{2y,6h}$); 2-year, 24-hour ($P_{2y,24h}$); 100-year, 6-hour ($P_{100y,6h}$); and 100-year, 24-hour ($P_{100y,24h}$) precipitation values. Values were computed for each

HAU as described in Section 3.3. Values of $P_{2y,6h}$ were 2.1, 1.9, and 2.0 in. for HAUs FC04, MG4, and CL2, respectively. Values of $P_{2y,24h}$ were as stated above for the three HAUs. Values of $P_{100y,6h}$ were 3.75 in. for all three HAUs. Values of $P_{100y,24h}$ were 9.0, 7.5, and 8.5 in. for HAUs FC04, MG4, and CL2, respectively.

Instantaneous peak flow values, calculated for each sub-HAU (exclusive of upstream drainage area), were used to generate storm hydrographs using the unit hydrograph approach described in Section 3.4. These storm hydrographs were then routed downstream to estimate instantaneous peak flow values at the outlet of the HAU. As in section 3.4, the Universal unit hydrograph (Figure 3-2) was used. The lag time for when a hydrograph from a given sub-HAU "arrives" at the HAU outlet was computed within the WMS modeling package using equation #16. The values of L (channel length) and S (slope) were computed within WMS from DEM data; the Manning's roughness coefficient used for all open channel routing reaches was 0.05; and estimated bank depth values from equation #17 were used to approximate hydraulic radius vales.

4.5 RESULTS

Relative changes in instantaneous peak flows due to connectivity of the road drainage system were calculated for each of the three HAUs by comparing the results of historic and current conditions using equation #9 (Section 3.1 above). Results are presented in Table 4-4.

Table 4-4: Modeled relative changes in peak flows at each HAU outlet due to road drainage connectivity. Results are percent change in the 2- year (Q_2), 5-year (Q_5), and 10-year (Q_{10}) events.

HAU	Q_2	Q_5	Q_{10}
MG4	1%	1%	1%
FC04	-3%	-3%	-3%
CL2	2%	2%	1%

The results of this analysis were also limited (as in section 3.0 above) to those peak flows having a recurrence interval of 2 years (Q_2), 5 years (Q_5) and ten years (Q_{10}) due to the modeling limitations discussed in section 3.5 above.

Modeling results for HAU MG4 (the HAU with the greatest percent increase in the effective drainage network [23%]; Table 4-1) indicate approximately a 1% increase in peak flows for the Q_2, Q_5, and Q_{10} events due to connectivity of the road drainage network (Table 4-4). The modeled hydrograph for the Q_2 event is given in Figure 4-9. Modeled hydrographs for the Q_5 and Q_{10} events (not shown) are identical in shape. Based on this modeling, it appears that road drainage connectivity results in a slightly earlier rise to peak, and a slightly higher instantaneous peak value as compared to the historical condition.

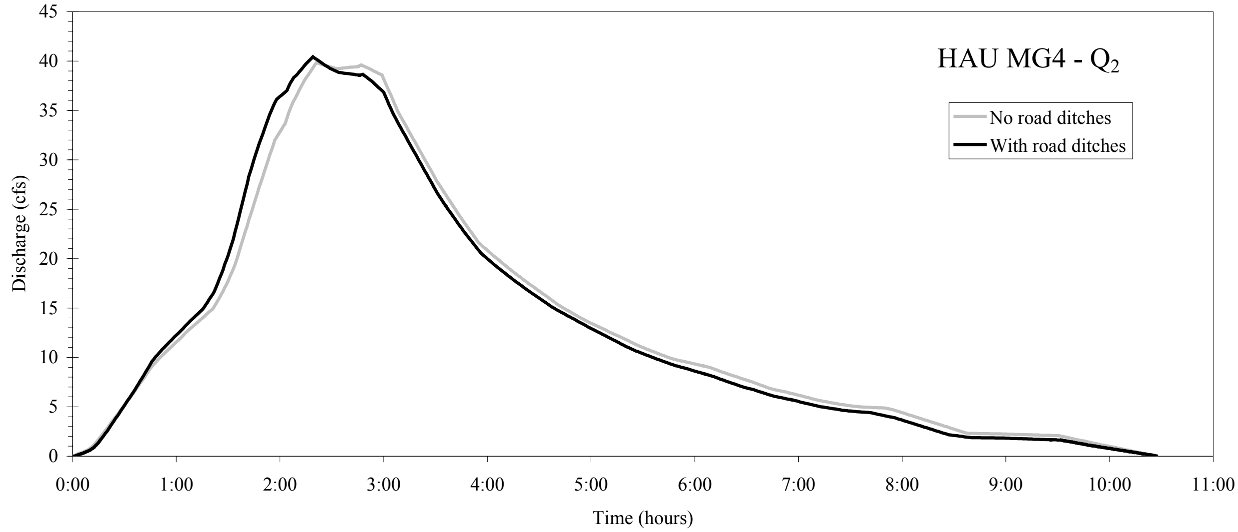

Figure 4-9: Modeled 2-year discharge event at the outlet of HAU MG4 for historic (i.e., no road drainage ditches) and current (i.e., with connected road ditches) conditions.

Modeling results for HAU FC04 (which represents a 15% increase in the effective drainage network; Table 4-1) indicate approximately a 3% <u>decrease</u> in peak flows for the Q_2, Q_5, and Q_{10} events due to connectivity of the road drainage network (Table 4-4). The modeled hydrograph for the Q_2 event is given in Figure 4-10.

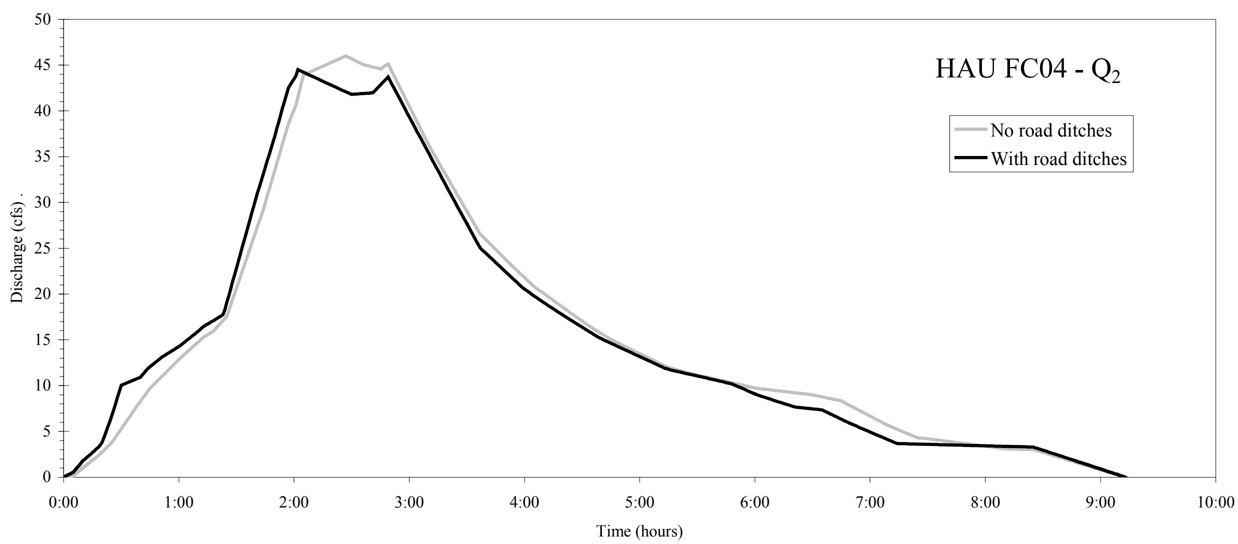

Figure 4-10: Modeled 2-year discharge event at the outlet of HAU FC04 for historic (i.e., no road drainage ditches) and current (i.e., with connected road ditches) conditions.

Modeled hydrographs for the Q_5 and Q_{10} events (not shown) are identical in shape. Based on this modeling, it appears that road drainage connectivity also results in a slightly earlier rise to peak, as compared to the historical condition. However, it appears that more rapid delivery of stormflow desynchronizes the overall storm runoff, resulting in a reduction in the magnitude of the peak streamflow.

Modeling results for HAU CL2 (representing a 15% increase in the effective drainage network; Table 4-1) indicate approximately a 2% increase in peak flows for the Q_2 and Q_5 events, and a 1% increase in the Q_{10} event, due to connectivity of the road drainage network (Table 4-4). The modeled hydrograph for the Q_2 event is given in Figure 4-11. Modeled hydrographs for the Q_5 and Q_{10} events (not shown) are identical in shape. Based on this modeling, it appears that road drainage connectivity results in a slightly earlier rise to peak as compared to the historical condition, and a slightly higher instantaneous peak value.

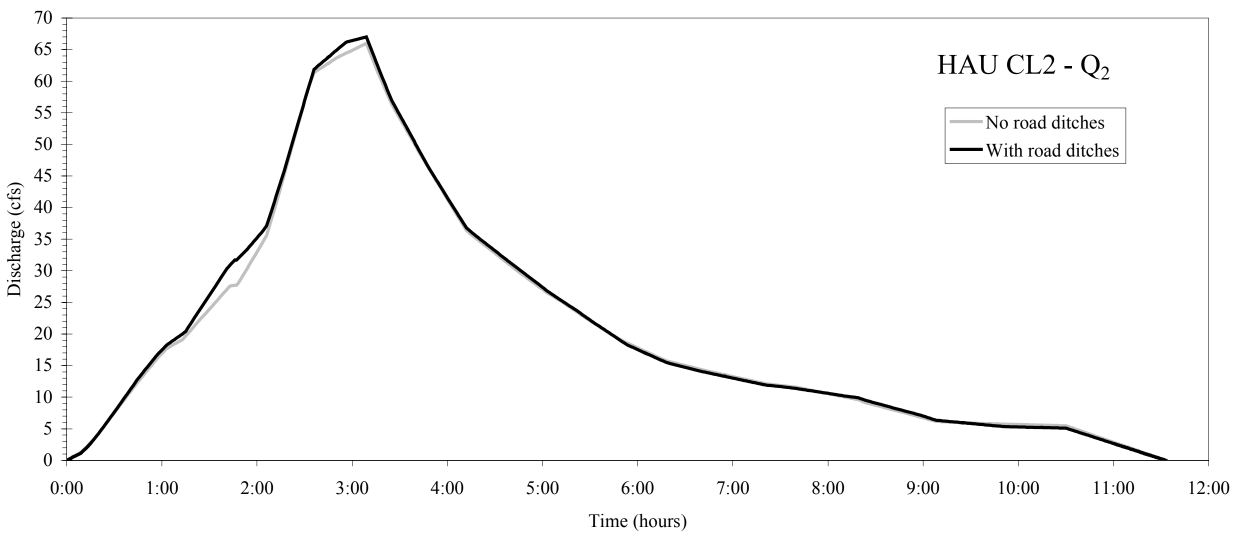

Figure 4-11: Modeled 2-year discharge event at the outlet of HAU CL2 for historic (i.e., no road drainage ditches) and current (i.e., with connected road ditches) conditions.

Given the collective results for the three modeled HAUs, it appears that road drainage connectivity results in a slightly earlier rise to peak compared to historic conditions. However, no consistent effect on the magnitude of peak flows is evident.

5.0 MAGNITUDE OF CHANGES IN PEAK FLOWS

The purpose of this portion of the assessment is to assess the magnitude of change in peak flows for each HAU (including upstream drainage area) posed by the relative changes modeled in the previous sections of this assessment. Estimates of baseline peak flow magnitudes (i.e., peak flow magnitudes that we would expect in the absence of any land management activities) are provided in Section 5.1 for each HAU in the watershed. In Section 5.2, the estimates of current peak flow magnitudes are provided using the appropriate relative changes from sections 2.0, 3.0, and 4.0 above. Finally, estimates are provided in Section 5.3, of the change in recurrence interval associated with current peak flow magnitude estimates. The results of this portion of the assessment will be used by the Channel Module analyst to evaluate the significance of any estimated changes in peak flows to flooding, scour, and sediment transport within and among HAUs.

5.1 ESTIMATED BASELINE PEAK FLOW MAGNITUDES

Baseline peak flow magnitudes for the Q_2, Q_5, Q_{10}, Q_{25}, Q_{50}, and Q_{100} events were estimated for each HAU (including upstream drainage area) using the following regional equations developed by Waananen and Crippen (1977) for the North Coast Region of California:

$$Q_2 = 3.52\ A^{0.90}\ P^{0.89}\ H^{-0.47} \qquad \text{(Equation \#18)}$$

$$Q_5 = 5.04\ A^{0.89}\ P^{0.91}\ H^{-0.35} \qquad \text{(Equation \#19)}$$

$$Q_{10} = 6.21\ A^{0.88}\ P^{0.93}\ H^{-0.27} \qquad \text{(Equation \#20)}$$

$$Q_{25} = 7.64\ A^{0.87}\ P^{0.94}\ H^{-0.17} \qquad \text{(Equation \#21)}$$

$$Q_{50} = 8.57\ A^{0.87}\ P^{0.96}\ H^{-0.08} \qquad \text{(Equation \#22)}$$

$$Q_{100} = 9.23\ A^{0.87}\ P^{0.97} \qquad \text{(Equation \#23)}$$

Where **A** is drainage area in mi^2, **P** is mean annual precipitation in in., and **H** is an altitude index. The altitude index is computed by averaging the elevations of two points along the main stream channel located at 10 and 85% of the distance from the mouth of the HAU to the basin divide. The altitude index (**H**) is expressed in thousands of feet (e.g., 2,500' = 2.5), with a minimum value of 1.0. Values of **P** were calculated for each HAU (including upstream drainage area) using PRISM precipitation maps (discussed in Section 1.3). Values of **H** were calculated from USGS 7.5' quad maps. Values of **A**, **P**, and **H** used in equations #18 - #23 are given in Table 5-

1, along with estimated baseline peak flow magnitudes for the Q_2, Q_5, Q_{10}, Q_{25}, Q_{50}, and Q_{100} events.

Table 5-1: Estimated baseline peak flow magnitudes (cfs).

Sub-basin Name	HAU	HAU area (mi^2)	Mean ann. precip. (in)	Altitude index	Predicted peak flow (cfs) by recurrence interval									
					$Q_{0.25}$	$Q_{0.5}$	Q_1	Q_2	Q_5	Q_{10}	Q_{15}	Q_{25}	Q_{50}	Q_{100}
South Fork	SF1	1.00	67	1.29	38	69	108	131	211	288	325	380	474	543
	SF2	0.27	63.1	1	13	23	35	43	67	91	100	118	144	162
	SF3	1.43	65.5	1.2	55	96	152	184	291	395	440	514	637	726
	SF4	0.56	59.5	1	25	43	66	79	123	166	185	214	260	292
	SF5	3.13	61.1	1.035	118	205	312	376	580	769	860	978	1,195	1,345
Little Freshwater	LF01	0.53	54.8	1	22	38	58	70	109	146	161	189	229	257
	LF02	0.13	54.1	1	6	11	17	20	32	43	47	56	69	77
	LF03	1.18	54	1	47	77	117	142	220	293	320	374	455	510
	LF04	0.72	53	1	28	49	75	90	140	187	205	241	292	327
	LF05	2.08	53.5	1	76	130	197	235	362	480	525	609	740	830
	LF06	0.22	53	1	9	16	25	30	48	65	71	84	102	115
	LF07	2.37	53.5	1	86	147	222	264	406	537	590	682	828	928
	LF08	1.01	52.3	1	39	67	100	120	186	249	275	318	386	433
	LF09	3.85	52.9	1	128	220	333	405	620	815	910	1,030	1,251	1,401
	LF10	0.68	51.2	1	27	46	70	83	129	172	190	221	268	300
	LF11	4.68	52.6	1	160	270	405	480	732	962	1,050	1,212	1,472	1,650
Graham Gulch	GG1	0.43	65.6	1.055	21	37	56	67	106	143	160	187	229	258
	GG2	0.80	67.8	1.35	29	55	86	106	172	237	270	314	394	454
	GG3	1.60	65.3	1.135	63	110	172	209	328	442	485	572	705	800
	GG4	0.19	58.6	1	9	16	25	30	47	64	70	83	101	113
	GG5	2.52	61.6	1	98	171	261	316	487	646	724	821	1,000	1,122
Cloney Gulch	CL1	0.80	65.7	1.07	35	61	95	115	182	245	273	317	390	440
	CL2	0.42	64.6	1	20	35	55	66	103	139	155	180	220	247
	CL3	2.62	62.3	1	108	185	280	332	511	677	750	860	1,048	1,176
	CL4	1.81	63.4	1	78	134	203	241	372	495	545	631	769	864
	CL5	4.70	62.2	1	177	310	460	560	857	1,130	1,240	1,426	1,737	1,950
McCready Gulch	MG1	0.64	60.1	1	28	49	75	91	142	190	213	245	298	335
	MG2	0.39	57	1	17	29	46	55	87	117	130	151	184	206
	MG3	1.14	58.7	1	48	82	125	149	231	308	340	394	479	538
	MG4	0.28	54.6	1	12	21	33	40	63	85	94	110	133	149
	MG5	2.01	56.7	1	77	130	200	240	369	490	535	623	758	850
School Forest	SC1	0.20	51.9	1	9	15	23	28	44	59	66	77	93	105
	SC2	0.17	52.3	1	7	13	20	24	38	51	56	67	81	91
	SC3	0.60	51.1	1	23	40	61	74	116	155	172	199	242	271
Upper Mainstem	FC01	1.40	72.9	2.2125	35	70	118	150	256	365	420	505	663	794
	FC02	2.71	72.2	1.93	72	138	230	286	477	669	780	908	1,177	1,394
	FC03	0.50	71.4	1.79	15	30	51	64	108	153	177	210	270	318
	FC04	0.33	71	1.645	11	22	36	46	76	108	123	147	188	220
	FC05	3.55	72	1.875	91	172	290	368	612	852	980	1,151	1,488	1,759
	FC06	7.40	69.6	1.38	228	410	650	800	1,271	1,714	1,950	2,227	2,800	3,228
	FC07	0.85	61.7	1	38	65	99	119	185	248	270	319	388	436
	FC08	8.78	67.9	1.315	275	487	760	933	1,470	1,971	2,250	2,544	3,182	3,654
	FC09	12.64	65.3	1.185	425	730	1,100	1,314	2,036	2,695	3,050	3,429	4,246	4,833
	FC10	13.14	64.8	1.14	432	741	1,125	1,377	2,121	2,798	3,100	3,544	4,372	4,961
Mainstem	FC11	15.72	64.2	1.1025	540	920	1,380	1,629	2,496	3,277	3,650	4,128	5,077	5,745
	FC12	20.92	63.5	1.04	700	1,175	1,775	2,145	3,253	4,237	4,775	5,292	6,473	7,290
	FC13	25.77	61.4	1	865	1,425	2,120	2,558	3,850	4,987	5,475	6,189	7,538	8,459
	FC14	29.25	60.5	1	980	1,600	2,400	2,830	4,253	5,500	6,010	6,816	8,299	9,313
	FC15	30.76	59.9	1	1,040	1,710	2,510	2,935	4,407	5,695	6,250	7,054	8,587	9,635

No regional equations are available for calculating baseline peak flow magnitudes for the partial-duration series events (i.e., the $Q_{0.25}$, $Q_{0.5}$, and Q_1 events), nor for the Q_{15} event in the annual series. Langbein (1949) demonstrated that the $Q_{0.5}$, $Q_{0.9}$, Q_1, $Q_{1.45}$, and $Q_{2.0}$ events from the partial duration series can be approximated using flood magnitudes for the $Q_{1.16}$, $Q_{1.50}$, $Q_{1.58}$, $Q_{2.00}$, and $Q_{2.54}$ events, respectively, from the annual series[5]. This relationship identified by Langbein was extended to approximate the $Q_{0.25}$ event from the partial-duration series using the flood magnitude for the $Q_{1.02}$ event from the annual series.

Estimates of the magnitude of the $Q_{0.25}$, $Q_{0.5}$, Q_1, and Q_{15} events were obtained by first plotting the probabilities (i.e., 1/recurrence interval) for the Q_2, Q_5, Q_{10}, Q_{25}, Q_{50}, and Q_{100} events against flood magnitude values computed using equations #18 - #23 for each HAU (Table 5-1). When plotted on log-probability paper, these values plot as a straight line. Flood magnitudes for the $Q_{1.02}$, $Q_{1.16}$, $Q_{1.58}$, and Q_{15} events were then interpolated from the plot and used as estimates of the $Q_{0.25}$, $Q_{0.5}$, Q_1, and Q_{15} events, respectively. Estimated values computed for each HAU are included in Table 5-1.

5.2 ESTIMATED CURRENT PEAK FLOW MAGNITUDES

The procedure for estimating current peak flow magnitudes given in the PALCO methodology (PALCO 2000, page 49) is to sum all of the relative changes in peak flows for each HAU, and then to adjust the baseline peak flow values (i.e., Table 5-1) by the summation of all relative changes. The approach taken in this assessment differed in that only the relative changes associated with canopy interception/evapotranspiration loss (i.e., Section 2.0) were used to adjust baseline values. The results from Section 3.0, relative changes due to compacted areas, were not included in this section for two reasons. First of all, this analyst has lower confidence in the results of the Rational Method modeling than in the canopy interception/evapotranspiration loss modeling. Second, and more importantly, a certain amount of compaction due to roads, skid trails, etc. is inherently included in the Caspar Creek equations that have been modified for use in the PALCO methodology, and that formed the basis for the analysis in Section 2.0. In the 10 treatment watersheds in Caspar Creek, the area compacted (due to roads and harvesting methods) ranged from 2-9%[6]. In the Freshwater Creek Watershed HAUs, compaction ranges from 1-17%. Therefore, it is estimated that the equations used in the canopy interception / evapotranspiration

[5] Note that the meaning of recurrence interval is different for these two series. Recurrence interval for the annual series means the average time interval within which a peak of a given size will occur as an annual maximum, while recurrence interval for the partial-duration series is the average frequency of occurrence between floods of a given size irrespective of their relation to the year (Dunne and Leopold 1978).

[6] Based on the reported proportion of area in roads, landings, skid trails, and firelines for the ten North Fork Caspar Creek treatment watersheds (see http://www.rsl.psw.fs.fed.us/projects/water/TribTreat.html for details)

loss modeling already account for a large portion (up to approximately 50%) of any compaction effects.

The results from Section 4.0, relative changes due to road drainage, were not included because of: (1) the lower confidence of the Rational Method modeling as previously discussed; (2) the analysis was only completed for three of the 49 HAUs in the watershed; and (3) the results were conflicting with regard to the effect on peak flows.

Estimated peak flow magnitudes for current conditions are presented for the partial-duration series events in Table 5-2, and for the annual series in Table 5-3. Tables 5-2 and 5-3 present the estimated baseline peak flow value (from Table 5-1), followed by the estimated discharge under current conditions given average antecedent wetness conditions. The range of expected current discharge values, given the range of antecedent wetness values used in Section 2.0, is given in parentheses.

Table 5-2: Estimated peak flow magnitude for partial-duration series events by HAU (Note: HAUs include upstream contributing area).

Sub-basin Name	HAU	$Q_{0.25}$		$Q_{0.5}$		Q_1	
		Baseline	Current	Baseline	Current	Baseline	Current
South Fork	SF1	38	43 (40 - 52)	69	77 (72 – 93)	108	119 (112 - 144)
	SF2	13	13 (13 - 13)	23	23 (23 – 23)	35	35 (35 - 36)
	SF3	55	61 (58 - 74)	96	106 (100 - 126)	152	165 (156 - 198)
	SF4	25	31 (28 - 42)	43	51 (46 - 70)	66	77 (70 - 106)
	SF5	118	140 (128 - 183)	205	237 (218 - 310)	312	356 (326 - 465)
Little Freshwater	LF01	22	27 (24 - 36)	38	45 (41 - 61)	58	68 (61 - 92)
	LF02	6	7 (6 – 9)	11	13 (12 - 16)	17	19 (18 - 24)
	LF03	47	55 (51 - 71)	77	89 (81 - 114)	117	133 (122 - 171)
	LF04	28	35 (31 - 50)	49	60 (53 - 85)	75	90 (80 - 128)
	LF05	76	92 (83 - 124)	130	154 (139 - 207)	197	229 (207 - 308)
	LF06	9	11 (10 - 15)	16	19 (17 - 26)	25	29 (26 - 39)
	LF07	86	104 (94 - 141)	147	174 (157 - 234)	222	258 (234 - 347)
	LF08	39	48 (43 - 67)	67	81 (72 - 111)	100	118 (106 - 163)
	LF09	128	155 (140 - 209)	220	260 (235 - 349)	333	386 (350 - 519)
	LF10	27	29 (28 - 33)	46	49 (47 - 56)	70	74 (71 - 85)
	LF11	160	189 (173 - 249)	270	313 (286 - 410)	405	462 (424 - 604)
Graham Gulch	GG1	21	23 (22 - 28)	37	41 (38 - 49)	56	61 (58 - 73)
	GG2	29	33 (31 - 40)	55	61 (57 - 74)	86	94 (89 - 115)
	GG3	63	72 (67 - 89)	110	123 (115 - 153)	172	190 (178 - 236)
	GG4	9	10 (10 - 13)	16	18 (17 - 23)	25	28 (26 - 36)
	GG5	98	113 (105 - 142)	171	193 (180 - 243)	261	291 (271 - 365)
Cloney Gulch	CL1	35	41 (38 - 54)	61	70 (65 - 92)	95	108 (99 - 140)
	CL2	20	23 (21 - 30)	35	39 (37 - 51)	55	61 (57 - 78)
	CL3	108	127 (117 - 168)	185	213 (196 - 280)	280	318 (292 - 416)
	CL4	78	90 (84 - 115)	134	152 (141 - 192)	203	227 (211 - 287)
	CL5	177	207 (191 - 270)	310	356 (327 - 462)	460	520 (479 - 674)
McCready Gulch	MG1	28	32 (30 - 41)	49	55 (51 - 69)	75	83 (77 - 105)
	MG2	17	20 (18 - 25)	29	33 (30 - 42)	46	51 (48 - 66)
	MG3	48	55 (51 - 69)	82	92 (86 - 116)	125	138 (129 - 173)
	MG4	12	13 (13 - 17)	21	23 (22 - 29)	33	36 (34 - 45)
	MG5	77	87 (82 - 110)	130	145 (136 - 182)	200	220 (206 - 276)

Table 5-2: Estimated peak flow magnitude for partial-duration series events by HAU (Note: HAUs include upstream contributing area).

Sub-basin Name	HAU	$Q_{0.25}$		$Q_{0.5}$		Q_1	
		Baseline	Current	Baseline	Current	Baseline	Current
School Forest	SC1	9	10 (9 - 11)	15	16 (15 - 19)	23	24 (23 - 28)
	SC2	7	8 (7 - 10)	13	15 (14 - 19)	20	22 (21 - 28)
	SC3	23	25 (24 - 28)	40	42 (41 - 49)	61	64 (62 - 74)
Upper Mainstem	FC01	35	36 (35 - 38)	70	72 (71 - 75)	118	121 (119 - 127)
	FC02	72	76 (74 - 84)	138	144 (140 - 160)	230	240 (233 - 264)
	FC03	15	16 (15 - 17)	30	31 (30 - 33)	51	53 (52 - 56)
	FC04	11	12 (11 - 13)	22	23 (22 - 25)	36	37 (36 - 41)
	FC05	91	96 (93 - 106)	172	180 (175 - 198)	290	301 (294 - 331)
	FC06	228	243 (235 - 274)	410	433 (419 - 487)	650	682 (660 - 765)
	FC07	38	39 (38 - 40)	65	66 (65 - 68)	99	100 (99 - 103)
	FC08	275	293 (283 - 331)	487	514 (497 - 578)	760	798 (772 - 895)
	FC09	425	469 (445 - 558)	730	794 (755 - 943)	1,100	1,186 (1,128 - 1,405)
	FC10	432	476 (452 - 566)	741	806 (766 - 955)	1,125	1,213 (1,153 - 1,434)
Mainstem	FC11	540	599 (567 - 720)	920	1,007 (953 - 1,205)	1,380	1,496 (1,418 - 1,787)
	FC12	700	785 (739 - 961)	1,175	1,298 (1,222 - 1,582)	1,775	1,941 (1,829 - 2,359)
	FC13	865	980 (917 – 1,214)	1,425	1,587 (1,487 - 1,960)	2,120	2,335 (2,190 - 2,876)
	FC14	980	1,106 (1,037 - 1,365)	1,600	1,777 (1,668 - 2,184)	2,400	2,635 (2,476 - 3,232)
	FC15	1,040	1,170 (1,099 - 1,437)	1,710	1,893 (1,780 - 2,317)	2,510	2,749 (2,587 - 3,356)

Table 5-3. Estimated peak flow magnitude for annual series events by HAU (Note: HAUs include upstream contributing area).

Sub-basin Name	HAU	Q_2		Q_5		Q_{10}		Q_{15}	
		Base-line	Current	Base-line	Current	Base-line	Current	Base-line	Current
South Fork	SF1	131	146 (142 - 158)	211	227 (223 - 235)	288	301 (297 - 305)	325	332 (329 - 334)
	SF2	43	43 (43 - 43)	67	67 (67 - 68)	91	91 (91 - 91)	100	100 (100 - 100)
	SF3	184	202 (198 - 218)	291	311 (306 - 321)	395	410 (405 - 415)	440	449 (444 - 451)
	SF4	79	94 (90 - 108)	123	139 (135 - 148)	166	178 (174 - 182)	185	192 (189 - 193)
	SF5	376	435 (421 - 488)	580	641 (626 - 673)	769	815 (801 - 831)	860	887 (874 - 893)
Little Fresh-water	LF01	70	83 (80 - 95)	109	123 (119 - 130)	146	157 (154 - 161)	161	167 (164 - 168)
	LF02	20	23 (22 - 25)	32	35 (34 - 36)	43	46 (45 - 46)	47	48 (48 - 49)
	LF03	142	163 (158 - 182)	220	242 (236 - 253)	293	309 (304 - 315)	320	329 (325 - 332)
	LF04	90	110 (106 - 129)	140	161 (156 - 173)	187	204 (198 - 209)	205	214 (210 - 216)
	LF05	235	278 (268 - 316)	362	406 (395 - 429)	480	513 (502 - 524)	525	544 (535 - 548)
	LF06	30	36 (35 - 41)	48	54 (52 - 57)	65	69 (68 - 71)	71	74 (72 - 74)
	LF07	264	312 (301 - 355)	406	455 (443 - 481)	537	574 (563 - 587)	590	611 (601 - 616)
	LF08	120	144 (139 - 166)	186	211 (205 - 225)	249	268 (262 - 274)	275	286 (281 - 288)
	LF09	405	477 (460 - 542)	620	694 (675 - 733)	815	871 (853 - 889)	910	942 (927 - 949)
	LF10	83	88 (87 - 93)	129	134 (133 - 137)	172	176 (175 - 178)	190	192 (191 - 193)
	LF11	480	555 (538 - 623)	732	810 (790 - 850)	962	1,020 (1,001 - 1,039)	1,050	1,082 (1,067 - 1,090)
Graham Gulch	GG1	67	74 (72 - 79)	106	113 (111 - 117)	143	149 (147 - 151)	160	163 (162 - 164)
	GG2	106	118 (115 - 128)	172	185 (182 - 192)	237	247 (244 - 250)	270	276 (273 - 277)
	GG3	209	234 (228 - 256)	328	355 (348 - 369)	442	462 (456 - 469)	485	496 (491 - 499)
	GG4	30	34 (33 - 38)	47	51 (50 - 54)	64	67 (66 - 68)	70	72 (71 - 72)
	GG5	316	357 (347 - 393)	487	529 (519 - 551)	646	678 (668 - 688)	724	742 (733 - 746)
Cloney Gulch	CL1	115	133 (129 - 149)	182	200 (195 - 210)	245	259 (255 - 264)	273	281 (277 - 283)
	CL2	66	74 (72 - 82)	103	112 (110 - 117)	139	146 (144 - 148)	155	159 (157 - 160)
	CL3	332	381 (370 - 428)	511	562 (549 - 589)	677	715 (703 - 728)	750	772 (761 - 777)
	CL4	241	272 (265 - 301)	372	405 (397 - 423)	495	520 (512 - 529)	545	559 (552 - 563)
	CL5	560	642 (622 - 717)	857	941 (920 - 986)	1,130	1,192 (1,172 - 1,213)	1,240	1,275 (1,258 - 1,283)
McCready Gulch	MG1	91	101 (99 - 112)	142	153 (150 - 159)	190	199 (196 - 201)	213	218 (215 - 219)
	MG2	55	62 (61 - 69)	87	94 (92 - 98)	117	122 (121 - 124)	130	133 (132 - 134)
	MG3	149	166 (162 - 182)	231	248 (244 - 258)	308	321 (317 - 325)	340	347 (344 - 349)
	MG4	40	44 (43 - 48)	63	67 (66 - 69)	85	88 (87 - 89)	94	96 (95 - 96)
	MG5	240	267 (260 - 293)	369	397 (390 - 413)	490	511 (504 - 518)	535	547 (541 - 549)
School Forest	SC1	28	30 (29 - 32)	44	46 (45 - 47)	59	61 (60 - 61)	66	67 (66 - 67)
	SC2	24	27 (26 - 30)	38	41 (40 - 43)	51	54 (53 - 54)	56	57 (57 - 58)
	SC3	74	79 (78 - 83)	116	120 (119 - 123)	155	158 (157 - 160)	172	174 (173 - 174)

Table 5-3. Estimated peak flow magnitude for annual series events by HAU (Note: HAUs include upstream contributing area).

Sub-basin Name	HAU	Q_2		Q_5		Q_{10}		Q_{15}	
		Base-line	Current	Base-line	Current	Base-line	Current	Base-line	Current
Upper Mainstem	FC01	150	153 (152 - 156)	256	260 (259 - 262)	365	368 (367 - 369)	420	422 (421 - 422)
	FC02	286	299 (296 - 311)	477	492 (488 - 500)	669	680 (677 - 684)	780	787 (784 - 789)
	FC03	64	66 (66 - 68)	108	111 (110 - 112)	153	155 (154 - 156)	177	178 (178 - 178)
	FC04	46	47 (47 - 49)	76	78 (78 - 79)	108	109 (109 - 110)	123	124 (123 - 124)
	FC05	368	384 (381 - 399)	612	630 (625 - 639)	852	867 (862 - 871)	980	988 (984 - 990)
	FC06	800	845 (834 - 885)	1,271	1,318 (1,306 - 1,343)	1,714	1,750 (1,739 - 1,762)	1,950	1,971 (1,961 - 1,976)
	FC07	119	120 (120 - 122)	185	187 (186 - 188)	248	250 (249 - 250)	270	271 (270 - 271)
	FC08	933	985 (973 – 1,033)	1,470	1,525 (1,511 - 1,554)	1,971	2,013 (2,000 - 2,027)	2,250	2,275 (2,263 - 2,280)
	FC09	1,314	1,429 (1,402 - 1,534)	2,036	2,155 (2,125 - 2,218)	2,695	2,785 (2,757 - 2,815)	3,050	3,102 (3,077 - 3,114)
	FC10	1,377	1,496 (1,468 - 1,605)	2,121	2,245 (2,213 - 2,310)	2,798	2,891 (2,861 - 2,921)	3,100	3,153 (3,127 - 3,165)
Mainstem	FC11	1,629	1,781 (1,746 - 1,920)	2,496	2,652 (2,612 - 2,735)	3,277	3,393 (3,357 - 3,432)	3,650	3,717 (3,685 - 3,732)
	FC12	2,145	2,368 (2,316 - 2,571)	3,253	3,479 (3,422 - 3,600)	4,237	4,405 (4,352 - 4,461)	4,775	4,873 (4,825 - 4,894)
	FC13	2,558	2,847 (2,779 - 3,110)	3,850	4,142 (4,068 - 4,296)	4,987	5,201 (5,134 - 5,273)	5,475	5,597 (5,538 - 5,624)
	FC14	2,830	3,140 (3,067 - 3,422)	4,253	4,565 (4,486 - 4,731)	5,500	5,729 (5,657 - 5,805)	6,010	6,139 (6,077 - 6,168)
	FC15	2,935	3,247 (3,173 - 3,531)	4,407	4,721 (4,641 - 4,888)	5,695	5,926 (5,853 - 6,002)	6,250	6,380 (6,317 - 6,410)

5.3 ESTIMATED CHANGE IN RECURRENCE INTERVAL

Estimates were made of the changes in recurrence interval associated with the current modeled peak flow magnitudes. Change in recurrence interval is defined here as the current recurrence interval of the baseline $Q_{0.25}$, $Q_{0.5}$, Q_1, Q_2, Q_5, Q_{10}, and Q_{15} peak flow magnitudes. For example, the baseline Q_{15} peak flow magnitude for HAU SF1 is 325 cfs (Table 5-3). The estimated Q_{15} peak flow magnitude under current conditions is 332 cfs (for average antecedent wetness conditions; Table 5-3). The question here is what is the current recurrence interval of a peak flow having a magnitude of 325 cfs?

Estimates of the change in recurrence interval were obtained by first plotting current $Q_{0.25}$, $Q_{0.5}$, Q_1, Q_2, Q_5, Q_{10}, and Q_{15} peak flow magnitudes against the associated probability of each event on the same log-probability graph as the baseline peak flow magnitudes (both baseline and current peak flow magnitudes plot as straight lines on log-probability paper). The current probability of occurrence associated with the baseline peak flow values could then be interpolated from the graph. Estimates of the current recurrence intervals associated with baseline peak flow magnitudes are given for each HAU in Table 5-4. To continue with the example given above, we can see from Table 5-4 that the current recurrence interval of the baseline Q_{15} peak flow for HAU SF1 is currently estimated to be 13.2 years (i.e., a peak flow of 325 cfs, estimated to have occurred on average every 15 years under baseline conditions is now estimated to occur on average every 13.2 years). Change in recurrence interval is greater in the lower-frequency higher-magnitude events (e.g., Q_{15}) than in the higher-frequency lower-

Table 5-4: Estimates of the current recurrence intervals associated with baseline peak flow magnitudes, by HAU (all estimates are for average antecedent wetness conditions).

Sub-basin Name	HAU	$Q_{0.25}$	$Q_{0.5}$	Q_1	Q_2	Q_5	Q_{10}	Q_{15}
South Fork	SF1	0.23	0.44	0.9	1.8	4.3	8.9	13.2
	SF2	0.25	0.50	1.0	2.0	5.0	10.0	15.0
	SF3	0.23	0.44	0.9	1.8	4.4	9.0	13.3
	SF4	0.22	0.38	0.8	1.7	3.8	8.2	11.8
	SF5	0.23	0.40	0.8	1.8	4.0	8.5	12.3
Little Freshwater	LF01	0.22	0.39	0.8	1.7	3.9	8.2	11.9
	LF02	0.23	0.42	0.8	1.8	4.1	8.6	12.6
	LF03	0.23	0.41	0.8	1.8	4.1	8.5	12.5
	LF04	0.22	0.36	0.7	1.7	3.7	7.9	11.3
	LF05	0.22	0.39	0.8	1.7	3.9	8.3	11.9
	LF06	0.22	0.39	0.8	1.7	3.9	8.3	11.9
	LF07	0.22	0.39	0.8	1.7	3.9	8.3	11.9
	LF08	0.22	0.37	0.8	1.7	3.8	8.1	11.6
	LF09	0.22	0.39	0.8	1.7	3.9	8.3	12.0
	LF10	0.24	0.46	0.9	1.9	4.6	9.3	13.9
	LF11	0.23	0.40	0.8	1.7	4.0	8.5	12.3
Graham Gulch	GG1	0.23	0.44	0.9	1.8	4.4	9.0	13.4
	GG2	0.23	0.44	0.9	1.8	4.3	8.9	13.1
	GG3	0.23	0.43	0.9	1.8	4.3	8.8	12.9
	GG4	0.23	0.41	0.8	1.8	4.1	8.6	12.5
	GG5	0.23	0.42	0.8	1.8	4.2	8.7	12.8
Cloney Gulch	CL1	0.23	0.41	0.8	1.8	4.0	8.5	12.4
	CL2	0.23	0.42	0.8	1.8	4.1	8.6	12.6
	CL3	0.23	0.40	0.8	1.8	4.0	8.5	12.3
	CL4	0.23	0.42	0.8	1.8	4.2	8.7	12.7
	CL5	0.23	0.41	0.8	1.8	4.1	8.5	12.4
McCready Gulch	MG1	0.23	0.42	0.8	1.8	4.2	8.7	12.8
	MG2	0.23	0.42	0.8	1.8	4.1	8.6	12.6
	MG3	0.23	0.42	0.8	1.8	4.2	8.7	12.8
	MG4	0.23	0.43	0.9	1.8	4.3	8.8	13.0
	MG5	0.23	0.43	0.8	1.8	4.2	8.8	12.9
School Forest	SC1	0.24	0.46	0.9	1.9	4.6	9.2	13.7
	SC2	0.23	0.42	0.8	1.8	4.2	8.7	12.7
	SC3	0.24	0.46	0.9	1.9	4.6	9.3	13.9
Upper Mainstem	FC01	0.24	0.49	1.0	2.0	5.0	9.8	14.8
	FC02	0.24	0.47	0.9	1.9	4.8	9.5	14.3
	FC03	0.24	0.48	1.0	1.9	4.9	9.6	14.6
	FC04	0.24	0.48	1.0	1.9	4.8	9.6	14.4
	FC05	0.24	0.48	0.9	1.9	4.8	9.5	14.3
	FC06	0.24	0.47	0.9	1.9	4.7	9.4	14.1
	FC07	0.25	0.50	1.0	2.0	5.0	9.9	15.0
	FC08	0.24	0.47	0.9	1.9	4.7	9.4	14.1
	FC09	0.24	0.45	0.9	1.9	4.5	9.1	13.5
	FC10	0.24	0.45	0.9	1.9	4.5	9.1	13.5
Mainstem	FC11	0.23	0.44	0.9	1.8	4.4	9.0	13.4
	FC12	0.23	0.44	0.9	1.8	4.3	8.9	13.2
	FC13	0.23	0.43	0.9	1.8	4.3	8.8	13.0
	FC14	0.23	0.43	0.9	1.8	4.3	8.9	13.1
	FC15	0.23	0.44	0.9	1.8	4.3	8.9	13.1

magnitude events (e.g., $Q_{0.25}$) because the relationship between discharge and recurrence interval is non-linear, with the curve flattening out as frequency increases.

Estimates of the current recurrence intervals associated with baseline $Q_{0.25}$ peak flow range from 0.25 years (i.e., no change) in HAUs SF2 and FC07; to 0.22 years for HAUs LF01, LF04, LF05, LF06, LF07, LF08, LF09, and SF4; with a median value of 0.23 years (Table 5-4). Estimates of the current recurrence intervals associated with baseline $Q_{0.5}$ peak flow range from 0.50 years (i.e., no change) in HAUs SF2 and FC07; to 0.36 years for HAU LF04; with a median value of 0.43 years (Table 5-4). Estimates of the current recurrence intervals associated with baseline Q_1 peak flow range from 1.0 years (i.e., no change) in HAUs SF2, FC01, FC03, FC04, and FC07; to 0.7 years for HAU LF04; with a median value of 0.9 years (Table 5-4).

For the annual series, estimates of the recurrence intervals associated with baseline Q_2 peak flow range from 2.0 years (i.e., no change) in HAUs SF2, FC01, and FC07; to 1.7 years for HAUs LF01, LF04, LF05, LF06, LF07, LF08, LF09, LF11, and SF4; with a median value of 1.8 years (Table 5-4). As discussed in Section 2.4, HAUs FC10 through FC15 (Figure 1-4, Table 1-2) drain to those portions of Freshwater Creek that are prone to flooding of private, non-PALCO property, and peak flows from the annual series are of a magnitude large enough to cause overbank flooding within these flood-prone HAUs. Estimates of the recurrence intervals associated with baseline Q_2 peak flows for these flood-prone HAUs are 1.9 years in FC10, and 1.8 years in FC11-FC15 (Table 5-4).

Estimates of the recurrence intervals associated with baseline Q_5 peak flow range from 5.0 years (i.e., no change) in HAUs FC01, FC07, and SF2; to 3.7 years in HAU LF04; with a median value of 4.3 years (Table 5-4). Estimates of the recurrence intervals associated with baseline Q_5 peak flows for the flood-prone HAUs are 4.5 years in HAU FC10, 4.4 years in HAU FC11, and 4.3 years in FC12-FC15 (Table 5-4).

Estimates of the recurrence intervals associated with baseline Q_{10} peak flow range from 10.0 years (i.e., no change) in HAU SF2; to 7.9 years in HAU LF04; with a median value of 8.8 years (Table 5-4). Estimates of the recurrence intervals associated with baseline Q_{10} peak flows for the flood-prone HAUs are 9.1 years in FC10, 9.0 years in FC11, 8.9 years in FC12 and FC14-FC15, and 8.8 years in FC13 (Table 5-4).

Estimates of the recurrence intervals associated with baseline Q_{15} peak flow range from 15.0 years (i.e., no change) in HAUs SF2 and FC07; to 11.3 years in HAU LF04; with a median value of 12.9 years (Table 5-4). Estimates of the recurrence intervals associated with baseline Q_{15} peak flows for the flood-prone HAUs are 13.5 years for HAU FC10, 13.4 years for FC11, 13.2 for FC12, 13.0 years for FC13, and 13.1 forFC14 and FC15 (Table 5-4).

6.0 SUMMARY OF FINDINGS

6.1 HARVEST EFFECTS

Estimated relative increases in peak flows due to harvest-related changes in canopy interception/evapotranspiration loss (Section 2.0) are greatest in the high-frequency, low-magnitude events; and decrease with increasing event size. These results are consistent with the findings of the North Fork Caspar Creek study (summarized in Ziemer 1998), and are not unexpected given that the modeling methodology used in this analysis was based on the Caspar Creek results (i.e., Lewis et al. in press).

Among the 49 Hydrologic Analysis Units within the Freshwater Watershed, the estimated percent increase in the peak flow having a recurrence interval of 0.25 years ranges from 1% to 27% with a median value of 13% for average antecedent wetness conditions, 2% to 80% (median value of 42%) for minimum antecedent wetness conditions, and from 0% to 12% (median value of 6%) under maximum antecedent wetness conditions. [Note: although minimum and maximum wetness values help define the potential range of responses for individual storms, average wetness values likely provide the best overall estimate of peak flow changes.] Based on these modeling results, the peak flow that formerly occurred on average every 0.25 years (i.e., 4 times per year) is now estimated to occur from 0.25 (i.e., no change) to 0.22 years among the 49 HAUs (assuming average antecedent wetness conditions). The estimated percent increase in the peak flow having a recurrence interval of 0.5 years ranges from 0% to 23% (median value of 11%) for average antecedent wetness conditions, 2% to 74% (median value of 39%) under minimum antecedent wetness conditions, and from 0% to 9% (median value of 4%) under maximum antecedent wetness conditions. Based on these modeling results, the peak flow that formerly occurred on average every 0.5 years (i.e., twice per year) is now estimated to occur from 0.5 (i.e., no change) to 0.36 years among the 49 HAUs (assuming average antecedent wetness conditions). The estimated percent increase in the peak flow having a recurrence interval of 1 year ranges from 0% to 20% (median value of 10%) for average antecedent wetness conditions, 1% to 71% (median value of 37%) under minimum antecedent wetness conditions, and from 0% 7% (median value of 3%) under maximum antecedent wetness conditions. Based on these modeling results, the peak flow that formerly occurred on average every 1.0 years (i.e., once per year) is now estimated to occur from 1.0 (i.e., no change) to 0.7 years among the 49 HAUs (assuming average antecedent wetness conditions).

Among the 49 Hydrologic Analysis Units within the Freshwater Watershed, the estimated percent increase in the peak flow having a recurrence interval of 2 years ranges from 0% to 23% (median value of 11%) for average antecedent wetness conditions, from 1% to 43% (median value of 22%) under minimum antecedent wetness conditions, and from 0% to 17% (median value of 9%) under maximum antecedent wetness conditions. Based on these modeling results, the peak flow that formerly occurred on average once every two years is now estimated to occur from once every 2.0 (i.e., no change) to once every 1.7 years among the 49 HAUs (assuming average antecedent wetness conditions). The estimated percent increase in the peak flow having a recurrence interval of 5 years ranges from 0% to 15% (median value of 8%) for average antecedent wetness conditions, from 0% to 23% (median value of 12%) under minimum antecedent wetness conditions, and from 0% to 11% (median value of 6%) under maximum antecedent wetness conditions. Based on these modeling results, the peak flow that formerly occurred on average once every five years is now estimated to occur from once every 5.0 (i.e., no change) to once every 3.7 years among the 49 HAUs (assuming average antecedent wetness conditions). The estimated percent increase in the peak flow having a recurrence interval of 10 years ranges from 0% to 9% (median value of 4%) for average antecedent wetness conditions, from 0% to 12% (median value of 6%) under minimum antecedent wetness conditions, and from 0% to 6% (median value of 3%) under maximum antecedent wetness conditions. Based on these modeling results, the peak flow that formerly occurred on average once every ten years is now estimated to occur from once every 10.0 (i.e., no change) to once every 7.9 years among the 49 HAUs (assuming average antecedent wetness conditions). The estimated percent increase in the peak flow having a recurrence interval of 15 years ranges from 0% to 4% (median value of 2%) for average antecedent wetness conditions, from 0% to 5% (median value of 3%) under minimum antecedent wetness conditions, and from 0% to 2% (median value of 1%) under maximum antecedent wetness conditions. Based on these modeling results, the peak flow that formerly occurred on average once every 15 years is now estimated to occur from once every 15.0 (i.e., no change) to once every 11.3 years among the 49 HAUs (assuming average antecedent wetness conditions).

Peak flows from the annual series (i.e., those peak flows having a recurrence interval of 2 to 15 years in this assessment) are of a magnitude large enough to cause overbank flooding, the severity of the flooding generally increasing with increasing peak flow recurrence interval. Hydrologic analysis units FC10 through FC15 drain to those portions of Freshwater Creek that are prone to flooding of private, non-PALCO property. Within these flood-prone HAUs, the estimated percent increase in the peak flow having a recurrence interval of 2 years ranges from 9% to 11% for average antecedent wetness conditions, from 17% to 22% under minimum antecedent wetness conditions, and from 7% to 9% under maximum antecedent wetness conditions. Based on these modeling results, the peak flow that formerly occurred on average once every two years is now estimated to occur from once every 1.9 to once every 1.8 years among the flood-prone HAUs (assuming average antecedent wetness conditions). The estimated percent increase in the peak flow having a recurrence interval of 5 years within these flood-prone

HAUs, ranges from 6% to 8% for average antecedent wetness conditions, from 9% to 12% under minimum antecedent wetness conditions, and from 4% to 6% under maximum antecedent wetness conditions. Based on these modeling results, the peak flow that formerly occurred on average once every five years is now estimated to occur from once every 4.5 to once every 4.3 years among the flood-prone HAUs (assuming average antecedent wetness conditions). The estimated percent increase in the peak flow having a recurrence interval of 10 years within these flood-prone HAUs, ranges from 3% to 4% for average antecedent wetness conditions, from 4% to 6% under minimum antecedent wetness conditions, and from 2% to 3% under maximum antecedent wetness conditions. Based on these modeling results, the peak flow that formerly occurred on average once every 10 years is now estimated to occur from once every 9.1 to once every 8.8 years among the flood-prone HAUs (assuming average antecedent wetness conditions). The estimated percent increase in the peak flow having a recurrence interval of 15 years is 2% within the flood-prone HAUs for average antecedent wetness conditions, 2% to 3% under minimum antecedent wetness conditions, and 1% under maximum antecedent wetness conditions. Based on these modeling results, the peak flow that formerly occurred on average once every 15 years is now estimated to occur from once every 13.5 to once every 13.0 years among the flood-prone HAUs (assuming average antecedent wetness conditions).

6.2 COMPACTED AREA EFFECTS

Estimates of the effects of compacted areas (i.e., roads, skid trails, residential development, etc.) on streamflow were made using a Rational Method modeling approach (Section 3.0). Modeling was limited to peak flow events having a recurrence interval of 2, 5, and 10 years due to model and data availability constraints. Unlike the modeled results from Section 2.0 for relative changes due to harvest effects on canopy interception/evapotranspiration loss, the results from the compacted-area modeling were constant over the range of recurrence intervals. The estimated percent increase in peak flows having a recurrence interval of 2, 5, and 10 years ranged from 0% to 4% (median value of 2%) among all 49 HAUs within the Freshwater Watershed. The estimated percent change in peak flows within the flood-prone HAUs for peak flows having a recurrence interval of 2, 5, and 10 years was 1% for HAU FC10 and 2% for HAUs FC11-FC15.

The estimates of relative changes due to compacted areas from Section 3.0 were not included in the overall estimates of changes in peak flow magnitudes, or changes in recurrence interval summarized above, for two reasons. First of all, this analyst has lower confidence in the results of the Rational Method modeling than in the canopy interception/evapotranspiration loss modeling. Second, and more importantly, a certain amount of compaction due to roads, skid trails, etc. is inherently included in the Caspar Creek equations that have been modified for use in the PALCO methodology, and that form the basis for the estimated harvest effects presented above. It should also be noted that the estimated effects are well within the measurement errors of open channel flow.

6.3 ROAD DRAINAGE CONNECTIVITY EFFECTS

The connectivity of the road drainage system to the stream system was assessed in section 4.0 of this assessment. Information on road drainage connectivity was only available for PALCO lands within the watershed. The percent increase in the effective drainage network (i.e., length of connected ditches/length of stream; expressed as a percentage) ranged from 0% (i.e., no connected ditches) in 12 of the 49 HAUs to 23%, with a median value of 6%. The limited extent to which the road system is connected to the stream system in the Freshwater Watershed has resulted in a relatively small increase in the effective drainage density as compared to other locations such as the HJ Andrews forest in the Oregon Cascades where Wemple et al. (1996) found an estimated 21 to 50% increase in the effective drainage density, or two sub-basins in the Deschutes River watershed in the Washington Cascades where Bowling and Lettenmaier (1997) found the effective channel network density to have increased by 64% and 52% due to road construction.

Relative changes in peak flows due to connectivity of the road drainage system were also modeled using a Rational Method modeling approach. A primary simplifying assumption required to use this modeling approach was that road drainage ditches capture 100% of the water moving from upslope areas. Although this assumption has been shown to be valid in some locations (e.g., McGee 2000), it is probably wrong for the Freshwater Watershed, given the relatively deep soil profiles found in the area. The result is that the estimated effects on peak flows presented here are probably overestimates. The complexity of the analysis and time constraints limited the modeling effort to three of the HAUs with the highest percent increase in the effective drainage network. As with the compaction assessment, modeling was limited to peak flow events having recurrence intervals of 2, 5, and 10 years due to model and data availability constraints. Modeling results for HAU MG4 (the HAU with the greatest percent increase in the effective drainage network, 23%) showed a 1% increase in peak flows having recurrence intervals of 2, 5, and 10 years. Modeling results for HAU FC04 (15% increase in the effective drainage network) showed a 3% <u>decrease</u> in peak flows having recurrence intervals of 2, 5, and 10 years. Modeling results for HAU CL2 (15% increase in the effective drainage network) showed a 2% increase in peak flows having recurrence intervals of 2 and 5 years, and a 1% increase in peak flows having a recurrence interval of 10 years.

Based on this modeling, it appears that road drainage connectivity generally results in a slightly earlier rise to peak as compared to the historical condition. These results are consistent with current hypotheses on road drainage effects (e.g., Wemple et al. 1996). The value of the instantaneous peak flow, however, may be slightly higher or slightly lower than the historical condition, depending on whether the arrangement of connected road ditches serves to synchronize or desynchronize overall storm runoff. This interpretation is also consistent with what has been observed in empirical studies (e.g., King and Tennyson 1984).

The estimates of relative changes due to connectivity of the road drainage system to the stream system from Section 4.0 were not included in the overall estimates of changes in peak flow magnitudes, or changes in recurrence interval summarized above, for two reasons. First of all, this analyst has lower confidence in the results of the Rational Method as previously discussed, and because the analysis was only completed for three of the 49 HAUs in the watershed. Additionally, based on the analysis completed for the three HAUs discussed above, and consistent with current theory, road drainage connectivity can act to either increase or decrease the magnitude of a given peak flow. It should also be noted that the estimated effects are well within the measurement errors of open channel flow.

7.0 CONFIDENCE DISCUSSION

In the following discussion, various aspects of this report are evaluated qualitatively. These rankings of confidence refer to the ratio between the estimates in this report and truth. More relevant to an appraisal of the quality of this document would be a comparison to what information can be gleaned with the best available technology and currently available data. By that standard, confidence is considerably higher than stated below. It must also be kept in mind that the appraisals of other aspects of the environment contain equal or greater uncertainties. Consequently, the quality of these analyses are comparable to evaluations of the various natural resources under consideration. Nonetheless, the reasons for confidence or lack thereof are noted below.

Two approaches to evaluating the flood history of the Freshwater Watershed were presented in Section 1.5 of this report. The first approach used historic records from the Little River stream gage as a surrogate for the Freshwater Watershed. An evaluation was performed of the appropriateness of using the Little River gage record to represent conditions in the Freshwater Watershed. Although basin parameters for the watershed upstream of the Little River gage compare well with basin parameters for Freshwater, a comparison of anecdotal flood observations from Freshwater to the Little River record reveals that there are apparently many large events that occur in Freshwater that have no corresponding peak at the Little River gage. This lack of agreement is to be expected since the two watersheds are small enough for their peak flows to be affected by individual convective cells within a frontal system and far enough separated that it is unlikely that they would both be routinely affected by the same part of a weather system. The second approach used to evaluate flood history in the Freshwater Watershed was to develop a synthetic hydrograph from hourly rainfall records. Of the long-term records available in the area, the Eureka record provided the best data source to use for the Freshwater Watershed; however, the overall relationship was only fair. Confidence is moderate that the results of these two analyses accurately represent flood conditions in the Freshwater Watershed for any individual storm; however, confidence is high that taken together these two sources of information provide a reasonable approximation of long-term flooding trends in the watershed at a decadal scale.

Confidence is high that the equations developed to explain observed peak flow changes in the North Fork Caspar Creek study (i.e., Lewis et al. in press) are applicable to the Freshwater Watershed. The two watersheds are very similar with respect to the relevant basin characteristics. Soils in the Freshwater Watershed are primarily loam to clay loam, 30–70 in. deep, and are characterized for the Caspar Creek as clay loams, from 1 to 2 meters in depth (Henry 1998). Slopes in the Freshwater Watershed are gentler than in Caspar Creek;

approximately 82% of the watershed area of Freshwater has slopes <30% and 18% has slopes >30%, as compared to 35% and 65%, respectively, for Caspar Creek (Henry 1998). Rainfall in Freshwater averages 60 in. annually, as compared to 47 in. for Caspar Creek; in both watersheds, approximately 90% of the annual precipitation occurs from October through April. Elevations in Freshwater range from sea level to 2,850 ft, as compared to Caspar Creek where elevations range from 120 to 1,050 ft. Both watersheds are located primarily within the coastal redwood vegetation zone. Furthermore, using both systematic and random cross-validation techniques, Lewis et al. (in press) concluded that their model was not over-fitted to the developmental data. This ensures that its use in other similar areas is likely to yield accurate predictions of peak flows.

Confidence is variable for the quality of the input data used for modeling canopy interception/evapotranspiration loss, compaction effects, and road drainage effects. Confidence in the harvest information (location and extent) is high, while confidence in residual post-harvest canopy cover information is only moderate. Confidence is moderate in the soils data used to estimate runoff-coefficients for the compaction modeling; new soil surveys currently being completed by the NRCS will improve this information for future analyses. Confidence is high in the locations of road drainage ditches that deliver surface water to streams, as this was based on a 100% survey of the PALCO road system (PWA 1999). Confidence is low that the current GIS coverage accurately identifies the location and extent of all small streams in the watershed.

Confidence is low in the compacted area and road drainage modeling due to an overall lack of confidence by this analyst in the Rational Method model. However, the estimated effects are so low that it is unlikely that the true effects would appreciably alter the peak flow estimates based on interception and evapotranspiration losses alone. Results from these analyses are best used to prioritize road abandonment and "storm-proofing" activities among the 49 HAUs within the watershed.

Finally, confidence is moderate in the regional equations used to estimate baseline peak flow magnitudes. The lack of long-term streamflow records from within or adjacent to the Freshwater Watershed limit our ability to develop more accurate local equations. However, confidence in the baseline peak flow magnitudes affects the absolute value of a particular flow but has no effect on the estimated percentage increases attributed to forest management.

8.0 MONITORING RECOMMENDATIONS

Since this assessment has found that estimates of peak flow increases based solely on an equation adapted from the North Fork of Caspar Creek analysis (Lewis et al. in press) are adequate to describe changes due to forest management, they may become one of the tools used to manage PALCO lands in the Freshwater Watershed. Data collection should be focused on improving input to that equation. A field-sampling strategy should be developed to accurately estimate post-harvest residual crown closure over each Timber Harvest Plan (THP) as soon as the entire plan is completed. These estimates should be made to the nearest 5%, and Table 2-1 of this report could be revised to accommodate these more precise estimates. The Freshwater Creek database could be revised annually to incorporate these new data, as well as their associated THP completion dates. The updated information could then be used to reproduce new versions of Tables 2-3 and 5-4. These annual updates could be used to monitor trends in forest management effects on peak flows and as a guide to the scheduling of future harvest in the watershed.

Good stream gage records from within the watershed are also necessary to monitor flooding over time, and would also be important to developing more basin-specific estimates of peak flow magnitudes. Establishing new stations, or maintaining the existing stations, would involve the long-term commitment of considerable resources. Any long-term stations installed in the watershed should: (1) be located in a straight reach, (2) have a single control that governs all stages, (3) have a stable bed, and (4) have channel geometry that is either naturally or artificially made unchangeable.

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Appendix D

Freshwater Creek Watershed Analysis

Riparian Function Assessment

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The Freshwater Riparian Function Assessment was a collaborative effort both within this module and with other module teams. Kent Doughty of Duke Engineering & Services (DE&S) was the Assessment Team Leader. Dennis Halligan of Natural Resources Management (NRM) assisted on team coordination. DE&S completed the analysis and prepared the report in cooperation with Pacific Lumber Company, the Scientific Review Team (SRT), and the Freshwater Watershed Assessment Team. Frank Mileham of NRM provided Class I and II aerial photo interpretation and conducted much of the fieldwork including data collection for the detailed plot inventory. NRM also provided modeling expertise on the forest growth model CRYPTOS and prepared the GIS. The SRT was closely involved in the development and review of the Methods for the Watershed Assessment (PALCO 2000). John Peters (SRT member for the U.S. Fish and Wildlife Service [USFWS]) contributed the analysis for applying CRYPTOS model results to yield vertical canopy closure estimates. He also worked on compilation of the published LWD source distance recruitment curves.

EXECUTIVE SUMMARY

The Riparian Assessment provides quantitative information on the past, current, and future functional conditions within riparian forests of the Freshwater basin. The pre-European forest condition in the Freshwater was redwood – fir forests except for within ½ mile of Three Corners and the uppermost portion of upper Freshwater Creek. Today's riparian condition reflects a harvest history of intensive clearcut logging approximately 70 years ago. Riparian stands within most of the Freshwater are densely stocked with medium to large conifers; the quadratic mean diameter is in excess of 20 in. for 75% of the streambank length in the basin.

Mixed stands of redwoods and hardwoods occupy 10% of the total streambank length in the basin. Mixed stands are more prevalent along Class I streams, especially in lower Freshwater Creek; there are almost no hardwoods along Class II streams. Forest growth models were used to document that stands with a significant hardwood component will not provide functional LWD to the adjacent streams during the next 40 years or more unless silvicultural practices target a conversion to conifer dominance. Areas naturally vegetated with hardwoods and areas influenced by development may limit the feasibility for conversion. Hardwood inclusion stands can provide substantial nutrient sources to stream productivity, and the amount of hardwoods in the Freshwater is not so extensive as to pose a risk to basin channel stability and channel structure.

Harvesting within the last 25-30 years has limited the near term LWD recruitment potential for 10% of both Class I and Class II streambank length. In most of these areas, partial harvest occurred such that trees are available for recruitment but not in quantities or sizes considered functioning. While short-term LWD recruitment is limited, model results confirm that these stands are expected to provide suitable long-term recruitment potential within the next 20 – 40 years.

The size of key piece wood that functions in a stream channel is proportionate to the size of the channel. The stocking density for the majority of riparian stands in the Freshwater provides good recruitment potential for functional LWD. A continuous supply of LWD can be expected to maintain the amounts of existing in-channel LWD, which currently exceed PFCM targets, except along the lower mainstem Freshwater Creek where wood of all sizes is transported out of basin. Suppression mortality within redwood-dominated stands is a relatively minor component of wood recruitment. Bank erosion, historical disturbance, disease, and breakage generally account for a greater proportion of LWD than suppression.

Elevated summer temperatures due to riparian management within the Freshwater basin do not pose an adverse condition for salmonids and other cold water biota. Within the Freshwater basin, field measured and modeled canopy closure estimates are high; canopy cover over the channel is generally high; most of the basin is affected by a cool marine fog climate regime; and summer water temperatures are cold.

RECOMMENDATIONS

Harvest opportunities exist within the default ACP riparian RMZs while helping to achieve or maintain properly functioning conditions for riparian forests in the Freshwater basin. CRYPTOS was used to model riparian forest stand growth over a 40-year period. Riparian stands in the Freshwater basin are mostly even-age owing to extensive harvest about 70 years ago. The pre-dominant and dominant crown layers are comprised of relatively few larger residual trees pre-dating the last major harvest entry. The majority of trees occur in the co-dominant and intermediate crown positions. A selective reduction of the basal area within these two crown layers will accelerate diameter growth of the intermediate and suppressed crown layers. Conifers in these lower layers will therefore more quickly attain key piece size thereby maintaining LWD recruitment potential.

It is recommended that application of plot data collection in future watersheds focus on riparian types not found in the Freshwater but common elsewhere. Replication in other basins of plot data within stand types listed in the consolidated stand types for the Freshwater Assessment will ensure that comparisons are appropriate and increase the data robustness. Prescriptions can then be developed that are both specific to on-site conditions and consistent among watersheds.

The ACP includes an expansion of the riparian management zone width where slopes adjacent to the riparian area exceed 50% so that LWD recruitment opportunities and wood functions relative to mass wasting are accommodated into riparian management. The role of mass wasting as a wood source to the stream and the function of root strength in minimizing mass wasting vary dependent upon site conditions. It is recommended that the methods for watershed analysis be reviewed so that these interactions can be accommodated within Synthesis discussions. It may not be necessary in many areas to include the steep slopes expanded width within the riparian assessment area for watershed analysis. Those areas where there is a important relationship between mass wasting and LWD recruitment/function can best be addressed in Synthesis discussions, thereby pinpointing locations within a basin where this is an important consideration. The Assessment Team’s evaluation can then be included in the Causal Mechanism Reports.

It is recommended that existing temperature data for the region be evaluated to develop nomograph relationships based on mapping attributes. Emphasis should be placed on areas outside of the coastal fog zone. Verifying the regional stream length necessary for a stream to reach equilibrium is also recommended. Sullivan et al. (1990) concluded that small streams come to equilibrium with ambient conditions within distances of 1,000 to 3,000 ft and that the equilibrium distance is a function of stream size.

Collecting additional information on the longevity of downed wood, particularly LWD protruding into the channel, is recommended.

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1.0 INTRODUCTION

There are three primary objectives of the Riparian Function Module:

1. Determine existing riparian stand structure and composition and its potential to provide Properly Functioning Conditions (PFCs) for riparian forests and buffers, including overstory tree canopy closure, adequate supplies of functional and key piece large woody debris (LWD) to streams and the riparian forest floor, functional riparian snags, riparian forest floor organic material, streambank stability, desired stream temperature regimes, and, in general, the functions of late successional forest habitat.

2. Contribute to an ongoing improved knowledge of properly functioning stand requirements.

3. Determine riparian situations where silvicultural activities are compatible with or will help achieve or maintain PFCs for riparian forest and buffers.

This report describes the results of the riparian assessment for the Freshwater basin. This basin encompasses 32 mi^2 with the mouth of Freshwater Creek draining into Humboldt Bay after flowing through Freshwater and Eureka sloughs. Approximately 77% of the watershed is owned by Pacific Lumber Company (PALCO) and managed for timber production.

This assessment is specific to Freshwater; however, it is PALCO's intention to use riparian stand data collected in the Freshwater basin along with similar data for other watersheds to characterize riparian stand types typical across the land base affected by the PALCO HCP/ACP.

The reviewer is referred to the Methods to Complete Watershed Analysis on Pacific Lumber Company Lands in Northern California (PALCO 2000), for a detailed discussion of methods used in this assessment. Methods are only summarized within the assessment report. All modifications to the methods contained in PALCO (2000) are described.

The Freshwater Riparian Assessment is a Level II assessment with the exception that current riparian conditions for Class III streams were only assessed based on aerial photo interpretation (Level I method). The Level II assessment includes both aerial photo interpretation of riparian stand conditions and field verification. Supplemental methods used in this assessment include detailed stand inventories and modeling of future riparian stand growth. Riparian areas with similar existing conditions and factors affecting the probability of achieving and/or maintaining PFCs are grouped into riparian situations.

2.0 CRITICAL QUESTIONS

The following critical questions are designed to help guide the Riparian Function Assessment and produce the information necessary for the Assessment Team to understand the riparian characteristics and processes within the watershed:

- What is the historical distribution of riparian forest types?
- What is the current condition of the riparian zone relative to its ability to function properly (as initially defined by the National Marine Fisheries Service [NMFS] in the PFC Matrix or as later modified based on the results of Watershed Analysis)?
- Where riparian forests are not currently functioning properly, in what situations could recovery to PFCs be accelerated through silvicultural activities?
- Where riparian forests are currently functioning properly, what silvicultural activities are compatible with maintenance of these PFCs?
- What riparian areas are unlikely to ever function properly (e.g., roads, naturally sparse areas, and development)?
- How do the properly functioning habitat conditions for riparian forest buffers (as defined by NMFS in the PFC Matrix; Attachment D-1) compare to existing local conditions for late successional forest habitat characteristic of historical riparian forests?
- What is the existing and pre-settlement hardwood component of riparian stands within Class I sub-basins?

3.0 ASSUMPTIONS

Several assumptions form the foundation for the Riparian Function Assessment. These assumptions are based on the best available information from the scientific literature on how riparian ecosystems function. Defining these assumptions at the onset of Watershed Analysis fosters a shared perspective among participants.

3.1 GENERAL

- Riparian forest stand development pathways are dependent upon the species composition and disturbance regimes. Within ecological vegetation zones, stand conditions are also influenced by the stand's landscape position within a watershed.

- The PFC Matrix is based on a premise that large wood recruited to channels will yield greater benefits than small wood in maintaining the geomorphic and biological function.

- Riparian buffers at least 170 ft wide for Class I streams or 130 ft for Class II streams and meeting the criteria of the PFC Matrix provide sustainable LWD to the channel and the forest floor as well as most, if not all, riparian functions. (Functionality may be provided by less dense stands or within a narrower area than the assessment width.) Wood may be recruited to the channel from distances beyond 170 ft where mass wasting acts as a recruitment mechanism.

- A riparian forest stand capable of providing sufficient, sustainable, and functional LWD including key pieces also provides sufficient fine organic matter and litter, assuming minimal ground disturbance within the functional riparian width.

- Forest practices can affect stand species composition, density, tree size regimes, structural character, and the rate of stand development.

3.2 LWD RECRUITMENT

- Channel morphology is strongly influenced by LWD (Keller and Swanson 1979), particularly in low-gradient, unconfined stream reaches (Montgomery and Buffington 1993).

- The probability of a tree falling into the channel diminishes with distance from the channel (Murphy and Koski 1989, McDade et al. 1990, Reid and Hilton 1998, McKinley 1997).

- LWD recruitment and depletion rates may vary considerably due to the dependence on episodic events, but over time can be described by average annual rates within similar stand development and stand management conditions.

- Hardwood-dominated riparian stands are not capable of supplying sufficient long-term LWD inputs to the stream channel but may provide other riparian functions.

- The size of key piece and functional LWD varies with stream size; LWD must be larger to remain functional in larger channels.

- The stability of LWD on the riparian forest floor is greater than within the stream channel.

3.3 CANOPY COVER AND STREAM TEMPERATURE

- Forest practices may influence stream temperature regimes directly by reducing riparian canopy cover through harvest or indirectly through mass wasting processes (Sullivan et al. 1990).

- Forest practices may influence riparian microclimate regimes that, in turn, influence stream temperature (Sullivan et al. 1990).

- Air temperature, and to a lesser extent relative humidity, strongly influences water temperature; hotter areas have higher stream temperature regimes.

- Small tributaries may significantly influence water temperature in their receiving streams if they are large enough (on the order of 20% of the combined flow) (Caldwell et al. 1991). Lesser flows may influence thermal refugia within highly localized stream environments at the point of inflow (Adams and Sullivan 1990).

- Stream temperature can both warm up and cool down along its course due to the amount of canopy cover, water depth, and microclimate. By the time a free-flowing stream has traveled a regionally specific distance (or farther) under relatively uniform canopy closure, water temperatures will be in equilibrium with local environmental conditions. In the Pacific Northwest, this distance has been found to be on the order of 1,000 to 3,000 ft (Sullivan et al. 1990); a similar distance to reach equilibrium is assumed for northern California streams since the same principles of heat transfer apply.

- When riparian canopy cover levels are below target levels, maximum water temperature standards may be exceeded. Microclimate can either increase or decrease the maximum equilibrium water temperature.

- The distance over which a free-flowing stream reaches equilibrium is inversely proportionate to average water depth (Adams and Sullivan 1990).

- As channel width increases, the ability of riparian shade to moderate water temperatures diminishes.

- Canopy closure (within the riparian forest as measured with a spherical densiometer) of at least 85% is assumed to provide the stream with thermal protection.

- Maintaining a maximum weekly average temperature (MWAT) of no more than 16.8^{o}C protects cold-water aquatic biota (Brungs and Jones 1997).

4.0 ASSESSMENT AREA

The Freshwater Riparian Function Assessment evaluates riparian functions for lands within 170 ft and 100 ft (slope distance) on either side of the bankfull channel or channel migration zone (CMZ) for all Class I and Class II waters, respectively. A 100-ft assessment zone was established for Class II waters in order that plot data for Class I and Class II streams would be comparable. The assessment area along Class I streams was subdivided into inner band (0-100 ft) and outer band (100–170 ft). The riparian condition on near bank (0-30 ft) was distinguished in detailed plot inventories.

Areas within 100 ft adjacent to Class III streams are also included as a Level I assessment of existing stand type with no field verification as to either stand condition or the completeness of the Class III drainage network.

The Channels Assessment Team concluded that there were no mappable CMZs on PALCO lands within the Freshwater basin. Therefore, the assessment area was not laterally expanded. A width expansion to include areas with steep slopes (>50%) adjacent to the riparian assessment area described above was not incorporated into this assessment. A discussion of the interaction of steep slopes, mass wasting potential, and subsequent wood recruitment to the channel occurred during Synthesis. The Mass Wasting Report (Appendix A) includes an estimate of the order of magnitude recruitment potential of wood from upslope mass wasting. The Stream Channels Module (Appendix E) includes a synthesis analysis of the estimated LWD recruitment from small streambank slumps. Mass wasting was not found to be a primary recruitment mechanism of wood to Class I and II channels in the Freshwater drainage. Therefore, an expansion of the riparian assessment area to include the steep slope provision of the ACP is not necessary to assess riparian functions within the context of watershed analysis for the Freshwater basin. This statement regarding the assessment area neither negates nor supports the steep slope provision of the ACP regarding RMZ widths. It is only concluding that the steep slope provision needs to be evaluated on a site-specific basis relative to mass wasting potential.

5.0 METHODS

The methods for the Riparian Function Assessment are fully described in Methods to Complete Watershed Analysis on Pacific Lumber Company Lands in Northern California PALCO (2000). In summary, background information on historical and current riparian vegetation patterns and the land use practices affecting those patterns was compiled. Future stand conditions were modeled. The assessment relies on both aerial photo interpretation and field investigations.

5.1 AERIAL PHOTO INTERPRETATION OF RIPARIAN STAND CONDITION

Aerial photos analysis for the Freshwater Riparian Function Assessment primarily utilized 1997 color 1:12,000 photos. Older photos were referenced to verify the approximate average age of trees in riparian stands affected by harvesting within the photo history period. Historical photo years included 1994, 1987, 1974, 1966, and 1947. The assessment area for Class I and II streams was divided into an inner band (0–30 ft horizontal slope distance perpendicular to the stream); the next horizontal band extended from 30 ft from the bankfull edge to a distance of 100 ft. These two bands were only distinguished during detailed plot field inventories; the aerial photo interpretation categorized riparian type for the inner 0–100 ft). The outer band extended from 100 ft to 170 ft. This outer band was only assessed for Class I streams. The analyst consulted with the Fisheries Assessment Team so that stream sections originally mapped as Class II but found to be inhabited by fish were assessed for the entire 170 ft on either side of the channel. The riparian condition was distinguished for each side of the channel for Class I and II streams.

The riparian conditions within 100 ft adjacent to each side of Class III streams were also typed based on aerial photo interpretation. These interpretations were not field verified. The assessment area on Class III streams was expanded to 100 ft on either side of the channel since the results of the Amphibian Assessment were not available until Synthesis, but it was recognized that the Class II/III boundaries as initially located on base maps were subject to change based on the results of Watershed Analysis. Inclusion of up to 100 ft on either side of the mapped Class III streams provides similar information for Class III streams as collected for Class II streams. In the event that amphibians are found on streams previously not known to support amphibian populations, the Synthesis discussions of riparian function are not limited by the assessment area. The riparian condition was rarely different from side to side of these small streams. Therefore, the riparian condition was not distinguished for individual streambanks for Class III streams.

Based on aerial photo interpretation, Riparian Channel Units (RCU) are delineated. Each RCU represents the smallest linear segment of riparian classification except for individual field plot data. An RCU is the riparian area adjacent to one bank of a stream reach where the riparian vegetation is similar for stand type, dominant tree size class, and density. Anomalies and/or longitudinal variability for vegetation may exist within an RCU when generalization is necessary to create coherent mapping units. For example, redwoods may be interspersed with small groups of hardwoods along a stream segment; however, a single RCU depicting mixed species may be sufficient to characterize the reach as a whole. Generally, an RCU is no less than 1,000 ft in length, except where sharply contrasting differences affect LWD recruitment; minimum length may be as short as 200 ft. The numbering scheme used for identifying RCUs was based on the Channel Assessment's numbering scheme to facilitate Synthesis discussions. The end points for RCUs sharing the same channel identifier number were adjusted to coincide with the end points or nodes for the channel classification (i.e., a single channel segment may correspond to one or more RCUs, but the end points for each will match).

The riparian condition for each RCU was characterized according to criteria for the California Wildlife Habitat Relationships (CWHR) System (Mayer and Laudenslayer 1988; Garrison et al. 1996). See Tables 5-1 and 5-2.

Table 5-1: CWHR standards for tree size.

CWHR	CWHR Size Class	Conifer Crown Diameter	Hardwood Crown Diameter	Diameter at Breast Height (dbh)
1	Seedling Tree	N/A	N/A	<1”
2	Sapling Tree	N/A	<15’	1-6”
3	Pole Tree	<12’	15-30’	6-11”
4	Small Tree	12-24’	30-45’	11-24”
5a	Medium/Large Tree	24-30’	>45’-50’	24-30”
5b	Large Tree	>30’	>50’	>30”
6	Multilayered	Size class 5 trees over a distinct layer of size class 4 or 3 trees; total canopy exceeds 60% closure.		

Table 5-2: CWHR standards for canopy closure.

CWHR	CWHR Closure Class	Crown Closure
S	Sparse Cover	10-24%
P	Open Cover	25-39%
M	Moderate Cover	40-59%
D	Dense Cover	60-100%

The dominant species within each RCU was also noted. As an example, a redwood-dominated stand where most of the trees are 12–24 in. dbh and the crown closure exceeds 60% would be characterized as RDW4D. Dominant species were not identified for hardwood dominated stands; these were simply noted as hardwood (HWD). Similarly, mixed stands of redwoods and hardwoods were identified as either RDW/HWD or HWD/RDW, depending on species dominance.

Both reconnaissance field surveys and detailed stand inventory methods were applied. The reconnaissance surveys served to visually verify the categories of stand conditions designated by the aerial photo interpreter. Since road access is generally good throughout the basin, more than 50% of the Class I and II riparian stands were visually inspected.

5.2 DETAILED PLOT INVENTORIES

The detailed inventories consisted of data collection within multiple 1/10-acre plots. Plot inventory methods are described in the watershed methods report (PALCO 2000). Data on species, diameter, and height were recorded for all standing trees. Dimensions and decay condition of all snags with a diameter of at least 10 in. dbh were noted. The number of pieces of downed wood (minimum diameter 10 in. at larger end) within each plot was also recorded. The direction of fall and cause of mortality for each piece of downed wood was noted where it could be distinguished. The plots were distributed among the various riparian stand types identified during the photo analysis, as well as distributed throughout the basin. An effort was made to locate riparian plots along stream reaches where instream habitat conditions were being field inventoried by the Fisheries Assessment Team. This approach provided a complete inventory of the riparian/aquatic conditions at these sites.

5.3 ANALYTICAL METHODS

The hand-delineated map of RCUs was digitized and data entered into a Geographic Information System (GIS). The stream length associated with each RCU was computed by the GIS. Data for RCUs were then exported from GIS to a spreadsheet for analysis. Consolidation of CWHR riparian typing was necessary to develop interpretations of riparian conditions meaningful to prescriptions and management. The approach for this consolidation is discussed in the results section of this report.

The detailed plot data were analyzed to characterize average conditions within each of the A, B, and C groups of data (these groups designate horizontal plot distance from the stream's edge as described later). Data were also analyzed according to groupings of adjacent stream gradient to determine if the latter affected riparian conditions in a discernable trend. Plot data were also compiled according to the CWHR classification assigned to the RCU encompassing each plot.

The compiled plot data were then applied to a forest stand growth model to predict future growth patterns of the riparian stands within the Freshwater drainage. The forest growth model used was CRYPTOS (Wensel et al. 1987). The Cooperative Redwood Yield Project Timber Output Simulator is a young-growth redwood and Douglas-fir growth model created as a product of a research cooperative between the University of California, Berkeley and six major northcoast industrial forest landowners. This will be the model primarily relied upon for modeling future stand growth within most of the HCP lands subject to this optional and supplemental Level II Watershed Analysis procedure. CRYPTOS was designed specifically to model changes that take place in the forest types of the north coastal region of California. This model is based on data from Mendocino, Humboldt, and Del Norte counties. It is the only widely used and recognized growth model for young-growth redwood. It is accepted by the California Department of Forestry for growth projections on Northern California coastal forestlands.

6.0 RESULTS FOR RIPARIAN STAND CONDITIONS AND LWD FUNCTIONS

6.1 HISTORICAL RIPARIAN VEGETATION REGIMES AND LAND USE EFFECTS

Redwood, (*Sequoia sempervirens*), is endemic to the western United States, restricted to approximately 725 linear kilometers (km) of coastal forest in California and extreme southern Oregon. It ranges inland up to 72 km but generally no farther than 50 km from the coast, mirroring the extent of the coastal fog belt (Johnston 1994, Ornduff 1998). It is the dominant tree species within much of this area, but does not form the sort of continuous distribution characteristic of more widespread conifers (Johnston 1994). Other important tree species in this area include Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), western hemlock (*Tsuga heterophylla*), Sitka spruce (*Picea sitchensis*), tanoak (*Lithocarpus densiflorus*), and Pacific madrone (*Arbutus menziesii*) (Olsen et al. 1990, Ornduff 1998). Redwood plant communities are prevalent throughout most of the Freshwater basin.

Sequoia sempervirens "almost without exception" sprouts from the root crown, trunk, or stump following damage or harvest (Rydelius and Libby 1993). Olsen et al. (1990) cite work that examined 163 second-growth stands and found the majority of stems originated from sprouts. These sprouts represent the same genetic individual as the original tree, potentially maintaining an individual through multiple turnover of stems (Rydelius and Libby 1993, Viers 1996). Five or more root crown sprouts forming a ring around a stump is not unusual, with each sprout forming its own root system over time (Olsen et al. 1990). Sprouts are generally considered to form strong trees, and can grow to near 2 m high in their first year, giving them an advantage over competitors, including *S. sempervirens* seedlings produced via sexual reproduction (Olsen et al. 1990, Rydelius and Libby 1993, Ornduff 1998). However, there is some suggestion that trees formed from sprouts may be less wind-firm than those germinated from seed (Johnston 1994).

Redwood is a monoecious species with separate male and female flowers that reaches reproductive age in 5 to 15 years (Olsen et al. 1990). For unknown reasons, *S. sempervirens* often exhibits low (1-3%) seed viability. Seeds from older trees are more likely to be viable. Seed crops are strongly inconsistent in their timing and distribution, with some areas completely lacking for years at a time (Muelder and Hansen 1961, Olsen et al. 1990, Ornduff 1998). Although seed viability is relatively low, redwood seedlings are capable of colonizing flood-swept areas provided competition from other plant species is not severe.

Although viable seeds germinate well in most situations, redwood seedling establishment in undisturbed, mature stands is poor to nonexistent. Seedlings are generally killed by moisture stress (the seedlings lack root hairs) or soil-borne pathogens (Florence 1965, Schubert and Adams 1971, Rydelius and Libby 1993, Olsen et al. 1990, Ornduff 1998). Seeds that germinate in disturbed or otherwise exposed soils fare better; indeed, most observers note that redwood seeds must germinate on soils disturbed by fire or harvest to become established as seedlings (Cooper 1965, Florence 1965, Rydelius and Libby 1993, Olsen et al. 1990, Ornduff 1998). Once established, redwood seedlings grow can grow at a prodigious rate (46 cm annually, and 2 m annually as saplings) under good or moderate conditions (Olsen et al. 1990). Under less ideal conditions, they can remain in a suppressed state for many years, often dying back and resprouting multiple times (Olsen et al. 1990).

The pre-European forest condition in Freshwater was redwood – fir forests except for within ½ mile of Three Corners and the uppermost portion of upper Freshwater Creek (Figure 6-1). The very lowest portion of the basin consists of grass tide flats. Tidal flooding and wind born high salt spray aerosols have probably always prevented redwoods from establishing in the very lowest portion of the watershed. Currently, the portion of the Freshwater basin within about ½ mile of Three Corners and downstream is part of the coastal prairie-shrub mosaic characterized by *Baccaris* sp., *Danthonia* sp., and *Festuca* sp. Sitka spruce and Douglas-fir both salt spray tolerant species, were likely more prevalent along the edge of the tidal zone as forests quickly transitioned to redwood–fir plant communities. Redwoods are the dominant species throughout the watershed for both current and historical (pre-European) forests for almost the entire Freshwater drainage; redwoods probably accounted for about 70% overstory canopy closure for old-growth forests (Zinke 1988). Douglas-fir, grand-fir, and hemlock are other common conifer species of this plant community and contribute another 15% overstory canopy. Total overstory canopy for old-growth redwood forests typically does not exceed 85% when averaged over stands. Common understory plants of this plant community include *Polystichium munitum, Vaccimium ovatum,* and *Vacinium parviloium*.

Based on an elevational vegetation transect survey by Zinke (1988) in northern Humboldt County, it is probable that the highest elevations in the upper Freshwater sub-basin were historically Douglas-fir - tanoak plant communities (Figure 6-1). Douglas-fir and tanoak are the most prevalent tree species within this plant community; madrone may also occur. The existing vegetation is consistent with this interpretation.

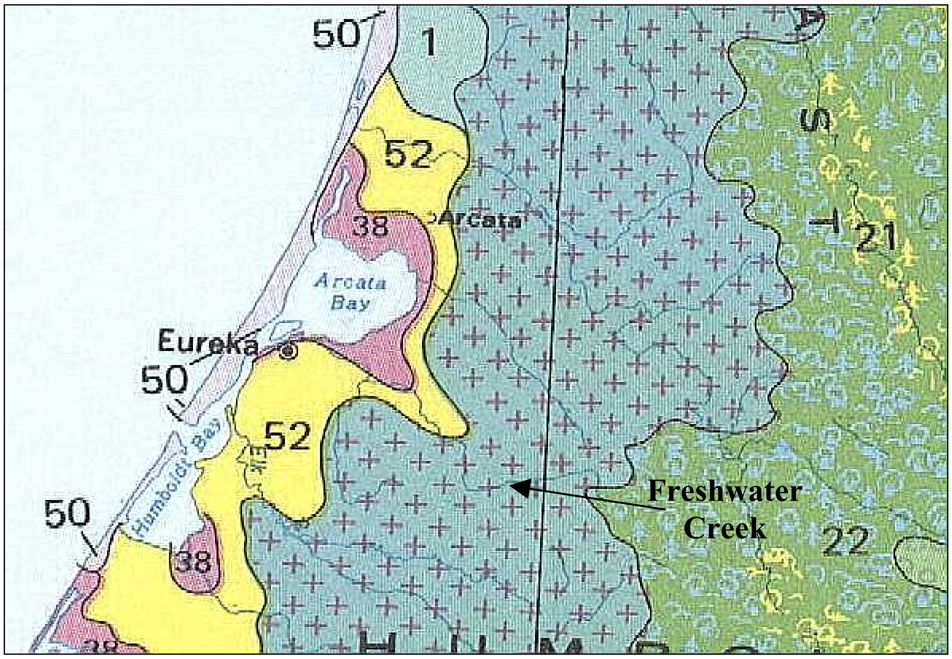

Figure 6-1: Pre-European Vegetation Map. Freshwater basin was mostly vegetated by redwood forests (blue "+" hatching). A small portion of the extreme lower watershed is within the grassland tide areas (map code 52). The highest elevations are in the Douglas-fir vegetation zone (Barbour and Major 1988).

Pre-European riparian forests likely had younger redwood stands growing closest to channels in lower Freshwater where periodic major flood disturbance toppled trees. Flood deposits of sediment created ideal conditions for redwood germination. Seedlings will generate as even-aged stands dating from the time of sediment deposition. These seedlings end up as suppressed or intermediate understory crowns, except along the stream margin where light is let in through the overstory grove. The unprecedented floods of 1861-1862 (Harden 1995), which coincided with the earliest logging entries, are an example of this flooding dynamic affecting riparian forest condition. Redwoods growing in areas of alluvial deposits also set out a new set of surface roots following deposition.

Detailed stand data are not available for historical old-growth conditions in the Freshwater basin, but comparable stand data for nearby areas provides similar information. Table 6-1 presents stand data based on a complete inventory of 2,796 acres of virgin old-growth redwood stands in lower Redwood Creek near Orick, CA. The total basal area is 560 ft^2 per acre with about 81% of the basal area contained within trees >40 in. dbh. Few hardwoods occurred in this stand—about 3-6 trees per acre (TPA) mostly in the 12-36 in. dbh size class. For these old-growth stands, there are 14 redwoods/acre $\geq$40 in. dbh and 18 conifer/acre $\geq$40 in. dbh. This compares with the PFC Matrix standards of 23.8 redwoods per acre at >32 in. dbh and 17.4 TPA >40 in. This suggests the PFC Matrix standard may not be achievable in Freshwater and may warrant review.

Table 6-1: Stand character for an old-growth redwood forest.[1]

Density in trees (by size class) per acre				
dbh (in inches)	**Redwood**	**Douglas-fir**	**Other Conifer**	**All Conifers**
08 – 36	16.10	3.33	13.96	33.39
40 – 48	4.05	1.03	0.14	5.52
50 – 58	2.70	1.00	0.11	3.81
60 – 78	3.90	1.07	0.05	5.02
80 – 98	2.11	0.12	0.01	2.24
100 – 118	1.01			1.01
>119	0.56			0.56
TOTAL	**30.43**	**6.55**	**14.57**	**51.55**

[1] Based on complete inventory of 2,796 acres along lower Redwood Creek, CA. Unpublished data from NRM Corporation, Eureka, CA.

6.2 LAND USE IN THE FRESHWATER

Logging in the Freshwater basin began in the 1860s in the School Forest sub-basin of the lower watershed. Steam donkey and railroad logging spread up the drainage in the 1870s through the turn of the century. These early entries included McCready Creek (1870s), lower Cloney Gulch (1880s and 1890s), Falls Gulch (1880s), Graham Gulch (1880s and 1890s), and lower Little Freshwater Creek (1870s and 1890s). Railroad logging recommenced in the 1920s along the mainstem of Freshwater Creek within the Little Freshwater Creek drainage and lower portions along South Fork Creek. Railroad grades were commonly placed within the riparian areas or up the stream channel; examples of streamside railroad grades include McCready, Cloney, Graham, and portions of the South Fork. Railroad timbers and logging debris used to fill crossings of small lateral tributaries still contribute to in-channel woody debris within some stream sections. By the end of the 1930s, the remainder of riparian areas along Little Freshwater Creek, the South Fork, and most of the main stem had been clearcut harvested. Only isolated remnant old-growth trees, mostly Douglas-fir and grand fir, were left within riparian areas at the end of this harvest sequence. In the 1960s lower basin areas of second-growth were selectively thinned. Between 1966 and 1974, approximately 49 miles of haul roads were constructed in the basin. Some of the main truck roads utilized the existing railroad grades within riparian areas. More recent road construction generally avoided parallel road construction within the riparian areas. During the interim growth period from the first major entry, harvest disturbance within the riparian areas was minimal and generally was selective cutting. Both selective harvest and clearcut harvesting techniques are evident on more recent aerial photos (1990 – 1997). Since about 1987, riparian buffers of 100 ft width on either side have been left where clearcut harvest units adjoined Class I and II streams. While harvesting and other activities within these buffers have generally been minimal within the Freshwater basin, the California Forest Practice Rules do not preclude selected harvest within these buffers.

6.3 CURRENT RIPARIAN CONDITION

The majority of the riparian forest in the freshwater is approximately 70-year-old second-growth redwood stands. These stands are even-aged with a fairly uniform overstory canopy. Many of the riparian stands in the basin were first coded as CWHR size class 4 based solely on aerial photos. It was also noted from the photos that the size class for these stands appeared to be on the boundary between CWHR codes 4 and 5. The recovery period since the last major harvest entry also is consistent with redwoods attaining this diameter size. Field reconnaissance surveys determined that a number of these stands are more appropriately coded as size class 5 since dominant and co-dominant crown trees (overstory) exceeded 24 in. dbh. The mapping was adjusted according to the results of the field survey.

Map D-1 depicts the distribution of CWHR riparian stand types in the Freshwater basin. The methods state that coding would note both overstory and understory; however, this proved problematic with too many codes to map effectively. The coding is based on the dominant and co-dominant overstory canopy.

It became evident early in the analysis that a consolidation of the CWHR types would be necessary to achieve study results meaningful for prescription application. The CWHR coding system as described in the Watershed Analysis methods documents (PALCO 2000) includes a multitude of forest stand types. For redwood stands, mixed stand, and hardwood stands, there are 60 different overstory forest stand classifications. Many of these stand types were either not represented in the Freshwater basin or only present in a small percentage of the total streambank length. Several of the CWHR groups mapped during aerial photo interpretation did not prove to be substantively different based on an analysis of the corresponding plot data.

The results of detailed plot data described later in this section were used to consolidate the CWHR types. Table 6-2 summarizes the distribution of these consolidated stand types. The distribution of consolidated CWHR types are shown on Map D-1b.

Sixty eight percent of the Class I/II streambank length in the Freshwater basin is in CWHR size class 5 redwood plant communities. Sixty percent of the Class III streambank length was in size class 5. All of these stands were within the sub-group 5a (24-30 in. dbh). On average, the density of redwoods within the sub-group size class 5b (>30 in.) ranged from 0-13 trees per acre or 22% of area. This was not sufficient stocking to define dominance by this size class within riparian stands of the Freshwater basin.

Table 6-2: Summary of consolidated riparian stands for Freshwater basin.

		Percent Total Streambank Length[1]			
Code	**Description**	**Class I & II**	**Class I**	**Class II**	**Class III**
LC	Large/Medium Redwood: QMD 21.4 in.; >90% CC (RDW5d and RDW5M)	68.4%	51.4%	77.8%	59.3%
SC	Small tree Redwood: QMD 20.3 in.; >90% CC (RDW4D and RDW4M)	4.8%	2.3%	6.2%	22.9%
YC	Young Redwood: QMD 15.7 in.; 40-90% CC (RDW 2-3D/M)	4.4%	3.5%	4.8%	11.0%
SP	Sparse to Open Redwoods: QMD 16.1 in; <40% CC for Dom/Co-Dom (RDWS and RDWP)	6.1%	6.4%	5.9%	6.9%
CH	Mixed redwood/hardwood: QMD 17.8 in, % CC variable (RDW/HWD, HWD/RDW)	10.1%	21.3%	4.0%	
G	Grass	2.2%	4.4%	1.0%	
H	Hardwoods	4.1%	10.8%	0.4%	

[1]Streambank = 2 * channel length

Mixed stands of redwoods and hardwoods occupy 10% of the total streambank length in the basin. Mixed stands are more prevalent along Class I streams. Hardwoods account for 4% of the streambank length for all streams or 11% of Class I streambank length. There are almost no hardwoods along Class II streams. Most of the hardwood stands are concentrated in the lower residential reaches of Freshwater Creek. Mixed stands with a hardwood component also occur along the uppermost reaches of upper Freshwater Creek. Although these areas have been previously harvested, the natural vegetation in pre-European times for upper Freshwater Creek (upstream of PALCO lands) was Douglas-fir/tanoak (Barbour and Major 1988).

Where there are adjacent harvest units, logging has occurred in the outer 100-170 ft as evidenced on maps by reduced CWHR size class and/or density. Relatively little recent harvest activity (after 1974) has occurred within 0-100 ft of mapped Class I and II streams.

The majority of Class III streambanks are vegetated with large redwoods. About 18% of the streambank length of Class IIIs has been affected by harvests subsequent to the initial entries 70 years ago. The CWHR codes for Class III streams are based only on aerial photo interpretation with no field verification of either the actual location of these streams or field verification of stand type. Since differences in stand condition between banks for Class IIIs were rare, the mapping treats the left and right bank riparian condition as identical. The mapping width for Class III streams was 50 ft either side of the mapped channel.

6.3.1 Detailed Plot Inventories

Supplemental methods applied in the Freshwater Riparian Function Assessment include detailed plot inventories. In total, 50 plots at 25 different sites were established for field inventories. The locations of these plots are shown in Map D-1. Sites were selected to represent the range of CWHR types mapped from the aerial photos, as well as attempting to distribute plots geographically across the watershed. Where the above priority allowed, plots were located adjacent to stream reaches where fish habitat data were being collected. Paired plots, one on each bank, were established at each sample site.

The dimensions of the plots were designed to provide stratification by distance from the channel consistent with the default riparian management zone prescriptions listed in the ACP. Figure 6-2 shows the plot dimensions. The corner points for approximately rectangular 1/10th acre plots adjusted for slope and running parallel to the stream were flagged for the three riparian band widths: A =0-30 ft, B=30-100 ft, C = 100-170 ft.

A team of experienced timber cruisers inventoried all standing trees >10 in. dbh by species, diameter, crown position, and crown ratio. Any damage to trees that could lead to mortality was noted. All trees <10 in. dbh were inventoried within 1/50th acre subplots. All downed wood and snags >10 in. diameter were inventoried for species, decay class, direction of fall, and dimensions. Canopy closure was measured at two points with a spherical densiometer within each 1/10th acre plot. Site characteristics of slope and aspect were recorded. A detailed description of methods and field forms is provided in PALCO (2000).

Field data were entered and analyzed by Natural Resources Management (NRM) using data reduction software developed by NRM. Plot data were initially stratified by stream size class and stream gradient. Sorting the riparian plot data by stream size and stream gradient did not show distinct groupings for any of the three riparian band widths.

Data were analyzed independently for each of the band widths and in combination: A, B, C, AB, ABC. The A and B plots were highly similar. Recent clearcut and selective harvests affected some of the C plots (100 – 170 ft from channel).

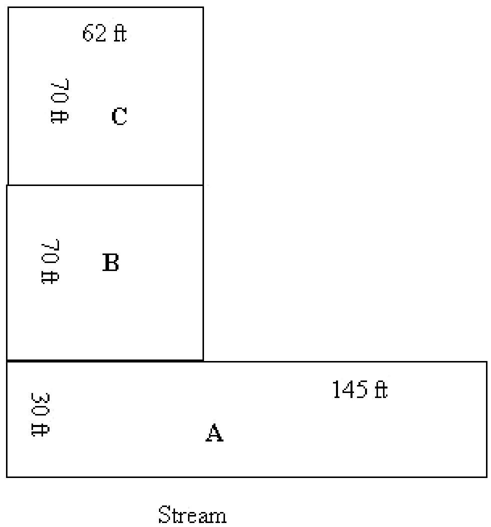

Figure 6-2: Riparian inventory plot dimensions.

Subsequent analysis of the larger CWHR size classes excluded C plot data to avoid biasing the stand condition due to this edge effect.

Detailed summaries for the plot data, sorted by riparian band width (A, B, C) and compiled by CWHR type, are provided in Attachment D-1. The total trees per acre and redwoods per acre for each consolidated stand type are reported in Figures 6-3 and 6-4. About 80% of the trees are redwoods. Douglas-fir and grand fir are co-dominant species. Incidental conifer species include hemlock, Sitka spruce, Port Orford cedar (*Chamaecyparis lawsoniana*).

Hardwoods include alder (*Alnus* spp.) and maple (*Acer* spp.) in mixed conifer/hardwood stands. Species within hardwood stands include tanoak and alder. Shrubby willow species were not inventoried since they do not contribute LWD.

The Quadratic Mean Diameter (QMD) varied little among riparian band widths when all data were analyzed as a single stand condition (i.e., stratified according to the consolidated stand types). QMDs for each riparian band width are: A=20 in., B=21.1 in., AB=20.5 in., and C=19.6 in. The largest individual trees are redwoods with diameters up to 120 in. dbh.

The average trees per acre were computed for each crown layer (Attachment D-1). Tree counts and diameter measurements were tallied in the field during plot inventories for each crown layer. The Pre-dominant crown species for medium and large CWHR size class stands (4/5) are Douglas-fir and grand fir. These largest trees are remnants not cut during the initial harvest entries. The mean diameter for redwoods in the dominant crown is 45 in. dbh; redwoods in the co-dominant crown have a mean diameter of 28 in. dbh.

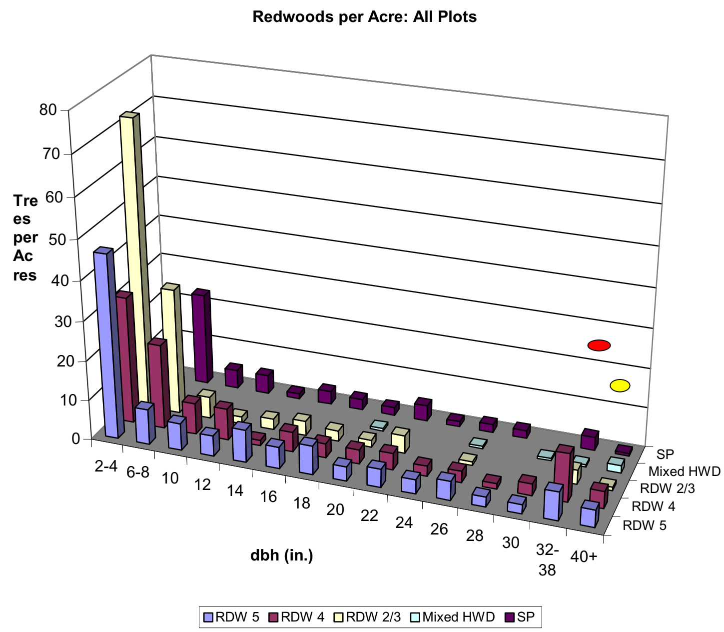

Figure 6-3: Redwood trees per acre for all Freshwater plots. The circular markers are the PFCM target stocking densities for large redwood TPA.

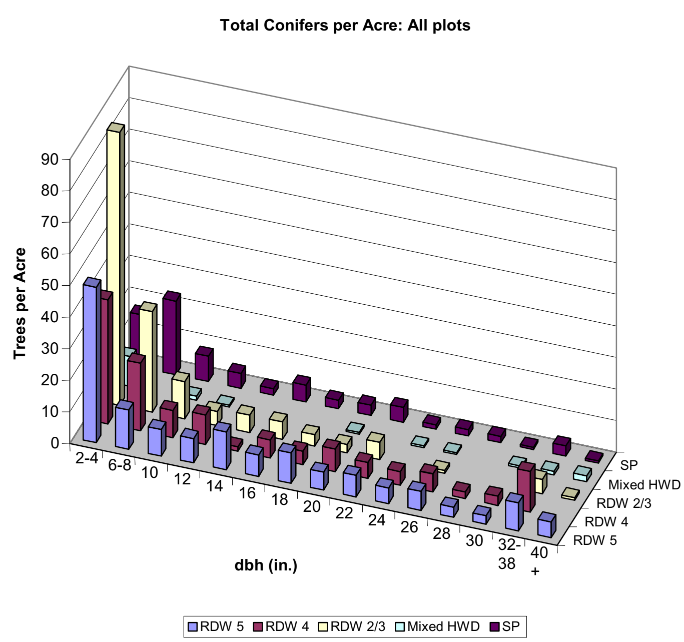

Figure 6-4: Total conifer trees per acre for all Freshwater plots.

Table 6-3 summarizes the results of an analysis of plot data for the purpose of consolidating CWHR codes. The C plots were distinguished from A and B plots where adjacent clearcut units affected the tree density within the outer 170 ft of riparian area. When adjacent harvest units impinged within the 170-ft assessment area, the plots were typically grouped in the sparse to open category or young stands. C plot data for the consolidated groups 4 and 5 were unaffected by harvest edge effects. Note that Table 6-3 compares data for RDW5 A/B plots to RDW5 C plots.

The QMD, reported in Table 6-3 are computed from 100% field inventories of trees greater than 5 in. dbh, whereas aerial photo interpretation of CWHR size class is biased for overstory trees (i.e., cannot account for understory tree diameters when viewing aerial photos). This analysis of plot data demonstrates that CWHR coding overestimates QMD for the larger size classes (CWHR codes 4 and 5). This finding is consistent with the results of other studies (Garrison 1993).

Greater variability exists among plots for the young redwood stands (CWHR 2/3), sparse to open redwood stands, and the mixed hardwood stands. This variability is evidenced by the greater confidence intervals of ±48%, ±68%, and ±37% for young, hardwood, and sparse/open stands, respectively (standard error of 1 standard deviation ± 10%). The confidence intervals were calculated on the volume of conifer timber. Therefore, it is logical that the mixed hardwood stands would have the greatest variability since the proportion of softwood is less.

The differences between the consolidated RDW5 and the RDW4 groups are relatively small. Trees in the intermediate and suppressed crown layers have similar stocking and size densities for these two groups. Trees in the co-dominant crown layers of the RDW5 group are slightly larger. The QMDs are comparable (21.4 in. for RDW5 and 20.3 in. for RDW4). The lower reported conifer trees per acre within the RDW4 plots relative to the RDW5 plots is likely an artifact of sample size. The total trees per acre would be expected to be the same or less as the stand QMD increases. The close similarities between the size class 4 and 5 stands reflects a harvest history for the Freshwater basin in which nearly the entire basin was clearcut harvested 60-80 years ago. The result is uniform forests, with the majority of riparian stands just at or approaching the size class 5 distinction of 24 in. dbh trees.

The character of crown layers within each of the consolidated CWHR groups is indicative of redwood forest growth dynamics. Individual redwood trees show a low susceptibility to suppression mortality. Growth of individual understory trees slows as the overhead crown layers shades them. A review of the plot summary data in Attachment D-2 indicates that the intermediate crown layer for the RDW4 group is similar to that of the younger RDW2/3 stands.

Table 6-3: Consolidated riparian stand types for Freshwater WAU.

RDW5 – AB plots	
A&B plots for size class 5; Moderate to Dense crown closure (56 plots)	
QMD	21.4 inches
Total TPA conifer	149.5
Total TPA hardwood	36.3
RDW TPA > 32" dbh	11.5
RDW TPA > 40" dbh	4.3
Mean dbh dominant crown	44" dbh @ 2.1 tpa
Mean dbh co-dominant crown	27" dbh @ 44.3 tpa
C.I. for volume conifer	± 11%
Snags/acre	3.4
RDW5 –C plots	
C plots for size class 5; Moderate to Dense crown closure (15 plots)	
QMD	22.8 inches
Total TPA conifer	159.3
Total TPA hardwood	96.0
RDW TPA > 32" dbh	10.6
RDW TPA > 40" dbh	5.3
Mean dbh dominant crown	42" @ 1.3 tpa
Mean dbh co-dominant crown	29" @ 33.3 tpa
Snags/acre	2.7
RDW 4M/D	
A, B and C plots for size class 4: Moderate to Dense crown closure (14 plots)	
QMD	20.3 inches
Total TPA conifer	135.0
Total TPA hardwood	42.1
RDW TPA > 32" dbh	16.4
RDW TPA > 40" dbh	4.3
Mean dbh dominant crown	46" @ 1.4 tpa
Mean dbh co-dominant crown	26" @ 49.3 tpa
C.I. for volume conifer	± 22%
Snags/acre	4.5
RDW2/3: Labeled YC – young conifer	
A, B and C plots for size class 2 and 3: Mod. to Dense crown closure (11 plots)	
QMD	15.7 inches
Total TPA conifer	163.6
Total TPA hardwood	89.1
RDW TPA > 32" dbh	3.6
RDW TPA > 40" dbh	0.9
Mean dbh dominant crown	27" @ 2.7 tpa
Mean dbh co-dominant crown	19" @ 25.5
C.I. for volume conifer	± 48%
Snags/acre	4.5
RDW/HWD: Label CH – mixed stands conifer and hardwood	
A and B plots for size class 3, 4, 5 mixed stands "RDWHWD" and "HWD/RDW" (16 plots)	
QMD	17.8 inches
Total TPA conifer	16.9
Total TPA hardwood	53.8
RDW TPA > 32" dbh	2.5
RDW TPA > 40" dbh	1.9
Mean dbh dominant crown	53" @ 1.9
Mean dbh co-dominant crown	19" @ 10.6
C.I. for volume conifer	± 68%
Snags/acre	2.5 alder
RDW SP	
A,B, and C plots for sparse or open crown closure redwood stands (15 plots)	
QMD	16.1 inches
Total TPA conifer	80.7
Total TPA hardwood	44.7
RDW TPA > 32" dbh	4.1
RDW TPA > 40" dbh	0.7
Mean dbh dominant crown	56" @ 0.7
Mean dbh co-dominant crown	24" @ 17.3
C.I. for volume conifer	± 37%
Snags/acre	5.3

A suppressed crown layer has developed in the RDW4 stands (17.1 redwood/acre), but suppression is minimal within the younger stands (3.6 redwood/acre). The growth of the shorter understory trees in RDW4 has slowed. Average diameters of redwoods in the intermediate and suppressed crowns continue to show little increase as the dominant crown layer increases over time to achieve the larger size class 5 (>24 in. dbh). There is only a 2 in. increase (13 in. vs. 11 in. dbh) for average diameter of suppressed crown layer trees between the RDW5 plots and the much younger RDW2/3 plots; however, the number of trees in the lower crown layers is much greater in the older stands.

6.3.2 Snags and Downed Woody Debris

All snags at least 10 in. dbh were inventoried for plots. Downed wood was also inventoried within plots. The size, direction of fall, species, and decay class for each piece were recorded. On average, there are 4.1 snags/acre within riparian areas of the Freshwater Class I and II streams. Most of these snags are of conifer origin and are less than 24 in. dbh. Disease and breakage appear to be the primary causes for snags and downed wood on the riparian forest floor. These two factors also contribute LWD to the stream. The number of trees succumbing to bank erosion was underestimated in the plot inventory surveys. Crews did not count wood that had fallen into the stream (i.e., mostly out of plot).

Table 6-4 summarizes the downed wood plot data. A complete listing of downed wood attributes is provided in Attachment D-1. Differences for downed wood amounts were not apparent among the CWHR stand types.

Table 6-4: Woody debris on the riparian forest floor. Data are from detailed plot inventories. Only pieces with a minimum diameter of 10 in. were counted.

Stand Size	No. Plots	No. Pieces	% Pieces RDW	Avg Length (ft)	Avg Mid. Dia. (in.)	Avg Decay Class[a]	Cum Vol /Acre (ft^3/ac)	Cum Vol (m^3/ha)	Cum Vol Metric tons/ha)[b]
RDW5	56	72	61%	32.3	25.3	2.3	1826	21	48
RDW4	22	30	63%	34.8	22.3	2.3	1220	14	32
RDW3	11	30	43%	34.6	27.3	2.5	3868	44	102
ALL	89	132	58%	33.4	25.1	2.3	1992	23	53

[a] Decay class: 1 = Recent (last 2 years), 2 = hard, 3 = soft, 4 = decomposed
Only pieces with a minimum diameter of 10 in. were counted.

[b] Cumulative volume converted to metric tons based on an assumption of 5.4 kg per board foot. Other publications reporting LWD volume in metric ton units did not specify a conversion factor but it assumed that this provides at least an approximate comparison.

The amount of wood on the forest floor was also comparable among all riparian band widths. Most of the downed wood showed little decay and was still firm. The downed wood was disproportionately large relative to the size distribution of standing trees. Of the pieces inventoried, 87% had a mid-point diameter greater than 32 in. This difference could be due to one or more factors. Larger pieces require longer to decay. Some of the downed wood is likely a legacy from prior to the initial harvest entries. Although windthrow was not severe to the point of large proportions of riparian areas blowing down, it is a primary recruitment mechanism. Windthrow is more pronounced on larger trees within a stand (Stathers et al. 1994). Finally, the survey may have introduced bias since larger pieces of downed wood tend to be more visible and are not as readily buried in the forest detritus. Many areas were burned before and after the initial harvest (PWA 1999); this action would have reduced the amount of remnant woody debris on the forest floor.

There is no PFC established for pieces or volume of redwood downed wood. The PFC does give a target of 29 pieces/acre downed wood within Douglas-fir stands. This compares with 14.3 pieces/acre within the Freshwater riparian redwood stands. Agee (1993) discusses the level of wood debris in redwood forests, and Bingham (1992) states the redwood forests contain 22 to 29 metric tons of wood debris per acre. Bingham and Sawyer (1988) report a volume of 957 m^3 per hectare with a log mass of 200 metric tons per hectare. However, Finney (1991) gives a log mass of from 10 to 280 metric tons/ hectare and Greenlee (1983) gives 186 metric tons per hectare as the mass of woody debris.

Figure 6-5 shows the direction of fall relative to the stream channel for pieces inventoried within the riparian plots (not inclusive of in-channel LWD). The direction of fall could be determined for 64 out of 220 LWD pieces inventoried. There appears to be a bias for trees to fall toward the channel. In total, 55% of the inventoried pieces fell within a 45-degree arc to the channel; 84% of the pieces fell toward the channel (180 degree arc). The total sample size of downed wood is too small to be conclusive as to a bias toward trees falling toward the stream.

6.4 FUNCTIONAL SIZE OF LWD RELATIVE TO STAND CONDITION

A properly functioning riparian forest must be stocked with trees of sufficient size diameter to provide potential recruitment of functional LWD. The majority of LWD in a stream channel is recruited from the adjacent riparian forest (WDNR 1997). In some basins, mass wasting can act as an important recruitment mechanism of wood from upslope areas. To be functional, the riparian stand must provide both the total pieces of LWD in the channel as well as key piece LWD. The Properly Functioning Condition Matrix (NMFS 1997) defines key piece LWD as a log or rootwad that:

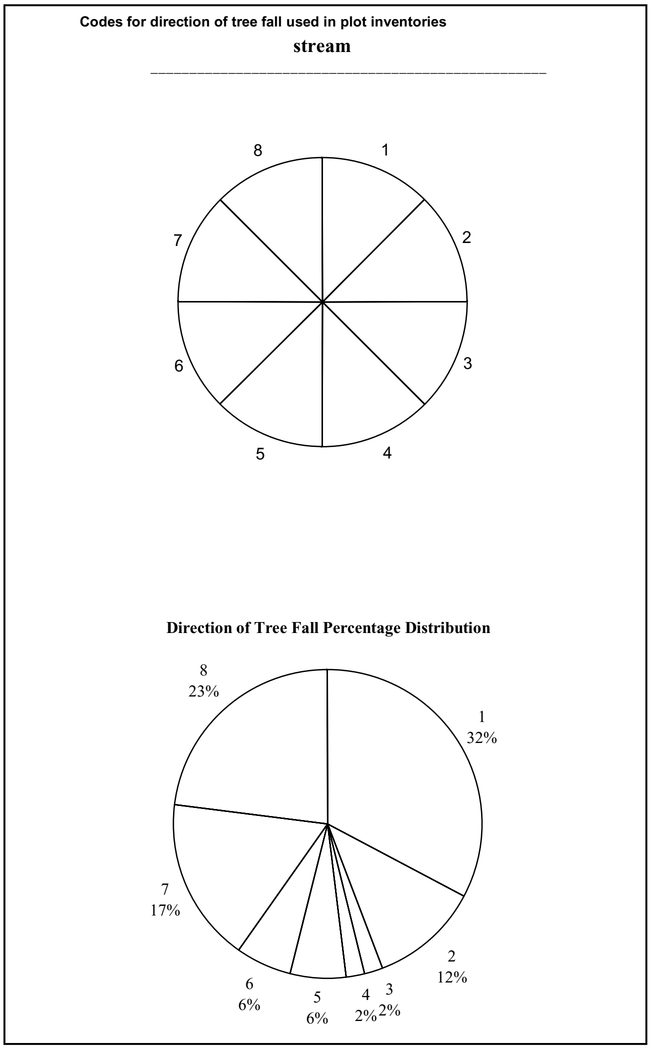

Figure 6-5: Direction of fall for downed wood within Freshwater riparian plots. Sample size equals 64 pieces; only pieces with a minimum diameter of 10 in. were counted.

- Is independently stable in the stream bankfull width (not functionally held by another factor, [i.e., pinned by another log, buried, trapped against a rock or bedform, etc.]); and

- Retains (or has the potential to retain) other pieces of organic debris.

The size of key piece wood that functions in a stream channel is proportionate to the size of the channel. Fox (1994) reports target amounts and sizes of key piece LWD as a function of stream width. Functional key piece diameters (Fox 1994) were compared to riparian stand stocking densities for the Freshwater basin. The trees per acre (TPA) that are sufficiently large to provide key piece LWD for the adjacent channel are defined in Table 6-5. The values reported in Table 6-5 are conifer trees per acre. The table does not imply that all trees of a functional size will actually be recruited to the channel. The taper of the bole and probability of direction of tree fall, as well as tree height, each affect the likelihood of an individual tree actually providing functional size wood to the stream.

The conifer TPA for RDW5 and RDW4 stands provides good recruitment potential for functional LWD. A continuous supply of LWD can be expected maintain existing in-channel LWD. Although the exact recruitment rate of these streams is difficult to define due to its partial dependence on stochastic events, the stocking densities compare well to functional needs and old-growth forest stocking levels. Nearby redwood old-growth stands along the lower Redwood Creek had an average of 52 TPA conifers of $\geq$8 in. dbh (see Table 6-1). Stocking rates reported in Table 6.5 were used to identify near term properly functioning riparian areas based on LWD recruitment potential (Map D-2). Consolidated stands with less than 20 conifer trees per acre with a dbh at or greater than key piece size for a give channel geomorphic unit were defined as non functional. Those stands with at least 33 trees per acre meeting this criteria were identified as properly functioning for LWD recruitment. All others were assigned to moderate function.

Table 6-5: Current trees per acre in Freshwater riparian stands with a diameter (dbh) equal or greater than key piece size.

CGU[1]	Bankfull Width (ft)	Key Piece Diameter[2] KPD (in.)	TPA conifer with dbh $\geq$ key piece size (Fox 1994)				
			RDW5	RDW4	RDW2/3	RDW/HWD	SP
C1	25	22	38	38	12	5	15
C2	14	16	60	55	24	6	26
C3 small	3.8	12	80	66	34	6	33
C3 large	16	16	60	55	24	6	26
C4	5	12	80	66	34	6	33
GG1	20	22	38	38	12	5	15
CG	24	22	38	38	12	5	15
MS1	43	25	26	29	6	4	9
MS2	50	28	20	23	5	4	7
MS3	46	28	20	23	5	4	7
U1 small	3.6	12	80	66	34	6	33
U1 large	26	22	38	38	12	5	15
U2	2.7	12	80	66	34	6	33
U3	3.3	12	80	66	34	6	33
U4	6	12	80	66	34	6	33

[1]CGU = channel geomorphic unit as defined in the Channel Assessment Module (Appendix E)
[2]KPD = key piece diameter (Fox 1994)

6.5 FUTURE STAND CONDITIONS

Future riparian stand conditions were evaluated using both qualitative and quantitative approaches. A qualitative assessment of factors limiting achievement of proper functioning condition relied on aerial photo interpretation and field inspections. For each Riparian Condition Unit (RCU) coded as hardwood, mixed hardwood/redwood, or sparse to open density, factors contributing to this condition were noted. GIS was used to measure the total streambank length affected by various activities.

6.5.1 Limitations to Achieving Proper Function

Aerial photos and field notes were reviewed to determine factors likely to limit attainment of proper functional condition without silvicultural intervention. Table 6-6 lists the percent of riparian streambank length for all Class I and II streams where attainment of proper function is not expected (inclusive of PALCO and non-PALCO lands in the Freshwater basin). In some instances, more than one factor may limit riparian forest growth; however, only the factor most limiting long-term LWD recruitment was recorded to avoid duplicative counting of stream reaches. Some limiting factors (indicated with an asterisk in Table 6-6) are likely to permanently prevent development of properly functioning conditions. In the remaining cases changes in management or forest re-growth could eliminate the limiting factor over time. The condition for each streambank was evaluated independently (i.e., the percentages are based on streambank length that is twice the stream length).

Table 6-6: Activities limiting riparian function. Percentages are expressed as a percent of the entire streambank length within each riparian width/stream class.

		Class I	Class I	Class II
Limiting Activity	**Riparian Condition**	**0-100 ft**	**100-170 ft**	**0-100 ft**
Development*	Shrubs or hardwoods	14.6%	9%	0.5%
Flood disturbance	RDW/HWD-3D	2.0%		0.3%
Harvest	RDW3-D & RDW3-M	5.2%		
Harvest with narrow buffer	Leads to RDW-5P	2.6%		2.9%
Harvest – clearcut	RDW-2D & RDW-2P	2.1%	9.4%	4.2%
Harvest - partial cut	Leads to RDW-5P	0.4%		3.2%
Mass wasting	Hardwood stands	0.3%		0.3%
Other hardwoods	Hardwood stands	0.6%		
Tidal/marsh*	Grass	3.8%	3.8%	
Roads within riparian*	RDW2/3 & HWD			0.2%
Harvest resulting in mixed redwood/hardwoods	RDW/HWD-3P		3.7%	
Total Percent of streambank length		32%	26%	12%

Roads parallel to the channel can be a primary factor limiting riparian forests in many forested watersheds. The Freshwater basin has a legacy of roads constructed on old railroad grades which paralleled many of the main sub-basin streams. Although trees are absent from the active road bed, the surrounding riparian zone is often fully forested with second-growth redwoods >24 in. dbh (RDW5D). Lower Graham Gulch is an example. LWD recruitment potential was not considered limited in these situations since the existing stand is capable of providing an ongoing source of LWD of functional size. Given this, roads did not end up being a principal limiting factor for riparian stands in the Freshwater basin, although the road network certainly provides the opportunity for other activities to affect riparian condition.

Riparian conditions within 100 ft of Class I and II streams are limited for 32% and 11%, respectively, based on streambank length. Most of this impaired riparian zone is in the lower Freshwater basin downstream of PALCOs ownership. In total, development in the lower basin including homes, commercial activities, and non-forestry roads affects 15% of the total streambank length for the Freshwater drainage. Development is limited to the lower Freshwater Creek. The riparian vegetation consists of a narrow band of shrubs or deciduous trees for much of lower Freshwater Creek. Without enhancement, long-term LWD recruitment will not likely be sufficient nor improve from the current condition of a lack of in-channel LWD. The most downstream portion of the watershed is within the tidal influence. Redwood forests are naturally limited along Freshwater Creek to a point approximately ½ mile upstream of Three Corners. Overbank flooding and soil saturation maintain mixed stands of conifers and hardwoods for about 2% of the Class I streambank length.

The entire Freshwater basin has been affected by historical harvests. Harvesting within the last 25 to 30 years has limited the near term LWD recruitment potential from the 0-100 ft riparian width area for 10% of both Class I and Class II streambank length. In most of these areas partial harvest occurred such that trees are available for recruitment but not in quantities or sizes considered functioning. Clearcut harvesting practices prior to recent forest practice rules (mostly pre-1973) have reduced stand age along 2% of the streambanks for Class I streams. These areas remain as hardwoods or young redwood plantations. Riparian buffers substantially less than 100 ft occur along 3% of the Class I streambank length; these areas are mostly vegetated by open stands of ≥24 in. dbh redwoods. The type of harvest was not noted for the other 5% of harvest-affected Class I streambank length. These reaches are in the CWHR3D category. While short-term LWD recruitment is limited, for all these areas these stands are expected to provide suitable long-term recruitment potential.

Four percent of Class II streambank length has been recently clearcut within 0–100 ft; in most cases, some trees were retained in these areas but the buffer width may be less than 100 ft. These stands were coded as RDW2D or RDW2P. Short-term LWD recruitment is limited, but these stands will provide good long-term recruitment potential. Buffers less than 100 ft wide occur along 3% of the Class II streambank length. Partial cutting has created open stands of mostly ≥24 in. dbh trees for another 3% of the Class II streambanks.

Mass wasting, sediment deposits at the mouths of tributaries, and small inner gorge landslides result in small inclusions of hardwood stands. The role of small streambank slides as an LWD recruitment mechanism is discussed later. A slow-moving earth slump maintains a mid-reach portion of Graham Gulch in mixed hardwoods.

Within the outer 100–170 ft distance from Class I channels, clearcut harvesting has greatly reduced or eliminated riparian forests along only 4% of the streambank length. Another 8% of the length is currently vegetated with redwood saplings (1-6 in. dbh) following clearcut harvesting.

6.5.2 Riparian Stand Modeling

The forest stand growth model CRYPTOS (Wensel et al. 1987) was used to quantitatively assess future riparian stand conditions. Most of the data that went into producing the CRYPTOS model came from stands between 15 and 90 years age, and trees between 4 and 45 in. dbh. The model grows trees based on site index of the land, position of the individual trees in the stand (dominant, co-dominant, intermediate, or suppressed), live crown ratios of each tree, diameter and height of the trees, and species (Figure 6-6). Outputs of the model include volume per acre in board feet or cubic feet, basal area in square feet per acre, crown closure by diameter class, tree diameter distribution in number of trees per acre, heights by diameter class, and live crown ratios by diameter class. Mortality trees need to be accounted for each model period as these are the trees available for LWD recruitment.

A modeling period of 40 years was selected since this encompassed the HCP time period. In addition, this model period is well within the model's capabilities when applied to the older CWHR4 and CWHR5 stands. These stands are approximately 70 years old now; as CRYPTOS was developed using maximum stand ages of about 90 years, extrapolating too far into the future must be done with caution. CRYPTOS model projections are limited to about 150 years maximum.

A new redwood plantation stand was modeled, as well as the consolidated CWHR stand types occurring in the Freshwater basin. Trees in the modeled plantation stand began reaching 24 in. dbh at 60 to 80 years. This finding is consistent with field observations for the Freshwater drainage.

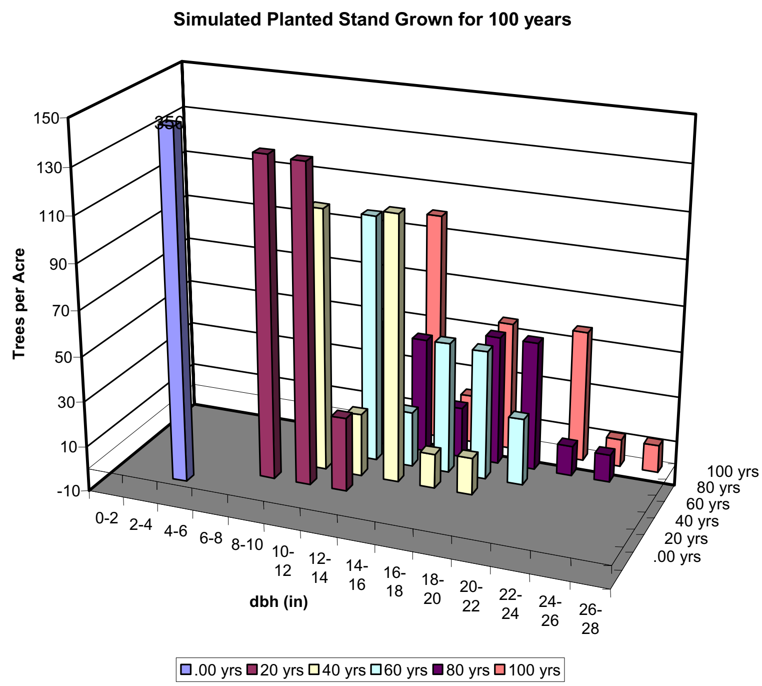

Figure 6-6: Simulated redwood plantation. CRYPTOS model trees/acre over a 100-year model period based on site indices for the Freshwater basin. The TPA decreases over time as individual trees get larger in diameter.

The modeled stand planted at 350 TPA resulted in 257 TPA at 100 years with diameters in excess of 13.9 in. This would be a very dense stand when comparing to about 72 TPA at size classes $\geq$ 14 in. dbh for Freshwater CWHR5 riparian stands. Differences between the modeled plantation stand TPA and existing CWHR5 conditions are attributable to different replanting strategies, pre-commercial thinnings not accounted for in the modeled stand, and inherent variability. The change in TPA over the model period is shown in Figure 6-7. The planted stand tends toward even-age and height. Similarly, most of the stands in the Freshwater are even-aged second-growth stands.

Data from the plot inventories summarized for each of the consolidated CWHR stand types were applied to the CRYPTOS model to evaluate future stand condition. CRYPTOS was used to model the basal area (Table 6-7) and trees per acre (Table 6-8 and Figures 6-8 and 6-9) over a 40-year period for each of the existing riparian stand conditions. Riparian stands in Freshwater basin are mostly even-age owing to extensive harvest about 70 years ago. Complete results of CRYPTOS modeling runs are provided in Attachment D-2.

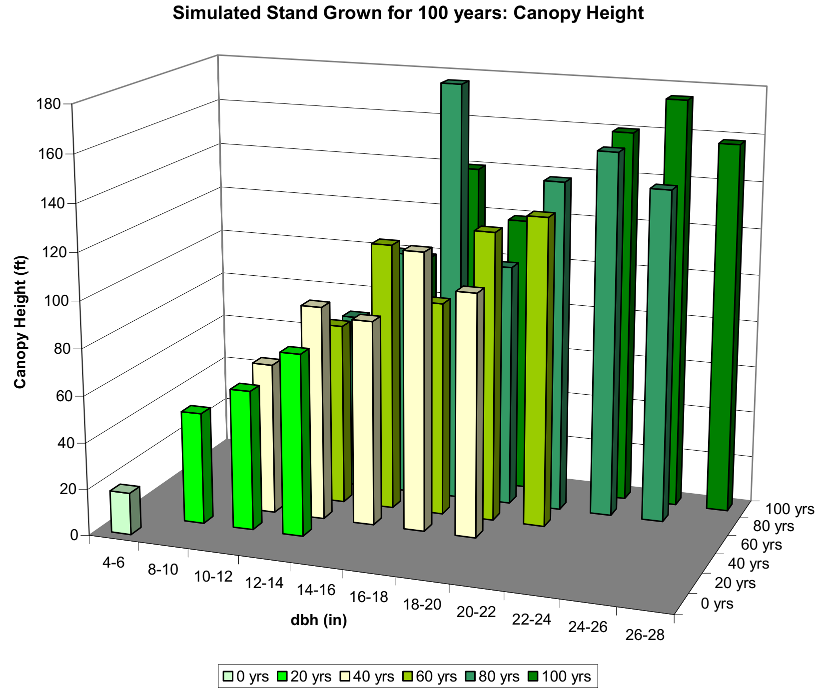

Figure 6-7: Canopy height for future stand condition for simulated redwood plantation. CRYPTOS modeling was used to predict future overstory crown height using typical site index for Freshwater riparian areas. Note the stand grows toward even height of approximately 160 ft.

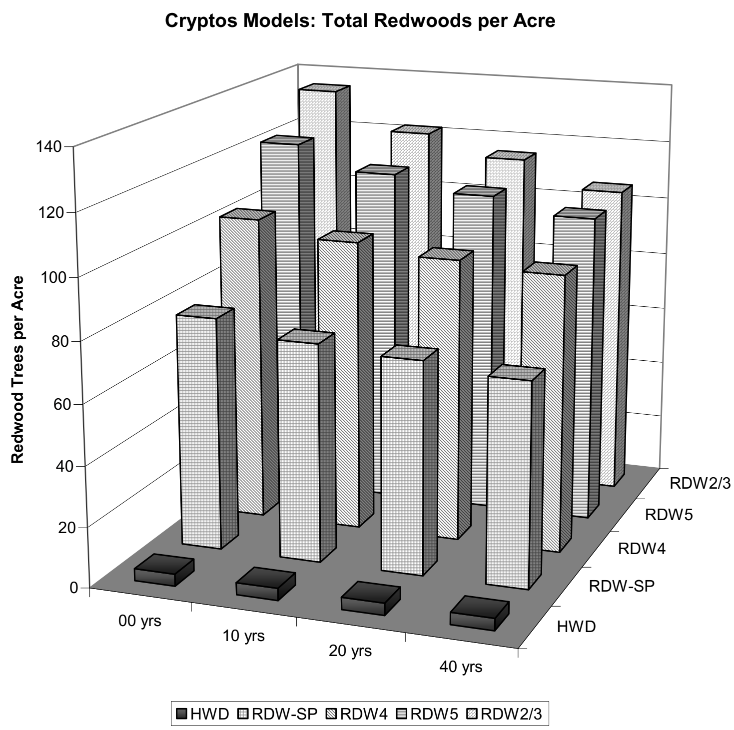

Figure 6-8: Future change in redwood trees per acre. CRYPTOS model results for consolidated riparian stands within the Freshwater basin.

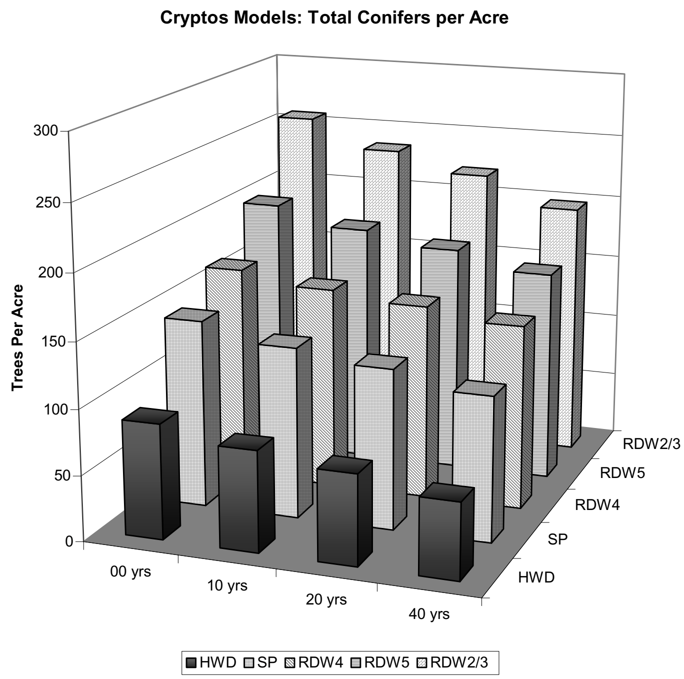

Figure 6-9: Total conifer trees per acre.

Table 6-7: Basal area for Freshwater riparian stand groups.

		RDW5	RDW4	RDW2/3	RDW-SP	HWD
		Basal Area (ft^2)				
Current	Redwoods	219	190	150	87	30
	Total	290	276	198	113	92
10 yrs	Redwoods	250	212	188	112	33
	Total	329	308	252	145	107
20 yrs	Redwoods	288	242	235	144	36
	Total	379	348	317	188	126
40 yrs	Redwoods	367	304	328	216	43
	Total	479	429	435	277	161

Table 6-8: Trees per acre for Freshwater riparian stand groups.

		RDW5	RDW4	RDW2/3	RDW-SP	HWD
Current	Trees/Acre Redwoods	122	103	135	78	4
	Total	200	165	257	144	88
10 yrs	Redwoods	114	98	122	73	4
	Total	186	156	235	131	77
20 yrs	Redwoods	109	95	115	71	4
	Total	176	150	220	123	69
40 yrs	Redwoods	104	93	106	68	4
	Total	163	142	198	111	58

Model results confirm what empirical observations and the key piece analysis had indicated–both near term and long-term LWD recruitment potential are good for the majority of riparian stands in the Freshwater basin. The large tree (RDW5) and small tree (RDW4) riparian stands currently have approximately 38 TPA at ≥22 in. dbh. At 40 years, CRYPTOS predicts that the number of trees per acre at ≥22 in. dbh will increase to 63 TPA and 52 TPA for RDW5 and RDW4, respectively. The stocking for very large diameter redwoods (≥40 in. dbh) will double in the next 40 years but will remain a relatively small component of the stand; only 12 TPA will occur in the RDW5 stands 40 years from now.

The young (CWHR2/3) moderate to dense redwood-dominated stands currently have a QMD of 15.7 in. Immediate LWD recruitment potential is limited for RDW2/3 riparian stands (3.5%, 4.8%, and 11% of riparian area for Class I, II, and II streams, respectively). These stands currently provide key piece functional size LWD as defined by Fox (1994) to small Class II and III streams (bankfull stream width ≤15 ft). There are, on average, currently about 34 TPA at ≥12 in. dbh within these young stands (RDW2/3). These stands will achieve 43 TPA at ≥22 in. dbh within 40 years. This future stocking is sufficient to provide key piece LWD to all but the mainstem Freshwater Creek. In 40 years, these stands will achieve 8 TPA at ≥40 in. dbh.

Near term recruitment potential for sparse and open redwood stands is poor; there are few trees of key piece size for LWD (≥22 in. diameter for all but headwater streams). These stands will only provide limited LWD recruitment opportunities for key piece LWD to stream channels with an average bankfull width of ≥20 ft during the next 20 years. The density of larger trees increases to 53 TPA at ≥22 in. dbh at 40 years. Therefore, long-term recruitment potential for these stands is good. These stands currently have only 1 TPA >40 in. dbh, and there is expected be only a slight increase of very large trees over the next 40 years assuming no silvicultural management.

Mixed redwood/hardwood and hardwood riparian stands have a QMD of 17.8 in., and the stocking of key piece size conifers will remain relatively low (<17 TPA at ≥ 22 in. dbh) for the next 40 years or longer. These stands contain few, if any, larger diameter (≥ 40 in. dbh) trees. These areas of poor LWD recruitment potential occur primarily in the lower Freshwater basin and uppermost upper Freshwater sub-basin; these areas are not owned by PALCO. Long term potential to achieve properly functioning condition is shown in Map D-3.

6.6 LWD RECRUITMENT MECHANISMS

Total LWD recruitment to a stream is a function of the rate of debris entering the channel and the rate of export. Wood recruitment may enter by a variety of natural processes including bank erosion, windthrow, disease, suppression mortality, breakage, landslides, and downstream transport within the channel (Keller et al. 1995). These processes often work in concert. The dominant process of wood recruitment varies by stream channel type, forest stand condition, and geologic setting.

A substantial portion of the LWD in the channels of the Freshwater basin is part of the legacy of historical management. Redwoods are highly resistant to decay, and the residence time of larger debris pieces can be centuries (Keller et al. 1995). Today, remnant woody debris from the time of the first harvest entry and earlier are present in the channels and on the forest floor. Logging debris accounted for 40% of the downed wood on the riparian forest floor within the surveyed plots.

Stand modeling confirms that suppression mortality within redwood-dominated stands is a relatively minor component of wood recruitment and is confined to smaller diameter classes. Bank erosion, historical disturbance, disease, and breakage generally account for a greater proportion of mortality than suppression.

While windthrow does not appear to be a dramatic problem for most areas of the Freshwater basin, it is a primary LWD recruitment mechanism. Excessive windthrow as evidenced by large portions of stands, particularly edges of buffers, was only apparent in the vicinity of the confluence of the South Fork with Freshwater Creek. Elsewhere, windthrow within the surveyed plots was dispersed over time and space. The cause of fall could be determined for 110 of 220 pieces of downed wood inventoried in the plots. Approximately one third of the pieces with a known cause of fall were attributed to windthrow. In-channel LWD inventories as reported in the Channels Module also note windthrow as a primary recruitment mechanism. The recruitment mechanism could be inferred for 433 out of 1,428 pieces of in-channel LWD inventoried. Windthrow was the recruitment mechanism for 40% of the wood for which the recruitment mechanism could be inferred, or 12.4% of all in-channel LWD inventoried. Windfall pieces in both the channel and the riparian area were highly dispersed (i.e., windthrow serves as an individual tree recruitment mechanism in the Freshwater drainage as opposed to cataclysmic events in which entire stands blow down during severe events).

Small streambank slides associated with bank erosion are one source of LWD to the channel. These features are found throughout much of the Freshwater drainage and were mapped by the Channel Module Team. This recruitment mechanism is most evident for stream channels of moderate to steep gradient (3.5% – 20%) within consolidated geology, and within steep gradients (>6.5%) within unconsolidated geology. Recruitment due to small streambank slides also occurs throughout Graham Gulch. On average, small streambank slides account for 0.4 piece

LWD/km/year and 0.004 key piece/100 ft channel/year recruited to the channel. Mass wasting including small bank slides accounted for 3.3% of all the LWD inventoried as reported in the Channels Module.

The LWD recruitment rate from bank erosion exclusive of small slide areas was also a primary recruitment mechanism throughout much of the Freshwater basin. One quarter of the in-channel LWD for which the recruitment mechanism could be inferred (104 out of 433 pieces) were attributed to bank erosion. This equates to 7.2% of all in-channel LWD inventoried. The importance of bank erosion for recruitment generally increases in a downstream progression within watersheds (Keller et al. 1995). Martin and Benda (In press) estimated that LWD recruitment rates from bank erosion exceeded mortality recruitment from Sitka spruce/hemlock old-growth forests at a point within a drainage basin in Southeast Alaska when the channel width reached 12 m. Locally, Keller et al. (1995) noted bank erosion to be the predominant recruitment mechanism for Prairie Creek, which is a low gradient meandering stream with a well-developed floodplain dominated by redwood.

6.7 RECRUITMENT RATES

LWD recruited to the channel within the last two years was identified during Freshwater field studies by the Channel Module Team. The input rate of wood is shown in Table 6-9 based on recruitment within the last two years. This period includes a large flood event that may bias the recent recruitment rate relative to long-term rates.

Table 6-9: Recent recruitment of LWD to channels

CGU	LWD m^3/km/yr	St. Dev	St. Error	# reaches sampled
C1	157	184	82	6
C2/3	13	16	7	2
GG/CG	48	49	22	5
MS1/2/3	24	42	19	7
U1	297	26	15	3

Based on actual in-channel wood counts of LWD recruited within an estimated period of no more than two years.

The Table 6-9 recruitment rates are considerably higher than those reported in the literature for other locations; differences are likely affected by the larger volume/piece for redwoods, as well as differences in methods for estimating recruitment rates. In a hemlock/Sitka spruce old-growth forest in Southeast Alaska, Martin and Benda (In press) reported a systematic increase in recruitment rates with increasing drainage area. They estimated recruitment rates ranged from 1 m^3/km/yr for the smallest drainage areas to about 16 m^3/km/yr at 60 – 80 km^2 (i.e., 0.4 to 6.4 trees per year based on an average volume of 2.5 m^3).

The amount of wood in the channel is a function of both the LWD recruitment rate and longevity of wood in the channel or depletion rate. Wood longevity is affected by many factors including species decay resistance, size of channel and corresponding stream power available to move wood, and the size of individual pieces of LWD. Murphy and Koski (1989) reported instream LWD longevity to range from 33-48 years for small LWD (10-30 cm diameter) to 77-125 years for large pieces (>90 cm) for hemlock and spruce in a Southeast Alaska forest. They reported a weighted mean average residence time for LWD of 54 years, but variation among channel types was noted. Their calculations more realistically represent the average time required for 100% turnover in LWD volume since the calculations are based on an exponential decay function arising from the computed half life of dated pieces. Redwoods are far more resistant to decay so residence times should be greater assuming no differences in stream ability to transport pieces. Keller et al. (1995) dated pieces of wood in Prairie Creek and Little Lost Man; both of these drainages are undisturbed redwood forest basins. The dated redwood LWD had been in the channel for 50 years to periods exceeding 200 years. This suggests that larger pieces of LWD of redwood origin can last several centuries within mid order channels. Given the harvest history in the Freshwater basin, the observed remnant old-growth pieces of redwood in the channels (exclusive of the lower mainstem) are at least nearly a century old.

6.8 RECRUITMENT SOURCE DISTANCES

The probability of a tree falling into the channel is inversely related to its source distance from the channel. Trees growing with roots in the streambank are most likely to be recruited to the channel due to their proximity and bank undercutting. The root diameter is approximately similar to the crown diameter (i.e., trees located from 0-30 ft from bank provide bank root strength).

Away from the streambank, the probability of a tree falling into the stream is a function of its height. Assuming random probability of fall direction and equal tree height, the horizontal arc in which a falling tree will intersect the stream is inversely related to distance from the stream. Fifteen published LWD source distance curves (9 empirical and 6 theoretical) are plotted in Figure 6-10. Two generalized curve equations were tested to see which yielded the best least squares fit to the 15 curves. The tanh function produced the lowest sum of squares for 8 of 15 curves (53%), including 5 of 9 empirical curves (55%) and 3 of 5 theoretical curves (50%). Table 6-10 summarizes the source data for each curve and the best-fit curve coefficients. The 15 curves can be grouped into three groups. The tanh coefficient (k) clusters are: low (flat curve) $0.015 < k < 0.18$; middle $0.023 < k < 0.028$ and high (initially steep curve) $0.036 < k < 0.058$. Table 6-11 compares the attributes for the curves based on the percent of the 15 published curves fitting each curve coefficient group.

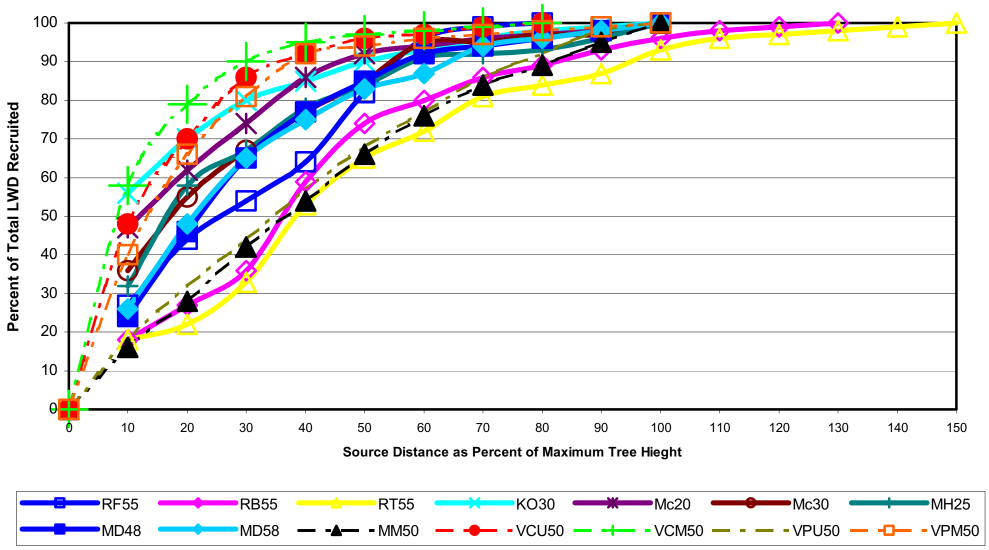

Figure 6-10: Published LWD source distance recruitment curves. Fifteen published source distance curves are depicted. See Table 6-10 for codes in figure legend

Figures 6-11 and 6-12 depict the recruitment source distance curves for empirical and theoretical (model) data sets, respectively. Computing LWD source distance as percent of maximum tree height standardized the data. The two graphs each show a best-fit curve, which was plotted using the hyperbolic tangent equation; the “k” coefficient was calculated as the median value of the individual “k” values within each group.

Source distance data were collected in the Freshwater basin by the Channels Module and Fisheries Module teams. Data were collected throughout Class I and II streams in the basin. The point of origin could be located for 158 out of a total of 1,446 pieces LWD inventoried. LWD source distances within the Freshwater basin are depicted in Figure 6-13 as a function of the co-dominant crown layer height. The majority of the Freshwater riparian areas are characterized by 4RWD or 5RWD (redwood plant communities with QMD >24 in.). Lower mainstem LWD data were screened so that the remaining data were primarily from stream sections bordered by these older second-growth forest types. LWD from structural enhancements and railroad structures were also not included in the computation of source distances. The LWD data were sorted by conifer and hardwood origin. The source distance for windthrow-derived LWD is plotted separately in Figure 6-13 since this is a primary recruitment mechanism.

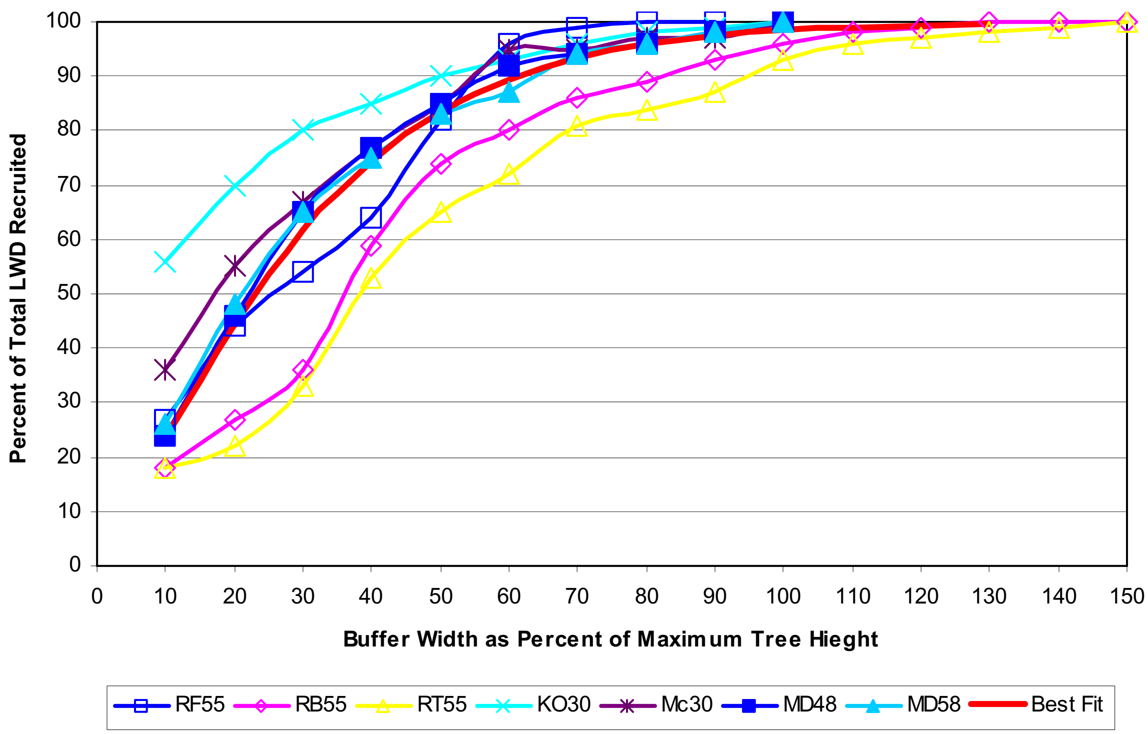

Figure 6-11: Source distance curves for empirical data.

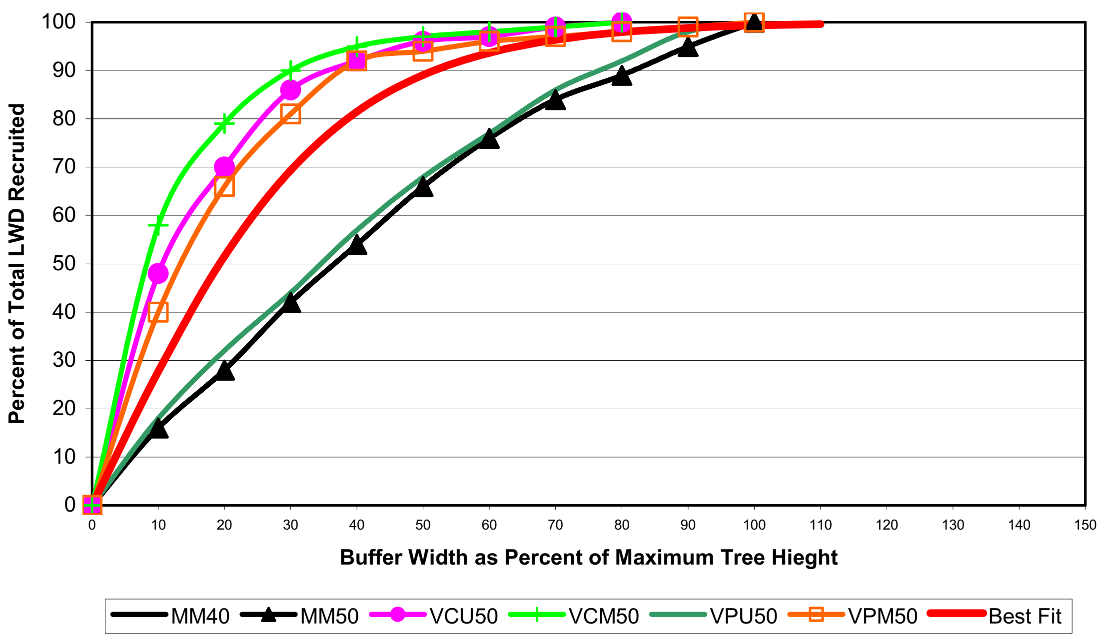

Figure 6-12: Source distance curves for modeled (theoretical) data.

Table 6-10: Comparison of published source distance curves for coarse woody debris delivery to streams.

Code	Authors	Empirical or Model?	Forest Type	Forest Condition	Adjacent Buffer, Clearcut, or Continuous Forest	Tree Height (m)	CWD Measure	Tree Fall Tendency	Least Squares Curve Parameters (x-Axis Standardized to % Max Tree Ht)			
									Beer-Lambert Equation		Hyp-Tangent Function	
									"k"	Least SS	"k"	Least SS
RB55	Reid & Hilton (1998)	Empirical	Redwood	Age 90-130	Buffer	55	Pieces	Downhill	0.023	483	0.017	209
RT55	Reid & Hilton (1998)	Empirical Trigger Trees	Redwood	Age 90-130	Buffer	55	Pieces	Downhill	0.020	384	0.015	163
RP55	Reid & Hilton (1998)	Empirical Trigger Trees	Redwood	Age 90-130	Forest	55	Pieces	Downhill	0.033	452	0.023	273
KO30	Murphy & Koski (1989)	Empirical	Spruce – Hemlock	Old-Growth	Forest	30	Pieces	Not Spec.	0.061	218	0.014	455
Mc20	McKinley (1997)	Empirical	Red alder	2nd Growth	Forest	20	Pieces	Not Spec.	-0.050	79	0.036	230
Mc30	McKinley (1997)	Empirical	Hemlock	2nd Growth	Forest	30	Pieces	Not Spec.	-0.040	50	0.028	131
MH25	McDade et al. (1990)	Empirical	Hardwood	Mature	Forest	25	Pieces	Random	0.039	37	0.028	157
MD48	McDade et al. (1990)	Empirical	Douglas-fir	Mature	Forest	48	Pieces	Random	0.035	101	0.025	7
MD58	McDade et al. (1990)	Empirical	Douglas-fir	Old-Growth	Forest	58	Pieces	Random	0.035	44	0.025	27
MM40	McDade et al. (1990)	Model	Douglas-fir	Not Spec.	Forest	40	Pieces	Random	0.023		0.016	139
MM50	McDade et al. (1990)	Model	Douglas-fir	Not Spec.	Forest	50	Pieces	Random	0.023	401	0.016	139
VPU50	VanSickle & Gregory (1990)	Model	Douglas-fir	Uniform Ht.	Not Spec.	50	Pieces	Variable probability, depending on slope and distance to stream.	0.024	416	0.018	166
VPM50	VanSickle & Gregory (1990)	Model	Douglas-fir	Mixed Ht.	Not Spec.	50	Pieces		0.055	17	0.039	28
VCU50	VanSickle & Gregory (1990)	Model	Douglas-fir	Uniform Ht.	Not Spec.	50	Volume		0.063	7	0.045	54
VCM50	VanSickle & Gregory (1990)	Model	Douglas-fir	Mixed Ht.	Not Spec.	50	Volume		0.080	14	0.058	78

Equation Forms
Beer-Lambert form is LWD% = 100 * (1 – Exp(k * SD%) and Hyperbolic Tangent form is LWD% = 100 * tanh(k * SD%)
Where LWD% is cumulative LWD input as a percent of maximum potential; "k" is a local coefficient; and SD% is source distance as a percent of maximum adjacent tree Height

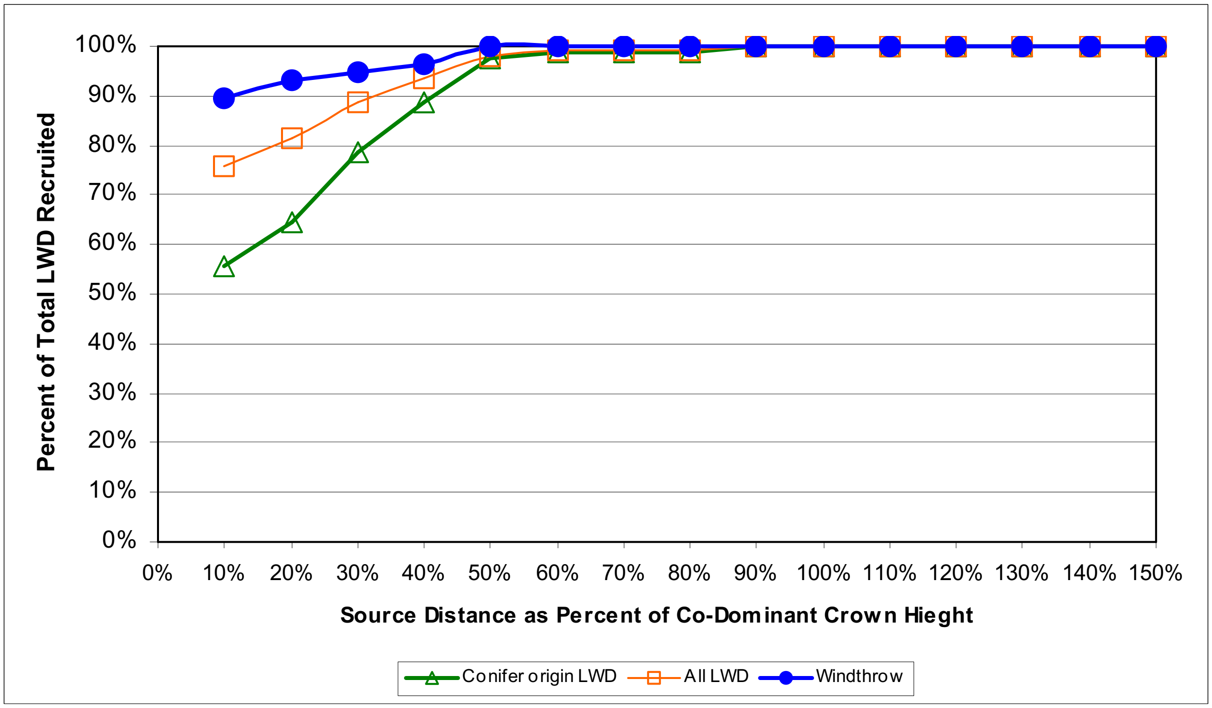

Figure 6-13: Source distance curves for Freshwater basin empirical data.

Source distances for LWD recruited by bank erosion are naturally small and are reflected in the two other curves shown in Figure 6-13. Source distances are computed as a function of tree height. The average height of trees in the co-dominant crown layer for these riparian types is 118 ft and 132 ft for 4RWD and 5RWD, respectively, based on direct measurements for plot inventory data. Tree height can also be estimated by the relationship between diameter and height. Based on data collected on PALCO lands, the relation is computed as Height = (5.552468 * DBH) + (-0.04358 * DBH^2), where DBH is measured in inches and height is estimated in feet; n = 16073 trees; r-square = 0.753; std error = 18.8 feet; and species predominantly redwood. Solving for the mean diameter of the co-dominant crown layer for 4RWD and 5RWD yields 114 ft to 118 ft. The LWD source distance data in Figure 6-13 are expressed as a function of a tree height of 118 ft.

Ninety percent of conifer origin LWD was recruited within 50 ft of the bankfull channel based on data collected on PALCO lands in the Freshwater basin. The inclusion of hardwood LWD has the effect of causing a greater proportion of the wood to be recruited closer to the channel. This is an expected result since hardwoods have a higher mortality rate, are typically found closer to the channel, and are not as tall as mature conifers. Windthrow appears to be a recruitment factor favoring areas close to the channel in the Freshwater basin (limited sample size of 58 pieces of LWD).

Table 6-11: Comparison of Study Attributes for LWD Source-Distance Curves.

Dichotomy	Percent of Curves in Each Group		
	Low (Midrange k-0.0165)	Mid (Midrange k-0.0255)	High (Midrange k-0.0255)
(1a) Empirical Curves (1b) Model Curves	40 60	100 0	40 60
(2a) Redwood Region Area (2b) Other Region Area	40 60	20 80	0 100
(3a) Downhill Falling tendency (3b) Random or Variable Falling Tendency	40 60	20 80	0 100
(4a) Buffer Adjacent or Near a Clearcut (4b) Buffer Adjacent Continuous Forest	40 60	0 100	0 100
(5a) Old-Growth Forest (5b) Mature, Second-Growth or Unspecified Age	0 100	20 80	20 80
(6a) LWD Study Attribute is Number of Pieces (6b) LWD Study Attribute is Cubic Volume	0 100	100 0	60 40
(7a) Maximum Tree Height >= 50 Meters (7b) Maximum Tree Height < 50 Meters	80 20	40 60	60 40

Each box shows the percentage split between (a) and (b) for the attributes described in the left hand column. The tanh coefficient "*k*" is equivalent to the shape of the recruitment source distance curve (i.e., a low *k* equates to a flat curve and a high *k* equates to an initially steep curve; the latter indicating most recruitment is from within a shorter distance from the stream).

Soils are moister close to the channel, making trees more prone to windthrow. The conifer origin LWD source distance recruitment curve in Figure 6-13 compares closest with empirical data from Murphy and Koski (1989). Like the Freshwater data, this latter study suggests that a greater proportion of LWD is recruited from closer to the channel relative to data reported for other studies. Bank erosion was a primary recruitment mechanism for the Freshwater, as well as within basins where Murphy and Koski (1989) collected their data.

There is inherent variability within LWD source distance data collected across forest types, stand ages, and areas subjected to different land use and climatic patterns. LWD accumulates over a long period of time. The standing riparian forest at the time of data collection may differ significantly from the forest stand condition at the time older wood was recruited. Details on data collection and analytical methods for the empirical data reported in the literature vary among authors. As an example, the method for determining maximum tree height is rarely reported but can affect the calculation normalized data expressed as a percentage of maximum tree height. Table 6-10 compares studies; however, a review of the original data would benefit a comparison among studies.

7.0 RESULTS FOR CANOPY CLOSURE

7.1 BACKGROUND INFORMATION

Water temperature is an important factor regulating aquatic life. The metabolism, feeding abilities, nutrient requirements, and growth rates of fish are either directly or indirectly influenced by water temperature. Temperature can also regulate competitive interactions among aquatic species and plays a strong role in a fish's susceptibility to diseases. Habitat suitability for other aquatic life including amphibians is affected by temperature regimes. The EPA (Brungs and Jones 1977) has guidelines for establishing temperature criteria for freshwater fish. Brungs and Jones (1977) describe the use of both maximum weekly average temperature (MWAT) and the short-term lethal exposure limit. The Properly Functioning Conditions Matrix (PFCM) (NMFS 1997) uses the MWAT as the temperature criteria to protect cold water biota, particularly anadromous fish populations. Brungs and Jones (1977) state that, “To maintain growth of aquatic organisms at rates necessary for sustaining actively growing and reproducing populations, the MWAT in the zone normally inhabited by the species at the season should not exceed the optimum temperature (OT) plus one-third of the range between the optimum temperature and the ultimate upper incipient lethal temperature (UUILT) of the species.”

$$MWAT = OT + (1/3)\ (UUILT - OT)$$

The OT is a physiological optimum and can be based on several different indicators of fish health. Brungs and Jones (1977) suggest that growth rate is the most sensitive function and integrates all physiological responses. The UUILT is the “breaking point” between the highest temperature that an animal can acclimate to and the lowest of the extreme upper temperature that will kill an organism. The MWAT for summer rearing coho was estimated by NMFS as 16.8^{o}C based on an OT of 13.2^{o}C based on Bjornn and Reiser (1991) and a UUILT of 24^{o}C. This value is slightly below the lethal limit reported in some publications; Brungs and Jones (1977) suggest a conservative approach to setting the UUILT. Other publications have reported both higher OTs and UUILTs for coho.

Stream temperature dynamics have been widely studied, and the physics of heat transfer is one of the better understood processes in natural watershed management. Changes in water temperature regimes in streams can arise from climatic changes or from human activities. Stream temperature is best thought of as an energy balance. A stream’s temperature is constantly adjusting to maintain equilibrium with its surrounding environment. Six primary heat transfer processes occur simultaneously, some of which add heat energy to the stream while others dissipate heat (TVA 1972, Brown 1969, Theurer et al. 1984, Adams and Sullivan 1990). The net heat flux determines the water body's temperature. Once a stream achieves this equilibrium temperature regime (typically occurring within a stream reach length of 2,000 ft or less for small to moderate streams (Caldwell et al. 1991, Robinson et al. 1995, Sullivan et al. 1990), it will continue to follow the same daily temperature pattern until the channel or climatic variables affecting the heat transfer processes change. Larger streams have greater mass, and cool groundwater inflow is a lesser proportion of total flow. Therefore, larger streams take longer to respond to changes in ambient conditions. While there are many specific climatic and physical variables accounted for in the stream heat energy balance, a sensitivity analysis of stream heating processes performed by Adams and Sullivan (1990) showed that four primary environmental variables regulate heat input and output and thereby determine flowing water temperature. These are ambient air temperatures at the stream surface, riparian canopy, stream depth, and groundwater inflow. Bartholow (1989) and Chapra (1997) rank air temperature as the most important variable influencing water temperature. Sullivan et al. (1990) note the importance of relative humidity's influence on water temperature; humidity tends to have greater influence in coastal areas where humidity is high.

Summer stream temperature increases due to the removal of riparian vegetation have been well documented (see Holtby 1988, Rishel et al. 1982, Swift and Messer 1971, Brown et al. 1971, and Levno and Rothacher 1967). These studies generally support the findings of Brown and Krygier (1967) that loss of riparian vegetation results in larger daily temperature variations and elevated monthly and annual temperatures.

7.2 METHODS FOR EVALUATING CANOPY EFFECTS ON TEMPERATURE

Several approaches to assessing riparian condition relative to its ability to maintain suitable stream temperatures for cool water biota were applied in the Freshwater analysis. Canopy cover (i.e., percent of overhead area screened from the sky by vegetation projecting over waters) was estimated from aerial photos and verified through field measurements. Canopy closure (the proportion of an overhead area within the riparian stand covered by tree crowns) was measured in the field with a spherical densiometer. Note that canopy cover applies to vegetation overhanging the channel while canopy closure is measured in the riparian stand and is distinct from the channel measurements. Future canopy closure was modeled with a correction factor applied to account for tree crown overlap. Finally, measured water temperature data collected by PALCO monitoring teams, the Fisheries Assessment Team, and the Amphibian Assessment Team were evaluated relative to the MWAT criteria of 16.8^{o}C.

Estimates of canopy cover over the channel were determined through aerial photograph analysis to the nearest 10% using the following guides for shade estimates (WDNR 1997):

Stream surface not visible	>85% shade
Stream surface slightly visible or visible in patches	70-85% shade
Stream surface visible but banks are not visible	40-70% shade
Stream surface visible and banks visible at times	20-40% shade
Stream surface and banks visible	0-20% shade

Field measurements of canopy cover over the channel were collected by use of a spherical convex densiometer. Values were recorded for each of four quadrant positions (upstream, downstream, and facing each bank) as described in Flosi and Reynolds (1994). A set of measurements was recorded for every fourth habitat unit within the channel adjacent to the RCU (or at 50-m intervals, whichever is less). A minimum of five sets of measurements were recorded for an RCU. All measurements were taken from the low-water thalweg. The canopy cover estimate at all of the measurement points were then averaged to yield the canopy cover estimate for the RCU. Canopy cover estimates were made as part of the fish habitat and amphibian habitat surveys. Canopy closure within the riparian stands was measured at two points within each 1/10th acre plot as part of the detailed riparian timber inventory.

7.3 RESULTS FOR RIPARIAN CANOPY AND STREAM TEMPERATURE

7.3.1 Canopy Cover over the Stream Channel

A high percentage of canopy cover occurs for most channels in the Freshwater drainage. Canopy cover averaged 81% (range 72% - 90% and st. dev $\pm$ 5%) for streams with adjacent mature second-growth redwood stands (RDW5D and RDW5M). Canopy cover measurements were made on 20 stream reaches having this riparian type. For channels with an adjacent sparse (RDW5S) riparian stand, canopy cover (over the channel) remained in excess of 85% for Class II and III streams. Young redwood stands (RDW3D) can still provide more than 85% canopy cover when the adjacent channel is small (<25 ft bankfull width). Canopy cover within mixed redwood/hardwood stands was slightly less with an average 75% canopy cover. The lowest canopy cover occurred along the lower Freshwater Creek below PALCO's ownership where riparian vegetation is often limited to shrubby growth along the banks.

Estimates of canopy cover made from the aerial photos generally corresponded well with field measurements, except for the closed canopy estimates. Those segments with 75-85% canopy closure over the channel as measured in the field were often assigned a rating of >90% canopy cover based on aerial photo criteria. The average canopy cover values as field measured over channels with a convex densiometer are reported by sub-basin in Table 7-1.

Table 7-1: Canopy cover over the channel for sub-basins of the Freshwater

Sub-Basin	% Canopy Cover (Field data)[1]	No. Reaches Surveyed	Aerial photo assessment of % Canopy Cover[2]
Lower Freshwater	71	4	70% – ≥90%
Upper Freshwater	79	6	70% – ≥90%
South Fork	84	5	≥90%
Little Freshwater	82	5	70% – ≥90%
McCready	78	2	≥90%
Cloney	80	3	≥90%
Graham	82	3	70% – ≥90%
School Forest	86	1	≥90%

[1] *Field measurements are based on multiple densiometer measurements of angular canopy cover as measured from the center of the stream channel.*

[2] *Aerial photo interpretation is based on visual criteria described in the PALCO Methods for Watershed Analysis (May 2000) and reflects an overhead vertical view.*

7.3.2 Canopy Closure

Canopy closure within the riparian stands was also typically a high percentage, with most stands types having >90% canopy closure. Table 7-2 reports the average canopy closure for each of the consolidated stand types. Data are from the detailed plot inventories and were collected with a spherical densiometer. Canopy closure conditions are also depicted in Map D-4.

Only the sparse to open stands had a canopy closure lower than the PFCM target of 85%. This condition occurs for approximately 6% of the streambank length for both Class I and Class II waters in the Freshwater basin. The causes of reduced canopy closure in sparse and open stands are as follows

Class I streams: Percent of total streambank length

- Pre-1974 clear cuts in the riparian area (0.7%)
- Narrow buffers reduce average riparian canopy closure (2.7%)
- Development (0.7%)

- Partial cut (0.5%)
- Other harvest 1.7%

Class II streams: Percent of total streambank length

- Narrow buffers reduce average riparian canopy closure (5%)
- Partial cut (0.8%)

Table 7-2: Canopy closure for consolidated riparian stand types.

Code	Description	% Canopy Closure
LC	Large/Medium Redwood: QMD 21.4 in.; >90%CC (RDW5d and RDW5M)	A & B plots 93% C plots 91%
SC	Small tree Redwood: QMD 20.3 in.; >90%CC (RDW4D and RDW4M)	86%
YC	Young Redwood: QMD 15.7 in.; 40-90%CC (RDW 2-3D/M)	90%
SP	Sparse to Open Redwoods: QMD 16.1 in; <40%CC for Dom/Co-Dominant (RDWS and RDWP)	62%
CH	Mixed redwood/hardwood: QMD 17.8 in, %CC variable (RDW/HWD, HWD/RDW)	94%
G	Grass	NA
H	Hardwoods	NA

7.4 HISTORICAL CANOPY CONDITION

The Freshwater basin was historically (pre-European) vegetated with redwood-fir forests, except in the lowermost portions (within ½ mile of Three Corners) and the upper headwaters of upper Freshwater Creek. The lowermost portion of the watershed is within the tidal zone; grassy vegetation in this area provides virtually no canopy cover greater than 1 m in height. The uppermost portion of the Freshwater basin, outside of PALCO ownership, was likely Douglas-fir and tanoak forest along riparian areas. These stands likely provided nearly complete canopy cover since the streams are small. Pre-European canopy cover for streams within redwood-fir plant communities were likely high as well.

Zinke (1988) (in Barbour and Major 1988) presents the following canopy closures for overstory plants for forest cover types found in redwood forests and associated north coast forests in Table 7-3.

Table 7-3: Canopy closure (densiometer) for old-growth forests

Tree Species	Canopy closure in redwood-fir forests (%)	Canopy closure in redwood-Douglas-fir-hardwood forests (%)	Canopy closure in Douglas-fir-hardwood forests (%)
Redwood	70	50	
Douglas-fir	5	5	50
Madrone		20	20
Tanoak		20	20
Grand fir	5		
Coast hemlock	5		
California bay			10
TOTAL	85	95	100

The canopy closure for pre-European riparian stands within the majority of the Freshwater basin would be representative of redwood-fir forests reported in Table 7-3; however, the values reported in Table 7-3 cannot be used directly to determine pre-European canopy cover over streams because they do not account for canopy reductions caused by the stream opening. As stream width increases, the percent canopy cover over the stream must decrease when the bankfull width exceeds the crown radius. Maximum canopy cover over the mainstem Freshwater Creek when old-growth conditions prevailed would have been less than 85% due to the wide stream width as well as areas of localized bank erosion and bar development.

7.5 FUTURE CANOPY CONDITION

The ability to evaluate future stand condition relative to the canopy's ability to provide thermal regulation to the stream is important to resource management. A modeling approach was applied to evaluate future canopy closure within the riparian stand. The application of CRYPTOS model results allows evaluation of future canopy condition based on current conditions. It also provides managers with a tool to evaluate the effectiveness of prescriptions. Canopy closure in this modeling effort is defined as the vertical canopy closure, which is inherently less than the angular canopy closure (the latter being the equivalent of the canopy closure measurement using a densiometer). A model which relies upon readily available and quantifiable stand parameters is preferable to reliance on the need for measuring parameters that are: (1) difficult to measure, (2) are prone to measurement bias, or (3) rely on subjective estimates (Olson et al. 1998). The quantitative analysis of future canopy conditions in the Freshwater basin is based on canopy closure within the riparian stand. As discussed in a later section, the relationship of canopy closure in the riparian stand to stream temperature regulation has not been fully established.

CRYPTOS model outputs include estimates for percent canopy closure for each crown layer in a stand at each time output step. This calculation is based on a tree crown model developed by Mitchell (1975), Wensel et al. (1987) for Douglas-fir and redwoods, as well as Paine and Hann (1982) for tanoak. The computations within CRYPTOS do no account for crown overlap among trees. Adjusting values for overlap is necessary when applying to an analysis of incipient light/ radiative heat interception. Several algorithms have been applied to growth yield models to account for tree crown overlap that are applicable to redwood forest communities found within the PALCO HCP lands. The development of these algorithms is fully explained in Olson et al. (1998). The steps used in applying these algorithms to compute vertical canopy closure for future conditions for the riparian stands occurring in the Freshwater drainage are outlined in Attachment D-3. The uncorrected and corrected for overlap estimates of canopy closure at each time step for each consolidated riparian type are provided in tabular form in Attachment D-3. A summary table of corrected canopy closure estimates for the next 40 years is also provided in Table 7-4.

The reduced canopy closure within sparse to open stands is expected to increase to 70% vertical non-overlapped canopy cover within 40 years. The sparse and open stands currently have 43% vertical canopy cover. Since spherical densiometers tend to overestimate canopy closure within the range of 50% – 75% canopy closure (Robards et al. 1999), this 70% value may measure in the field as levels near the PFCM target of 85%. Similarly, the redwood-hardwood RCUs will reach or exceed the PFCM target within 40 years.

Table 7-4: Percent vertical canopy closure within riparian units. CRYPTOS model results corrected for tree canopy overlap

	Stand Type					
Year	**RDW5**	**RDW4**	**RDW2/3**	**RDW-SP**	**RDW/HWD**	**Plantation**
Current	77	79	71	43	42	35
10	80	82	78	50	49	
20	84	84	83	59	57	
30	87	86	87	65	64	
40	89	88	90	70	69	83

7.6 MEASURED WATER TEMPERATURES AND MARITIME CLIMATE INFLUENCE

Instantaneous and continuous recording water temperature data have been collected for numerous stream locations throughout the Freshwater basin. These temperature records are representative of Class I, II, and III streams within various sub-basins. The maximum temperatures measured in the Freshwater Temperature data are reported in the Fisheries Assessment Report found temperatures ranged from 19.7°C measured in the mainstem of Freshwater in 1997 to 13°C measured in a headwater tributary the same year. The maximum weekly average temperatures (MWATs) ranged from 12.6°C to 17°C from early July through late October. Average summer water temperatures during all three sampling years ranged from 11.6°C to 16°C. The riparian condition for the stream reaches where temperature data were collected reflect the distribution of riparian types in the basin (i.e., most sites had dense redwood stands of >24 in. dbh trees); however, data are inclusive of sites with sparse stands, young plantation stands, and shrubby riparian vegetation. Even when canopy cover was as low as 70% due to a narrow, shrub-dominated buffer, the maximum weekly average water temperatures ranged from 12.6°C to 16.8°C from early July through late October. The lack of differences in stream temperature regimes despite differences in riparian canopy cover suggests that stream temperatures in the Freshwater basin are strongly influenced by a cool maritime climate. Maximum water temperatures in the Freshwater drainage are cool relative to streams for the larger northern California region (Lewis et al. 2000).

Summer climate regimes of the Freshwater basin are influenced by the inshore flow of coastal fog as inland temperatures rise. This phenomenon serves to maintain cool air temperatures and corresponding cool stream temperatures in the Freshwater basin. Lewis et al. (2000) found air temperature within northern coastal California to be a function of distance from the coast. This temperature distribution differs from an inverse relationship between elevation and temperature due to adiabatic heating (Sullivan et al. 1990). Using a Parameter-elevation Regression on independent slopes model (PRISM), Lewis et al. (2000) examined 30-year records of air temperature for northern California. These data were then used to map the extent of the coastal influence zone (Figure 7-1). The entire Freshwater drainage lies within the coastal influence zone and, thus, cool summer temperatures prevail. Water temperature data were not available for streams in the upper headwaters of upper Freshwater Creek. This area is outside of PALCO's ownership and lies within a different vegetation zone than the rest of the basin. The cooling influence of fog on warm summer days may be less of a factor in regulating water temperature within the headwaters of upper Freshwater Creek. Subsequently, warmer temperature regimes would be expected, except where cool groundwater inflow dominates the discharge in first order stream channels.

Based on field measurements and a regional analysis of climatic conditions, it is evident that the Freshwater basin does not experience stream temperature conditions that are adverse for salmonids and other cold water biota. This conclusion cannot be extrapolated to other watersheds without review. Within the Freshwater basin, field measured and modeled canopy closure estimates are high; canopy cover over the channel is generally high; most of the basin is affected by a cool marine fog climate regime; and summer water temperatures are cold.

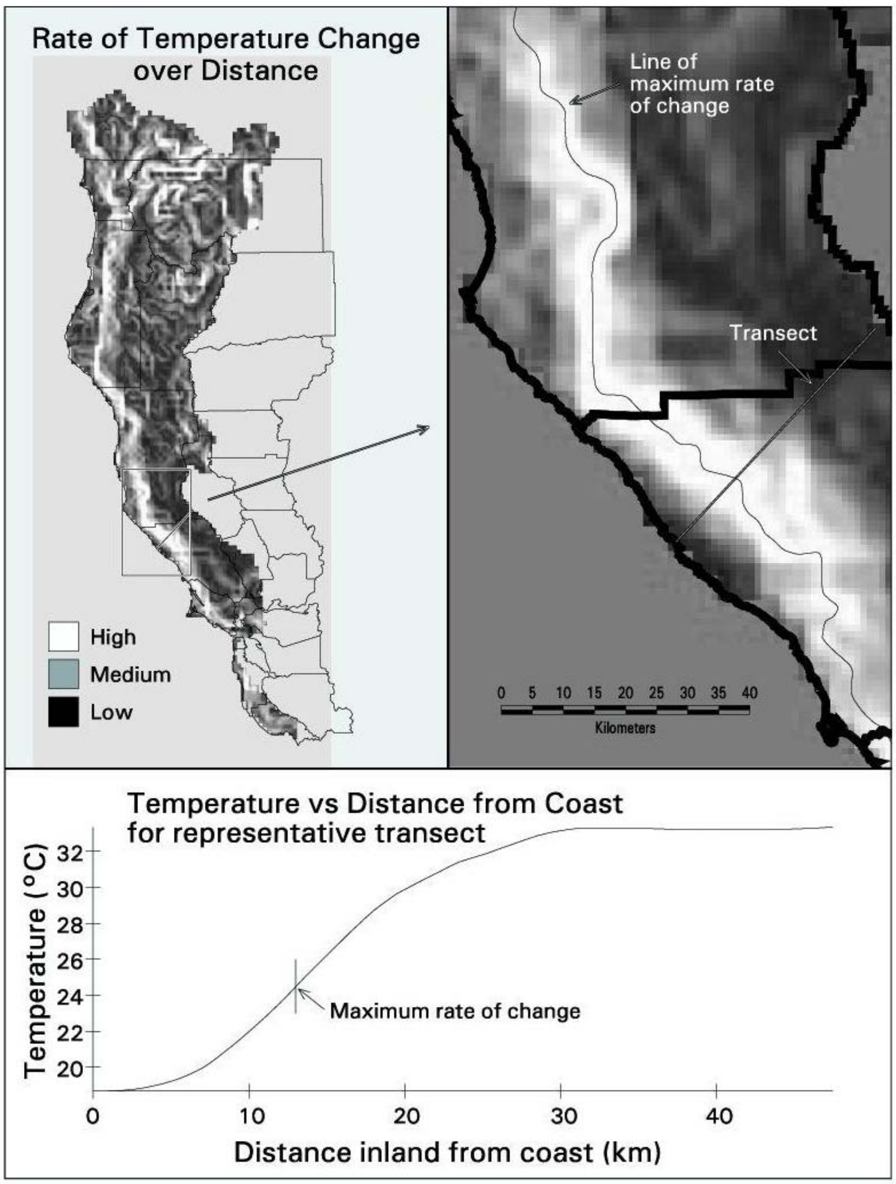

Figure 7-1: Coastal fog influence zone. (Lewis et al. 2000)

8.0 CONFIDENCE IN ASSESSMENT

The methods used in the Level II riparian assessment for the Freshwater basin provide a high level of confidence in the reported results. Supplemental methods were employed to ensure a characterization of historical, current, and future riparian conditions; the Riparian Assessment Team considers the information suitable to develop prescriptions when combined with the findings of other resource assessments for the Freshwater Watershed Analysis.

Professional foresters with extensive local experience completed aerial photo interpretation. Original color aerial photographs were used; electronically scanned images were initially reviewed but they did not have sufficient resolution. The initial aerial photo identification of the CWHR code tended to underestimate size class 5. The majority of riparian stands in the Freshwater drainage have a co-dominant crown layer comprised of redwoods with diameters near the break point for the CWHR class 4/5 distinction. Field verification by visual reconnaissance was completed for more than 85% of the Class I and II stream reaches. Those riparian segments initially coded as size class 4 were adjusted to size class 5 where visual field inspection warranted.

A comparison of CWHR size classification based on aerial photo interpretation with field verification and the detailed inventory plot data showed consistent results. The quadratic mean diameter as defined for use in CWHR aerial photo classification (QMDair) consistently over-biased on size class 5 redwood stands. The QMD calculated from plot data (QMDplot) is based on all trees in the plot with >5 in. dbh. The QMD plot for size class 5 plots was 21.4-22.8 in. As discussed for riparian resources in the Methods for Watershed Analysis (PALCO 2000), the over bias is due to the QMDair being based only on upper canopy trees, as the understory is not visible in moderate and densely stocked stands.

The plot data also provide a high level of confidence in aerial photo classification for other size classes. Aerial photo classification of stand size class is conservative relative to actual stand size in the Freshwater basin. The QMD plot for size class 4 stands was 20.3 in., which corresponds with the 12 to 24 in. range for CWHR class 4. The QMD plot for class 2/3 stands was 15.7 in. for class 2/3 combined; aerial photo interpretation under biased size class for this CWHR range of 1-11 in. dbh.

Aerial photograph analysis underestimated density class; aerial photo interpretation was deliberately conservative. For 35 out of 92 riparian segments where riparian canopy closure was measured, aerial air photo call underestimated by at least one density class. This underestimate bias applies to both inner 100-ft and outer 100-170 ft riparian bands. The aerial photo analyst defined CWHR density class as a function of the crown cover for the size class defining the CWHR code for a segment. The total crown closure as measured during plot inventories accounts for all crown layers so field estimates of canopy closure are greater. The field measurements are also based on convex densiometer readings which have been shown to overestimate vertical canopy closure due to the wider angle of measurement (Robards et al. 1999).

9.0 MODIFICATIONS AND RECCOMENDATIONS

The Freshwater Watershed Analysis is the first in a series of watershed analyses PALCO will be conducting under the HCP agreement. This section documents modifications to the methods described in the Methods for Watershed Analysis (PALCO 2000) as applied in the Freshwater assessment and recommends modifications for future analyses in other basins.

The assessment width was adjusted to 0-30 ft, 0-100 ft, and for Class I streams a third band of 100-170 ft. The default prescription for Class II streams is a riparian buffer width of 130 ft. To compile plot data for efficiency and statistical rigor, it is necessary to keep the assessment widths consistent for Class I and II streams. Delineation of the outer band for RCUs along Class I streams in the Freshwater basin was based on changes in the visual stand character. It is recommended that breakpoints for CWHR coding be based on RCU delineation for the 0-100 ft band and that the outer band endpoints be forced to match the inner band breakpoints. Inconsistent endpoints for the two band widths caused difficulty for using GIS to analyze the data.

The CWHR coding as described in the methods generates numerous stand types. While this may be appropriate in some applications, watershed analysis relies on evaluating riparian function at a watershed scale. Data compilation is necessary to identify processes and trends in a basin. A consolidation of CWHR codes was necessary for meaningful analysis. It is recommended that future watershed analyses only utilize a consolidated stand code similar to that developed for the Freshwater Riparian Function Assessment. Some additional stand types not found in the Freshwater basin may need to be added. The Freshwater Riparian Function Assessment did not include the understory within the CWHR code; however, understory crown layer data were available from the plot inventories. It is recommended that the methods be modified to not include coding of the understory in the CWHR codes unless the analyst believes specific information for a watershed is necessary for prescriptions development.

The intent of collecting plot data is to compile data among watersheds to be representative of riparian conditions across the landscape encompassed within the PALCO HCP lands. It is recommended that application of plot data collection in future watersheds focus on riparian types not found in the Freshwater but common elsewhere. Replication in other basins of plot data within stand types listed in the consolidated stand types for the Freshwater assessment will ensure that comparisons are appropriate and increase the data robustness.

The methods allows for adapting the criteria for proper function as applied within a specific area. The PFCM itself is not altered, but the criteria applied in a particular basin are adapted to fit the situation. The PFCM identifies key piece size. The evaluation of functional ability to recruit LWD was based on stocking densities of conifers with a diameter (dbh) greater than or equal to the key piece size. This modification is particularly warranted where in-channel LWD includes very large remnant pieces that can be expected to last for centuries in all but large river systems.

The Freshwater field assessment used different rating systems for documenting the decay level for downed wood on the forest floor and LWD in the channel. The consistent use of a single decay system is recommended. The rating system used by Grette (1985) is suggested as a tool that would allow better comparisons between in-channel wood data and forest floor woody debris data. Similarly, the literature lacks standardization of the metrics to quantify the amount of LWD; this situation makes it difficult to compare data among basins and regions.

Several studies are referenced that reported the age of downed wood as estimated from aging trees growing on the surface of the log. Collecting additional information on the longevity of downed wood, particularly LWD protruding into the channel, is recommended. Counting rings from cores or cross sections of nurse trees growing on logs partially in the channel is a relatively quick task that can be accomplished while collecting other field data on riparian condition. Murphy and Koski (1989) and Keller et al. (1995) provide a description for efficiently aging downed wood.

The canopy cover data from the aerial photo interpretation and the field measurements were not used for defining proper function because the PFCM relies upon canopy closure. The situation is further confused by the PFCM specifying a criterion for canopy closure based on densiometer measurements, which have been shown to be biased as well as inconsistent with most forest growth model predictions for crown closure. It is recommended that existing temperature data for the region be evaluated to develop nomograph relationships based on mapping attributes. Lewis et al. (2000) have made significant contributions to this effort. An analysis of those relationships and database relative to the MWAT criteria would likely prove to be a meaningful management tool. Emphasis should be placed on areas outside of the coastal fog zone that Lewis et al. (2000) have already generally defined. Currently, there is a dis-connect between the PFC for canopy closure and the objective of providing suitable water temperatures for cold water biota. While canopy closure within the riparian zone may have some as yet unquantified relationship to microclimate, the majority of stream temperature studies focus on canopy over the channel. The physics of heat flux for water bodies demonstrates that blocking net solar radiation (both long wave and short wave) influences a stream's equilibrium temperature. The canopy primarily provides this blocking over the channel.

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Appendix E

Freshwater Creek Watershed Analysis

Stream Channel Assessment

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EXECUTIVE SUMMARY

Stream channels of Freshwater Creek were classified into different groups (Channel Geomorphic Units, or CGUs) that have similar channel forms and processes and that are expected to respond similarly to changes in watershed inputs of sediment, wood, and water. Channel slope and geologic factors were the primary criteria for channel classification. Slope classes for channel classification purposes were 0-3%, 3-6.5%, 6.5-20%, and >20%. CGUs in the 0-3% slope class contain most of the fish habitat in the Freshwater. Spawning habitat is most abundant in C-type channels, and limited in U-type channels. Channels draining watersheds with weak sedimentary rocks of the Wildcat (the "U"-type CGUs) have characteristics that distinguish them from channels draining watersheds with Franciscan sedimentary rocks ("C"-type CGUs). U-type channels typically have abundant sand and silt, with very little cobble and gravel, whereas C-type channels have much more gravel and cobble. Channels that flow over exposures of Franciscan or Yager sedimentary rocks (the "C"-type CGUs) and also drain watersheds composed primarily of Wildcat rocks were grouped with channels draining Franciscan watersheds. The other major channel groups were the mainstem of Graham Gulch (CGU "GG") and the mainstem of Cloney Gulch (CGU "CG"), which had unique geologic characteristics, and the mainstem reaches ("MS"-type CGUs) of Freshwater Creek below the South Fork. The mainstem between Graham Gulch and Little Freshwater Creek is referred to as CGU MS2, while the reach below Little Freshwater is referred to as CGU MS3. MS2 and MS3 together are sometimes referred to as Lower Freshwater, and include the lowland areas prone to flooding. These lower mainstem reaches are bounded by floodplain sediments and bedrock on the channel margins; however, the channel is rarely confined by valley walls. The extent of bedrock exposed diminishes in MS3, and the abundance of sand in the bed increases.

Sediment source inventories and erosion modeling described in the Mass Wasting and Surface Erosion Modules were collated to produce a sediment input budget for Freshwater Creek, focused on the period 1942-1997. The sediment input budget allocates sources to background (natural) and management causes. For the period 1988-1997, the sediment input budget further distinguishes between legacy management sources and contemporary management sources. In addition, sediment transport was analyzed and bedload transport and routing modeled to investigate watershed scale aggradation issues. The bedload routing model predicts that a period of decades is required for gravel size material to be transported from the upper watershed to the lower watershed. Sand-size material is probably routed from source areas to lower Freshwater over a period of about a decade. The sediment input budget and the sediment transport model results were compared to data collected at a citizen-operated gage site in Freshwater and to bedload transport data from an adjacent watershed and to Caspar Creek data. These comparisons indicate that the sediment budget produces estimates that are in good agreement with the available data, and that the sediment budget is a valid tool for development of management prescriptions pertaining to erosion and sedimentation.

The impact of erosion on channel sedimentation status was assessed using a combination of channel survey data, channel monitoring data, and other applicable indices. For most of the watershed, a weight-of-evidence approach was used to assess the sedimentation status of channels. Few subbasins have consistent evidence of sedimentation. In lower Freshwater, data from historic cross-section and bed elevation surveys, observations by residents, and the sediment routing model were used to estimate the probable maximum range of bed aggradation. For MS2, maximum local aggradation was estimated to be 3 ft; there is evidence that this degree of aggradation is not present in the entire reach. For MS3, maximum aggradation was estimated at 1 ft.

Potential changes in flood frequency were quantitatively assessed. Increases in peak runoff estimated in the Hydrologic Change Module were considered along with potential aggradation. Flood frequency increases were predicted for relatively frequent floods; less effect was predicted for less frequent floods. The analysis indicates that peak flow changes alone have less impact than channel aggradation on changes in flood frequency. The potential effect of peak flow increases on scour of the streambed was also modeled. The assessment suggests that scour depth is not significantly affected by peak flow increases of the magnitude expected. The scour model used instead suggests that the grain size distribution is the dominant control on scour depth.

Large woody debris (LWD) abundance and function were also assessed. With the exception of MS-type CGUs, channels were on average well-stocked with LWD. Field surveys found that over 95% recently recruited LWD was from sources within 50 ft of the channel. A wide range of LWD sizes are capable of forming pools; LWD of 1 to 2 ft diameter commonly forms pools in the Freshwater.

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1.0 INTRODUCTION

The Stream Channel Assessment for the Freshwater Creek Watershed Analysis consists of multiple components, ranging from qualitative assessment to quantitative analysis and application of numerical sediment transport models. The Channel Assessment is based on detailed surveys and general site assessment, focused field investigations, and compilation of historic information and local observations. The approach and methods are described in greater detail in PALCO's Watershed Analysis Methods (PALCO 2000).

A great deal of information was available for this Watershed Analysis, including extensive inventory of both upslope and in-stream sediment sources, a few historic channel surveys and assessments, and detailed geologic mapping. The combination of prior and current research efforts makes this Watershed Analysis relatively data rich. The abundance of data from different sources and of different types presents challenges with respect to presentation and interpretation of the data.

A sediment budget, including both input and routing elements, has been constructed from Pacific Watershed Associates (PWA) erosion source inventories, the Surface Erosion and Mass Wasting Modules (Appendices B and A, respectively), and sediment transport modeling in the Stream Channel Module. The sediment budget provides context for understanding the balance between sediment inputs and sediment transport in the Class I stream channel network. The sediment routing analysis helps to address some of the residents' concerns about flooding, provides an assessment of sediment storage dynamics at the subbasin scale, and provides context for the development of alternatives.

1.1 CRITICAL QUESTIONS

The following critical questions were used to guide the analysis to produce the information necessary for the Watershed Analysis Team to understand stream channel processes in the Freshwater Watershed. To reduce the overlap between specific critical questions, the report is structured according to five major components addressing the major categories of critical questions. Nevertheless, significant overlap between critical questions remains, even at the level of the major categories. First, the report presents a description of the Channel Geomorphic Units (CGUs). This section would typically be the chief product of a Washington DNR Level II analysis. Second, the report presents the sediment budget, summarizing sediment delivered to the stream channel from upslope and near stream sources. Third the report covers sediment storage, transport, and routing using a mix of qualitative, quantitative, and modeling approaches.

Fourth, the report covers channel erosion, stability and response to hydrologic change. Fifth, the report covers woody debris and channel relationships. Finally, the report concludes with a summary of the analysis findings.

1.1.1 General Critical Questions

- What is the spatial distribution of channel response types?
- Is there evidence of channel change from historic conditions?
- What do existing channel conditions indicate about past and present active geomorphic processes?
- What are the likely responses of channel reaches to potential changes in input factors?
- What are the dominant channel- and habitat-forming processes in different parts of the channel network?

1.1.2 Supplemental Critical Questions (SCQ)

1.1.2.1 Sediment Storage, Transport, and Routing

- SCQ 1.1: What portions of the channel network are prone to aggradation in response to erosion and sediment delivery in the watershed?
- SCQ 1.2: What is the spatial and temporal distribution of flooding in relation to channel morphology?
- SCQ 1.3: What is the volume and distribution of stored sediment in the channel system?
- SCQ 1.4: What is the size distribution of stored sediment within the channel network and/or each storage compartment?
- SCQ 1.5: What are attrition rates for coarse sediment (cobbles and gravel) delivered to the channel system from the major bedrock types found in the watershed?
- SCQ 1.6: What is the character and magnitude of local channel response proximate to recent sediment input events (e.g., landslides)?

- SCQ 1.7: What is the timing of channel response to changed sediment inputs (i.e., what are the likely relative rates of sediment transport from source areas to depositional area of the channel network)?

- SCQ 1.8: Are there patterns at the watershed scale suggesting that the spatial distribution of stored sediment or grain sizes are affected by watershed sediment inputs?

1.1.2.2 Channel Erosion, Stability, and Response to Hydrologic Change

- SCQ 2.1: What is the relationship between peak storm runoff, channel sedimentation, and erosion and sediment transport? Alternatively, how do increases in peak runoff: (1) alter erosional processes? (2) alter sediment transport processes? (3) alter sedimentation processes (deposition)?

- SCQ 2.2: What is the cause, distribution (spatial and temporal), frequency, and volumetric importance of channel erosion along streams in response reaches?

- SCQ 2.3: How have channel conditions changed over time at the scale that can be observed in historic aerial photography and/or ground photography, and from field observations of anthropogenic features that record previous channel locations or conditions, and what are the implications regarding channel migration processes?

1.1.2.3 Woody Debris and Channel Relationships

- SCQ 3.1: What is the relationship between in-channel large woody debris (LWD), channel class, and formation of fish habitat features (pools, side-channels and other off-channel refugia, and patches of spawning gravel)?

- SCQ 3.2: What is the relationship between in-channel LWD, sediment storage, and sediment routing in different portions of the channel network?

1.1.2.4 Sediment Sources

- SCQ 4.1: What is the magnitude and distribution (spatial and temporal) of sediment delivery to streams from mass wasting, bank erosion, and other upland sediment sources?

- SCQ 4.2: What is the distribution of sediment sizes delivered to the channel system from various input mechanisms?

1.2 METHODS OVERVIEW

PWA collected field data over a period of about 1 year, including a period prior to initiation of the Watershed Analysis. The type of data collected and the objectives of field investigations changed significantly over this period. Field survey sites are shown in Figure 2-1, in the next chapter. Note that in addition to the sites shown on this map, the vast majority of the Class I channel network on PALCO's ownership was mapped and surveyed.

1.2.1 Bank Erosion and Stream-Side Landslide Inventory

The methods employed for the survey of stream-side sediment sources are described here because they are not part of the Watershed Analysis Methods. These sediment source surveys were conducted for another purpose, but we have utilized the data for Watershed Analysis.

Prior to the initiation of the Freshwater Watershed Analysis, streamside sediment sources were inventoried along the entire anadromous channel network (Class I streams) located on PALCO lands. In total, 17.5 miles (28 kilometers) of channel were inventoried between January and April, 1999. Bank erosion and streamside landslides with volumes greater than 10 cubic yards were identified, measured, and recorded on data forms and enlarged aerial photo base maps at a scale of approximately 1 inch = 250 ft. LWD accumulations were also mapped. This effort documented the distribution of "key piece" accumulations that play a structural role in the channel by altering channel hydraulics, or storing sediment.

1.2.2 Intensive Study Reaches

As indicated in the Watershed Analysis Methods, there may be different levels of detail and intensity of field data collection. Intensive surveys in selected reaches of Class I streams were primarily intended to provide detailed data on channel slope and channel cross-sections, active channel sediment storage, and grain size distribution. These data were critical for the sediment transport and sediment routing elements of the sediment budget. In addition, LWD volume and characteristics were intensively measured in these reaches to supplement LWD comparable monitoring data collected at PALCO monitoring sites.

Longitudinal profiles and channel cross-sections have been monumented and surveyed in each of the tributary subbasins, and in three reaches of the lower mainstem. Two sets of surveys have been established, each with different goals. PALCO established monitoring stations in 1997 that include long-profile thalweg surveys and three cross-sections spaced at 100-ft intervals. For this Watershed Analysis, PWA established additional cross-section and longitudinal profile surveys to characterize channel geometry, grain size, and gradient parameters for sediment routing calculations.

1.2.2.1 Channel Stored Sediment

The approximate volume of channel stored sediment was estimated along most of the study reaches (all located in the Class I channel network). Quantitative estimates were made for the volume and size distribution of sediment stored in bars, behind log jams, and along the channel bed. The information on size distribution is based on an estimate of the d50 and d84 along each bar or channel unit. Surface and subsurface Wolman pebble counts on some of the bars provide a means of estimating the general bias of the estimates.

1.2.2.2 LWD inventory

The distribution and functions of LWD were assessed at three separate scales:

1) Detailed inventories were conducted at the reach scale (over distances of 600 to 1,000 ft), and

2) locations of key piece accumulations were mapped at the larger channel scale (over distances of 2 to 4 miles), and

3) qualitative assessments of the abundance and function of LWD were noted during the reach characterization process.

The LWD inventory method is described in the Methods CD (April 2000 version). This inventory collects information on each piece of wood larger than a given size. Information is obtained on certain key metrics that have been used to characterize LWD distribution in other areas. The level of detail required for these inventories limits the proportion of the channel network that can be covered. Key pieces were mapped in the Class I channel network on PALCO ownership during the channel sediment source investigation (described above).

1.2.3 Reach Characterization

The reach characterization protocol is presented in the April 2000 Watershed Analysis Methods document, Stream Channel Module, Appendix A. The intent of the reach characterization process is to document channel conditions representative of distinctive channel types along the river continuum and across different geologic formations. Survey data included measurements of channel and valley geometry and systematic observations of riparian, floodplain, streambank and streambed characteristics.

1.2.4 Small Streams Investigation

A supplemental investigation of the smallest headwater channels (primarily Class III and some Class II channels) was conducted during the field phase of the analysis. The conclusions of this investigation are discussed in Critical Question 2.1. The Based on field observations from the sediment source inventory in Freshwater Creek (PWA 1999), it was hypothesized that incision of low order stream channels or unchanneled headwater swales may have occurred in response to hydrologic changes brought about by first cycle clearcut harvesting and burning in the basin. To test this hypothesis, inventory sites were selected from around the Freshwater Creek watershed, and within the unlogged Headwaters Forest, to provide field evidence that could be used to estimate the general magnitude of the erosion generated by this potential response process.

1.3 BASIN CHARACTERISTICS INFLUENCING CHANNEL PROCESSES

1.3.1 Geologic Mapping Units Found in Freshwater Creek Watershed

Channel and hillslope processes are strongly influenced by the underlying geologic materials. In the Freshwater Creek Watershed, five different geologic units interact to produce different channel types and different basin morphologies. (See the Mass Wasting Module Report for a more detailed geologic overview and the geologic map of Freshwater.) The Stream Channel Assessment Team relied primarily upon the map of Knudsen (1993) in development of the assessment. This map has only minor differences relative to the map presented in the Mass Wasting Module, and we do not believe that any significant differences in the Stream Channel Assessment would result from use of one map versus the other.

1.3.2 Summary of Geologic Properties in the Major Geologic Terranes

Geologic conditions control channel form and processes and strongly influence aquatic conditions. The Freshwater Watershed contains three major geologic terranes: Wildcat, Yager, and Franciscan Central belt, as described below.

The members of the **Wildcat Group** are soft and homogeneous, consisting of poorly consolidated mudstone, sandstone, and conglomerate. This makes for relatively simple channel forms in these reaches. The longitudinal profiles of channels in the Wildcat Group are characteristically steep in their upper reaches, and quickly transition to long, low-gradient channels. Substrate in these channels is predominantly sand and silt, with local accumulations of gravel. Gravels derived from the Wildcat are typically very soft and can be broken between one's fingers.

LWD is the dominant habitat-forming element in channels underlain by the Wildcat Group. Wildcat slopes are a major source of fine sediment following ground-disturbing activities. Surfaces denuded of vegetation and burned showed signs of rilling, with relatively minor concentrations of water.

Rocks from the **Yager terrane** are much harder, consisting of well-indurated sandstone, shale, and conglomerate. These rocks generate larger classes of gravel and cobble. Yager sandstone and conglomerate clasts can travel down channels and not immediately crumble. However, the shale member of the Yager will crumble in one season on the gravel bar if exposed to more than a few wetting and drying cycles. For this reason, attrition in the Yager is bimodal: the sandstones are competent, and the shales are weak.

The **Franciscan Central belt terrane** has the most lithologic diversity, consisting of greywacke, shale, chert, and schist. Short reaches of complex channels occur at contacts between lithologies. Some of these contacts appear to be fault-related. Large landslides are more common in the Franciscan, and these features can dominate channel morphology. Graham Gulch is an example of this channel dominance in the Freshwater.

In McCready Gulch and Cloney, the Franciscan appears in otherwise Wildcat-dominated channels due to faulting and stratigraphic relations.

Channel confinement varies most in the lower river due to local topographic influences. Most of the basin’s channels are confined and entrenched. Broad floodplains are mostly absent, except in the lower watershed where channel confinement and entrenchment both decrease.

The tectonic and stratigraphic relations between the five geologic formations determine where each of the different units appears (Figure 1-1). For example, the Yager terrane is located stratigraphically below the deposits of the Wildcat Group; it is most often exposed in locations where stream channels have cut down through the overlying sediments, or where faults have offset typical stratigraphic relations, bringing older geologic materials to the surface. Channel Geomorphic Unit (CGU) C1 in Little Freshwater Creek is an example of this process (see Section 2.0 for a description of the CGUs).

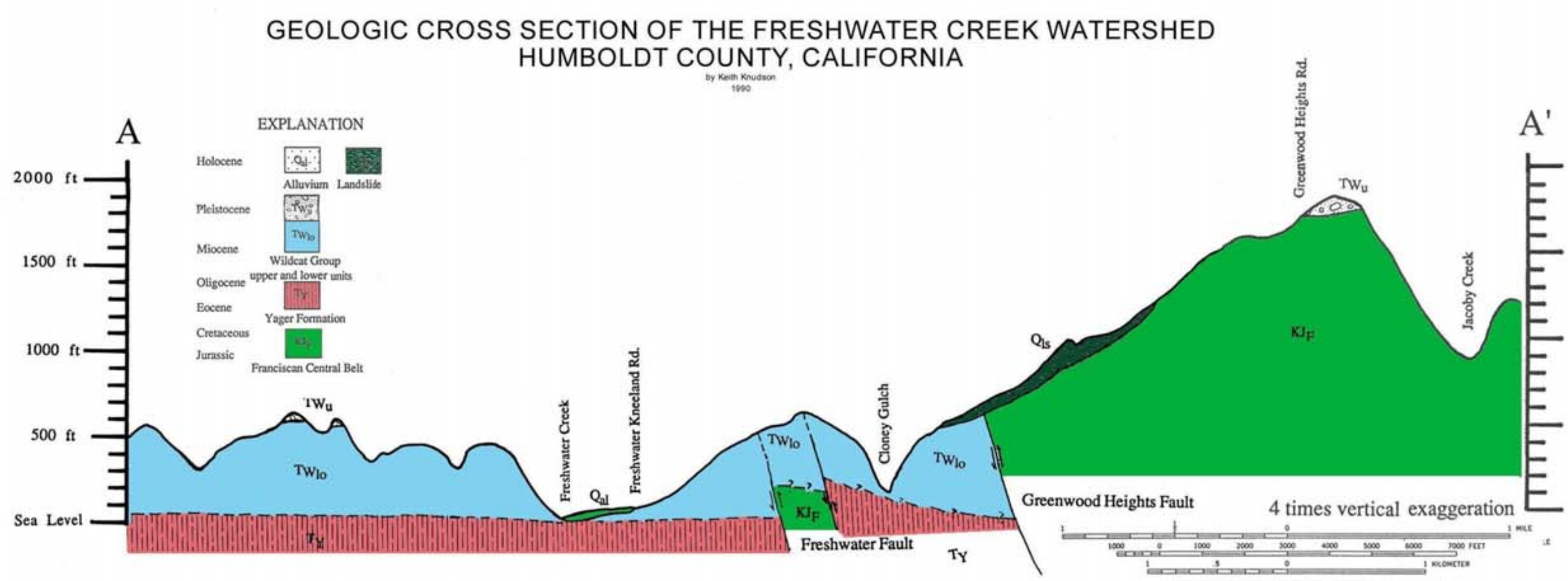


Figure 1-1: Geologic cross-section of the Freshwater watershed.

1.3.3 Channel Gradient Factors

Channel slope is one of the most important factors influencing channel form and processes. Longitudinal profiles derived from topographic maps (Figure 1-2) show the general differences in relief and in the distribution of channel gradients in basins underlain by the Franciscan Formation, and by the Wildcat Group. Some channels are underlain by a combination of bedrock types (e.g. Wildcat and Yager).

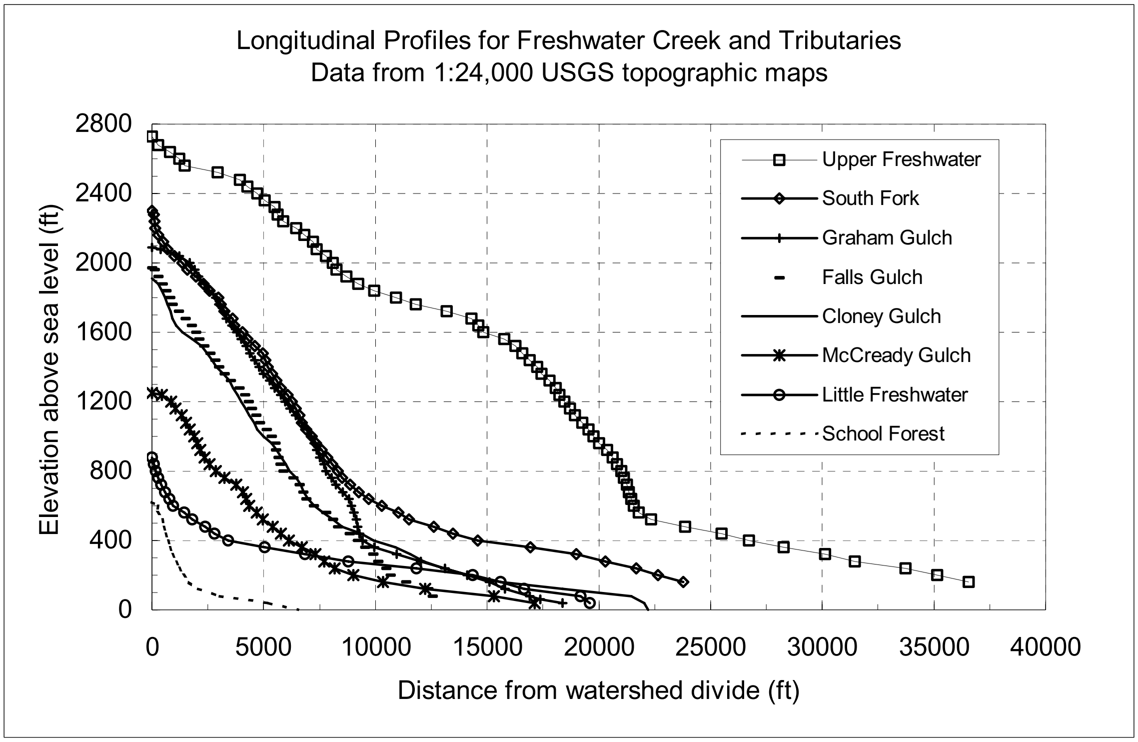


Figure 1-2: Longitudinal profiles for tributary basins to Freshwater Creek.

Comparison of longitudinal profiles is a useful tool for understanding the spatial distribution of processes and potential channel response to disturbance in a basin. Different geologic formations often exhibit characteristically different longitudinal profiles. For example, if one compares the differences in longitudinal profiles in watersheds underlain by Franciscan bedrock versus those in the Wildcat Group, it becomes apparent that the distribution of channel gradients is very different. The longitudinal profile for Little Freshwater Creek is very steep at the upper end of the channel, but quickly transitions to a long, low-gradient channel. In contrast, Upper Freshwater Creek has a stepped longitudinal profile with alternating steep and low-gradient reaches. Abrupt transitions in channel gradient correspond to faults mapped by Knudsen (1993). The shape of the longitudinal profile reflects the overall resistance of the bedrock geology in which the channels evolve. Channels with a mixture of geologic types have longitudinal profiles intermediate between the two end members described above.

2.0 GENERAL CHANNEL CONDITIONS

Channel Geomorphic Units (CGUs) are process groups that share certain key watershed characteristics, such as geology, channel gradient, and confinement (in the WDNR and revised PALCO Methods, CGUs are referred to as Geomorphic Map Units [GMUs]). CGUs can be used to subdivide the channel into discrete segments that are likely to respond similarly to different types of input or disturbance. For this analysis, CGUs are based primarily on channel gradient and the hardness, or resistance, of geologic formation underlying the channel. Different geologic formations have been lumped together based on their ability to generate coarse substrate and resistant outcrops in channels (i.e., consolidated or unconsolidated bedrock). This grouping reflects the role of bedrock type in the formation of fish habitat elements, bedrock roughness elements, and spawning gravel. Some exception CGUs have been defined to account for unique channel properties or processes related to either fish habitat or flood hazard.

For purposes of basin stratification (in the sampling sense), it is generally useful to group subbasins by their dominant geologic types (Table 2-1).

Table 2- 1: **Distribution of CGUs and geologic types in Freshwater channels and subbasins. See text below, for description of CGUs.**

Sub-watersheds	CGU	Basin Geology	Channel Geology
Upper Freshwater	C1-C4	KJf, Tw	KJf, Ty
South Fork	C1-C4	KJf, Tw	KJf, Ty
Graham Gulch	GG	KJf, Tw, Qls	KJf, Ty, (Tw), Qls
Cloney Gulch	CG	KJf, Tw	KJf, Tw, (Ty)
McCready Gulch	U1-U4; C1-C2	Tw (KJf)	Tw, KJf
Little Freshwater	U1-U4; C1-C2	Tw	Tw, Ty
Lower Mainstem			
Roelof's/MSBSF	MS1	KJf, Tw	Tw, Qal (Ty)
Langlois reach	MS2	Qal	Tw, Qal (Ty)
Harper reach	MS2	Qal	Qal, Tw
Hippen's reach	MS3	Qal	Qal, Tw

KJf = Franciscan Central belt terrane
Tw = Wildcat Group
Ty = Yager terrane
Q = Quaternary deposits (al – alluvium; ls – landslide).
Parentheses indicate minimal presence of this unit.

In Freshwater Creek, however, overall basin geology frequently differs from channel geology (the geology exposed along the stream channel) due to stratigraphic and tectonic relations. Basin geology refers to the material underlying an individual subwatershed area. In general, basin geology defines the context of watershed processes active in the basin, directly influencing relief, soil and subsoil properties, and erosional processes. Channel geology is more relevant at the reach scale, since local variations in bedrock strongly influence channel morphology, substrate, and habitat elements.

2.1 SUMMARY OF CHANNEL GEOMORPHIC UNITS

2.1.1 CGU Classes

Four separate CGU classes were defined in the Freshwater Creek watershed, consisting of a total of 13 separate CGUs. The CGU classes include:

U = unconsolidated bedrock (Wildcat Group)
C = consolidated bedrock (Franciscan Central belt terrane and Yager terrane)
MS = mainstem reaches (alluvial deposits and fluvial terraces)
Exceptions = Graham Gulch and Cloney Gulch mainstem (mixed geology, unique influences)

2.1.1.1 Lower Mainstem CGUs

The "MS" CGUs include three reaches, defined by their channel morphology and potential for flooding. Relatively high flood potential in MS2 and MS3 is demonstrated by both local experience of flooding and the Army Corps flood hazard map for the area (presented as Figure 5-2 later in this report). In addition, farther upstream (i.e., in MS1), the channel is steeper and incised in higher terraces. The ratio of terrace height to bankfull depth (TH:BD in Table 2-2) is <2 for MS2 and MS3; in MS1, the ratio is >3. This morphology, compared to that in MS2 and MS3 reach, suggests lower flood frequency in MS1. The Lower Mainstem CGUs include:

- MS1 = mainstem between South Fork and Graham Gulch; moderate-low gradient; no flooding
- MS2 = mainstem between Graham Gulch and Little Freshwater; low gradient, flood impacts
- MS3 = mainstem between Little Freshwater and Three Corners; very low gradient, flood impacts

2.1.1.2 Exception CGUs

Two CGU exceptions were defined based on properties unique to these channel segments, including: (1) elevated sediment loads, (2) continued influences of abandoned railroad features in the channel, and (3) combined influences of different geologic formations (i.e., the channels flow across multiple geologic formations). These exceptions include:

- **GG = Graham Gulch mainstem:** The mainstem of Graham Gulch is severely impacted by sediment derived from an earthflow in the upper third of the basin. Elevated sediment loads result in more mobile bedforms and concentrated inputs of LWD. Abandoned railroad features trap LWD, causing large jams in places. Graham Gulch flows across both the Kneeland Fault and the Freshwater Fault, resulting in abruptly juxtaposed geologic formations.

- **CG = Cloney Gulch mainstem**: Cloney Gulch also flows across these faults and has a mix of lithologic inputs. Approximately half of the basin is underlain by Franciscan Coastal belt rocks, while the other half is underlain by Wildcat sediments. There are also many remnant railroad features in the upper mainstem, which trap sediment and LWD. Although Cloney Gulch is considered somewhat unique for the reasons stated above, it is similar to CGU C1 in most respects.

2.1.1.3 Gradient Classes

Initially, we divided the channel network into five gradient classes (based on Montgomery and Buffington [1997]). However, the lowest two gradient classes were lumped for the final CGU classification based on similar fish habitat utilization in these two gradient classes. Both the "U" and "C" CGUs include four individual channel gradient classes:

U1 or C1 = 0 to 3%
U2 or C2 = 3 to 6.5%
U3 or C3 = 6.5 to 20%
U4 or C4 = >20%

2.2 CGU CHARACTERISTICS

A variety of field data were used to describe typical stream channel conditions and to infer the probable effect of changes in watershed inputs of sediment, wood, and water on stream channel conditions. These data include measured variables and ordinal (ranked) variables. A description of each CGU group and each CGU follows the presentation of summary data. These relatively brief descriptions focus on dominant channel characteristics and general locations of each CGU in the watershed. Interpretations of each CGU with respect to current conditions and the anticipated effect of changed inputs were developed collaboratively with the Fisheries Assessment and Amphibian Module leaders, and are presented in the Synthesis Module. Additional descriptive data regarding conditions in CGUs are presented in the Fisheries Assessment and Amphibian Modules.

2.2.1 Methods

This portion of the analysis relied primarily on data collected using the reach characterization protocol (presented in the April 2000 Watershed Analysis Methods document, Stream Channel Module, Appendix A). The intent of the reach characterization process is to document channel conditions representative of distinctive channel types along the river continuum and across different geologic formations. Survey data included measurements of channel and valley geometry and systematic observations of riparian, floodplain, streambank, and streambed characteristics. A map of field sites is given in Figure 2-1.

Field observations of channel conditions during sediment source surveys of 17 miles of Class I streams distributed throughout all subbasins (see Section 3.1) also contributed to the development of CGUs. LWD accumulations were also mapped. This effort documented the distribution of "key piece" accumulations that play a structural role in the channel by altering channel hydraulics or storing sediment. Such complete survey data for channels accessible to anadromous fish is unprecedented in Watershed Analysis and provided an unusually complete impression of the range of channel conditions

A brief description of each CGU is presented in Section 2.4. The location and distribution of CGUs is shown in map form in Figure 2-2. Annotated photographic images of many of the CGUs and other views of the Freshwater Watershed are provided in Attachment E-1.

2.2.2 Results

Values used for interpretative purposes are generally the mean values; however, the variability of data is indicated by the standard error of the mean in the summary table (Table 2-2). Ordinal data, typically numeric values where 0 represent none, 1 represents sparse or few, 2 represents common or moderate, and 3 represents dominance or great abundance, are presented graphically (Figure 2-5). The graphical plots have bars displaying the data range and dots on the

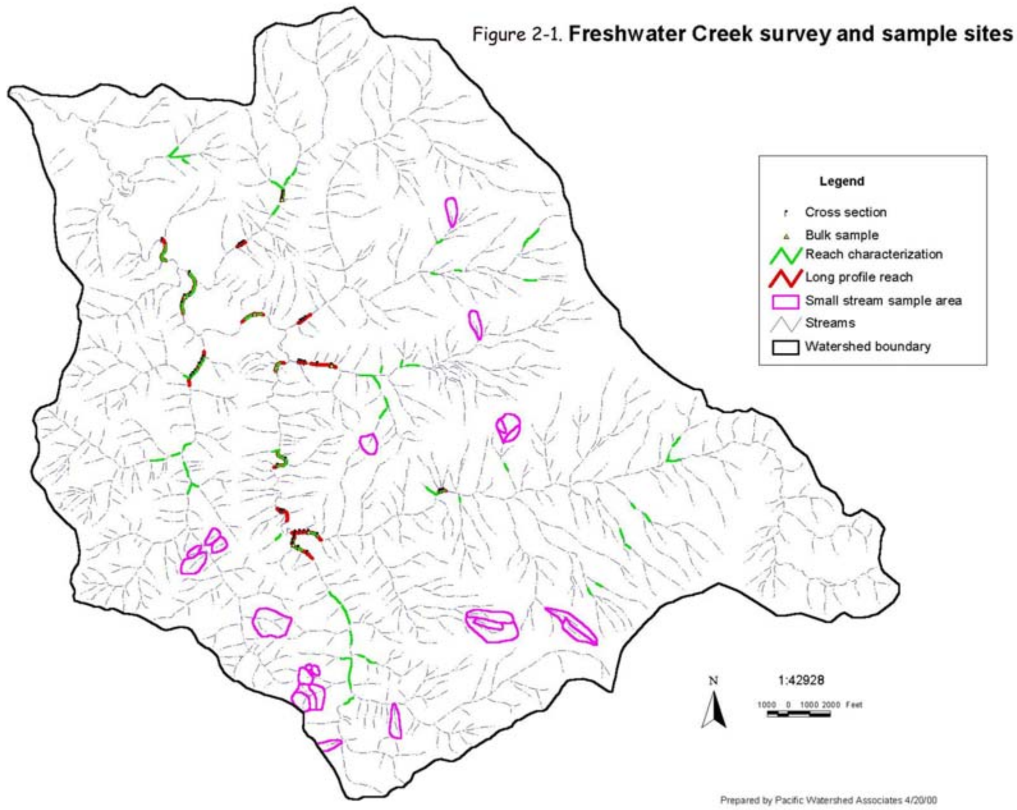


Figure 2-1 Sample Location Map

Figure 2-2 Location and Distribution of CGUs

bars indicating the mean value for each CGU. A separate plot is presented for each ordinal variable. Summary data used to help define and characterize CGUs are presented in Tables 2-2 and 2-3 and Figures 2-3 and 2-4.

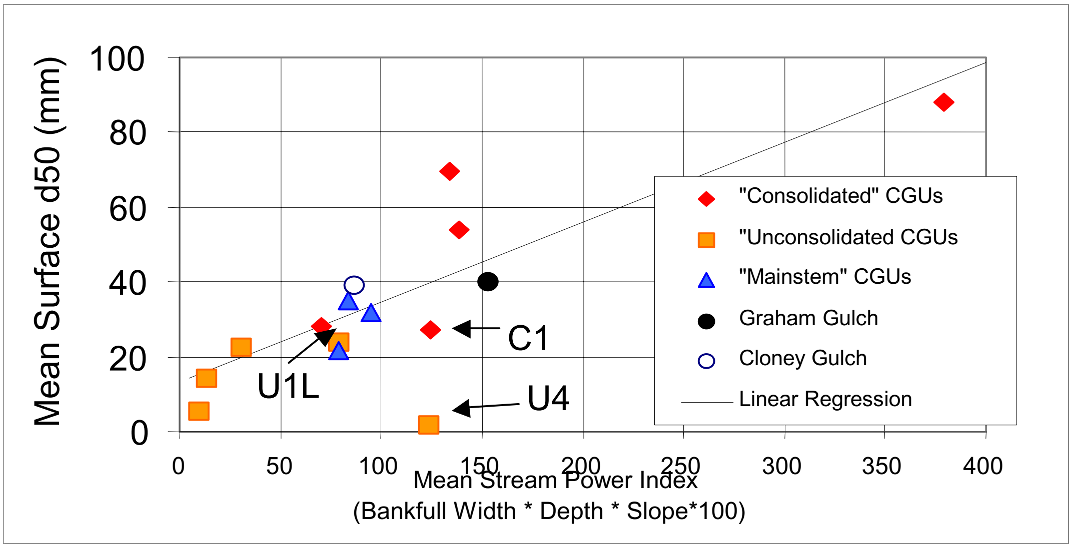


Figure 2-3: Plot of CGU mean stream power index versus mean CGU d50. The trendline has r-square of 0.77. CGU U4 is excluded from the trendline as an outlier; this channel type is steep and has a sandy channel bed devoid of gravel because of the parent geology. Note that the CGUs with fish habitat are clustered in the center of the plot.

Among the variables measured in the field, the essential elements of the channel geometry are used to help establish a simple geomorphic basis for comparison of CGUs. For this purpose, the product of bankfull width, depth, and slope is defined as the "stream power index." The stream power index indicates relative stream energy and is used to validate the channel classification. To this end, the mean surface d50 of the bed material was plotted as a function of the mean value of the stream power index (see Section 5.3.1 for a more detailed discussion). It would be expected that the size of bed material would be correlated with stream power. A trend line through these data suggests that typical CGU channel geometry (as represented by the stream power index) correlates with mean surface d50 (Figure 2-3). Moreover, Table 2-3 shows that the three major CGU groups (Unconsolidated, Consolidated, and Mainstem) can be clearly distinguished from one another on the basis of the stream power index and the range of median grain size. These relationships help establish the geomorphic basis for delineation of CGUs.

Table 2- 2: Mean and standard error for measured stream characteristics in each CGU.

CGU	Number of Sites		Drainage Area (ac.)	Channel Slope (%)	Bankfull Width (ft)	Bankfull Depth (ft)	SPI [(1)]	Unit SPI [(2)]	Mobile D50 (mm)	Surface D50 (mm)	Surface D84 (mm)	Max. Hillslope Angle (%)	Ave. Hillslope Angle (%)	Valley Width (ft)	Terrace Height (ft)	Reach Length (ft)	BW:BD	VW:BW	TH:BD
C1	12	Mean	2493	1.8	25	2.7	125	4.8	10	27	78	79	61	63	5.7	560	8.7	4.0	2.5
		Std. Error	495	0.2	3.5	0.2	31	0.7	10	5	9	9	5	10	0.4	103	0.8	0.3	0.2
C2	9	Mean	1400	4.4	14	2.3	134	10	21	70	183	78	58	44	5.5	417	6.5	4.2	2.5
		Std. Error	436	0.6	2	0.3	29	2	7	26	46	7	4	6	1.2	85	1.2	1.2	0.1
C3 (large)	5	Mean	1546	13	16	2.0	379	25	11	88	165	74	56	38	na	330	3.5	6.9	3.6
		Std. Error	754	2.0	3.9	0.3	82	3	4	34	48	7	6	5	na	20	0.4	0.9	0.6
C3 (small)	17	Mean	101	16	3.8	1.0	70	16	8	28	96	80	52	20	4.4	240	7.9	2.6	2.0
		Std. Error	19	0.8	0.9	0.1	24	2	2	4	15	5	4	1.8	0.6	37	1.0	0.5	na
C4	5	Mean	159	25	5	1.1	139	27	13	54	202	87	57	18	2.8	330	4.3	4.6	3.9
		Std. Error	76	3.9	1	0.2	75	6	7	14	75	8	7	3	0.3	44	0.8	1.0	0.4
U1 (large)	3	Mean	2329	0.9	26	4.25	79	3.1	13	24	51	63	50	70	6.8	333	7.1	2.7	1.8
		Std. Error	594	0.2	1.2	0.5	6	0.4	12	11	26	3	0	10	0.9	88	1.0	0.6	0
U1 (small)	4	Mean	160	1.9	3.6	1.5	9.4	2.7	1	5.5	69	73	56	68	3.9	200	2.5	18.7	2.7
		Std. Error	9	0.4	0.2	0.1	0.8	0.4	0	2.6	39	1	2	5	0.4	20	0.1	1.3	0.2
U2	3	Mean	92	4.5	2.7	1	13	4.6	1	14	63	58	47	57	3	150	2.8	29.3	2.4
		Std. Error	34	0.8	0.6	0.3	6.2	1.8	0	8	13	24	21	22	0.4	28.9	0.4	18.7	0.1
U3	4	Mean	139	13	3.3	0.8	31	8.3	11	23	53	70	56	24	5.8	150	3.8	9.4	4.8
		Std. Error	99	2.7	1.6	0.3	18	1.2	5	10	18	2.9	4.3	7.2	3.0	29	0.7	1.3	1.3
U4	4	Mean	9.5	19.5	6.0	1.0	124	20	1	2	10	66	51	6.8	n	276	6.0	1.2	--
		Std. Error	3.7	3.5	1.2	0.0	41	3.5	--	--	--	5.9	4.3	0.9	--	39	1.2	0.1	--
GG	5	Mean	1296	4.4	20	2.1	153	9	4	40	116	123	73	50	5.3	436	9.4	3.2	2.7
		Std. Error	148	0.9	2.5	0.2	29	2	3	11	29	13	5	13	0.5	105	0.5	0.9	0.1
CG	1	Value	3009	0.9	24.0	4.0	86	3.6	--	39	73	--	--	--	9.7	1000	6	--	2.4
MS1	4	Mean	8035	0.7	43	3.4	95	2.2	16	32	77	35	15	175	10	713	12.9	4.1	3.1
		Std. Error	139	0.1	7.8	0.4	27	0.3	--	6	13	--	--	--	0.9	205	2.3	--	0.4
MS2	1	Value	13154	0.4	50	4.2	84	1.68	10	35	70	10	10	450	7	1000	11.9	9.0	1.7
MS3	3	Mean	18318	0.4	46	4.5	79	1.7	7	22	59	15	3	500	6.8	1200	11.7	11.0	1.9
		Std. Error	581	0.03	2	1.0	21	0.5	3	2	6	13	2	0	1	346	3.3	0.6	0.9

[1] SPI: is the stream power index, equal to the product of bankfull width and depth and slope in percent.

[2] Unit SPI: is the SPI per unit channel width. The index of stream power is used as an indicator of stream energy.

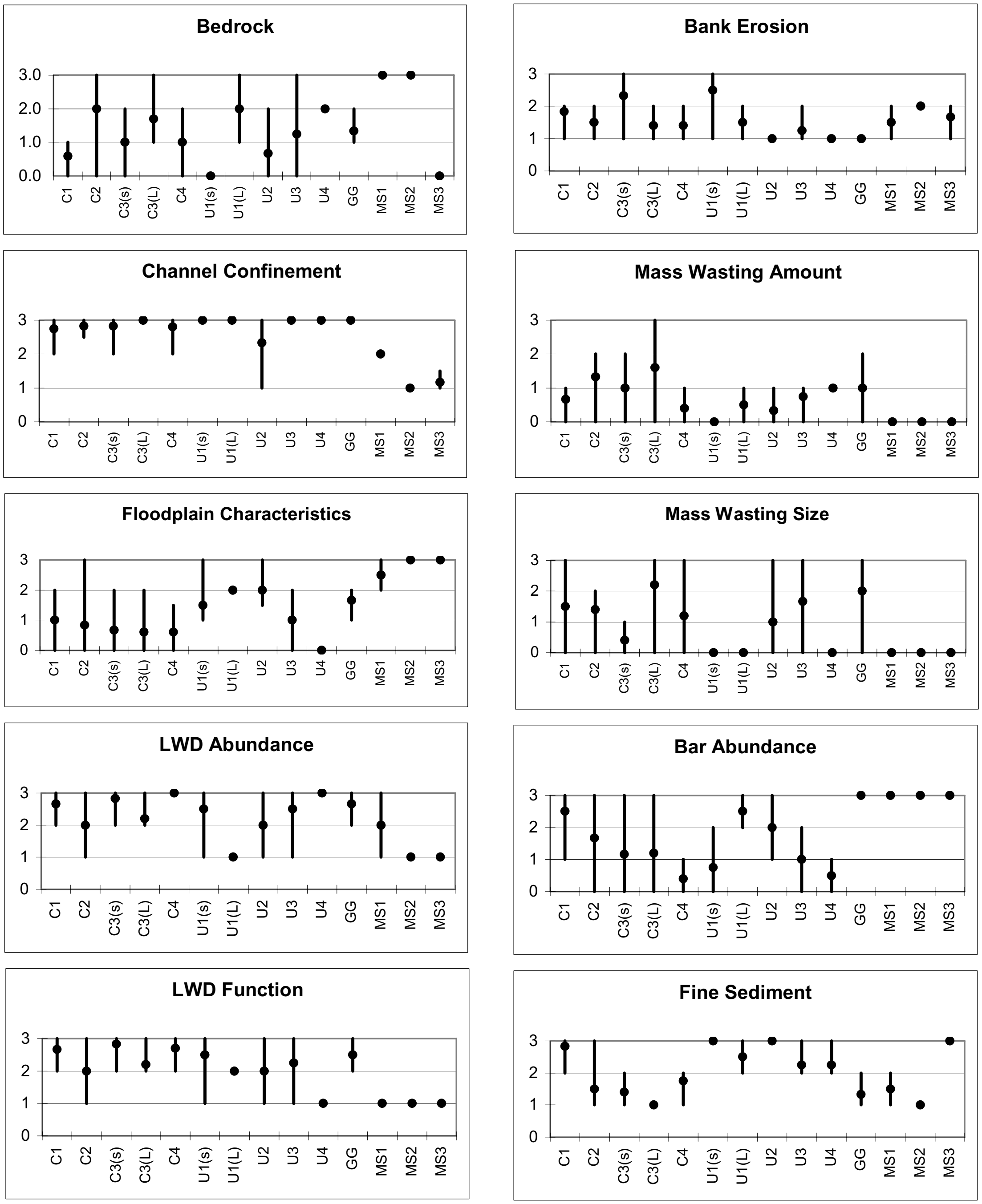


Figure 2-5: Summary of selected stream characteristics expressed as ordinal data. The field definitions for ordinal data are summarized in the following table. These data support CGU delineation; however, they are also used in some to help answer some critical questions. These data are also used to help develop CGU "vulnerability" assessments in the Synthesis Module.

Legend for Figure 2-5: Summary of field definitions for ordinal data.

Bedrock:
0=none
1=present but minimal
2=common
3=dominant

Channel Confinement
1=unconfined
2=moderately confined
3=confined

Floodplain Characteristics
0=no floodplain or terrace
1=terrace with no evidence of historic flow
2=discontinuous but significant floodplain
3=continuous or nearly continuous floodplain

LWD abundance
0=none
1=sparse
2=common
3=abundant

LWD function
1=minimal
2=functional
3=dominant

Bank erosion/ Mass Wasting Amount
0=none
1=sparse, <5% of channel length
2=common, 5-20% of length
3=abundant, >20% of length

Mass wasting size
1=small, height up to 5x bank height
2=medium, height 5-10x bank height
3=large, height >10x bank height

Bar abundance
0=none
1=few
2=common
3=abundant

Fine sediment
0=none
1=sparse
2=moderate
3=abundant

Table 2-3: Summary of the range of values of d50 and stream power indices for the three dominant CGU groups. The higher stream power for the Consolidated CGUs reflects the steeper channel gradient for a given drainage area found in the more resistant Franciscan bedrock. This contrasts sharply with the Unconsolidated CGUs where easily eroded Wildcat Formation rocks have relatively low channel gradient for a given drainage area relative to the Franciscan. The data are shown in Figure 2-3 above.

CGU Group	d50 Range (mm)	Stream Power Index Range
Unconsolidated	1-25	10-125
Consolidated	25-90	70-380
Mainstem	20-35	80-95

2.3 Channel Migration

In the upper watershed and tributaries, channels generally cannot be clearly observed, owing to riparian canopy closure. These tributary basins, and upper mainstem reach of the Freshwater, have steep streamside slopes, are frequently bounded by bedrock, and have relatively narrow, confined channels (see Figure 3-5 regarding Channel Confinement and Floodplain Characteristics). Surveys of these channels revealed bank erosion processes but no significant lateral channel migration. Therefore, it was concluded there is little potential for significant channel migration, except locally in CGU U1-L.

In lower Freshwater (CGUs MS2 and MS3), where channel confinement (Figure 3-5) and the ratio between terrace heights and bankfull depth (Table 2-3) declines, a well-established floodplain exists, and there appears to be potential for channel migration (Figure 5-1). However, it was apparent that there have not been major changes in channel location and planform geometry since the 1940s. In areas of the watershed where the channel can be seen in aerial photography (i.e., lower Freshwater below Graham Gulch), this was confirmed by comparing channel position in the 1948 aerial photography with the 1997 aerial photography (Figure 5-1). This was also consistent with channel position shown in the 1975 Army Corp flood zone map (Figure 5-2).

In contrast to some other northcoast streams (e.g., Bear Creek, Jordan Creek, and Cuneo Creek), Freshwater Creek does not show major changes in planimetric channel form over the period of historic record (1941 to present). There are likely a few reasons for this lack of observed channel changes. First, the predominance of fine sediment coming from three of the major subbasins reduces the volume of coarse sediment that would typically induce episodes of channel migration. This reduces the likelihood of coarse sediment accumulations of sufficient volume that could induce channel avulsion or rapid bank erosion that causes channel widening or lateral channel migration.

Another potential cause of channel avulsion is accumulation of woody debris in large jams, which induce rapid bank erosion or formation of a new channel. The history of land use in Freshwater probably has reduced woody debris abundance in the lower Freshwater; however, the lowest recruitment potential for LWD exists along the banks of lower Freshwater (see the Riparian Function Module for further discussion). This is due to the absence of large coniferous trees and the predominance of hardwoods, shrubs, and grasses in the riparian zone. Consequently, LWD abundance in these reaches is low (see Section 7.1) and woody debris jams rarely form. Where jams do form, channel avulsion and migration can occur under modern conditions (see Section 7.1.1).

In 1948 aerial photography, there is weak evidence of side channels or overbank flood channels over an area <1,000 ft in length at the confluence of Cloney Gulch and Freshwater Creek. The evidence consists of arcuate stands of riparian hardwood trees in positions consistent with such channels. The channels themselves are not visible, and these stands could record the position of channels in decades prior to 1948. These stands of trees may have other origins. Local residents stated that this area was subject to gravel mining, which could also explain the conditions observed in 1948 photography.

The absence of lateral channel migration in lower Freshwater suggests that erosion and sedimentation process in the watershed are relatively modest (see Section 5.1). As noted above, low gradient channels that receive significant and rapid coarse sediment inputs from upstream areas typically respond by widening and or migrating laterally, or both.

2.4 CGU DESCRIPTIONS

2.4.1 Consolidated Bedrock Reaches (CGUs C1 - C4)

Both the Franciscan Central belt terrane and the Yager terrane consist mostly of well-lithified marine sedimentary and meta-sedimentary rocks, which have the potential to provide competent substrate for aquatic organisms. The Franciscan Central belt terrane is far more diverse lithologically than the Yager terrane; for purposes of providing coarse bed material to channels, however, they have similar characteristics.

The two terranes differ in terms of their overall structure and slope-forming processes. The Central belt terrane is a tectonic melange, or mixture of accreted materials derived from diverse geologic sources. It consists of blocks of hard rock floating in a matrix of sheared material. The sheared matrix consists primarily of fine-grained materials (sand, silt, and clay), while the blocks can range from gravel and cobble-sizes to huge boulders. When boulders are introduced to the channels through earthflows or large landslides, they can dramatically influence channel form and processes. For example, large boulders in the channels effectively reduce channel widths, create short cascade reaches, and trap wood, leading to the formation of stable LWD accumulations. Large stream-side landslides and earthflows occur mostly in the portions of the watershed underlain by Franciscan Central belt terrane.

The Yager terrane consists almost entirely of sandstone, shale, and conglomerate. While the Yager terrane is locally sheared and faulted, it is far more homogeneous in composition than the Central belt terrane. The sandstone and conglomerate units are relatively resistant and form good spawning substrate and amphibian habitat. However, the shale unit is extremely friable when exposed to wetting and drying cycles, disintegrating readily following transport and deposition on the surface of gravel bars.

C1 - Low Gradient Reaches (0-3% in Consolidated Bedrock)

Descriptive Characteristics

Summary Values for C1			
Channel Slope (%)	1.8	Bankfull Width: Bankfull Depth	8.7
Bankfull Width (ft)	24.9	Valley Width: Bankfull Width	4.0
Bankfull Depth (ft)	2.7	Terrace Height: Bankfull Depth	2.5
Valley Side Slope (%)	60.8	Mean d50 (mm)	27
Valley Width (ft)	62.5	Mean d84 (mm)	78
Terrace Height (ft)	5.7	Mean d50 for mobile patches (mm)	10

CGU C1 is moderately powerful with relatively confined and entrenched channels. Streambeds are dominated by gravel and cobble, with bedrock exposed in banks and occasionally in the bed. Mobile gravel and cobbles are deposited on bars and in association with LWD. Gravel bars are abundant. Reach average median grain sizes range from about 50 mm in Upper Freshwater to about 20 mm in McCready Gulch and South Fork Freshwater. Coarser material is relatively abundant in Upper Freshwater. Channel morphology in C1 reaches include predominantly pool riffle, with some plane-bed reaches. Channel substrates vary considerably, depending in part on watershed lithology. Fine sediment is relatively abundant (Figure 5-12), and deposits of sand are often present in pools (Table 5-5).

Most of the C1 reaches are located in the lower portions of Upper Freshwater Creek and the South Fork of Freshwater Creek. Shorter, less continuous C1 reaches are found in portions of McCready Gulch (downstream of Horse Gulch), where faulting has thrust Franciscan rocks into a matrix of Wildcat sands. C1 reaches are also found in the middle mainstem of Little Freshwater Creek, where the channel has incised through the Wildcat sands to the underlying Yager Formation. In Little Freshwater Creek, the C1 reaches are especially significant, since they provide some of the only competent rock in the basin. The low-gradient nature of these reaches and the more competent nature of the substrate make this CGU the most productive one for salmonid spawning and rearing.

C2 - Moderate Gradient Reaches (3-6.5% in Consolidated Bedrock)

Descriptive Characteristics

Channel Slope (%)	4.4	Bankfull Width: Bankfull Depth	6.5
Bankfull Width (ft)	13.9	Valley Width: Bankfull Width	4.2
Bankfull Depth (ft)	2.3	Terrace Height: Bankfull Depth	2.5
Valley Side Slope (%)	58.3	Mean d50 (mm)	70
Valley Width (ft)	43.9	Mean d84 (mm)	183
Terrace Height (ft)	5.5	Mean d50 for mobile patches (mm)	21

CGU C2 is a moderately powerful channel, comparable to C1, but with a distinctly coarser substrate. It has cobble/gravel bed channels with bedrock commonly exposed in the banks and bed. Mobile gravel and cobbles are deposited on bars and in association with LWD, but bar abundance is lower than in C1. Average median grain size is much coarser than in C1. Channel morphology is predominantly pool-riffle and step-pool, with steps formed either by LWD accumulations, bedrock, or boulder accumulations in the channel.

C2 reaches are found in the middle and upper mainstem reaches of Upper Freshwater and the South Fork. Shorter, more isolated C2 segments are also found in the mainstem of Little Freshwater Creek and some of its tributaries, where the channel has incised through the overlying Wildcat sands (see description above for C1 segments).

C3 - High Gradient Reaches (6.5-20% in Consolidated Bedrock)

CGU C3 was found to have two sub-groups differentiated as a function of drainage area and stream power. The sub-group C3-Large has an average drainage area of about 1,500 acres, while the sub-group C3-Small has an average drainage area of about 100 acres.

Descriptive Characteristics

Summary Values for C3 (large)			
Channel Slope (%)	13.0	Bankfull Width: Bankfull Depth	7.9
Bankfull Width (ft)	16.4	Valley Width: Bankfull Width	2.6
Bankfull Depth (ft)	2.0	Terrace Height: Bankfull Depth	2.0
Valley Side Slope (%)	56.0	Mean d50 (mm)	88
Valley Width (ft)	37.6	Mean d84 (mm)	165
Terrace Height (ft)	Na	Mean d50 for mobile patches (mm)	11

CGU C3-L has the highest stream power index in the watershed. It is narrow and entrenched and has boulder/cobble bed channels with bedrock commonly exposed in the banks and bed. Channel morphology is cascade and step-pool. Mobile gravel and cobbles are deposited in forced bars associated with LWD, boulders, and in regions of lower slope, but bar abundance is lower than in C1 and C2. Average median grain size is about 90 mm.

Summary Values for C3 (small)			
Channel Slope (%)	15.6	Bankfull Width: Bankfull Depth	3.5
Bankfull Width (ft)	3.8	Valley Width: Bankfull Width	6.9
Bankfull Depth (ft)	1.0	Terrace Height: Bankfull Depth	3.6
Valley Side Slope (%)	52.4	Mean d50 (mm)	28
Valley Width (ft)	19.7	Mean d84 (mm)	96
Terrace Height (ft)	4.4	Mean d50 for mobile patches (mm)	8

CGU C3-S has the lowest stream power of the consolidated CGUs. In C3-S channels, gravel/cobble bed channels occur with some bedrock exposed in the banks and bed. Channels are much less confined by valley walls than C3-L but are similarly entrenched. Channel morphology is cascade and step-pool. Mobile gravel is deposited in forced bars associated with LWD, boulders, and in regions of lower slope, but bar abundance is lower than in C1 and C2 and comparable to C3-L. Average median grain size is about 30 mm.

With the exception of some short cascades in mainstem reaches, most C3 channels are found in the lower portions of tributaries to Upper Freshwater, South Fork, Graham Gulch, Cloney Gulch, and McCready Gulch. Most of the barriers to anadromous fish migration are found within the C3 reaches, which can be very steep (>15-40%) for short distances, often with relatively low gradient channels above the barriers. Many of these barriers occur along possible faults, or at sudden transitions from a less resistant geologic member to a more geologic member. Most of the steep reaches (fish barriers) consist of large accumulations of blueschist boulders and bedrock outcrops. C3 channels with steep sideslopes have more frequent streamside landslides. Channel reaches in the vicinity of these landslides are often full of large boulders and coarse channel substrate.

C4 - Very High Gradient Reaches (>20% in Consolidated Bedrock)

Descriptive Characteristics

Summary Values for C4			
Channel Slope (%)	24.6	Bankfull Width: Bankfull Depth	4.3
Bankfull Width (ft)	4.6	Valley Width: Bankfull Width	4.6
Bankfull Depth (ft)	1.1	Terrace Height: Bankfull Depth	3.9
Valley Side Slope (%)	57.0	Mean d50 (mm)	54
Valley Width (ft)	17.8	Mean d84 (mm)	202
Terrace Height (ft)	2.8	Mean d50 for mobile patches (mm)	13

CGU C4 has a stream power index similar to C1 and C2 and has gravel/cobble/boulder bed channels with some bedrock exposed in the banks and bed. Channel morphology is cascade with occasional step-pool forms. Mobile gravel is deposited in forced bars associated with LWD, boulders, and in regions of lower slope, but bar abundance is very low. Average median grain size is about 55 mm. C4 channels have a large range of morphologic variability but typically have a stepped profile due to the heterogeneous nature of the Franciscan formation. Steps and cascades in these channels can be formed by boulders, clay-rich colluvial wedges, LWD, or roots from nearby trees or stumps. Banks in the C4 units are more cohesive than banks in U4 units due to a higher clay content in the Franciscan derived soils.

C4 reaches include the upper portions of the channel network in the northeast half of the Freshwater Creek Watershed. There are no C4 channels consisting of Yager bedrock, because these smaller channels have generally not incised deep enough to penetrate the overlying Wildcat Group sediments.

2.4.2 Unconsolidated Bedrock Reaches (CGUs U1 - U4)

Channels developed in the unconsolidated Wildcat Group tend to have a fairly uniform longitudinal profile due to the sandy, homogeneous parent material, and easily weathered and eroded bedrock (see Figure 1-2). The profile characteristically has a long low-gradient mainstem with a rapid transition to steep-gradient channel in the upper mainstem reaches. Ridges in the Wildcat Group tend to be narrow, especially where two channel heads approach each other from opposite directions. The landscape is generally more dissected in the Wildcat Group, with higher drainage densities and abrupt, steep headwall channels.

U1 - Low Gradient Reaches (0-3% in Unconsolidated Bedrock)

CGU U1 was found to have two sub-groups differentiated as a function of drainage area and stream power. The sub-group U1-Large has an average drainage area of about 2,300 acres, while the sub-group U1-Small has an average drainage area of about 160 acres. Similarly, the stream power index for U1-L is much higher than for U1-S.

Descriptive Characteristics

Summary Values for U1 (Large)			
Channel Slope (%)	0.9	Bankfull Width: Bankfull Depth	7.1
Bankfull Width (ft)	26.0	Valley Width: Bankfull Width	2.7
Bankfull Depth (ft)	4.3	Terrace Height: Bankfull Depth	1.8
Valley Side Slope (%)	50.0	Mean d50 (mm)	24
Valley Width (ft)	70.0	Mean d84 (mm)	51
Terrace Height (ft)	6.8	Mean d50 for mobile patches (mm)	13

CGU U1-L has the highest stream power index among unconsolidated CGUs; however, this stream power is only as great as the lowest stream power index for consolidated CGUs. U1-L has gravelly sand bedded channels with Wildcat Formation bedrock commonly exposed in the banks and bed. Channels are not very entrenched, with relatively continuous floodplain surfaces extending along the channels. Channel morphology is pool-riffle and plane bed. Mobile gravel is deposited in sandy bars associated stream bends and LWD; bar abundance is high. Average median grain size on bars is about 25 mm, but the dominant substrate is sand.

Descriptive Characteristics

Summary Values for U1 (Small)			
Channel Slope (%)	1.9	Bankfull Width: Bankfull Depth	2.5
Bankfull Width (ft)	3.6	Valley Width: Bankfull Width	18.7
Bankfull Depth (ft)	1.5	Terrace Height: Bankfull Depth	2.7
Valley Side Slope (%)	56.3	Mean d50 (mm)	6
Valley Width (ft)	67.5	Mean d84 (mm)	69
Terrace Height (ft)	3.9	Mean d50 for mobile patches (mm)	1

In contrast to U1-L, the channel of U1-S is quite narrow relative to its valley, but the degree of entrenchment is greater. Stream power index is one of the lowest among CGUs in Freshwater. CGU U1-S has sand bedded channels with some gravel. Bedrock is not typically exposed in the banks and bed. Channel morphology is pool-riffle and plane bed. Mobile gravel is deposited in sandy bars associated with abundant LWD; bar abundance is low. Average median grain size on bars is about 6 mm.

U1 reaches are found in the lower mainstem of Little Freshwater and McCready Gulch, which are both predominantly underlain by Wildcat Group sandstone and mudstone. They tend to be dominated by fine sediments with fine alluvial bank material. Broad floodplains and terraces are common along many U1 channels, especially in Little Freshwater Creek. LWD can provide complex rearing habitat, but spawning habitat is very limited due to a lack of coarse substrate.

U2 - Moderate Gradient Reaches (3-6.5% in Unconsolidated Bedrock)

Descriptive Characteristics

Summary Values for U2			
Channel Slope (%)	4.5	Bankfull Width: Bankfull Depth	2.8
Bankfull Width (ft)	2.7	Valley Width: Bankfull Width	29.3
Bankfull Depth (ft)	1.0	Terrace Height: Bankfull Depth	2.4
Valley Side Slope (%)	46.7	Mean d50 (mm)	14
Valley Width (ft)	56.7	Mean d84 (mm)	63
Terrace Height (ft)	3.0	Mean d50 for mobile patches (mm)	1

CGU U2 has similarities to U1-S. Stream power index is very low, and the channel is narrow in comparison to valley width. CGU U2 has sand bedded channels with some gravel. Bedrock is occasionally exposed in the banks and bed. Despite low stream power index, channels are scoured to Wildcat bedrock in many places. Channel morphology is step-pool and pool-riffle. LWD accumulations create step-pool morphology. Mobile gravel is deposited in sandy bars associated with abundant LWD; bar abundance is high. Average median grain size on bars is about 15 mm.

U2 reaches are found in the upper mainstem of the Little Freshwater Creek, McCready Gulch, School Forest, South Fork, Graham Gulch, and Cloney Gulch, and in the lower reaches of the largest tributaries of these basins.

U3 - High Gradient Reaches (6.5-20% in Unconsolidated Bedrock)

Descriptive Characteristics

Summary Values for U3			
Channel Slope (%)	13.0	Bankfull Width: Bankfull Depth	3.8
Bankfull Width (ft)	3.3	Valley Width: Bankfull Width	9.4
Bankfull Depth (ft)	0.8	Terrace Height: Bankfull Depth	4.8
Valley Side Slope (%)	56.3	Mean d50 (mm)	23
Valley Width (ft)	24.3	Mean d84 (mm)	53
Terrace Height (ft)	5.8	Mean d50 for mobile patches (mm)	11

CGU U3 channels have relatively low stream power index, but greater than U1-S and U2. Channels are also more confined than U1-S and U2 channels, but channels are nevertheless relatively wide compared to the valley floor. U3 channels have some bedrock exposed in the banks and bed; mobile bed material in bars is sandy gravel. Average median grain size on bars is about 25 mm. Channel morphology is cascade and step-pool. Mobile sediment is deposited in forced bars associated with LWD, boulders, and in regions of lower slope, but bar abundance is lower than in U1-L and U2, and comparable to U2-S. Coarse substrates are often lacking, due to an absence of resistant material in the underlying geology. Wood and roots from trees adjacent to the channels often play especially important roles in these channels due to the lack of cobble or boulder substrate, or cohesive soil matrix.

U3 channels are found in the tributary basins to Little Freshwater Creek, McCready Gulch, School Forest, and portions of the South Fork. These channels generally have step-pool morphologies, and many of these channels show signs of channel incision, resulting in deeply entrenched or notched channels. This notching may be a result of rapid erosion following first cycle logging (PWA 1999).

U4 - Very High Gradient Reaches (>20% in Unconsolidated Bedrock)

Descriptive Characteristics

Summary Values for U4			
Channel Slope (%)	19.5	Bankfull Width: Bankfull Depth	6.0
Bankfull Width (ft)	6.0	Valley Width: Bankfull Width	1.2
Bankfull Depth (ft)	1.0	Terrace Height: Bankfull Depth	--
Valley Side Slope (%)	51.3	Mean d50 (mm)	2
Valley Width (ft)	6.8	Mean d84 (mm)	10
Terrace Height (ft)	--	Mean d50 for mobile patches (mm)	1

CGU U4 channels have relatively abundant bedrock exposed in the banks and bed; mobile bed material in bars is sandy with little gravel. U4 has the highest stream power index in the unconsolidated CGU group. Channel morphology is cascade and colluvial. Mobile sediment is deposited in forced bars associated with LWD and in regions of lower slope, but bar abundance is low. Average median grain size on bars is about 2 mm.

U4 reaches are found in the upper reaches of all of each of the Wildcat-dominated basins. Many of these reaches also show signs of historic incision, similar to U3 channels. The median grain size on the bed is anomalously low relative to stream power and reflects largely the absence of coarse substrate in these headwater channels. Bedrock, however, is relatively abundant for a small channel, which probably indicates some degree of channel scour from first cycle harvesting.

2.4.3 Mainstem Reaches

The lower mainstem of Freshwater Creek extends from the confluence of the South Fork and Upper Freshwater tributaries to Three Corners Market, near the Bridge at Myrtle Avenue. Channel gradient decreases gradually from 0.009 to 0.001, and bed material becomes finer in the downstream direction (for example, average d50 values shift from 35 mm to 15 mm or less).

MS1 - Mainstem, Reach 1

Descriptive Characteristics

Summary Values for MS1			
Channel Slope (%)	0.7	Bankfull Width: Bankfull Depth	12.9
Bankfull Width (ft)	42.8	Valley Width: Bankfull Width	4.1
Bankfull Depth (ft)	3.4	Terrace Height: Bankfull Depth	3.1
Valley Side Slope (%)	15.0	Mean d50 (mm)	32
Valley Width (ft)	175.0	Mean d84 (mm)	77
Terrace Height (ft)	10.0	Mean d50 for mobile patches (mm)	16

CGU MS1 has intermediate stream power among all CGUs, but the highest by a small margin among the Mainstem CGUs. MS1 has gravel/cobble bed channels with bedrock exposed in banks and occasionally in the bed. Channel morphology is pool-riffle and plane bed. Mobile gravel and cobbles are deposited on bars and in association with LWD. Reach average median grain size is about 35 mm.

MS1 includes the mainstem of Freshwater Creek, from the confluence of the South Fork and Upper Freshwater Creek to the confluence with Graham Gulch. The upper portion of this reach has incised into Yager terrane shale, forming a deep gorge with well-exposed fluvial strath terraces. Terrace heights decrease toward the lower end of the reach, but in general the channel in confined by fluvial terraces with minimal floodplain development.

In contrast to mainstem reaches of each of the tributary basins (primarily C1 channels), LWD accumulation is sparse in most of MS1. This is caused in part by relatively large channel width and depth that reduces the stability of LWD, but also due to historic management (stream cleaning mandated by California Department of Fish and Game [CDFG] and first cycle timber harvest) that has reduced LWD load in these channels.

MS2 - Mainstem, Reach 2

Descriptive Characteristics

Summary Values for MS2			
Channel Slope (%)	0.4	Bankfull Width: Bankfull Depth	11.9
Bankfull Width (ft)	50.0	Valley Width: Bankfull Width	9.0
Bankfull Depth (ft)	4.2	Terrace Height: Bankfull Depth	1.7
Valley Side Slope (%)	10.0	Mean d50 (mm)	35
Valley Width (ft)	450.0	Mean d84 (mm)	70
Terrace Height (ft)	7	Mean d50 for mobile patches (mm)	10

The stream power index for CGU MS2 declines slightly relative to MS1, and to a greater degree relative to its other tributaries (Graham Gulch and Cloney Gulch). Channel slope, confinement, and entrenchment all decline in MS2 relative to areas upstream, making it prone to sediment deposition. It is also the upstream-most reach with a well-developed floodplain. CGU MS2 has gravel/cobble bed channels with bedrock exposed in banks throughout, and in the bed in the upper third of the CGU. Wildcat bedrock is visible along the banks of much of this reach, except near Freshwater Park where Yager terrane sandstone and shale are exposed. Exposed bedrock in these reaches indicate that there are limits to the amount of channel scour that can occur. There are accumulations of sand and fine sediment in pools. Channel morphology is pool-riffle and plane bed. There is very little LWD in this CGU. Reach average median grain size is about 30-35 mm.

MS2 extends from the confluence with Graham Gulch to the confluence with Little Freshwater Creek. Flooding in this reach has been significant, resulting in property damages and general nuisance to residents. Residents report localized channel aggradation in this reach on the order of 1 to 3 ft. This estimate is plausible in some locations, but there is also evidence for net scour in the channel. For example, the Army Corps of Engineers measured the distance from the bottom of the Steele Lane bridge to the active channel bed in 1974. When we repeated this measurement at the bridge, we found that the channel bed has degraded on the order of 3-4 ft.

The same measurement at the bridge at Freshwater Park indicated no net change in bed elevation. While these measurements represent only two sites, they show that the patterns of channel aggradation and degradation are spatially variable. See Section 5.1 for a full analysis of evidence of aggradation.

MS3 - Mainstem, Reach 3

Descriptive Characteristics

Summary Values for MS3			
Channel Slope (%)	0.4	Bankfull Width: Bankfull Depth	11.7
Bankfull Width (ft)	46	Valley Width: Bankfull Width	11.0
Bankfull Depth (ft)	4.5	Terrace Height: Bankfull Depth	1.9
Valley Side Slope (%)	3	Mean d50 (mm)	22
Valley Width (ft)	500	Mean d84 (mm)	59
Terrace Height (ft)	6.8	Mean d50 for mobile patches (mm)	7

The stream power index in CGU MS3 is the lowest of mainstem CGUs, but the decline is not great relative to MS2. This is a very low gradient reach (0.001-0.004), with a broad floodplain. Channel confinement and entrenchment are generally similar to MS2, although the floodplain widens substantially in MS3 relative to MS2. MS3 has a sandy-gravel bed with alluvial banks. Sub-reaches alternate between gravelly conditions and sandy conditions, apparently reflecting local variations in channel gradient. Channel morphology is pool-riffle and plane bed. Reach average median grain size is about 15 mm.

MS3 extends from Little Freshwater Creek to the bridge on Myrtle Avenue (the downstream extent of the study area). The lower reach of MS2 is morphologically similar to upper MS3, but the contribution of fine sediment from Little Freshwater Creek influences channel morphology and provides a convenient place for a reach break. Below Little Freshwater Creek (and for a few hundred ft immediately above), the channel widens and the proportion of fine sediment stored in the bed and bars increases. In part, this is related to the input of fine sediment from this Wildcat Group dominated subbasin. In addition, it is in part attributable to the low channel gradient, which presumably reflects some decline in stream energy.

There is very little wood accumulation in MS3, partly due to increased channel widths and flood discharges, and partly due to the intervention of local residents, who have removed at least one large log jam in this reach in recent years. The riparian forest along this reach is dominated by alder and tall willow. Much of the wood in the channel is associated with mortality or toppling of these trees; conifers are sparse in this reach, and LWD recruitment potential is low.

Small Mainstem Tributaries

There are numerous smaller tributaries to the lower mainstem that flow across the broad alluvial flats. With the exception of portions of the School Forest Watershed, these channels were not evaluated as part of this Watershed Analysis, since nearly all of these channels are on non-PALCO lands. These channels are probably similar to CGUs U1-S and U2.

2.4.4 Exception Reaches

The middle and lower mainstem reaches of Graham Gulch and Cloney Gulch have unique channel morphological features and sediment transport processes. At least two faults bisect these channels, resulting in rapid changes in channel geology over relatively short distances. These channels therefore have characteristic of both unconsolidated and consolidated geologies.

Both Graham Gulch and Cloney Gulch had railroad grades and/or corduroy roads constructed in the mainstem channel. The remains of these railroad grades remain in portions of the channels today and function as anomalous LWD accumulations. (Note: see the channel photos in digital attachment.)

GG - Graham Gulch

Descriptive Characteristics

Summary Values for GG			
Channel Slope (%)	4.4	Bankfull Width: Bankfull Depth	9.4
Bankfull Width (ft)	20.0	Valley Width: Bankfull Width	3.2
Bankfull Depth (ft)	2.1	Terrace Height: Bankfull Depth	2.7
Valley Side Slope (%)	72.5	Mean d50 (mm)	40
Valley Width (ft)	50.0	Mean d84 (mm)	116
Terrace Height (ft)	5.3	Mean d50 for mobile patches (mm)	4

Graham Gulch is a unique CGU because of elevated sediment loads, the presence of remnant railroad features in the channel, and geologic complexities resulting from faulting and lithologic variability. CGU GG has a gravel bed with occasional bedrock outcrops in the banks. Gravel bars are abundant. Channel morphology is pool-riffle and plane bed. Reach average median grain size is about 30-40 mm. The lower mainstem of Graham Gulch is severely impacted by sediment, resulting from one large point source and multiple smaller point sources adjacent to the channel.

Sediment production in Graham Gulch increased dramatically following the January 1997 flood. Remobilization of an earthflow and erosion of a remnant landslide dam deposit have introduced over 5,000 cubic yards of sediment to the channel. Much of this material (along with existing channel-stored sediment) moved downstream in the form of a hyperconcentrated flow, aggrading the channel in many places. The magnitude of aggradation varies spatially, but in the lower mainstem, bed aggradation is on the order of 1 to 3 ft. Much of this bed material is still fairly mobile; with continued inputs of sediment from the earthflow, the lower mainstem of Graham Gulch is likely to be severely impacted by sediment for at least a decade. Coarse bed material delivers directly to the upstream boundary of CGU MS2, where aggradation and flooding hazards are most significant in the watershed.

CG - Cloney Gulch

Descriptive Characteristics

Summary Values for CG			
Channel Slope (%)	0.9	Bankfull Width: Bankfull Depth	6.0
Bankfull Width (ft)	24.0	Valley Width: Bankfull Width	--
Bankfull Depth (ft)	4.0	Terrace Height: Bankfull Depth	2.4
Valley Side Slope (%)	--	Mean d50 (mm)	39
Valley Width (ft)	--	Mean d84 (mm)	73
Terrace Height (ft)	9.7	Mean d50 for mobile patches (mm)	--

CGU CG has a gravel bed with occasional bedrock outcrops in the banks. Channel morphology is pool-riffle and plane bed. Field observations in Cloney Gulch were made during the near-stream sediment source surveys (Section 3.1). Data were also available from the PALCO long-term monitoring station and from the Fisheries Assessment Module. In most respects, it is similar to CGU C1.

Cloney Gulch was designated as a CGU exception due primarily to geologic complexities and the presence of remnant railroad features in the channel. The mainstem of Cloney Gulch flows through all three dominant geologic formations found in the basin. The Freshwater Fault and Greenwood Heights Fault cut through lower mainstem of Cloney Gulch, juxtaposing different lithologies. The high proportion of Franciscan Central belt terrane rocks contributes significant quantities of gravel and cobble to the mainstem of Cloney Gulch, creating more favorable habitat conditions than would otherwise be expected given the prominence of the Wildcat geology in this watershed. South Fork Freshwater has a somewhat similar mix of lithology. Some of the best-preserved railroad features are found in Cloney Gulch. These features continue to influence sediment transport and storage processes in a manner that does not occur in the other basins. This is manifested by reaches where railroad ties lay in place in or adjacent to the current location of the channel.

3.0 SEDIMENT SOURCES

This section summarizes the sediment budget constructed for Freshwater, focusing primarily on sediment sources. It is intended to address the supplemental critical questions on sediment sources (SCQ 4.1 and 4.2). The sediment budget for sediment inputs was prepared through a coordinated effort of Mass Wasting, Surface Erosion, and Stream Channel Module analysts. Measurement of sediment inputs from near stream sources (bank erosion and small-scale streamside mass wasting) for Freshwater was completed as part of the Stream Channel Module. The Mass Wasting and Surface Erosion Module reports present discussions of the methods used to estimate sediment sources relevant to their modules.

3.1 BANK EROSION AND STREAM-SIDE LANDSLIDE INVENTORY

Bank erosion features and streamside landslides were inventoried during the sediment source investigation for Freshwater Creek (PWA 1999) to document the distribution and volumetric importance of these features. Inventories were conducted on each of the mainstem reaches of the major tributary subbasins in PALCO's ownership. The mainstem of Freshwater Creek was inventoried from the South Fork confluence downstream to the PALCO property line (approximately 1 mile upstream of Graham Gulch). No in-stream sediment source inventories were conducted below this point.

In total, 17.5 miles (28 km) of channel were inventoried between January and April 1999. Bank erosion and streamside landslides with volumes greater than 10 cubic yards were identified, measured, and recorded on data forms and enlarged aerial-photo base maps at a scale of approximately 1 inch = 250 ft. These maps are provided in digital format in Attachment E-2. LWD accumulations were also mapped. This effort documented the distribution of "key piece" accumulations that play a structural role in the channel by altering channel hydraulics or storing sediment. In the office, data were entered into a database and map features were transferred to mylar overlays. The resulting channel strip maps provide an overview of the distribution of sediment sources in the riparian and inner gorge areas (see channel strip maps in data attachment). Additional detailed field observations recorded on field maps were entered into a second database. Such complete survey data for channels accessible to anadromous fish are unprecedented in watershed analysis and provided an unusually complete impression of the range of channel conditions.

3.1.1 Field Methods

The methods employed for the survey of stream-side sediment sources are described here because they are not part of the Watershed Analysis Methods. These sediment source surveys were conducted for another purpose, but we have utilized the data for this Watershed Analysis.

Two crews of three people identified and described the sediment sources in the riparian zone and inner gorge area. Attention was directed to identifying near channel sediment sources, since upslope sediment sources were already addressed in the landslide and road inventories conducted as a separate part of the sediment source investigation (PWA 1999). High water conditions prevented access to the channels on numerous occasions. This inventory effort required approximately 850 person hours in the field, plus additional time for data entry and mapping transfer and analysis.

Site referencing was accomplished by sequentially pulling a 100-meter tape up the channel while mapping and collecting data on erosion sites. Stations were flagged at 50-meter intervals while linear erosion features, such as bank erosion, were measured with reference to this tape. Landslide dimensions were determined by direct measurement with tapes; landslide depths, ages, and activity levels were estimated or established by consensus among two to three surveyors.

3.1.2 Data Collected

The information gathered at each site quantitatively describes the volume of sediment eroded and delivered, as well as the activity and age of each feature. Large volume (>~500 cubic yards) or complicated features were sketched on the back of the field forms. Data categories on the field form include: site #, station #, erosion type, location (left bank/right bank), length, width, depth, volume, delivery (%), hillslope gradient, activity level, approximate age of erosion feature, land use association, geomorphic association, notes, and sketch (if necessary).

3.1.3 Results

In total, 457 features were identified and categorized according to four general types of in-stream sediment sources: bank erosion features (82%), debris landslides (15%), deep-seated landslides (2%), and gullies (1%). For this analysis, we distinguish only between bank erosion and streamside landslides.

While causal mechanisms were uncertain for many (22%) of the sediment sources, LWD was commonly associated with bank erosion features (36%), as were some in-stream fish habitat improvement structures (4%). Many features were located on the outside bends of meanders (24%), and some features appear to have been related to landslides (6%) influencing downstream channel configurations, leading to additional bank erosion. The remaining 8% were attributed to "other" identified causes.

The distribution of sediment sources was recorded on enlarged aerial photos, and transferred to mylar base maps. These maps are included in the digital data attachment (see Channel Strip Maps). Delivery processes appear to be closely related to the underlying geology. Bank erosion features were ubiquitous across all geologic types, but larger landslide features were found primarily in the areas underlain by the Franciscan Central belt terrane. Figures 3-1 and 3-2 summarize the volumetric distribution of sediment sources in each of the major subbasin of Freshwater Creek. These figures show that there is a large difference between volumes delivered from the predominantly Franciscan basins and the predominantly Wildcat basins.

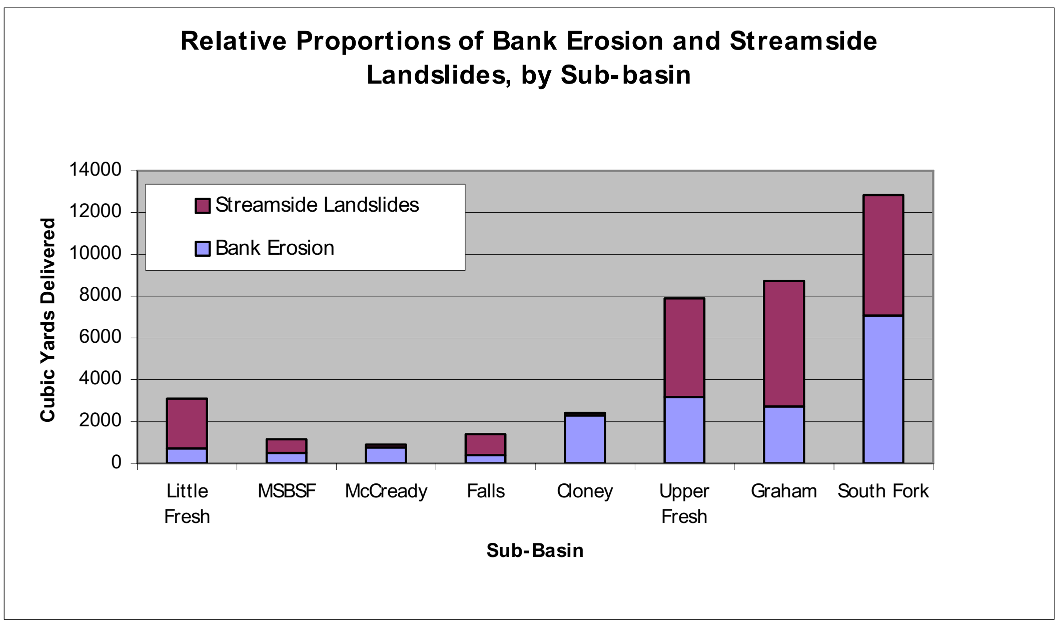


Figure 3-1: Relative proportions of bank erosion and streamside landslides by subbasin in Freshwater. "MSBSF" refers to the mainstem below the South Fork confluence; it is CGU MS1.

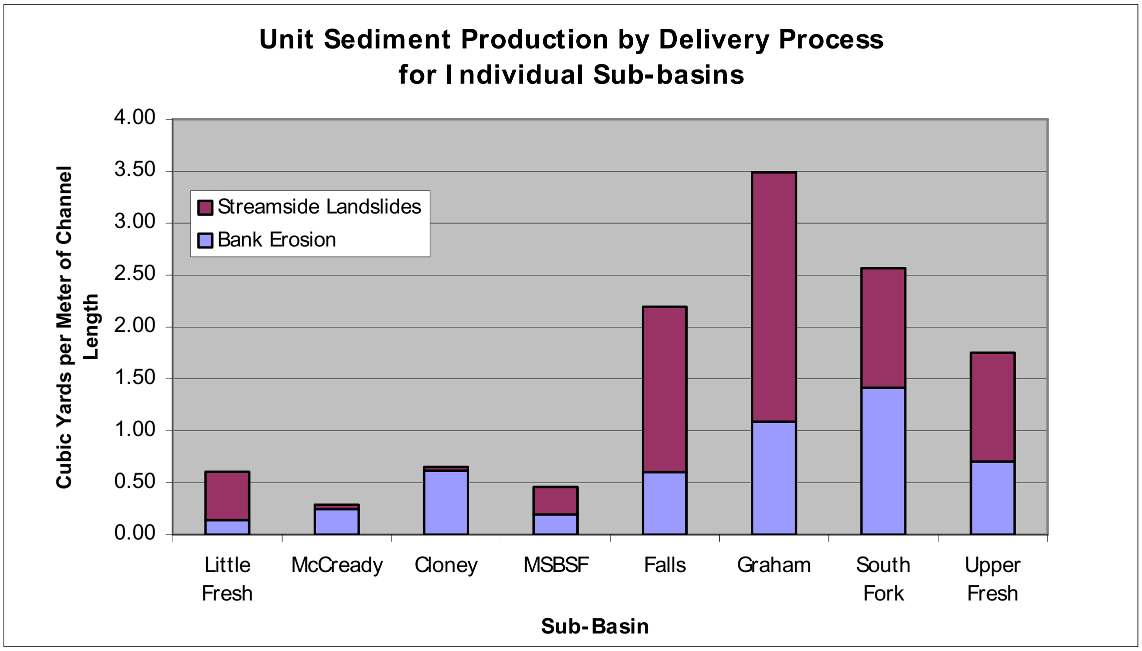


Figure 3-2: Sediment production per unit stream channel length by delivery process and subbasin. "MSBSF" refers to the mainstem below the South Fork confluence; it is CGU MS1.

The South Fork of Freshwater Creek has the most active combination of streamside landslides and bank erosion features. Most of the streamside landslides are located in the portions of the basin underlain by the Franciscan Central belt.

Unit sediment production is the total volume of sediment delivered divided by the length of the channel surveyed. Graham Gulch produces the most sediment per unit length because of channel disturbance associated with reactivation of a large deep-seated landslide in this reach in 1997.

3.2 SEDIMENT INPUTS FROM HEADWATER CHANNEL INCISION

Based on field observations from the sediment source inventory in Freshwater Creek (PWA 1999), it was hypothesized that incision of low order stream channels or unchanneled headwater swales may have occurred in response to hydrologic changes brought about by first cycle clearcut harvesting and burning in the basin. Clearcutting and broadcast burning increases runoff and may sufficiently alter both the subsurface and surface hydrology of unchanneled swales to cause headward extension of the first order channel system and enlargement of adjacent low order stream channels. This response would be in marked contrast to the behavior of similar swales and small channels in the undisturbed Headwaters Forest of the nearby Elk River Watershed where channels would be expected to have remained intact and unchanneled during the same time period. To test this hypothesis, inventory sites were selected from around the Freshwater Creek Watershed, and within the unlogged Headwaters Forest to provide field evidence that could be used to estimate the general magnitude of the erosion generated by this potential response process.

3.2.1 Small Stream Investigation Methods

For the 1999 sediment source investigation, 10 headwater watershed areas totaling 172 acres were examined for evidence of recent (historical) channel incision in the Freshwater Creek Watershed. They were located in the South Fork Freshwater Creek, Graham Gulch, School Forest, and Little Freshwater Creek; all but one were located within the Wildcat geologic terrane. Drainage areas ranged in size from 3.5 acres to 45.8 acres, and each small sub-watershed contained one or more stream channels or unchanneled swales. Sixty-one separate channel reaches exhibiting historic (post-first cycle) channel incision, totaling 9,056 ft, were identified and measured within the 10 study areas. Subsequently, additional observations were made to document channel processes in low order sub-watersheds that are underlain by Franciscan bedrock. At this latter set of sites, however, the harvest history included tractor harvest, thus precluding development of estimates of headwater channel incision attributable only to hydrologic change in sub-watersheds underlain by Franciscan bedrock.

The Wildcat sites sampled included channels within advanced second-growth areas (these had been harvested only once, about 60-70 years ago) and sites within recent cable yarded clearcuts that had been harvested for the second time sometime within the last 10 years. At each site, field personnel mapped and described selected first, second, and third order streams, paying particular attention to evidence of historic channel adjustments, including bank erosion and channel downcutting and large wood accumulations. Reaches exhibiting “recent” (historic) channel erosion were identified on the field map, and channel dimensions and erosion volumes were measured or estimated in the field. Wherever possible, the approximate age of the erosion (pre-first cycle, post-first cycle, post-second cycle) and the current activity level of the feature were estimated from local field evidence.

3.2.2 Small Stream Investigation Results

Although most low order channels in Wildcat geologic terrane experienced channel downcutting following first cycle harvesting, almost all of this erosion appears to have occurred decades ago, presumably shortly after the first harvesting. Recently clearcut areas do not show a similar second response to second cycle harvesting. Only two short segments within the recent clearcut areas appeared to exhibit renewed incision. Observations within most incised channels suggest that the original incision typically extended through the loose alluvial or colluvial material down to bedrock or other resistant subsurface materials. The age of the channel incision was inferred by local vegetative and geomorphic indicators and by the "stratigraphic" position of first cycle and second cycle logging debris and uncut (presumably pre-first cycle) logs and in-place stumps located within or spanning the channel. Nearly all the originally incised channels in Wildcat geologic terrain appear to be currently inactive as erosion sources, except for isolated bank erosion or collapse caused by undercutting or flow deflections around organic debris. This suggests that not only was additional incision not possible (because of the resistant bedrock substrate), but that the current channel capacity, which developed in response to the first period of incision (first cycle downcutting), has generally been sufficient to pass any increased flows experienced following second cycle clearcut harvesting. Widespread channel enlargement in recently harvested areas is not evident, nor are significant fresh deposits of alluvium that would suggest renewed incision and erosion following second cycle harvest. In summary, the incised channels were likely formed by gullying under increased flow conditions, primarily following the first cycle of harvest. These channels now appear to have stable base levels and have developed a stable cross sectional area relative to current peak flows and runoff.

Field evidence from a number of sample plots suggests that the first cycle harvesting was followed by widespread incision of the low order stream channels and extension of the first order drainage network into previously unchanneled headwater swales underlain by Wildcat bedrock geology. This erosional response in the headwater areas of each low order tributary was presumably triggered by increased runoff, and subsequent channelization, of colluvial fills that had developed in upland swales over thousands of years. Because of the incision process, Class 2 and Class 3 channels in Wildcat terrane are now more extensive than they were in the unmanaged forest. Channels have extended headward into the previously undissected valley fill deposits that would have been classified as unchanneled swales or a lower class of stream in the old-growth setting. Channel incision and extension have turned former groundwater or subsurface pipe systems into surface flow channel networks, and these are now classified as Class 3, first order channels.

Although the process of recent channel incision was ubiquitous in our relatively small sample of Wildcat headwater streams, it was not so common in small streams on Franciscan bedrock geologies. Here, channel profiles appear fundamentally different than those developed in Wildcat terrane. Subsurface piping is a common process in the homogeneous, fine-grained geologies of low order Wildcat subbasins, as evident in the undisturbed low order channels of the Headwaters Forest. In contrast, low order drainage channels, which have evolved on the relatively more rocky soils of Franciscan terrain, display relatively infrequent subsurface piping. As a result, increases in streamflow that likely followed first cycle logging in these areas produced only minimal channel adjustment and enlargement. The "notched" or gullied channels common on Wildcat terrane are comparatively rare in Franciscan terrane. The open Franciscan channels are more resistant to erosion than are subsurface pipes developed in the Wildcat, and the Franciscan bedrock geology yields rocky soils and colluvial material that is more resistant to scour by low order, Class 3 streams.

PWA (1999) originally estimated the sediment influx from low order channel incision following first cycle clearcutting to be approximately a total of 867,800 yd^3, with sediment input from channel incision in a harvested area occurred over a period of perhaps 10 years following the initial harvest. Because logging of the old-growth forests occurred over a period of 80 years (from 1860 to 1940), low order channel incision would have been dispersed over this period in a manner generally reflecting the harvesting history. A total of 6,045 yd^3 of erosion was measured from channel incision at the sample sites, for an average erosion rate of 0.67 yd^3/ft of eroded channel. On average, yield rates for first, second, and third order channel incision in Wildcat geologic terrain were calculated to be 0.60, 0.88, and 0.07 yd^3/ft of incision, respectively. Based on additional field sampling and observations conducted during the Watershed Analysis process, it is estimated that approximately 90% of low order Wildcat channels experienced this post-first cycle channel adjustment, and that perhaps 10% of similarly sized channels underlain by Franciscan and Yager bedrock experienced this adjustment.

Sediment budget values for sediment inputs presented for low-order valley fill erosion were derived by first determining the percentage of each subbasin underlain by Wildcat and Franciscan rocks and then multiplying these areas by measured drainage densities for different stream orders (i.e., first, second, third). The observed unit rates (yd^3/ft of channel length) of valley fill erosion were then applied for each stream order and adjusted by a factor representing the differential rates of valley fill erosion in different geologic types. For the Watershed Analysis sediment input budget, Franciscan channels were estimated to have eroded at 10% of the rate estimated for this process by PWA (1999). In the earlier study, a uniform rate of valley fill erosion was used across the watershed, regardless of geology. The foregoing calculations and estimates for erosion from low order valley incision are subject to substantial uncertainty, as are all components of historic sediment input estimates for other erosion sources.

In addition to investigating channel erosion processes, the small stream investigation also qualitatively assessed LWD abundance and function. Despite generally abundant LWD in Wildcat channels, it was rarely observed to be keyed into the enlarged channels, often spanning above the channel bed. Consequently, LWD did not play a very significant role in sediment storage. Similar LWD abundance and function were observed in Franciscan streams. Again, LWD tended to span above channels and was rarely a significant component of sediment storage. In these channels, however, the roots of trees were frequently embedded in the channel and are believed to help maintain channel grade, along with bedrock outcrops and relatively abundant boulders and cobbles. In the Headwaters Forest, LWD abundance was relatively low and did not appear to play a significant role in sediment storage. This was in part due to the tendency for channels of this size to flow in natural subterranean soil pipes.

3.3 SEDIMENT SIZE CLASSES

The size of sediment particles entering the stream system is the chief determinant controlling how fast the particles will move through the stream system, and where and how long they will likely settle. This information is used in this portion of the analysis and later in the sediment transport modeling effort (Section 4.0).

Information on the grain size distribution of Wildcat and Franciscan geologies in the Freshwater basin was provided by PALCO Geologist Tom Koler (pers. comm., 2000) based on 122 samples taken in the area. No samples were available for the minor geologic units (Yager, Quaternary alluvium). Areas underlain by Yager formation were grouped with Franciscan, and areas underlain by alluvium were grouped with Wildcat. Sediment contributed from each sediment source was separated into four grain size components: gravel (>4.75 mm); medium/coarse sand (2-4.75 mm); fine sand (0.075-2 mm); and silt/clay (<0.075 mm) (Table 3-1). These categories were selected in consultation with the Stream Channel, Fisheries Assessment, and Amphibian Module analysts to address the critical questions in each of the modules relating to the various effects of different sized sediments on the channel and habitat values (e.g., silt/clay contributes to turbidity, gravel provides spawning habitat but can also lead to channel aggradation).

For the sediment budget, the two coarser size fractions were collapsed to a single group >2 mm diameter. The sediment budget discussion defines sediment coarser than 2 mm as gravel, and material 0.074 – 2 mm as sand. These size class definitions are significant to the analysis of sediment routing (Section 3.5.1 and bedload transport modeling, Section 4.0) because of the characteristic transport modes of these different size fractions.

Table 3- 1: Summary of grain size and bulk density data for Freshwater watershed (adjusted to 100%).

Geology	Parameter	Coarse Gravel (>4.75 mm)	Fine Gravel (2–4.75 mm)	Fine Sand (2–0.074 mm)	Silt/Clay (<0.074 mm)	(Silt)	(Clay)	Bulk Density (lbs/cu ft)	tons/ yard³
Entire Soil Profile									
Franciscan	Average %	12.7	10.5	20.4	56.4	31.0	27.0	89.2	1.20
	Std Dev	20.1	9.4	14.8	24.0	12.0	15.3	6.2	0.08
Wildcat	Average %	3.1	4.6	15.6	76.7	45.1	32.0	91.2	1.23
	Std Dev	9.0	6.8	12.2	19.1	14.7	11.7	4.1	0.06
Surface (0-1 ft)									
Franciscan	Average %	21.5	16.2	16.5	45.8	27.1	24.0	90.3	1.22
	Std Dev	23.3	8.5	10.2	28.7	11.8	16.9	9.7	0.13
Wildcat	Average %	6.8	10.2	20.0	63.0	41.6	21.7	91.4	1.23
	Std Dev	15.1	12.9	13.1	23.9	17.6	11.0	7.6	0.10

Gravel is transported primarily as bedload. Sand sizes are transported either as bedload or suspended load, depending on flow conditions. Sediment finer than sand is transported in suspension. The mode of transport directly affects the rate of transport. Consequently, apportioning sediment inputs to these size classes allows for a detailed sediment routing analysis.

Sediment from each source within each subbasin was apportioned to the grain size categories based on the grain size of the underlying geology in each subbasin. The grain size distributions of the two measured geologic units were not greatly dissimilar, so differences in groupings would not change the results significantly. The measured grain size distributions were applied to the percent of each subbasin underlain by the different geologic units to produce a weighted average grain size distribution of sediment produced in each subbasin (Table 3-2).

Table 3-2: Grain size distribution used to apportion total sediment inputs by subbasin.

Subbasin	Percent Gravel (>4.75 mm)	Percent Med/Coarse Sand (2-4.75 mm)	Percent Fine Sand (0.075-2 mm)	Percent Silt and Clay (<0.075 mm)
Upper Freshwater	10%	9%	20%	60%
School Forest	2%	4%	16%	78%
McCready Gulch	3%	5%	16%	76%
Cloney Gulch	9%	9%	19%	63%
Graham Gulch	8%	8%	19%	64%
Lower Freshwater	3%	4%	16%	77%
South Fork	5%	6%	17%	72%
Little Freshwater	3%	5%	16%	77%

3.4 SEDIMENT BUDGET INPUTS

3.4.1 Overview

Sediment input budgets were calculated for each of eight subbasins in Freshwater Creek over seven time periods: first cycle (prior to 1942), 1942-1954, 1955-1966, 1967-1974, 1975-1987, 1988-1997, and 1998-2000. These periods are based primarily on the available aerial photo record. Sediment input rate estimates are based on field observations, interpretation of historic aerial photography, and modeling. All reported estimates are for sediment delivered to stream channels and exclude erosion that does not deliver sediment to streams. As described above (Section 3.3), inputs were categorized in size classes representing silt and clay, sand, and gravel. In addition, inputs were allocated to either management or background sources using the assumptions described below.

First cycle refers to the period following the first entry for logging in the watershed (prior to 1942). The lack of aerial photography prevented application of sediment budget techniques used for the period 1942-1997. Inputs estimated for the first cycle period are based only on estimated erosion of headwater channels that were roughly quantified in the small streams investigation (Section 3.2). Consequently, this is a relatively crude minimum estimate for erosion prior to 1942. The time period over which this erosion took place cannot be well constrained. The total erosion estimated for this source, about 715,000 tons, is equivalent to about 95% of the total estimated erosion for the period 1942-2000. The fate of this first cycle sediment has not been determined; however, it includes roughly 58,000 tons of bedload sediment. Transit times for this sediment are discussed later in Section 5.2.

For the most recent period (1998-2000), erosion data are estimates provided from the Surface Erosion Module. These estimates are based on road conditions in 1997 and on harvest history in 1999; they do not reflect the influence of ongoing erosion control work on the road network. The sediment budget was developed from the most recent photography (from 1997); hence, there are no landslide data incorporated in the mass wasting sediment source data for the period 1998-2000. Subsequent review of aerial photography from 2000 by PWA revealed 10 new landslides since 1997. These new slides represent additions of 6% of number of slides and 4% of the volume of sediment delivered relative to the period of record running from the 1940s to 1997. The additional 3-year increment from 1998-2000 adds about 5% to the period of record used for sediment budget calculations (1942-1997). Hence, landslide rates after 1997 are comparable to the long-term average, and the inclusion of the new data is not likely to significantly affect the sediment budget calculations or their interpretation.

Variation of sediment inputs over time can be illustrated using the data in many different ways. Of particular interest in this watershed are the input rates from 1988-1997, during which harvest rates were relatively high (about 7,360 acres in THPs, compared with about 2,060 acres for 1975-1987, and 3,430 acres for 1967-1974; see Surface Erosion Module Figure B3-6). Moreover, this period was punctuated by an episode of mass wasting triggered by unusual rainstorms where relatively intense storms occurred at a time of high antecedent precipitation. Sediment input rates for this period averaged about one-third higher than the long-term average (see Figure 3-3). In the Little Freshwater and Graham Gulch subbasins, sediment input rates for 1988-1997 were substantially higher than the long-term average as a result of the high incidence of landslides in 1997.

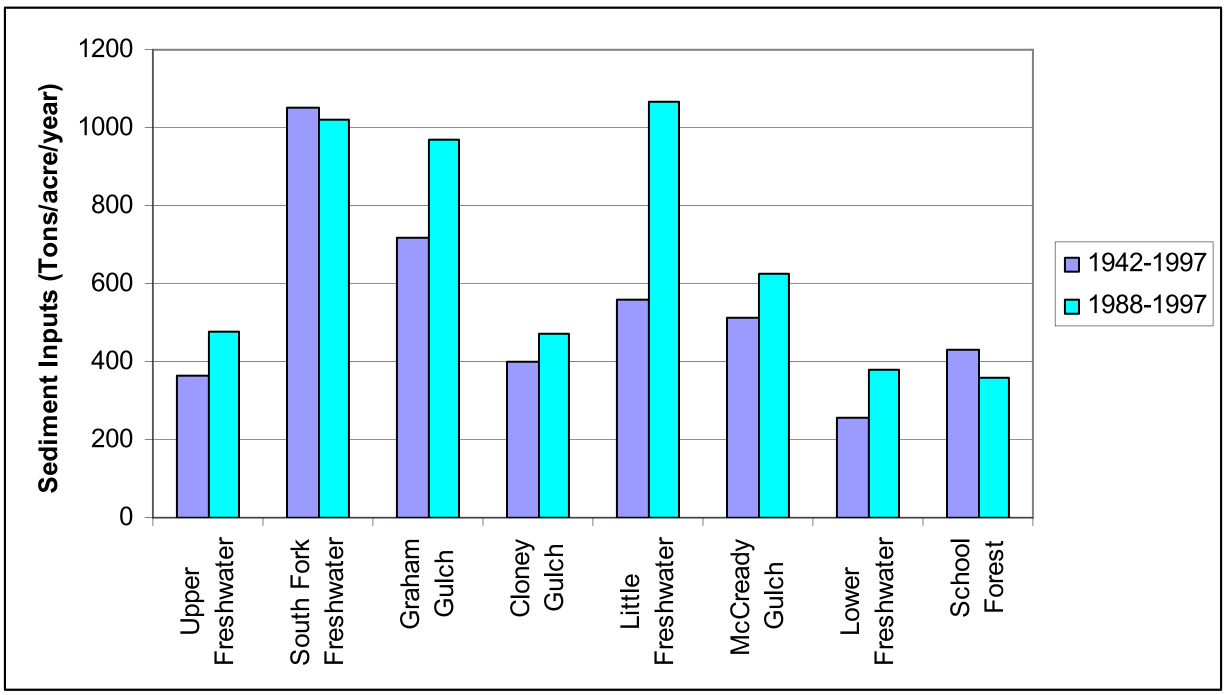


Figure 3-3: Total sediment inputs by subbasin comparing the long-term average for the period 1942-2000 and the most recent sediment budget interval representative of all sediment input processes (1988-1997).

The relatively high erosion rates from 1988-1997 are the highest in the period of record, but not by a very large margin. Figure 3-4 shows the average erosion rates for each of the sediment budget time intervals for Freshwater as a whole. Average rates range from 3000 to 6000 tons/acre/yr. Sediment input budget estimates are compared to measured sediment yield at the Salmon Forever gage in Section 3.5. Note that the first and last time intervals shown (first cycle and 1998-2000) are not directly comparable to the periods from 1942-1997.

3.4.2 Attribution of Sediment Inputs to Background and Management Sources

Natural erosion rates in a watershed with a 100+ year management history are virtually unknowable. A critical technique for retrospective erosion estimates—aerial photo interpretation/documentation of historic landslides—cannot be used for the period prior to the earliest aerial photography in Freshwater Creek (i.e., the 1940s). Accurate quantification of present-day sediment sources is also difficult.

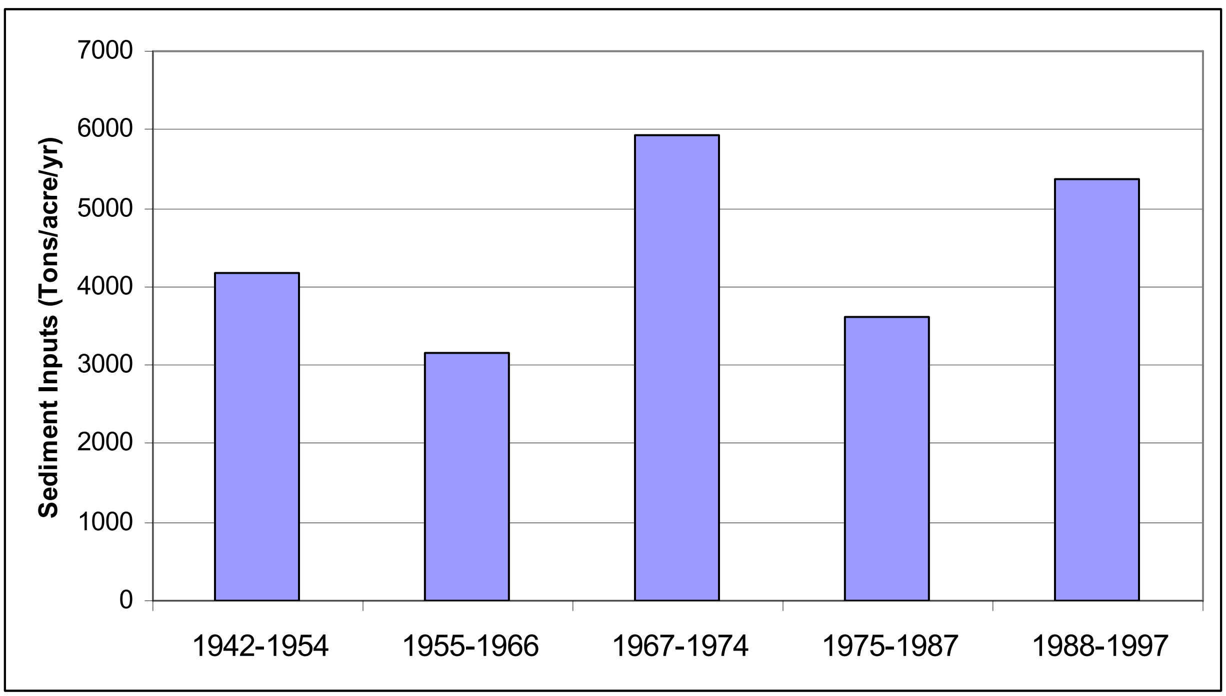


Figure 3-4: Total sediment inputs for the entire Freshwater watershed for all sediment budget time intervals.

Methodological limitations exist regarding detection and measurement of sediment sources, both in the field and from aerial photography. In addition, surface erosion models must be used to estimate erosion rates from roads and harvest areas. These methodological limitations create substantial uncertainty in the resulting sediment budget. Nevertheless, detailed sediment budgets such as the one described in this section represent the best available technique for quantifying erosion sources in a watershed. Similar sediment budget methods have been applied by the U.S. Environmental Protection Agency and the North Coast Regional Water Quality Control Board to develop the technical basis for Total Maximum Daily Load (TMDL) calculations for the Garcia, Noyo, South Fork Trinity, and South Fork Eel Rivers in northern California. Documents regarding these TMDL studies may be reviewed via the internet at: http://www.epa.gov/region09/water/tmdl/index.html.

In a retrospective sediment budget analysis such as this, it is necessary to make several assumptions to estimate the relative proportion of sediment attributable to either management or natural sources. The assumptions used to develop estimated background ("natural") sediment input rates were initially developed in conjunction with Mass Wasting and Surface Erosion analyst, and were later modified to accommodate modifications for the Cumulative Effects Assessment. The logic used to develop the necessary assumptions may vary, depending on the purpose of the sediment budget. There are two major purposes for development of this sediment budget. The first is to estimate sediment inputs and sediment routing over the full period of record for which suitable data were available and, further, to estimate the proportions of sediment inputs from natural sources and from management sources. Hence, a set of assumptions regarding sediment inputs and their allocation to either management or background sources was developed for the period 1942-1997 (Table 3-3a).

The second purpose of the sediment budget is to provide quantitative guidance for the development of management prescriptions that will reduce or avoid future sediment inputs from contemporary forest management practices. For the most recent sediment budget period (1988-1997) a somewhat different set of assumptions was developed to attribute sediment sources to either management or background sources (Table 3-3b). Again, the different treatment of the period 1988-1997 results from the need to develop prescriptions that relate to contemporary management practices.

For the full historic period (1942-1997), all sediment sources were attributed to either background or management (Table 3-3a), with the exception of shallow landslides not associated with roads and deep-seated landslides. Shallow landslides not associated with roads and deep-seated landslides may be attributable to management in some cases, but the level of certainty associated with the aerial photo/field interpretations is low relative to road-associated landslides. Consequently, these inputs are categorized separately because they may be more indeterminate in origin. We believe a significant portion of this sediment should be included in the background category, especially the deep-seated landslide sediment. As described below, the best evidence available indicates that about 60% of non-road related shallow landslide sediment is likely associated with management, and about 40% is background input. This allocation, however, is only applied explicitly to the period 1988-1997.

Table 3-3a: Summary of sediment budget inputs, data sources, attributions to background, management, or non-road related landslide categories.

Erosion Source	Method & Module	Attribution	Remarks
Soil Creep	Wash. DNR, Surface Erosion	Background	Calculated only for Class II and III channels to avoid "double counting" in Class I channels (see next entry)
Bank Erosion and Small Streamside Landslides	PWA Field Surveys of Class I Channels, Stream Channel	Half background, half management[1]	Comparable process/source area to Soil Creep; applied only to Class I channels
Deep-Seated Landslides	Aerial photo and field inventory, Mass Wasting and Stream Channel, PWA Sediment Source Investigation (SSI)	Landslides-Indeterminate[2]	Deep-seated landslides are generally considered much less sensitive to management than shallow landslides
Shallow Landslides in Harvest Units (not associated with roads)	Aerial photo and field inventory, Mass Wasting and PWA SSI	Landslides-Indeterminate[3]	Timber harvest or road drainage may have been factors contributing to some landslides; others will have occurred regardless of management
Surface Erosion of Landslides	Modeling, Surface Erosion	Management	Includes erosion from indeterminate shallow landslides
Surface Erosion in Harvest Units	WEPP Model, Surface Erosion	Management	Includes skid trails
Scour of Tractor Filled Channels (pre-Forest Practices Act)	Field inventory, PWA SSI	Management	Attributed to periods from 1955-1987, primarily 1967-1974
Low Order Valley Fill (fluvial erosion)	Field inventory, PWA SSI	Management	Accounts for all estimated "first cycle" erosion; relatively small source thereafter
Road-associated Shallow Landslides	Aerial photo and field inventory, Mass Wasting and PWA SSI	Management	Most likely associated with the road
Road Surface Erosion	SEDMOD Model (Wash. DNR method), Surface Erosion	Management	Hydrologic connectivity between roads and channels is a critical control on rate of sediment delivery
Gullies/Culvert Fill Failures	Field inventory, PWA SSI	Management	Direct observations and measurements of road-caused erosion

1. This source area would be expected to be a major source of background sediment inputs. Faced with unresolved uncertainty, we conservatively divided the input into equal parts attributed to management and background sources; our opinion is that more than half of the sediment from this source area would be background input. More detailed analysis of sediment sources for the period 1988-1997 indicates that the proportion allocated to management for the period 1942-1997 is probably overestimated.
2. Indeterminate attribution indicates that a significant proportion of these landslides may be of natural origin, however, the degree of uncertainty is relatively large, particularly compared to road-associated shallow landslides. Hence, this sediment source is categorized separately to emphasize this relatively high degree of uncertainty.
3. Indeterminate attribution indicates that a significant proportion of these landslides may be of natural origin, however, the degree of uncertainty is relatively large, particularly compared to road-associated shallow landslides. Hence, this sediment source is categorized separately to emphasize this relatively high degree of uncertainty. Based on sediment source inventories and comparison of landslide rates in harvest areas <15 years old, we believe that approximately 60% of these landslides and sediment delivery is likely to be attributable to management and 40% to background ("natural") sources.

Table 3-3b: Summary of sediment budget inputs and attributions to potentially ongoing management, legacy management, or background categories.

Management Sources	Legacy Sources	Background Sources
• Road surface erosion	• Bank erosion (Fish enhancement structures, RR ties, etc.)	• Deep-seated landslides
• Road-related landslides	• Scour of tractor Fill in Streams	• Shallow landslides
• Deep-seated landslides	• Erosion in Low-order valley fill	• Bank erosion
• Shallow landslides	• Streambank slides	• Soil creep
• Harvest-related surface erosion		• Streambank slides
• Harvest-related bank erosion		

To develop prescriptions that address sources of sediment triggered by contemporary or recent management practices (see the Cumulative Effects Module for additional details), it is necessary to separately categorize "legacy" sediment sources. These sources are itemized in Table 3-3b. In relation to Table 3-3a, certain management sources for the period 1988-1997 were classified as legacy sources because any ongoing erosion from these sources is believed to be associated with management practices no longer in use (e.g., near-stream harvest, filling of channels for use as skid trails) or unrelated to forest management (e.g., bank erosion related to instream habitat enhancement structures).

Although non-road related shallow landslides are more difficult to attribute to either management of background causes, we have estimated the approximate proportion of these shallow landslides that may be attributable to timber harvest. The resulting allocation of sediment to management and background sources is explicitly provided only for the period 1988-1997. Two approaches were used for this estimate. The first is based on results of the sediment source inventory (PWA [1998], Table 8), which categorizes sediment delivery from non-road related shallow landslides in Freshwater as originating from <15-year old and >15-year old forest stands over the period 1942-1997. If it is assumed that >15-year old stands approximate background mass wasting conditions, these data suggest that 60% of this sediment is attributable to harvest effects and 40% is attributable to natural sources over the period of record.

The assumption that >15-year old stands have landslide sediment delivery rates comparable to natural (old-growth) stands may appear to be of limited validity. However, there are several reasons why accelerated landslide rates caused by harvest would likely be significantly reduced after 15 years. Reduced root strength and increased soil moisture are the two most likely physical effects of harvest that could increase landslide frequency. There is evidence that these physical effects are significantly reduced within 15 years after harvest. First, 15 years of regrowth of redwood stands appears to be sufficient for hydrologic recovery based on experimental results at Caspar Creek (Ziemer 1998), suggesting that soil moisture increases following harvest that could increase landslide probability are reduced to background levels after 15 years. Second, root reinforcement to soil strength reaches a minimum <10 years after harvest and recovers substantially after 15 years due to growth of new roots (Sidle et al. 1985). Third, in redwood-dominated forests, roots of harvested trees are believed to recover more quickly because the species resprouts from stumps. Thus, landslide rates on forested slopes 15 years following clearcutting on redwood-dominated slopes would be expected to have much lower landslide rates than comparable slopes harvested less than 15 years previously. Nevertheless, background landslide rate estimates derived from comparison of less than and greater than 15-year-old stands following clearcutting should not be the only basis for estimating background landslide rates.

The second approach to estimate background landslide rates considers landslide rates observed in different forest stand types in Freshwater during the most recent period of record (1988-1997). The Mass Wasting Assessment summarized landslide rates per acre during this 10-year period. These data, summarized in Table 3-4, show that thinned stands have landslide rates lower than unthinned second-growth stands. However, in comparison to relatively high landslide rates in clearcuts, the thinned and unthinned second-growth landslide rates are of similar magnitude.

To estimate background landslide rates, these data could be used in different ways. One confounding aspect of the data is that thinned stands had lower landslide rates than unthinned second-growth stands on some landforms. A second problem is that it is more difficult to detect landslides from aerial photography in older second-growth than in recently harvested areas because of the greater canopy cover in the former. Consequently, landslide rates for older second-growth are probably underestimates.

Table 3-4: Landslide rates from different forest stand types for the 10-year period 1988-1997 in Freshwater. These data are summarized from the Mass Wasting Assessment.

Stand Type	No. of Landslides	Acres	Landslide Rate (ls/ac/10 yrs)
Recent Clearcuts	29	4,113	0.007
Second-growth (40-60 years old), thinned	10	6,717	0.002
Second-growth (40-60 years old)	10	3,857	0.003

For purposes of allocating past sediment sources to management and background sources in the historic sediment input budget, we can compare unthinned second-growth to clearcuts. Although the following estimates do not explicitly account for the potential influence of individual landforms, the proportion of area in different landforms is roughly comparable to these two stand types in Freshwater for the period. In addition, average landslide volumes from different stand types are quite similar, and there is little difference between comparison of landslide rates and volumes of delivered sediment. The following landslide rates are for a 10-year period from 1988 to 1997. Assuming that the background landslide rate is 0.003/ac and the clearcut (<15 years old) landslide rate is 0.007/ac/yr, the increment of landsliding attributable to harvest is 0.004 (i.e., 0.007-0.003). Consequently, about 57% (0.004/0.007) of past landslides from clearcuts are attributable to harvest, and about 43% are attributable to natural background rates of landsliding.

The foregoing estimate of landslide rates is based on a comparison of advanced second-growth stands to clearcut harvest treatments. These rates were developed to develop a quantitative estimate of the proportion of historic sediment inputs from harvest units that would be attributable to harvest and to background mass wasting. More recent harvest treatments (beginning in the late 1980s), are more likely to be commercial thinning operations than clearcuts. Estimated landslide rates from thinned second-growth are lower than or comparable to those in advanced second-growth. These data suggest that commercial thinning is a relatively benign silvicultural treatment that does not appear to result in significant increases in landslide rates. The data also suggest that many landslides in thinned second-growth are of natural origin. Because the majority of the timber harvest in Freshwater from 1988-1997 consisted of commercial thinning operations, and because many landslides in these units are implied to be of natural origin, it is likely that the rough 60/40 split in management/background sources for this landslide mechanism overestimates the actual fraction attributable to management in the period 1988-1997.

In summary, two sets of available data suggest that about 60% of non-road-related shallow landslides and associated sediment delivery in Freshwater are attributable to harvest. Uncertainties surrounding these estimates are substantial (see the above discussion of assumptions and in the Mass Wasting Assessment); however, similar results were obtained from the two different approaches used.

The following section presents a summary of selected data to illustrate the temporal and spatial variation of patterns of erosion in the watershed, as well as estimates of the relative proportions of sediment attributed to management and background (natural) causes. Data from all subbasins are presented in Attachment E-3.

3.4.3 Relative Magnitude of Sediment Sources and Size Classes

The sediment input budget estimates inputs according to a variety of specified sources (Table 3-3). Figure 3-5 displays the relative contributions by different source and sediment size classes over the entire watershed since 1942. For general interpretive purposes, these sources are grouped as background ("natural"), management-related (road-related surface erosion, road-related mass wasting, surface erosion from harvest areas, erosion of filled channels, erosion of headwater valley fills), and indeterminate (deep-seated landslides and landslides not associated with roads). The "indeterminate" status of deep-seated landslides and landslides not associated with roads reflects the uncertainty regarding whether these landslides were caused by forest management. Figure 3-6 illustrates the percentages of sediment inputs allocated accordingly.

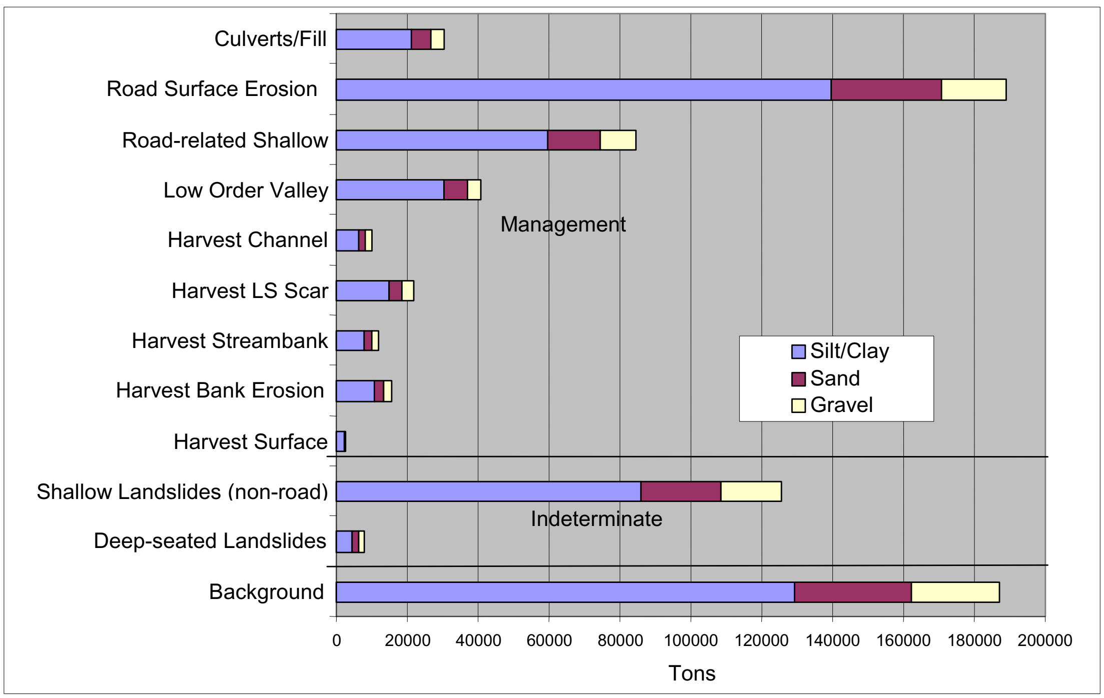


Figure 3-5: Total sediment inputs 1942-1997 by source and size class. "Indeterminate sources" refer to non-road related shallow landslides and deep-seated landslides.

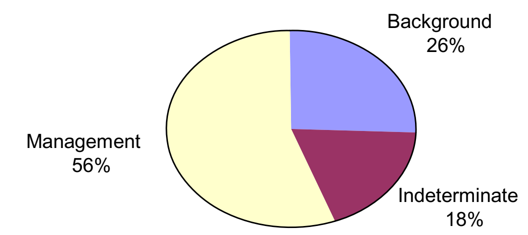


Figure 3-6: Percentage of sediment inputs for major source categories over the Freshwater watershed for the period 1942-1997. "Indeterminate sources" refer to non-road related shallow landslides and deep-seated landslides.

The proportion of sediment inputs from different sources varies among time periods, owing in part to different levels of management activity and in part to the influence of climatic events (major storms) on mass wasting processes. Figures 3-7 and 3-8 show the source and size allocations for sediment inputs for the entire Freshwater Watershed from 1988 to 1997. The distribution of sediment inputs for the period 1988-1997 is most representative of current conditions in the watershed. However, these inputs do not reflect ongoing erosion control measures being implemented on the road network. Most of the sediment sources for the period 1988-1997 categorized as management-related can be controlled to varying degrees by erosion control measures and/or changes in management practices. These sources account for about 85% of the management-related sources. The sediment sources that are **not** considered amenable to control are the categories bank erosion, small streamside landslides, and erosion of tractor filled channels. These sources account for about 15% of the management-related sources.

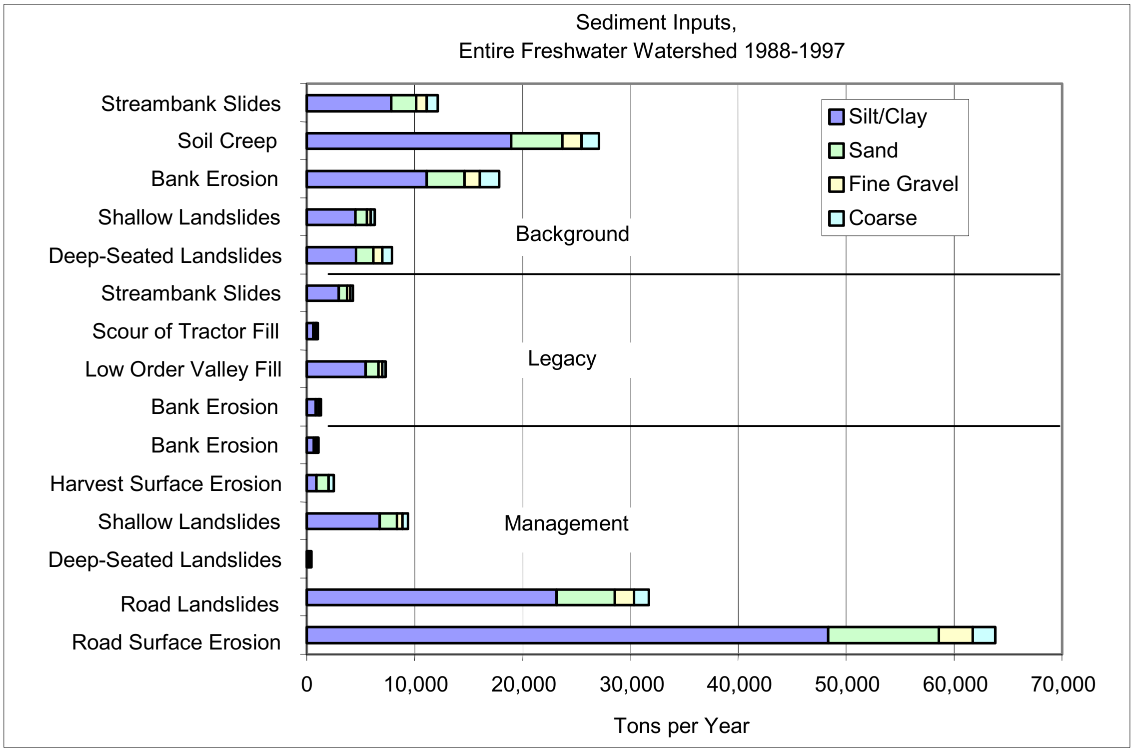


Figure 3-7: Total sediment inputs 1988-1997 by source and size class.

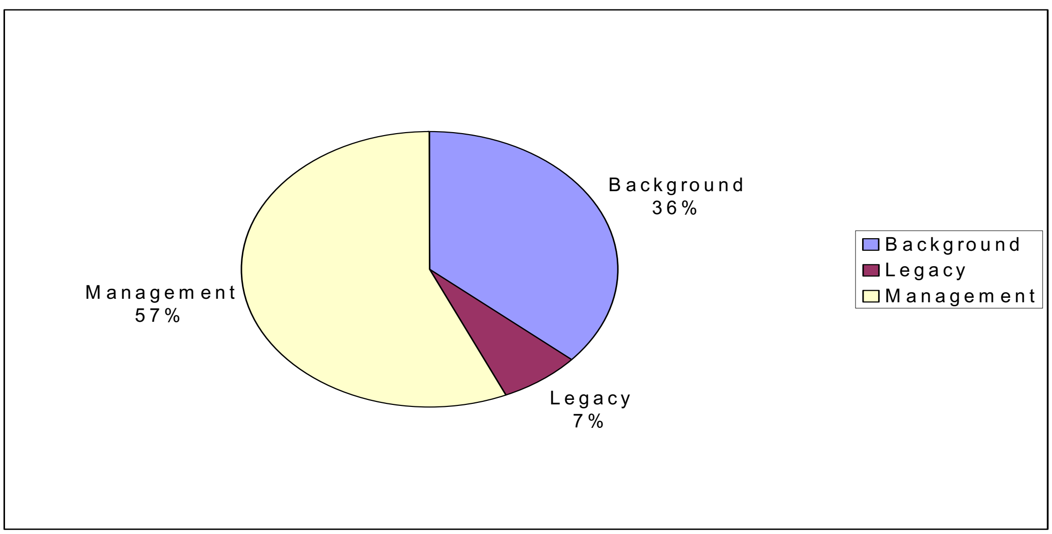


Figure 3-8: Percentage of sediment inputs for major source categories summed over the Freshwater Watershed for the period 1988-1997.

3.4.4 Suspended Load Inputs

The relative contribution of sediment in different size classes from sources attributed to management, background ("natural"), and indeterminate sources is also of interest. Table 3-5 and Figure 3-9 summarize sediment inputs for the <2 mm size class; this size class approximates the maximum expected suspended sediment yield. Over the period 1988-1997, estimated management related inputs <2 mm were about 62% above the long-term management-related input rate. Background inputs were about 34% above the long-term average, and landslide inputs were slightly less than the long-term average.

Table 3-5: Sediment inputs <2 mm for the Freshwater Watershed comparing sources attributed to management and to background erosion processes. This size class is representative of sediment transported in suspension. The sand fraction (>0.074 mm) is transported in intermittent suspension and has some characteristics of bedload.

Time Period	Background	Management	Indeterminate Landslides	Total
1942-1954	81	141	169	392
1955-1966	87	123	43	252
1967-1974	90	286	48	424
1975-1987	92	211	5	309
1988-1997	126	340	65	531
Long-term Average 1942-1997	94	210	68	372

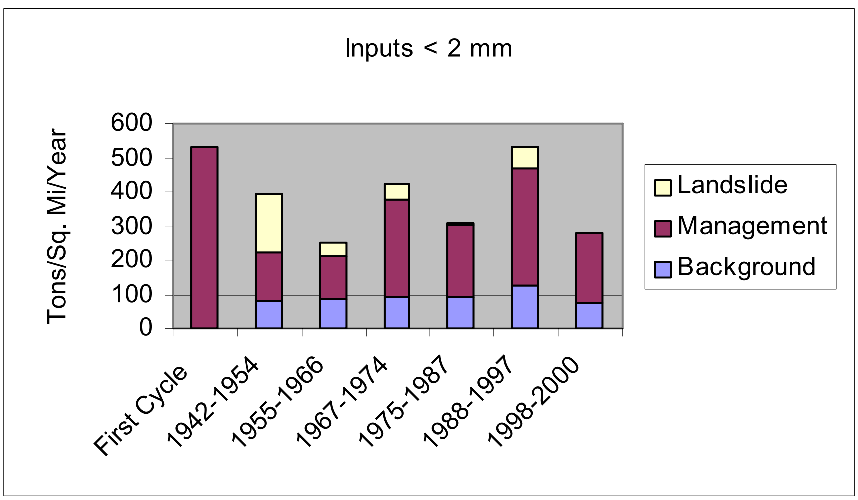


Figure 3-9: Sediment inputs <2 mm diameter for the entire Freshwater watershed apportioned by sediment budget time intervals and management versus background sources. This grain size class is approximately equivalent to suspended sediment load.

3.4.5 Bedload Inputs

For the >2 mm size fraction (bedload) attributed to management, background ("natural"), and indeterminate sources sediment input rates are summarized in Table 3-6 and Figure 3-10. Over the period 1988-1997, estimated management related inputs >2 mm were about 38% above the long-term management related input rate. Background inputs were about 50% above the long-term average, and landslide inputs were about the same as the long-term average.

Table 3-6: Sediment inputs >2 mm for Freshwater watershed comparing sources attributed to management and to background erosion processes. This size class is representative of sediment transported as bedload.

Time Period	Background	Management	Landslide	Total
1942-1954	11	24	26	61
1955-1966	13	22	8	42
1967-1974	14	33	9	56
1975-1987	14	19	1	34
1988-1997	21	36	11	68
Long-term Average 1942-1997	14	26	11	51

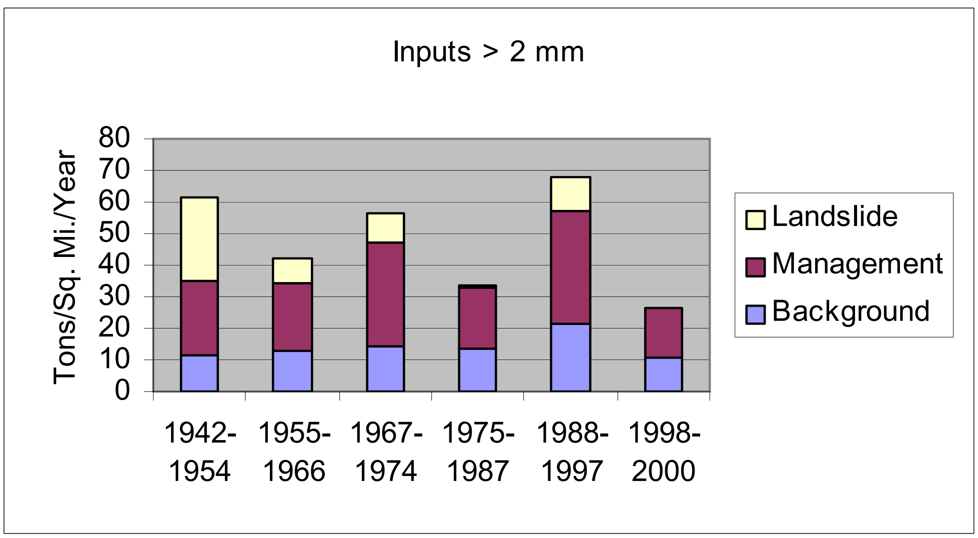


Figure 3-10: Sediment inputs >2 mm diameter for the entire Freshwater Watershed apportioned by sediment budget time intervals and management versus background sources. This grain size class is approximately equivalent to bedload sediment.

3.5 SEDIMENT BUDGET VALIDATION

In Table 3-7, the long-term average of total sediment inputs is presented for each subbasin. These totals include all sediment sizes from all sources for the period 1942 to 2000. The total long-term average input rate averaged over the entire watershed is 420 tons/mi^2/yr. For the drainage area contributing to the Salmon Forever gage site, equivalent to the combined inputs of

Upper Freshwater and South Fork subbasins, the long-term average sediment input rate is also 420 tons/mi^2/yr.

Table 3-7: Long-term sediment inputs by subbasin, 1942-1997.

Subbasin	Drainage Area (mi^2)	Sediment Inputs (tons, rounded to nearest 1000)	Average Input (t/mi^2/yr, rounded to nearest 10)
Upper Freshwater	10.0	200,000	350
South Fork	3.1	117,000	650
Graham Gulch	2.5	89,000	610
Cloney Gulch	4.7	94,000	350
Little Freshwater	4.7	133,000	490
McCready Gulch	2.0	60,000	520
Lower Freshwater	3.1	46,000	260
School Forest	0.6	15,000	430
Total	30.8	755,000	420

This input calculation is in good agreement with, but somewhat lower than, estimates of total sediment yield at the Salmon Forever gage (about 460 to 560 tons/mi^2/yr). The fact that sediment budget predictions are within about 10 to 25% of the sum of observed suspended sediment yield and estimated bedload yield indicates that the sediment budget is reliable enough to be used as a tool to predict erosion under different prescription scenarios.

3.5.1 Estimated Transport of Sediment Size Classes

To qualitatively verify the sediment transport mode/size class boundaries, grain size distributions from bulk sediment samples of streambed material (bars) in Freshwater are compared with the grain size distributions of sediment sources (Figure 3-11). Essentially, grain sizes that are absent from streambed material correspond to sediment sizes transported in suspension as wash load (material that does not deposit in the fluvial system).

As shown in Figure 3-11, 55 to 75% of the sediment inputs are silt and clay size (Section 3.3). Virtually none of this material is stored in the channel deposits (Section 5.3). Hence, silt and clay are appropriately characterized as wash load.

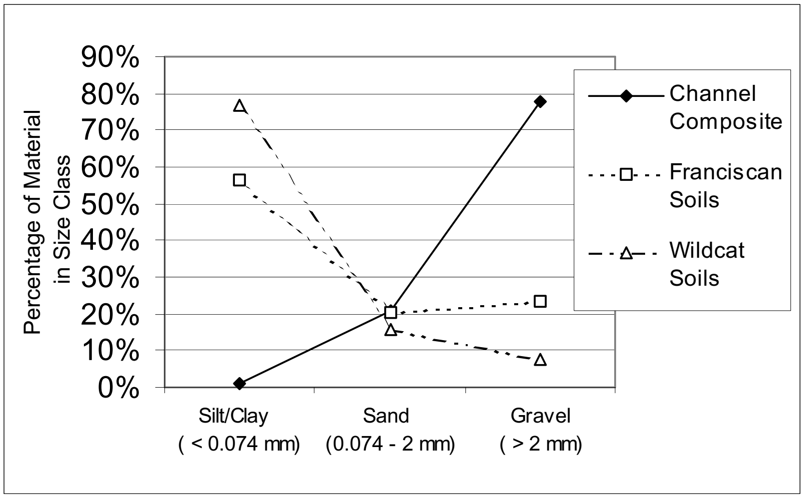


Figure 3-11: Comparison of sediment grain size distributions in soils developed in the two major bedrock types in Freshwater Creek and a composite distribution from seven bulk samples of sediment stored in gravel bars.

About 60% of the sediment coarser than silt and clay (>0.075 mm) delivered to streams is sand (<2 mm). Of the seven bulk sediment samples from channel deposits, an average 22% of bed sediment was sand (<2 mm). The range of values for sand in bed sediments was 5 to 33%. These data show that the percentage of sand input to channels is about 3 times greater than the percentage of sand in channel deposits. This indicates selective removal (more rapid transport) of sand from the channel system. This is consistent with transport as intermittent suspended load.

Sediment inputs of gravel (>2 mm) are not more than about one-fifth of the total in the relatively gravel-rich soils derived from Franciscan parent material. In contrast, about three-fourths of sediment in channel deposits sampled in the bulk samples is gravel. This indicates that gravel accumulates in the channel system because it is transported relatively slowly.

3.5.2 Suspended Sediment Yield

The Redwood Sciences Laboratory (RSL) computed suspended sediment yield from Salmon Forever gage data for part of Water Year (WY) 1999 beginning in January (http://www.rsl.psw.fs.fed.us/projects/water/freshwater/analysis.html). These suspended sediment yield estimates can be compared to the sediment budget inputs for the watershed area contributing to the gage site as a test of the accuracy of the sediment input budget.

For this half-year of record, the suspended sediment load was estimated to be about 235 tons/mi^2 (see Section 3.6.1. of the Fisheries Assessment Module for more information regarding Salmon Forever gage data and sediment yield data). Extrapolating crudely to a full year by doubling the reported yield for WY 1999, the annual yield can be estimated as 470 tons/mi^2/yr. A preliminary estimate of 375 tons/mi^2/yr of suspended sediment yield for WY 2000 was reported by Clark Fenton of Salmon Forever (e-mail, July 2000).

3.5.3 Calculation of Suspended Sediment Inputs

As described above, the silt and clay fraction of sediment inputs is expected to be transported in suspension as wash load, and would certainly be measured in the suspended yield. The sand fraction, however, is transported alternately in suspension and as bedload, depending on flow velocity and grain size. Substantial quantities of sand are collected in suspended sediment samples at the Salmon Forever gage (unpublished RSL data; sand size reported only as >0.074 mm). Hence, the minimum estimate for suspended load yield from the sediment input budget would be the average annual input in the silt/clay fraction. A more refined estimate would include some portion of the sand fraction.

The most recent time periods for which sediment input budgets have been prepared are 1988-1997 and 1998-2000 (Figure 3-12). The latter period does not include any data for large landslides as 1997 aerial photography was the most recent. While there was a significant quantity of landslide sediment generated in 1997 and accounted for in 1997 photography, it is believed that there has been little landslide activity since then. Sediment inputs for the period 1998-2000 are estimated based on background input rates from soil creep and mass wasting plus modeled surface erosion from harvest areas and roads only. Consequently, the 1988-1997 time period probably provides a better basis for comparison with WY 2000 suspended sediment yield data. The 1998-2000 time period is nevertheless considered, primarily because it includes the period when suspended sediment was measured at the Salmon Forever gage site. Given that the sand fraction is thought to be routed through the channel network over time periods on the order of several years to about a decade, it follows that a significant percentage of sand inputs generated in the period 1988-1997 would still be working through the channel network and would be reflected in suspended sediment samples.

Sediment input budgets for these time periods for the watershed area above the Salmon Forever gage are summarized in Table 3-8. The most representative sediment budget input data for comparison are that for 1988-1997, which includes landslide inputs, and the scenario that includes one-half of the sand input. This estimate of suspended sediment inputs, 386 tons/mi^2/yr, is in close agreement with the data collected at the Salmon Forever gage, which yields estimates ranging from approximately 375 tons/mi^2/yr (reported preliminary estimate for WY 2000) to 470 tons/mi^2/yr (extrapolated estimate for partial WY 1999 data).

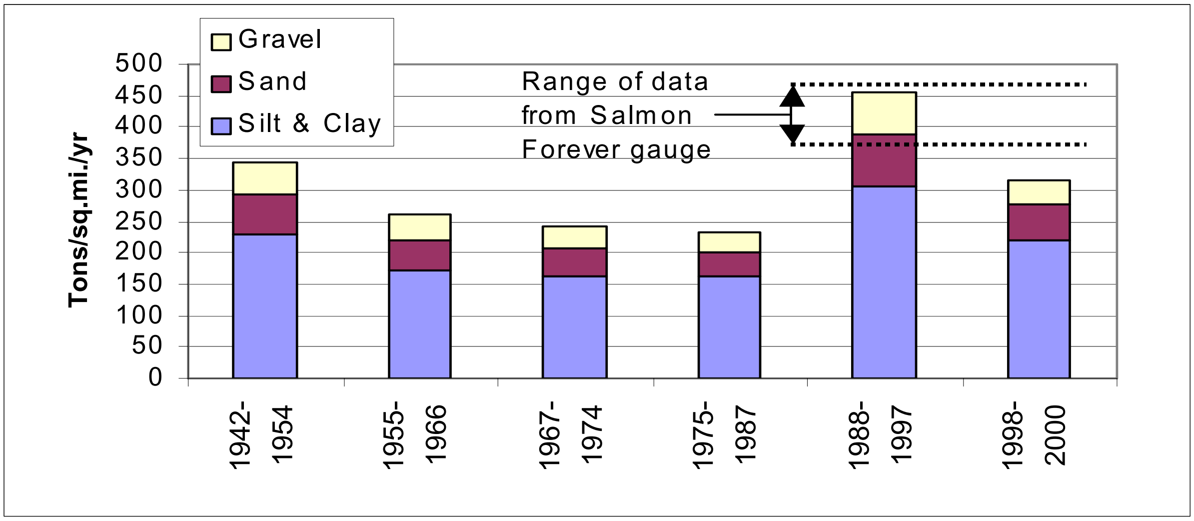


Figure 3-12: Sediment input budget for combined sub-watersheds contributing to the Salmon Forever gage site (drainage area about 13 mi^2). Sediment inputs for the period 1998-2000 include only inputs from the Surface Erosion Module and, therefore, are probably not the most representative of recent conditions. The period 1988-1997 includes substantial landslide inputs and is probably the best representation of recent inputs for purposes of comparison to the sediment yield estimate at the Salmon Forever gage.

Table 3-8: Sediment budget inputs for the watershed area draining to the Salmon Forever gage. Estimates of sediment yield measured at the gage site range from 375 to 470 tons/mi^2/yr.

Time Period	Silt/Clay + All Sand tons/mi^2/yr	Silt/Clay + ½ Sand tons/mi^2/yr	Silt/Clay Only tons/mi^2/yr
1988-1997	431	386	340
1998-2000	277	249	220

3.5.4 Bedload Sediment Transport

A bedload transport model was developed to analyze sediment routing through the major tributaries and the mainstem reaches of Freshwater Creek (see Section 4.0). Estimates of bedload transport rates from the bedload transport model can be compared with the suspended sediment yield estimates from the gage site as another test of the accuracy of the sediment budget.

Calculating the ratio of bedload and suspended load estimated for Freshwater at the gage site and comparing this ratio with that obtained for North Fork Caspar Creek also helps test the accuracy of the bedload transport model for long-term bedload yield estimates. The latter site has some of the best available data in the region, although there are geologic differences. Freshwater Creek contains extensive areas of soils derived from the Wildcat Formation and from the Central Belt Franciscan, whereas Caspar Creek soils are derived from the Coastal Belt Franciscan. In our opinion, these differences suggest that the sediment yield, and suspended sediment yield, would tend to be higher for Freshwater.

There is one known problem with comparing the Freshwater data in this way. The suspended sediment measured at the gage site and the bedload sediment transport estimated from the bedload routing model both include the sand fraction. Sand is transported both as bedload and in suspension. A fraction of the sediment calculated to be transported as bedload may in fact be transported (and measured) as suspended load. Hence, for purposes of calculating the ratio of bedload to suspended load, it is likely that the bedload fraction is overestimated.

The estimated long-term annual bedload transport capacity from the model for the Freshwater (Salmon Forever) gage site is 88 tons/mi^2/yr (Section 4.5.2, Table 4-4). Adding this value to the estimated suspended yield data for WY 2000 of 375 tons/mi^2/yr (a plausible value based on sediment input budget data for this portion of the watershed back through 1942, see Figure 3-12 above), the estimated total sediment yield is 463 tons/mi^2/yr. If the partial year 1999 suspended yield data are used (470 tons/mi^2/yr), the estimated total annual yield at the gage site would be 558 tons/mi^2/yr.

Of the total, 16% (88/558) to 19% (88/463) is bedload and 81% (375/463) to 84% (470/558) is suspended load. For North Fork Caspar Creek, there are two estimates of the relative percentages of bedload and suspended load. Napolitano (1996) estimated the ratio to be 15% bedload and 85% suspended load. Cafferata and Spittler (1998) estimated 30% bedload and 70% suspended load based on calculations by Jack Lewis of the Redwood Sciences Lab. Reid and Dunne (1996, Table 14, p. 114) report that bedload might represent 5 to 11% of the total load. The estimates for North Fork Caspar Creek and Reid and Dunne (1996) bracket the estimate for Freshwater, suggesting that the bedload transport rates estimated for Freshwater are reasonable. More precise validation of bedload transport rates is not possible based on currently available data.

3.5.5 Conclusions

The good agreement between sediment input budget estimates and suspended sediment yield measurements suggests that the sediment input budget can be used as a tool to develop prescriptions to minimize management-related erosion. Based on evaluation of the available data presented, it is concluded that the sediment input budget is sufficiently accurate to guide prioritization of efforts to control management-related sediment sources. The sediment budget identifies sediment source categories. During the prescriptions development, the sediment input budget models and observations can be recalculated to predict the effectiveness of different prescription scenarios. This approach suggests that the sediment input budget can be used to predict anticipated changes in suspended sediment yield resulting from prescriptions.

4.0 SEDIMENT ROUTING MODEL

This section presents a quantitative model of the history of sediment inputs and transport in the watershed. The purpose of this modeling is to understand and quantify the rate at which sediment is routed through the channel network. The model predictions are used to provide insight into possible increases in bed elevation (aggradation) and the time required to transport sediment from source areas in the upper watershed to flood-prone areas in the lower watershed. Model calculations of the quantity of bedload sediment transported and the approximate time required to transport bedload through the watershed are used in the analysis of flood hazards in lower Freshwater (Section 5.2.2). The calculations are also used to check the validity of the sediment budget (Section 3). The history of sediment inputs is provided by the Mass Wasting and Surface Erosion Modules, with summary and interpretation in Section 3.0 of this module. The Hydrologic Change Module provides information used to calculate sediment transport history. The implications of these analyses are discussed in other sections of this analysis. The discussion that follows in this section describes development, results, and validation of the bedload sediment transport model.

4.1 METHODS

Development of the bedload transport and routing model was a multi-step process using data collected during the 1999 field sampling effort and analysis results from the Hydrology, Mass Wasting, and Surface Erosion Modules. Figure 4-1 shows the steps followed in the modeling effort; the text below describes each of these steps.

4.1.1 Hydraulic Channel Data

Ten channel cross-sections were selected for development of bedload transport estimates. Cross-sections were located in the mainstem (1- MS1: Salmon Forever Gage Site, 2- MS2: Langlois, 3: MS3 – Harper's, 4: MS3-Hippen's) and six tributaries (5: Upper Freshwater, 6: South Fork, 7: Little Freshwater, 8: Graham Gulch, 9: Cloney Gulch and 10: McCready Gulch) (Figure 4-2). Selection of cross-sections that best represent each reach was based on preliminary hydraulic analyses with WinXSPro (USFS 1998), longitudinal profile data from which local bed slope was determined, and roughness conditions upstream and downstream of the cross-section

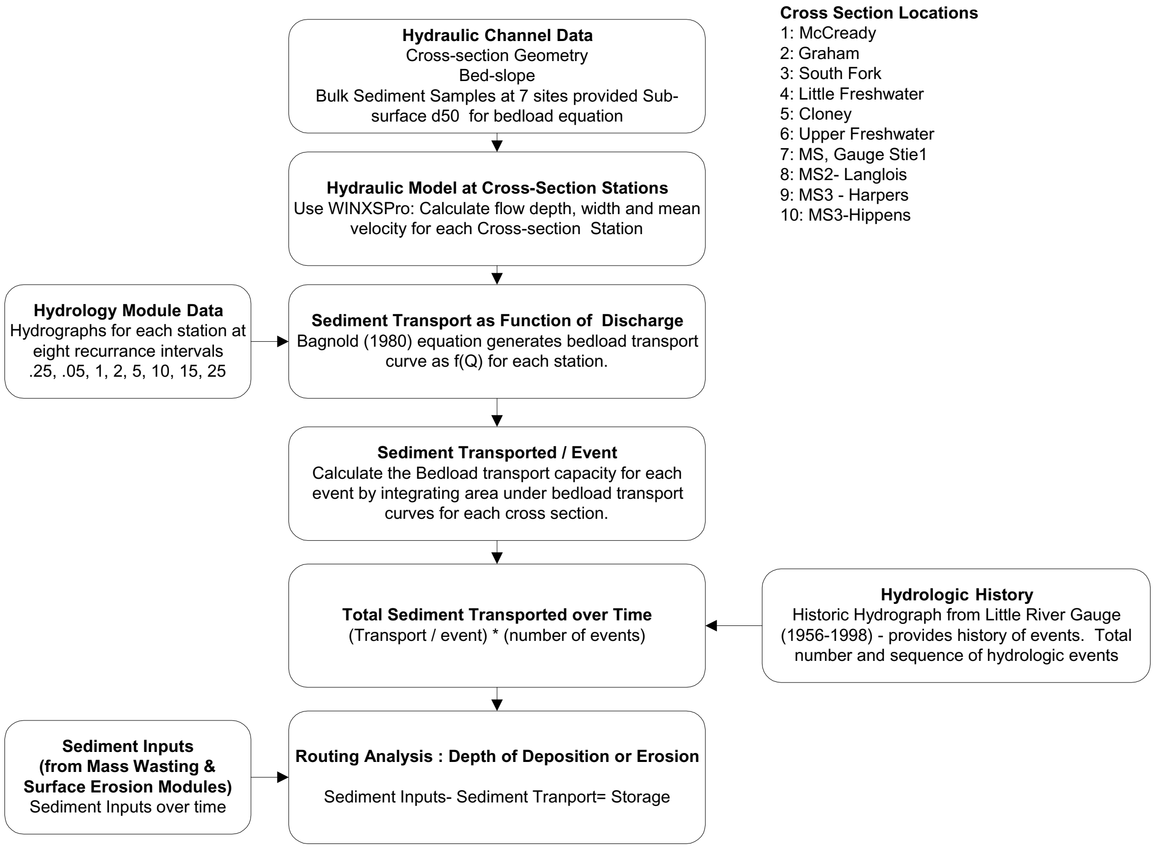


Figure 4-1: Flow chart of approach used for modeling sediment transport & routing in the Freshwater Watershed.

conditions. About half of the cross-sections had been established at PALCO monitoring sites. PWA established the others in 1999. The critical data collected in the field to support the hydraulic modeling for each cross-section were the bed slope and the cross-section (methods for this data collection are discussed in Section 5.1.3.1). Critical field data supporting the bedload transport component of the model was the median grain size of the bed material (subsurface d50 as calculated from the bulk sediment samples).

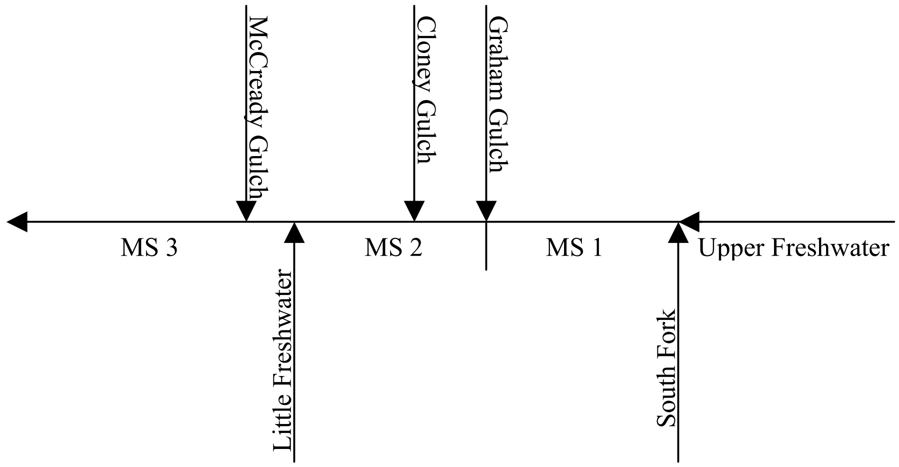


Figure 4-2: Diagram of Freshwater sediment routing model. Arrows indicate subbasin sediment inputs. Additional inputs to MS3 from smaller tributary subbasins are not shown in the diagram, but are included in the analysis.

4.1.2 Hydraulic Model at Cross-Sections

WinXSPro was used in to create a stage discharge relationship. Due to the lack of measured discharge data (except at the Salmon Forever gage), an empirically derived flow resistance equation provided in WinXSPro was used to model hydraulics at each cross-section. Jarrett's (1984) resistance equation was used where flow resistance (also known as roughness) is a function of the water surface slope (S) and hydraulic radius (R): n=0.39 $S^{0.38}R^{-0.16}$. WinXSPro uses this term to generate a mean channel velocity (v). In addition, WinXSPro allows the user to sub-divide the channel cross-section so that split channels and overbank flow areas can be handled separately, thus avoiding non-representative computations of R. Cross-sections were sub-divided to take advantage of this feature. For this analysis, values of n ranged approximately between 0.03 to 0.04 at bankfull. Discharge is calculated as Q=Av where A is the cross-sectional area.

4.1.3 Hydrology Module Data

Flow hydrographs were developed in the Hydrologic Change Module (Section 3). For each cross-section station, eight unit hydrographs were created based on the 0.25, 0.5, 1, 2, 5, 10, 15, and 25-year flood flow so that total bedload transport could be predicted for a flow event of any desired magnitude.

4.1.4 Sediment Transport/ Discharge Relationship

To calculate sediment transport rates, the output file with stage discharge information that WinXSPro generates after each hydraulic simulation was used. The key variables required for sediment transport calculations were width of the active bed, hydraulic radius, mean velocity, and discharge.

The approach we chose for calculating sediment transport rates uses stream power to assess bed load transport rates (Bagnold 1980). Gomez and Church (1989) and Reid and Dunne (1996) indicated that this equation was one of the most accurate predictors of bedload transport rates in studies comparing observed transport rates and transport rates calculated from equations. Gomez and Church (1989) define bedload as sediment coarser than 0.2 mm; we have adopted that convention here, but recognize that some of the sand is transported intermittently in suspension.

Using stream power per unit channel width (ω) and the threshold value of ω at which sediment begins to move (ω_0), a flow depth (Y) and the grain size of interest (D), and Y_r and D_r empirical reference values, the sediment transport rate i_b varies empirically as:

$$i_b = i_{br}\left[\frac{(\omega-\omega_0)}{(\omega-\omega_0)}\right]^{\frac{3}{2}}\left(\frac{Y}{Y_r}\right)^{-\frac{2}{3}}\left(\frac{D}{D_r}\right)^{-\frac{1}{2}}$$

D was represented by the median diameter of the bed material; this was the approach used by Gomez and Church (1989) to test the equation. The critical value at which stream power begins to initiate sediment transport is calculated as:

$$\omega_0 = 5.75(\lambda D\Theta_0)^{\frac{3}{2}}\left(\frac{g}{\rho}\right)^{\frac{1}{2}}\lg\left(12\frac{Y}{D}\right)$$

where λ is the excess suspended density of the sediment (ρ_s-ρ_f), ρ is the density of the water, g is the gravitational constant, and an assumed value of 0.04 represents the Shield's critical dimensional shear stress (Θ_0).

Resulting estimates of bedload transport were plotted as a function of water discharge for each recurrence interval at each cross-section. For convenience in computing cumulative bedload transport for model hydrographs (described below), regression equations were fitted to plots of bedload discharge as a function of water discharge. Owing to the deterministic character of the model, the fitted regressions were linear and had correlation coefficients very near 1. For cross-sections where overbank flow was predicted, separate regression equations were fitted for overbank flow conditions. The regression equations relating bedload transport to water discharge for each cross-section were then used in conjunction with the unit hydrograph that was generated for each reach location to predict bedload transport for specified flow events (see below).

4.1.5 Sediment Transported / Hydrologic Event

Flow hydrographs with one-minute time steps were developed in the Hydrologic Change Module (Section 3). For each cross-section station, eight unit hydrographs were created based on the 0.25, 0.5, 1, 2, 5, 10, 15, and 25-year flood flow. The predicted peak discharge for each station and each flow event was obtained from the Hydrologic Change Module. The bedload regression equation was used to determine bedload discharge for each time increment in the unit hydrograph (Table 4-1). For each flood event, the amount of sediment transported was determined by summing cumulative bedload discharge during the flow event. The estimated bedload transport capacity for a given storm event at a given cross-section station was thus established. These bedload transport capacities are summarized in Table 4-2.

4.1.6 Hydrologic History

Given the lack of a long-term gage site on Freshwater Creek, the Little River gage was used as a surrogate to determine when flood events occurred on Freshwater Creek. The period of record for Little River runs from 1956 to 1998. Recurrence intervals for a given discharge were determined by generating a Log Pearson III flood frequency curve.

The flow events from Little River were categorized according to recurrence interval classes as shown in Figure 4-3. Analysis of the data (Table 4-3) indicated that the number of low magnitude flows was under-represented. The record only included 17 0.5-year events. This is not unusual in USGS flow above threshold data. In the 43-year gage record, approximately 86 such events would be expected (two per year). These frequent, low-magnitude events are believed to account for a significant portion of total sediment transport (e.g., Andrews [1980]). Under-estimating their frequency would likely result in a significant under-estimate of historic bedload transport capacity. Consequently, we added 69 (86 expected less 17 recorded) events to the record. Because the timing of these hypothetical (and relatively common) hydrologic events is not known, they were distributed evenly over the period of time for which sediment transport is modeled (1942-1998).

Table 4-1: Equations predicting bedload transport as a function of stream discharge using Bagnold's (1980) bedload transport equation.

Station	Cross Section	Equation (x = stream discharge in cfs; result is bedload discharge in metric tons per minute)	Applicable Discharge Range (cfs)
McCready Gulch	MG5	$0.0000007x^2 + 0.001x - 0.0164$	N/A
Graham Gulch	GG5	$0.0043x - 0.2106$	N/A
South Fork Freshwater	SF5	$0.0008x-0.0429$ $0.0019x - 1.3106$	<1138 >1138
Little Freshwater	LF09	$0.0013x$ $0.0021x-0.2719$	<580 >580
Cloney Gulch	CG2	$0.0024x$	N/A
Upper Freshwater	FC08	$0.0009x - 0.0381$	N/A
Roelof's Gage	FC10	$0.0007x$ $0.0021x^{0.872}$	<2419 >2419
Langlois	FC12	$0.00008x^2 + 0.0000005x$ $-0.0009x^2 + 0.0002x + 0.1463$	<2542 >2542
Harper	FC13	$0.001x$ $0.017x^{0.6346}$	<2705 >2705
Hippen's	FC14	$0.0007x$ $0.0008x - 0.2771$ $0.0006x + 0.7466$	<2366 2366<Q<4080 >4080

Table 4-2: Peak discharge and cumulative bedload discharge for subbasin and reach modeling stations.

	McCready Gulch		Graham Gulch	
Recurrence Interval	Instantaneous Peak Discharge (cfs)	Cumulative Bedload Discharge for Event Hydrograph (short tons)	Instantaneous Peak Discharge (cfs)	Cumulative Bedload Discharge for Event Hydrograph (short tons)
0.25	87	13	113	29
0.5	145	28	193	94
1	220	47	291	188
2	267	60	357	253
5	397	95	529	427
10	511	127	678	580
15	588	148	742	646
25	635	162	846	754

Table 4-2: Peak discharge and cumulative bedload discharge for subbasin and reach modeling stations.

	South Fork Freshwater		Little Freshwater	
Recurrence Interval	Instantaneous Peak Discharge (cfs)	Cumulative Bedload Discharge for Event Hydrograph (short tons)	Instantaneous Peak Discharge (cfs)	Cumulative Bedload Discharge for Event Hydrograph (short tons)
0.25	140	9	189	83
0.5	237	28	313	138
1	356	54	462	203
2	435	71	555	244
5	641	118	810	418
10	815	159	1020	554
15	887	175	1050	573
25	1007	204	1248	703
	Cloney Gulch		**Upper Freshwater**	
Recurrence Interval	Instantaneous Peak Discharge (cfs)	Cumulative Bedload Discharge for Event Hydrograph (short tons)	Instantaneous Peak Discharge (cfs)	Cumulative Bedload Discharge for Event Hydrograph (short tons)
0.25	207	134	293	64
0.5	356	230	514	131
1	520	336	798	223
2	642	415	985	283
5	941	608	1525	459
10	1192	770	2013	618
15	1275	824	2275	703
25	1426	921	2569	799
	Roelof's Gage		**Langlois**	
Recurrence Interval	Instantaneous Peak Discharge (cfs)	Cumulative Bedload Discharge for Event Hydrograph (short tons)	Instantaneous Peak Discharge (cfs)	Cumulative Bedload Discharge for Event Hydrograph (short tons)
0.25	476	116	785	6
0.5	806	197	1298	17
1	1213	296	1941	37
2	1496	365	2368	55
5	2245	548	3479	159
10	2891	729	4405	228
15	3153	797	4873	260
25	3615	913	5398	295

Table 4-2: Peak discharge and cumulative bedload discharge for subbasin and reach modeling stations.

	Harper		Hippen's	
Recurrence Interval	Instantaneous Peak Discharge (cfs)	Cumulative Bedload Discharge for Event Hydrograph (short tons)	Instantaneous Peak Discharge (cfs)	Cumulative Bedload Discharge for Event Hydrograph (short tons)
0.25	980	330	1106	258
0.5	1587	535	1777	414
1	2335	787	2635	612
2	2847	951	3140	732
5	4142	1295	4565	1097
10	5201	1546	5729	1386
15	5597	1635	6139	1482
25	6313	1790	6952	1668

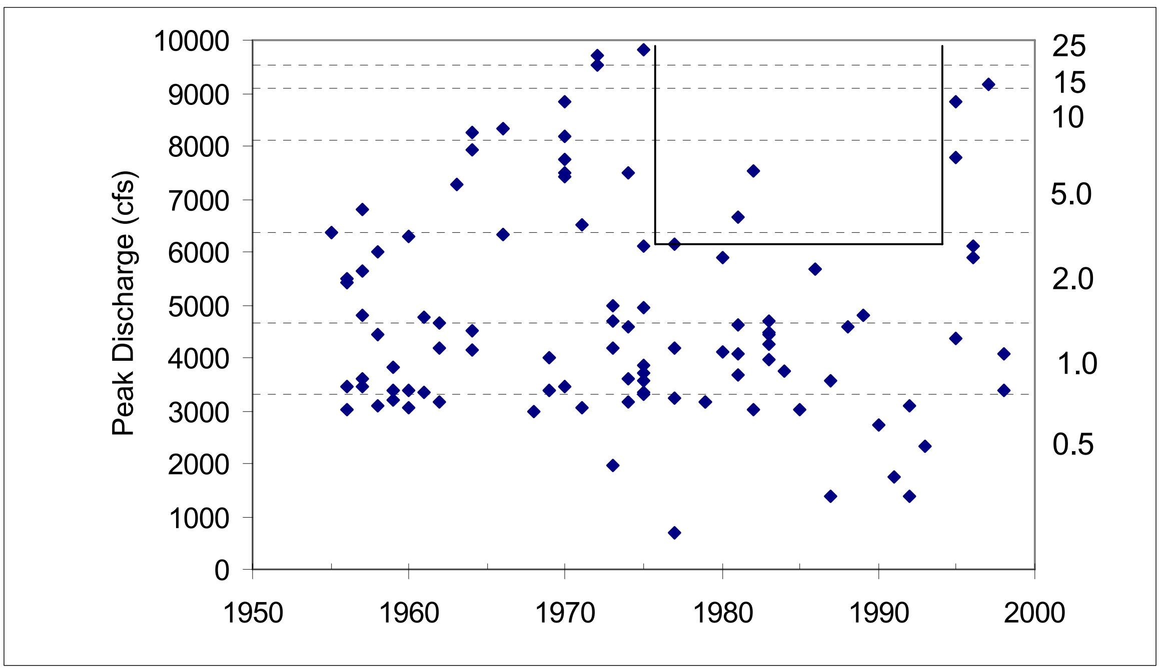


Figure 4-3: Little River peak flows above threshold (i.e., the partial duration series) from USGS gage data. The open box in the upper right corner of the plot emphasizes a period of about 20 years during which few floods of significance occurred. Reports of increased flooding by residents of lower Freshwater coincide with the end of this period of few floods.

Table 4-3: Events per recurrence interval category from Little River.

Recurrence Interval	Number of Events
0.5	18 recorded, 86 assumed for modeling
1	37
2	20
5	12
10	5
15	1
25	3

Note: The three lowest magnitude events in the record were categorized as 0.25-year events, and are excluded from these data. Although only 18 flow events of 0.5-year recurrence were recorded, this is an artifact of the USGS peak flow summary data which focuses on flows of higher magnitude.

4.1.7 Total Sediment Transport Over Time

Predicted sediment transport capacity for a storm event of a specified recurrence interval at modeling stations in the Freshwater Creek Watershed was determined as per Section 4.1.5 (Table 4-2). The number and magnitude of flow events during each water year at the Freshwater Creek modeling stations were determined from the Little River record (Figure 4-3, Table 4-1). Estimated annual bedload transport capacity for each station was then calculated as the sum of bedload transport capacity for the peak flow events in each water year. Thus, the bedload transport model produced estimated historic bedload transport capacity for Freshwater Creek modeling stations. The estimated mean annual bedload transport capacity for the period 1956-1998 was used to estimate total bedload capacity for the period from 1942 to 1955 at each station in Freshwater Creek. This extrapolation of model data was necessary to perform sediment routing calculations for the period 1942-1955. The predictions of bedload sediment transport capacity assume that there are no bedload supply limitations. The routing model considers potential sediment supply limitations by using the Freshwater sediment input budget (Section 3.0) to estimate inputs at the subbasin reach scale.

4.1.8 Sediment Inputs

The bedload sediment input of material coarser than 0.074 mm (the size boundary between silt and sand) to each subbasin for the period 1942-1997 was calculated through collaboration between the Mass Wasting, Surface Erosion, and Stream Channel Modules. Section 3.0 of this analysis presents the results of the sediment input budget created from these analyses.

4.1.9 Sediment Routing Analysis

The routing of bedload (i.e., the relationship between transport and storage of coarse sediment as it moves through the channel network) is modeled simply. The bedload sediment input of material coarser than 0.074 mm to each subbasin for the period 1942-1997 was compared with the bedload sediment transport calculation for each subbasin over the same period. For example, if inputs exceed transport capacity, net accumulation is predicted, and the downstream routing of sediment is equal to transport capacity. Conversely, if transport capacity exceeds sediment inputs, net erosion is predicted and downstream routing is limited to the available sediment supply. Initial conditions of in-channel sediment storage in 1942 are unknown in quantitative terms. Channel storage of bedload sediment was assumed to be zero in 1942. Although this initial condition is not realistic, the implications of this assumption can be considered when evaluating model results. Moreover, the primary purpose of the bedload routing model is to develop a quantitative assessment of time required to transport bedload sediment through the watershed, and this is largely unaffected by initial conditions.

As noted earlier, the bedload transport model is conceived to include sediment sizes as fine as 0.2 mm. Also as noted earlier, sediment in the sand size fraction (<2 mm) of bedload is transported in intermittent suspension and is routed through the watershed more quickly than gravel (>2 mm diameter). The ramifications of this aspect of the model are discussed in the analyses of aggradation and flood hazards (Section 5).

It was assumed that all sediment inputs were delivered to Class I channels. No estimates of sediment storage in Class II or III channels were made, despite the fact that such sediment is ultimately routed downstream. The role of woody debris in sediment storage in these headwater channels is neglected in this analysis. Incorporating sediment storage in Class II and III channels into the sediment routing analysis would probably reduce the modeled sediment inputs to the Class I channel network and increase the residence time of bedload sediment in the watershed. Such storage sites could also be sources of sediment as LWD decays or is disturbed by floods. The role of this storage element in Class II channels has not been examined in detail in this analysis. Background on this subject is presented in O'Connor and Harr (1994) and O'Connor (1994). Their studies suggest that if woody debris is actively accumulating in headwater channels, there will be a net increase in sediment storage and a corresponding decrease in delivery of sediment downstream.

In the headwater subbasins, a comparison of bedload inputs and outputs could be made directly to calculate an estimate of change in storage (i.e., channel aggradation or degradation).

For mainstem reaches (MS1, MS2, and MS3), in which sediment inputs are primarily routed by fluvial transport from upstream subbasins, mass balance considerations were used to determine values for delivery from upstream and to downstream reaches (Figure 4-2). For example, if inputs in a subbasin exceed modeled bedload transport, the output to downstream reaches was limited to the transport capacity. If bedload transport capacity exceeded sediment inputs, then the material routed downstream was limited to the sediment inputs. In this manner, a prediction was made regarding the change in storage of sediment over time.

The predicted change in storage is presented in terms of average depth of deposition (or erosion) for the time periods 1942-1997, 1988-1997 and 1975-1987. Field observations of channel width, map-derived calculations of channel length, and a density conversion factor of 1.68 tons/yd^3 for fluvial sediment were used to convert the change in mass to an equivalent unit depth of sediment deposition or erosion.

4.2 SEDIMENT ROUTING RESULTS

4.2.1 Bedload Transport Capacity Over Time

Estimated historic bedload transport capacity was calculated by adding together the bedload transport from individual storm events occurring in each water year for each station. These estimates are graphically displayed in Figure 4-4.

The MS2 reach as modeled has significantly lower transport rates than areas upstream. For reasons discussed below, the quantitative model result for MS2 is regarded as anomalous. Nevertheless, the qualitative result for MS2 suggesting potential bed aggradation is accepted as plausible, and the potential effects of such aggradation on flood frequency are analyzed in detail (Section 6.1).

4.2.2 Routing Analysis Results

Predicted change in storage was calculated for the time periods 1942 - 1997, 1988 - 1997, and 1975-1987. Different time periods were evaluated because the timing of bedload delivery from the upper watershed to the lower watershed is of interest with respect to suggestions by some that erosion related to forest management over the past decade has caused channel aggradation and contributed to increased flood frequency. The long-term record (1942 to 1997) is probably the best representation of sediment routing because imbalances in sediment supply (input) and bedload transport during shorter time intervals do not affect the calculations.

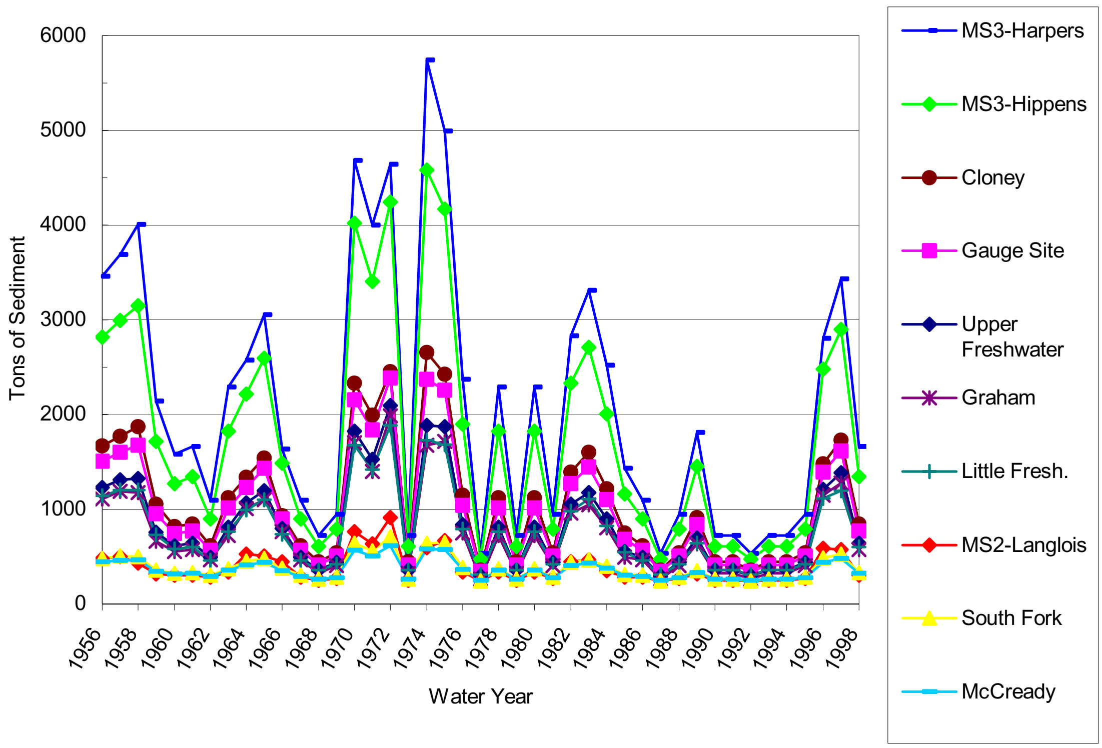


Figure 4-4: Modeled bedload sediment transport capacity over time for Freshwater subbasins and mainstem reaches (based on flow record at Little River, approximately 20 miles north).

The period 1988-1997 is presented to provide an assessment of bedload transport and modeled channel aggradation during the period in which more residents of lower Freshwater have reported increased flooding. The period 1975-1987 is included for comparison with the period 1988-1997.

The predicted change in storage is presented in terms of average depth of deposition (or erosion) for the time periods 1942-1997, 1988-1997, and 1975-1987. These results are illustrated in Figures 4-5, 4-6, and 4-7.

The channel aggradation predicted for MS2 (>10 ft) and degradation predicted for MS3 (about 3 ft) appears inconsistent with sediment storage observations. The downcutting predicted in the MS3 is probably a consequence of the predicted excessive deposition in the MS2 reach, thereby significantly reducing sediment supply to MS3. Consequently, the total inputs to MS2 and MS3 were combined and compared to the bedload output for MS3 (as shown in the last pair of columns in Figures 4-5, 4-6, and 4-7).

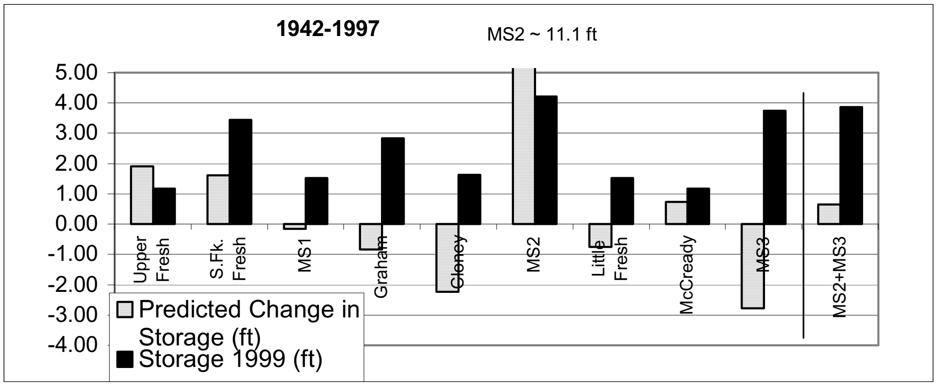


Figure 4-5: Predicted change in bedload storage and observed storage in 1999 in Freshwater subbasins and mainstem reaches for the period 1942-1997. Cloney Gulch storage is an estimate based on results from other subbasins with similar combinations of geology. The graphic for station MS2 is truncated to facilitate comparison with Figures 4-6 and 4-7.

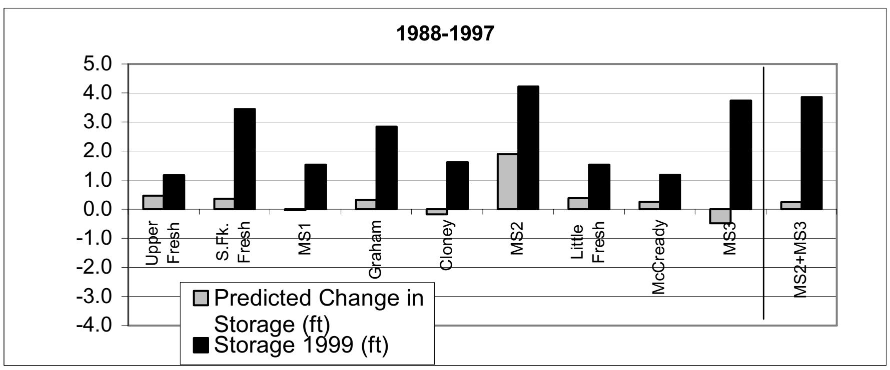


Figure 4-6: Predicted change in bedload storage and observed storage in 1999 in Freshwater subbasins and mainstem reaches for the period 1988-1997. Cloney Gulch storage is an estimate based on results from other subbasins with similar combinations of geology.

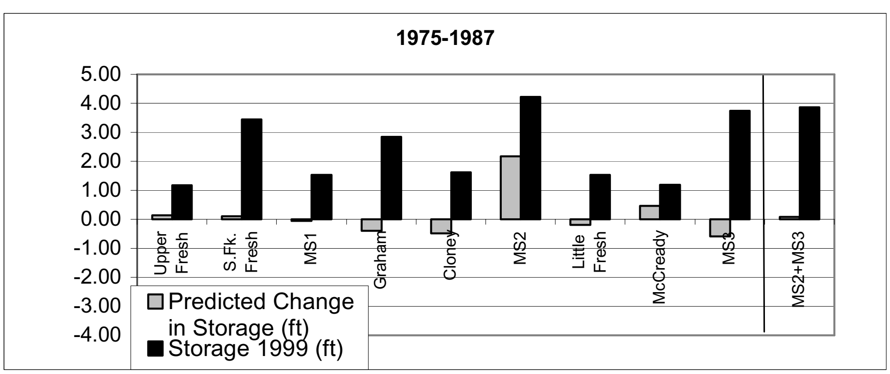


Figure 4-7: Predicted change in bedload storage and observed storage in 1999 in Freshwater subbasins and mainstem reaches for the period 1975-1987. Cloney Gulch storage is an estimate based on results from other subbasins with similar combinations of geology.

To estimate bed aggradation in lower Freshwater, combining reaches MS2 and MS3 is regarded as the most plausible interpretation of the model results over the longer term (1942-1997), as discussed below and in Section 5.

4.3 IMPLICATIONS OF THE ROUTING MODEL

4.3.1 Short-term Changes in Sediment Storage

The change in storage can be calculated for each period (about a decade in length) in the sediment budget; however, given the uncertainties of bedload transport modeling, we believe a more robust estimate is derived from analysis of the entire sediment budget period (1942-1997). This longer period allows fluctuations in estimated inputs and outputs to better equilibrate, which we believe will better represent long-term changes in sediment storage. In addition, given typical transit times for bedload sediment through watersheds (approximately decades—see Section 5.2), evaluation over much short time periods (e.g., a few years), would not conform with the spatial scale of this analysis. To evaluate shorter time intervals, the length of reaches evaluated should be much smaller, and the sediment routing model would become much more elaborate. Model results for the most recent decade-scale time periods are presented to assess the balance between sediment budget inputs and bedload transport model outputs in individual subbasins and reaches over these relatively short time scales.

Model predictions of net accumulation or deficit of bedload sediment are compared to estimated storage (Figures 4-5, 4-6, and 4-7) measured during field sampling in each reach in 1999 (see Section 5.1). Sediment storage data are plotted along side the predicted depth of accumulation or deficit. In general, the magnitude of predicted change in storage over decadal time periods (1988-1997 in Figure 4-6 and 1975-1987 in Figure 4-7) is much smaller than observed storage in 1999. This suggests that the quantity of sediment storage in channels is not very sensitive to decadal-scale inputs and routing of sediment.

Figure 4-6 summarizes the most recent time period for which full sediment budget data are available (1988-1997). The 1988-1997 period is of interest because it is during this period that timber harvest activity in the basin increased and in which an increase in flood frequency was reported by some residents. Note that the predicted increase in sediment storage in MS2 is about 2 ft, which is comparable to maximum reported short-term aggradation of 3 ft. As noted above, we regard the model behavior in this reach to be anomalous because of implausibly low bedload transport rates. Nevertheless, it shows that the bedload routing model transports a quantity of sediment into the reach from Cloney, Graham, and MS1 that is consistent with reported aggradation.

Figure 4-7 summarizes the period 1975-1987, which contrasts with the later period described above. The balance between inputs and outputs in this time interval is similar to the later period, with two exceptions. In 1975-1987, the model results suggest that Graham Gulch and Little Freshwater have declining bed elevations, while in the later period the model suggests that they are aggrading. These results indicate that the bedload routing model is sufficiently sensitive to predict major imbalances in sediment supply and transport capacity that may be interpreted as channel response to pulses of sediment input.

As noted above, the magnitude of predicted change in storage for the period 1942-1997 is generally much greater than in the shorter time periods. In Upper Freshwater, South Fork, and McCready Gulch, the increase in predicted storage is relatively close to sediment storage observed for 1999. Over shorter time periods, the increments of change in storage are much smaller than observed storage. Therefore, we used the 1942-1997 time period in the remainder of this analysis

4.3.2 Comparisons between Predicted and Observed Storage

Discrepancies between predicted aggradation or degradation of streambeds and current bedload storage are in part attributable to unknown initial conditions (sediment storage c. 1942), and in part to uncertainty of model predictions. Using other data, we were able to validate portions of the bedload transport model (see Section 4.5) and the sediment input budget (Section 3.0). The validation results indicate that the estimated inputs from the sediment budget and outputs from the transport model are reasonably accurate. Random error in model parameters and undefined initial sediment storage conditions probably account for the more obvious discrepancies.

The predictions for the period 1942-1997 (Figure 4-5) that appear to be clearly inconsistent with 1999 sediment storage estimates occur in Cloney Gulch, Graham Gulch, MS2, and MS3. In Cloney Gulch, the model predicted degradation of approximately 2 ft. Estimated storage in Cloney Gulch is not based on measurements in Cloney Gulch but, rather, is an estimate based on a composite average of other basins with similar geology. Cloney Gulch sediment storage was estimated to be just under 2 ft. The channel in Cloney Gulch is entrenched; therefore, long-term channel downcutting predicted by the model is not inconsistent with gross channel morphology.

However, the degree of entrenchment is not obviously greater than found in all the tributary watersheds.

The model predicted degradation of about 1 ft in Graham Gulch, compared with observed storage of about 3 ft. Graham Gulch is also entrenched, but 1999 sediment storage is relatively high. A plausible explanation for this discrepancy is the un-quantified but probably significant input from the large, deep-seated landslide in the 1940s that was reactivated in 1997. Sediment input was estimated for the 1997 event based on field observations near the toe of the landslide; no such estimate was made for inputs from this source in the 1940s.

In MS2, the magnitude of predicted channel aggradation (>10 ft) is clearly inconsistent with observed channel storage of approximately 4 ft. Deposition of the predicted volumes of sediment would likely induce significant channel avulsion and migration, which have not been observed over the past 50+ years. Although there is evidence that the middle portion of MS2 is aggraded by as much as 3 ft, the upper portion appears to be downcut. The local slope at the cross-section where bedload transport calculations were done is among the lowest in the reach and sub-surface median grain size is among the greatest observed in the watershed; these factors may account for some of the apparent over-prediction of aggradation. The magnitude of predicted change in storage in the MS2 reach is therefore regarded as an anomaly.

The degree of channel degradation predicted for MS3 (about 3 ft) also appears inconsistent with sediment storage estimates and relatively robust long-term cross-section observations (see Table 5-1 in Section 5). The downcutting predicted in the MS3 reach can be explained as a consequence of the model prediction of excessive deposition in the MS2 reach, thereby significantly reducing predicted sediment supply to the MS3 reach.

Consequently, the total inputs to MS2 and MS3 were combined and compared to the bedload output for MS3. In essence, this scenario replaces the extremely low bedload transport rate predicted for MS2 with the rate calculated for MS3, and distributes the resulting accumulation of sediment over the channel area of MS2 and MS3 combined. The result of this scenario predicts bed aggradation of about 0.6 ft over the period 1942-1997.

This result is in reasonably good agreement with measured changes in bed elevation based on comparisons between recent elevations and 1975 elevations reported by the Army Corps of Engineers. In the lower watershed, there are some cross-section sites that were originally surveyed by the Army Corps of Engineers in 1975. Some of these sites have been resurveyed; however, these sites could only be approximately relocated, and data were available for only three cross-sections (CDF 1998). The results of the California Department of Forestry (CDF) surveys are in Table 5-1 in Section 5.0. In their conclusion, it is stated that uncertainties associated with relocating the cross-sections and the absence of benchmarks limit the confidence in their conclusions. Their summary conclusion was that "…only minor channel aggradation may have occurred in the lower gradient reaches of Freshwater Creek, perhaps on the order of six inches to one foot."

4.4 ROUTING MODEL CONCLUSIONS

One of the major potential cumulative effects of forest management is downstream channel aggradation that could contribute to flood hazards in lower Freshwater. Considering the analyses presented above, as well as the limits of accuracy of the sediment budget and bedload transport model, it is concluded that aggradation in the lower mainstem of Freshwater Creek (MS2 and MS3) is plausible. The most reasonable interpretation of the model results suggest average aggradation in MS2 and MS3 combined over the period 1942-1997 of about 0.6 ft. This conclusion is consistent with the most robust data available on increases in channel bed elevation in the period 1975-1999 (CDF 1998).

This conclusion is supported by other data discussed above and in other sections of this report. These include the relatively high proportion of sediment stored in these reaches, the relatively fine median sediment sizes, the potential for significant overbank flow (with or without aggradation), declining bed slope relative to channels upstream, and the relatively high percentage of sediment <2 mm in MS3.

With respect to MS2, some of the data are not consistent with aggraded channel conditions, in particular the low concentration of sand in the bed sediments, low q_* values, and field observations in portions of the MS2 reach consistent with channel degradation.

4.5 MODEL VALIDATION

Validation of a complex model that requires many simplifying assumptions is difficult; however, assessment of the accuracy of the critical components is necessary to determine the level of confidence one has in its predictions. In this section, we evaluate the flow resistance equation used in the hydraulic analyses and the bedload transport predictions. Flow resistance is the single hydraulic parameter used to develop the bedload transport model that could not be directly measured in the field (such as bed slope, channel cross-section area, and sediment size). Consequently, the greatest uncertainty regarding the bedload model is the flow resistance parameter. An assessment of the accuracy of the flow resistance estimates used in the model is presented below.

4.5.1 Flow Resistance and Discharge

Flow resistance in streamflow modeling is generally the most difficult parameter to estimate among those required to estimate the relationship between stream stage (water elevation) and stream discharge. For this model, Manning's equation is used to relate the principal flow parameters of V (mean velocity), S (slope), R (hydraulic radius), and n (flow resistance): $V = k\ n^{-1}\ R^{2/3}\ S^{1/2}$. The variable k is 1 for metric units and 1.486 for Imperial units. Discharge is then computed as the product of V and channel cross-section area; the latter is uniquely related to R. Slope, hydraulic radius, and channel cross-section area are relatively easily obtained from field surveys. Methods are available to estimate flow resistance (e.g., Manning's n); however, their accuracy is not easily evaluated in the absence of discharge data. Given field survey data including channel cross-section and slope and streamflow data, Manning's equation can be solved for n, the roughness parameter.

One recent investigation of the relationship between stream stage and discharge that allowed calculations of Manning's n was prepared for PALCO by Rosgen and Kurz (2000). They conducted a study of channel hydraulics for bankfull flow conditions at several USGS gage stations in the region. That study evaluated watersheds ranging in area from 28 to 3,113 mi^2. The computed annual recurrence interval for bankfull flow conditions ranged from 1.14 to 1.33 years; the mean value is about 1.2 years. This is equivalent to about a 0.5-year recurrence interval in the partial flow duration series (Langbein 1960, see also the Hydrologic Change Module). For the three smallest watersheds investigated (Redwood Creek, Little River, and Bull Creek), Manning's n was calculated from gage data. Values of n ranged from 0.029 to 0.059; the average value was 0.044. These values of n establish an approximate range of values that could be expected at modeling stations in Freshwater.

Values of Manning's n could be calculated at one location in Freshwater, allowing for a test of Jarrett's resistance formula as applied by WinXSPro in modeling channel hydraulics. The value of n predicted by Jarrett's equation for the Salmon Forever gage site was compared to calculated values of Manning's n for near-bankfull flow conditions (about 1.2-year recurrence interval, annual series). Surveyed high water marks and discharge measured at the Salmon Forever gage for peak flow events of about 900 cfs that occurred in mid-January 2000 (Figure 4-8) were used to calculate n.

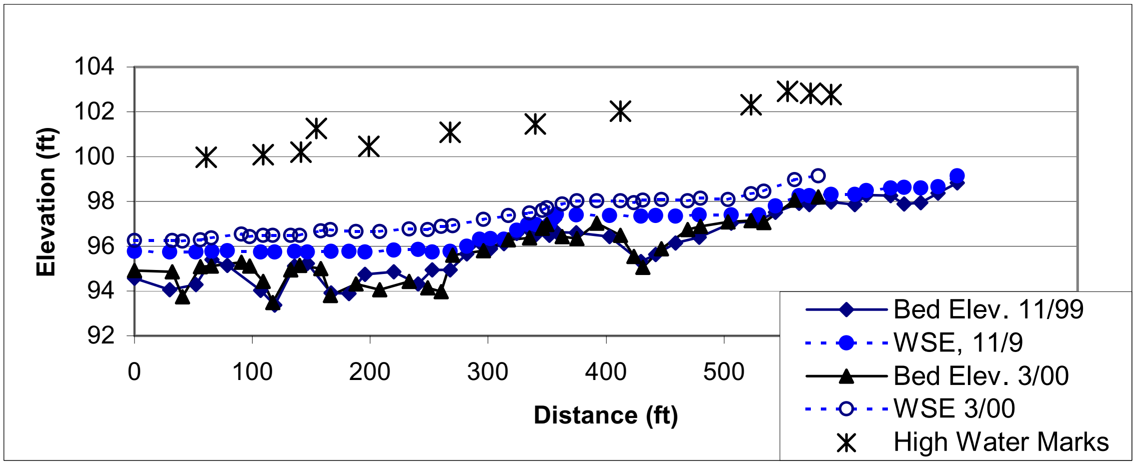


Figure 4-8: Thalweg profiles, water surface profiles, and bankfull high water marks from January 2000 at the Salmon Forever gage site. The stage recorder is at approximately 100 ft on the long profile.

This flow stage is approximately equal to the predicted discharge for bankfull flow (the 1.2-year recurrence interval flow, equivalent to the 0.5-year recurrence interval for) from the Hydrologic Change Module. In addition, the predicted stage and discharge were compared to the observed stage and discharge at this modeling station.

The predicted stream stage (water surface elevation) for a discharge of 900 cfs was about 0.5 ft higher than the observed high water marks, suggesting that Jarrett's resistance equation over-estimated Manning's n at the gage site. The hydraulic radius for observed flow was about 2.8 ft; the predicted value was about 3.1 ft. Manning's n according to Jarrett's equation for this discharge is about 0.04. Note that n = 0.04 is in the middle of the range of regional n values calculated by Rosgen and Kurz (2000). For the same discharge and the hydraulic radius associated with the surveyed high water mark, Manning's n was calculated to be about 0.031. The bed slope was 0.004, in close agreement with the water surface slope determined from the high water mark survey. For bankfull flow conditions, Jarrett's equation provides a conservative estimate of flow resistance, erring on the side of a higher stream stage for a given discharge. Jarrett's equation is a reasonably accurate predictor of Manning's n, which represents flow resistance.

The observed stage for the 900 cfs event conformed reasonably well with the usual field indicators for "bankfull flow." The hydrologic analysis performed for the Freshwater Watershed Analysis combined the results of the predicted peak flow increase caused by timber harvest (based on Caspar Creek experimental data), with the USGS regional flood frequency equations (refer to the Hydrologic Change Module) to predict discharge. For the Salmon Forever gage site, the observed discharge of 900 cfs was slightly greater than the 806 cfs discharge predicted for a

1.2-yr flow event (equivalent to 0.5-yr event in the partial duration series). Hence, observed and predicted bankfull flows appear to be in reasonable agreement.

4.5.2 Bedload Transport

Bedload sediment transport capacity was computed for each station as described above. The mean annual transport capacity for each station for the period 1956-1998 is given in Table 4-4. The predicted bedload yield (annual transport per unit watershed area) assuming bedload transport at capacity varies considerably among subbasins; the overall average rate is 128 tons/mi^2/yr. Nevertheless, there is some systematic variation with watershed area.

Table 4-4: Summary of estimated mean annual bedload transport capacity and yields for Freshwater subbasins.

HAU	Subbasin or Reach	Transport Capacity (t/yr)	Drainage Area (mi^2)	Potential Bedload Yield (t/mi^2/yr)
MG5	McCready	181	2.0	90
GG5	Graham	724	2.5	287
SF5	South Fork	204	3.1	65
LF11	Little Freshwater	812	4.7	174
CL5	Cloney	1293	4.7	275
	Average of Smaller Tributaries			178
FC08	Upper Freshwater	862	8.8	98
FC10	Gage Site (MS1)	1146	13.1	88
FC12	MS2	188	20.9	9
FC13	MS3-Harper’s	2916	25.8	113
FC14	MS3-Hippen’s	2330	29.3	80
	Average of Mainstem Sites			77
	Average of Mainstem Sites Excluding MS2			95
	Average for All Stations			128

In the group of smaller subbasins (area <4.8 mi^2), the average yield is 178 tons/mi^2/yr. In the group of larger mainstem reaches (area >8.7 mi^2), the average yield is 77 tons/mi^2/yr. If the estimate for MS2 is treated as an outlier and excluded from the average, the average for the mainstem reaches is 95 tons/mi^2/yr. The long-term average bedload yield from the routing model, which includes considerations of supply limitations (i.e., transport at capacity is not assumed) contributed from the watershed to MS2 is about 106 tons/mi^2/yr. These estimates can be compared to local bedload yield estimates for Jacoby Creek (the adjacent watershed to the north). In addition, they can be compared to estimated suspended load yields for Freshwater to determine the relative proportions of bedload and suspended load. The ratio of bedload to suspended load or total sediment load can be compared to values for other watersheds as a further test of the accuracy of these estimates.

Lisle et al. (2000) report that the bedload yield for material >2 mm diameter in Jacoby Creek is 43 tons/km^2/yr. This is equivalent to 123 tons/mi^2/yr, which is close to the average for bedload transport capacity for the stations in the Freshwater model and the bedload yield from the routing model to MS2. The Jacoby Creek yield is also bracketed by the sub-group averages for Freshwater. This indicates that the estimated bedload transport rates are reasonably accurate. If the Jacoby estimate included a portion of the sand fraction (0.075 to 2 mm diameter) that is transported as bedload, the bedload yield estimate for Jacoby Creek would presumably be somewhat larger.

The preliminary estimate of suspended sediment yield for WY 2000 reported by Clark Fenton (July 24, 2000 e-mail) for the Salmon Forever gage site is 375 tons/mi^2/yr. The estimate for the partial data for WY 1999 (January-May) was extrapolated to yield an estimate of about 470 tons/mi^2/yr (these estimates are discussed further in Section 3.0).

These suspended load estimates from the Salmon Forever gage can be added to the estimated annual bedload transport at the gage site to estimate both total sediment yield and the ratio of bedload to total load (suspended load plus bedload). Using Salmon Forever suspended sediment estimates for WY 2000, the estimated total sediment yield is 463 tons/mi^2/yr. Using the partial year 1999 suspended yield data from the Salmon Forever gage, the total yield would be 558 tons/mi^2/yr. Based on these estimates of total sediment yield, 16 to 19% of the total sediment load is bedload. These ratios should not be considered precise, but they do provide a reasonable approximation based on available data. In Jacoby Creek, Lisle et al. (2000) report that material >2 mm (the majority of the bedload) is 22% of the total load. For North Fork Caspar Creek, there are two estimates of the relative percentage of bedload in the total load. Napolitano (1996) estimated the ratio to be 15%. Cafferata and Spittler (1998) estimated 30% bedload based on calculations by Jack Lewis of the Redwood Sciences Lab. The estimates for North Fork Caspar Creek and Jacoby Creek are in reasonably good agreement with the estimate for Freshwater, suggesting that the bedload transport rates estimated for Freshwater are reasonably accurate. More precise validation of bedload transport rates is not possible based on currently available data.

4.6 CONFIDENCE

Sediment transport models are generally considered to provide order of magnitude estimates of actual transport. Prediction errors of 100% or greater are not uncommon. The Freshwater sediment transport model and routing model provides estimates of bedload yield within about 20% of measured bedload yield at Jacoby Creek, the watershed just north of Freshwater Creek. In addition, the model predicts a ratio of bedload yield to total sediment yield that conforms well to observations at Jacoby Creek and Caspar Creek. Finally, the hydraulic model used to calculate bedload transport was in reasonable agreement with flow observations for the highest flows on record at the Salmon Forever gage site on Freshwater Creek. Consequently, our confidence level in the model predictions is high relative to expectations regarding the accuracy of sediment transport models in general. Confidence in the absolute accuracy of model predictions regarding bedload sediment routing in Freshwater is moderate.

Overall, the bedload transport and routing models have produced results that are in very good agreement with observations in most respects. In any case, the model predictions regarding the magnitude and timing of bedload transport at the subbasin scale in Freshwater are of sufficiently high quality and accuracy to be used to help guide the development of management prescriptions for the Freshwater Watershed.

5.0 SEDIMENT STORAGE, TRANSPORT, & ROUTING

There are two primary impacts of channel sedimentation of concern in Freshwater Creek that are considered in Section 5.1. The main concern is that channel aggradation could reduce channel capacity and increase flood hazard in the inhabited areas of lower Freshwater. Evidence for aggradation is considered here; flood hazards are analyzed in Section 6. Second, the analysis considers evidence of potential sedimentation impacts in tributary and mainstem channels in the Class I (fish-bearing) channel network.

The quantity of sediment stored in the channel network and sediment travel time through Freshwater are discussed in Section 5.2. The relationship between stream power and sediment size distributions is discussed in Section 5.3. Likely attrition rates of bedload sediment and their implication for sediment routing are discussed in Section 5.4. Finally, effects of landslide sediment inputs on channels are discussed in Section 5.5.

5.1 EVIDENCE OF AGGRADATION

A variety of data and analyses were used to identify areas of potential aggradation and areas where aggradation is or is not occurring. First, portions of the watershed with channel and valley geomorphic characteristics indicating a higher potential for sediment accumulation are identified. Second, historic channel cross-section and bed elevation data are reviewed and compared to current conditions as a long-term indicator of potential aggradation. Observations by residents are also discussed. Finally, data on current channel conditions, existing monitoring data, and sediment routing model predictions (Section 4) are evaluated regarding evidence of high sediment load or aggradation. Data collected in the 1999 sampling effort were analyzed to provide short-term indications of aggradation, while monitoring data and bedload routing predictions provide successively longer periods of evaluation. The variety of approaches employed provides a broad basis for development and evaluation of hypothesis regarding aggradation.

5.1.1 Areas of Potential Aggradation Based on Channel and Valley Geometry

In general, the lowest gradient reaches in Freshwater (approximately less than or equal to 0.5%) of the channel network are expected to be most prone to aggradation due to simultaneous decreases in channel slope and increases in valley and floodplain width (e.g., Richards 1982, p.53). Under these circumstances, stream energy typically decreases, allowing for deposition of coarser sediment delivered from upstream. Depositional conditions are enhanced when channel confinement decreases, allowing high peak flows to spread onto adjacent floodplain surfaces and limiting the rate of increase of flow depth with increasing discharge. In addition, the nearby base level of Humboldt Bay creates a tidal influence that is reported to extend to the Howard Height's Bridge, about one-half mile from the upper limit of MS3. The tidal influence creates a backwater effect during high tides. The backwater effect causes a decline in water surface slope and is expected to create a corresponding decrease in sediment transport. Therefore, sediment deposition is expected to increase during periods of high tide that coincide with peak discharge events owing to backwater effects.

Tributaries and upper reaches of Freshwater Creek are significantly steeper than 0.5% and are markedly entrenched (i.e., incised) channels with narrow floodplains. In comparison with the lower reaches of Freshwater Creek, these reaches are unlikely to aggrade significantly in the long term. The degree of entrenchment and prominence of bedrock in these channels strongly suggest long-term incision in these areas. Potential short-term aggradation in these reaches is considered in Sections 5.1.3 and 6.2.

In Freshwater Creek, only CGUs MS2 and MS3 have gradients less than 0.5% and relatively unconfined channels. Table 5-1 shows reach average bed slope from field topographic surveys of about 1,000 ft of channel in the lowest gradient CGUs in the Freshwater Creek watershed. Figures 5-1 and 5-2 show the distribution of terraces and floodplain features in lower Freshwater. It is evident from the position of the channel and floodplain and terrace features that Freshwater Creek in MS2 and MS3 has been relatively static from 1948 through 1997. Hence, over the period of record, there have not been any major lateral shifts in channel position on the valley floor.

Table 5-1: Reach average bed slope from field surveys in lower Freshwater.

CGU	Location	Reach Average Channel Gradient
MS1	Salmon Forever Gage Site, above Graham Gulch	0.66 %
MS2	Langlois, below Cloney Gulch	0.41 %
MS3	Harper's, below Little Freshwater	0.35 %
MS3	Hippen's, below McCready Gulch	0.32 %

Figure 5-1: Distribution of floodplain and terrace features in the vicinity of Freshwater Park and areas downstream in 1997. The locations of these features are essentially unchanged relative to 1984 and 1975.

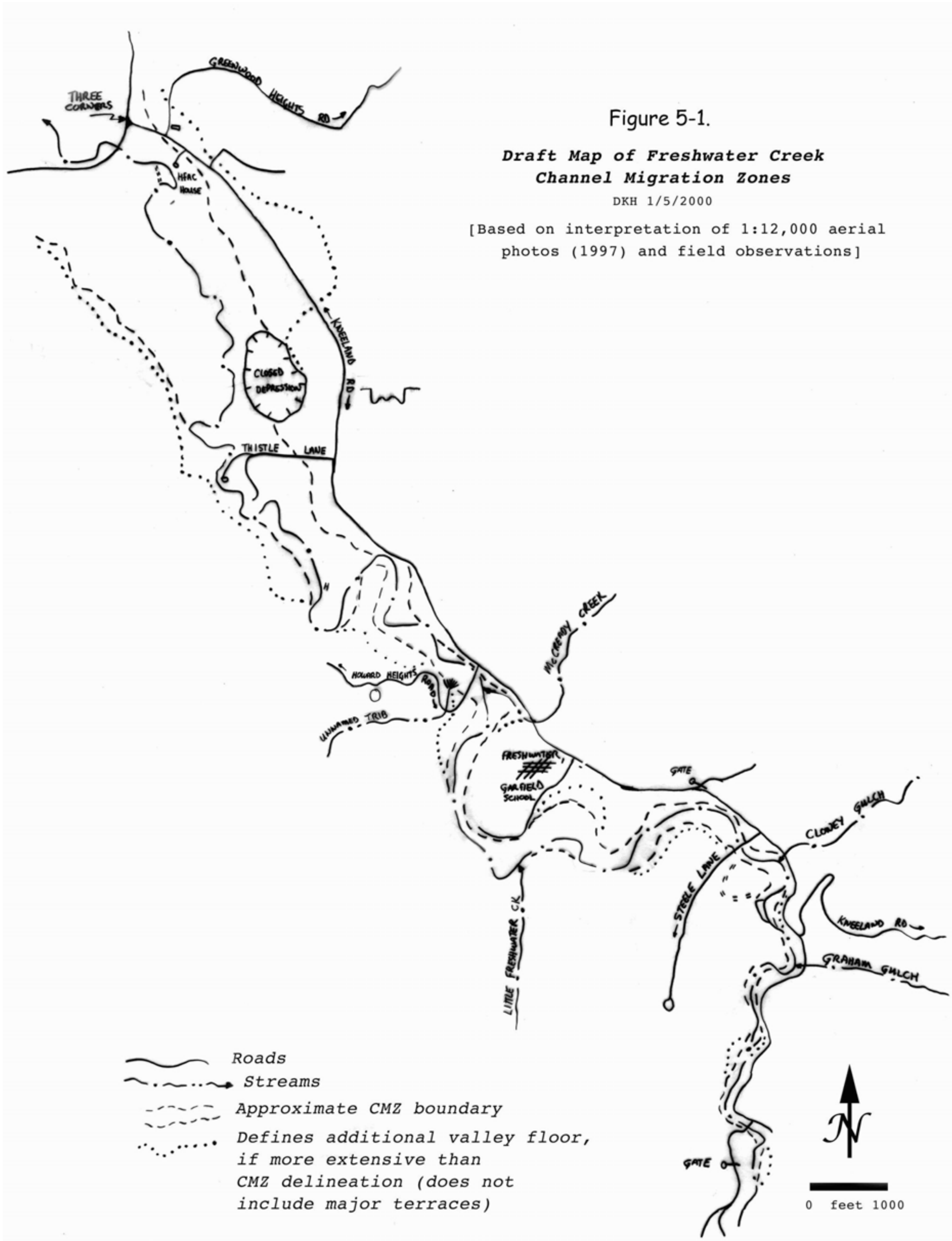
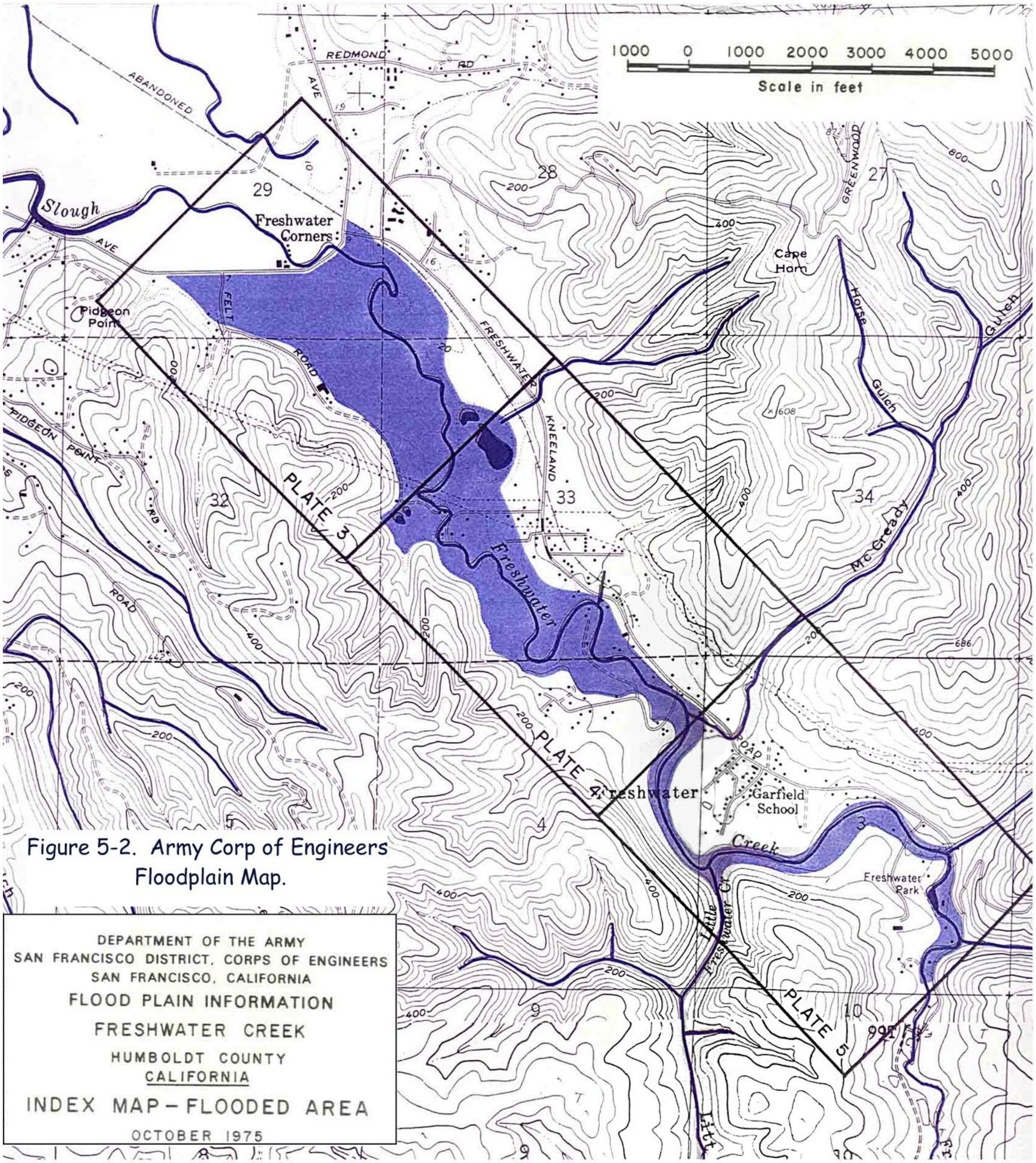


Figure 5-2: Extent of the floodplain in lower Freshwater; the upstream extent of the floodplain area coincides with the upper boundary of CGU MS2. Areas where residents have noted recent increases in flooding are within the flood hazard area boundaries identified in 1975.



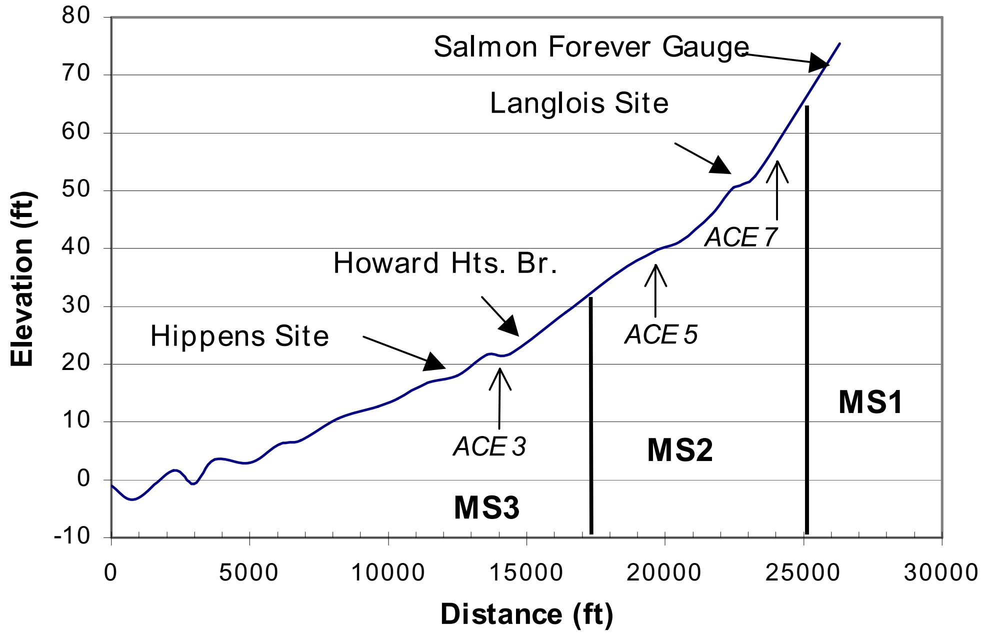


Figure 5-3: Longitudinal profile of lower Freshwater Creek (after U.S. Army Corps of Engineers 1975). Bold face and vertical dividing lines show the location of the CGUs in the lower mainstem. The boundary between MS2 and MS3 is the confluence of Little Freshwater. Italics and open arrows show locations of Army Corps of Engineers cross-section locations. Tidal influence has been reported by some residents to reach as far as the Howard Heights bridge.

Based on the foregoing data on channel and valley geometry, sediment deposition in MS2 would be expected due to two chief factors:

1. Rapid decline in slope and confinement of the channel at the upper end of the alluvial valley of Freshwater Creek relative to the areas upstream; and
2. Proximity of confluences of Freshwater Creek with two major tributary watersheds – Graham Gulch and Cloney Gulch – that would be expected to sharply increase the bedload sediment supply to the reach.

In addition, deposition in MS3 would be expected due to:

1. Continuing decline in channel gradient, particularly downstream of Howard Heights Bridge:

2. Bedload inputs (with increased sand and decreased gravel) from Little Freshwater Creek and McCready Gulch; and
3. The proximity of a local base level creating tidal induced backwater (Humboldt Bay).

In summary, general considerations of channel geomorphology indicate greater potential for sediment deposition in the lower watershed than in the upper watershed and tributaries.

5.1.2 Existing Data for Channel Aggradation

The need to employ indirect methods to assess aggradation derives from the lack of many well-monumented, long-term channel cross-section monitoring stations. In the upper watershed and tributaries, cross-section monitoring records extend for only a few years. Although these data show no evidence of short-term aggradation (PALCO 1999), the limited period of record does not provide direct evidence regarding long-term changes. There are three types of evidence regarding changes in channel bed elevation over a period of about the past 25 years. First, some inferences may be drawn from the stability of channel plan form over the past 50 or more years. Second, there are measurements of bed elevation that can be compared to 1975 measurements by the Army Corps of Engineers (ACE). Third, there are observations of local residents.

5.1.2.1 Channel Stability

Increases in bedload sediment from upstream that cause aggradation would typically be accompanied by adjustment of the channel to changed conditions. Increases in discharge and of bedload discharge may be expected to induce increases in channel width and stream meander wavelength, along with decreases in channel sinuosity (Richards 1982, Table 9.1, p. 255). Hence, general principles of fluvial geomorphology suggest that the marked absence of change in the channel pattern in lower Freshwater suggests that the channel has not been aggrading to a significant degree. The period 1948-1975 included the period that followed clearcut harvest of most of upper Freshwater, during which substantial erosion occurred and which did not appear to induce changes in channel pattern consistent with bed aggradation. The same can be said with respect to channel planform and location in 1997 photography (see Section 2.3).

5.1.2.2 Remeasurement of ACE Bed Elevations

In the lower watershed, there are some cross-section sites that were originally surveyed by he Army Corps of Engineers in 1975. Some of these sites have been resurveyed; however, these sites could only be approximately relocated, and data were available for only three cross-sections

(CDF 1998). The results of the CDF surveys are in Table 5-2. In their conclusion, it is stated the uncertainties associated with relocating the cross-sections and the absence of benchmarks limit the confidence in their conclusions. Their summary conclusion was that "…only minor channel aggradation may have occurred in the lower gradient reaches of Freshwater Creek, perhaps on the order of six inches to one foot."

Table 5-2: Summary of CDF investigation of aggradation in lower Freshwater.

Location	ACE X-Sec. #	Slope Gradient	CDF Interpretation	Watershed Analysis Reach
Approx. 1,000 ft downstream of Howard Heights Bridge	3	0.002 (0.2%)	"Very minimal channel aggradation…some evidence that the thalweg may have shifted slightly…"	MS3
Approx. 600 ft upstream of confluence with Little Freshwater (Hippen's Reach)	5	0.002 (0.2%)	"…it appears that approximately one foot of fine sediment may have accumulated at this low gradient location…"	MS2, but in the lower section of MS2 that is more typical of MS3
Between the dam and the bridge in Freshwater Park (Steele Lane Bridge – 100 ft upstream of Langlois)	7	0.008 (0.8%)	"…it appears that the channel has degraded at least two ft"	MS2, typical of the upper section of MS2

During the Watershed Analysis, we reviewed the Army Corps report and found that data regarding aggradation might also be obtained from the Howard Heights Bridge (MS3) and the Steele Lane Bridge (MS2). At these locations, the distance from the bridge "underclearance" to the bed was reported, and we re-measured these. As with the CDF efforts, uncertainties in reproducing the measurements were encountered. However, at Steele Lane, the channel bed apparently degraded as much as 4 ft. This is comparable to the CDF observation at ACE cross-section 7.

At the Howard Heights Bridge, between ACE cross-sections 3 and 5, the bed apparently aggraded about 0.65 to 1.65 ft, depending on where along the bridge one measures (the sloping bridge deck of the Howard Heights Bridge introduces some uncertainty in comparing 2000 data with 1975 ACE data). Channel morphology at ACE cross-section 5 is very different from the Langlois reach; the former is a multi-thread, heavily vegetated sandy-gravel channel while the latter is a relatively deep, narrow, single thread channel with a plane-bed gravel bottom and a narrow strip of vegetation along the banks. Channel morphology of the Langlois site is typical of most of MS2. In this lower, atypical reach of MS2 that begins a few hundred ft above the Little Freshwater confluence, sand deposition on the bed, banks, and floodplain surfaces is evident in many locations.

5.1.2.3 Resident Observations and Interpretation

Freshwater residents have produced at least two sets of observations on local changes in channel conditions. One pertains to MS2 and the other to MS3.

With respect to MS2, observations by long-time resident Rudy Langlois suggest local bed aggradation of as much as 3 ft based on his estimate of bed elevation change in relation to his water intake in Freshwater Creek. This location is nearly coincident with the Army Corps of Engineers (1975) cross-section 6; unfortunately attempts to locate the survey data were unsuccessful.

Despite the lack of independent confirmation (e.g., from an ACE cross-section or bed elevation), Langlois' observations are considered to represent the upper bound on the magnitude of local bed aggradation in the MS2 reach. There are several field observations pertaining to the MS2 reach that are inconsistent with bed aggradation. For example, observation at the Steele Lane Bridge and ACE cross-section 7 about 1,000 ft upstream from Langlois' is that the bed has degraded 2 ft (Table 5-1). This is supported by the observation that bedrock is exposed in both the channel bed and banks near Steele Lane. In addition, field observations in 2000 of the clearance between the Steele Lane Bridge bottom and the streambed indicate degradation of as much as 4 ft between 1975 and 2000. Finally, bedrock exposures in the lower banks were observed in the field to be common in the MS2 reach.

The apparently contradictory observations of aggradation and degradation in MS2 may merely reflect changes in a dynamic streambed and the pattern of stream gradient in this area. First, ACE cross-section 7 is in a steeper reach where slope is roughly 0.8%. A sharp decline in gradient to about 0.2-0.3% occurs just below the Steele Lane Bridge a few hundred ft downstream of Cloney Gulch. Langlois' observations of aggradation are located in this lower gradient reach. Degradation in the steeper reach is a possible contributing cause to aggradation of the lower gradient reach below. The lower gradient reach on the Langlois property should be sensitive to aggradation given the rapid 4-fold decline in channel slope.

Second, with respect to MS3, John H. Bair (letter from Bair, 10/19/2000) surveyed two cross-sections approximately relocated near Army Corps cross-section 3 (also resurveyed by CDF, Table 5-1), downstream of the Howard Height's bridge and upstream of the Hippen's site. Bair interprets one of his two cross-sections to be most comparable to the ACE cross-section 3, and compares the 1975 and 2000 cross-sections. Bair assumes no change in channel bed elevation owing to bedrock exposures in the channel bed, and instead concludes that deposition of fine sediment on the channel bank has reduced channel capacity by over 40%.

Despite his laudable effort to improve upon CDFs relocation of the cross-section, Bair ultimately relies on an interpretation of the bank slope profile in relation to the 1975 profile to choose which of his two cross-sections ("Cotton #2") best represents the location of the 1975 cross-section. Moreover, Bair states: "I deduced from field conditions that the location of Cotton cross-section 2 is 10 ft downstream of the high water channel outlet where ACOE cross-section 3 is located."

This latter statement clearly acknowledges that the comparison is made for two different locations. In some circumstances, a small discrepancy in the location of cross-sections for these purposes would not be expected to be of great consequence. In this case, however, Bair documents the termination of a "high water channel" just downstream of the Army Corps cross-section 3 and upstream of his Cotton cross-section 2.

The hydraulic consequences of this abrupt change in channel morphology are not discussed by Bair. It is possible that flow from the outlet of the high water channel on the right bank would cause turbulence in the main channel and an eddy on the channel margin along the left bank where accretion of sediment on the channel margin is hypothesized. Such an eddy could create a zone of deposition on the channel margin. This hypothesis is supported to some degree by Bair's survey data: the depth of the bankfull channel at Cotton cross-section 2 is about 2 ft deeper than in Cotton cross-section 1, suggesting some factor contributing to bed scour. Hence, it is also possible that there may have been similar deposits on the left bank precisely at this point in 1975.

In addition, Bair has not considered the possible influence of variation in the longitudinal bed profile of Freshwater Creek in his interpretation. The Army Corps (1975) study (Figure 4 in that study, reproduced at smaller scale in Figure 5-3) shows that cross-section 3 is located at a major gradient break in the longitudinal bed profile. Below this point, the average channel gradient calculated from the Army Corp profile is 0.0017. Above this point to the Steele Lane Bridge, the average channel gradient is 0.0034. Moreover, the local bed slope in the Army Corps profile over a distance of about 1,000 ft downstream is plotted as zero or near zero.

Hence, there are three abrupt changes in channel conditions at the location of Army Corp cross-section 3: a major break in bed slope at the scale of the lower Freshwater valley (from 0.0034 to 0.0017), a major break in bed slope at the local reach scale (from about 0.0034 to about nil), and the termination of a substantial high flow channel. All of these factors could contribute to a potential tendency for sediment deposition, or at least a substantial change in channel morphology, to say nothing of their likely effect on water elevation during peak flow periods. Regardless of their ultimate interpretation, these factors should be considered in assessing Bair's hypothesis regarding evidence of bank accretion at this location. Bair's interpretation of his cross-section data is that there has been 25 ft of lateral bank accretion relative to channel conditions in 1975 (he assumes no bed aggradation owing to bedrock controls in the floor of the channel). The interpretation that lateral accretion has occurred could be in error owing to the unusual potential for significant fluvial geomorphic changes downstream of the terminus of the high flow channel.

It is also worth noting that the change in channel bank full cross-sectional area (excluding the high flow channel) at the Cotton cross-section 1 (cross-section area of about 550 square ft) relative to the Army Corp cross-section (about 650 square ft) appears to be about 15% ([650-550]/650) compared to about 44% calculated by Bair for Cotton cross-section 2. This suggests that the hypothesized bank accretion is not uniform, supporting the notion that changes in local channel slope or other local factors may contribute to localized sediment deposition. Owing to these uncertainties and other considerations pertaining to fine sediment deposition in floodplain areas, the bank accretion process as a manifestation of potential channel aggradation is not explicitly analyzed. The reasons for this are discussed in the following section.

In the MS3 reach, the evidence for bed aggradation (i.e., increased bed elevation) as opposed to sedimentation on streambanks (i.e., bank accretion) includes two comparisons of bed elevation relative to ACE observations. First, comparisons of ACE 1975 observations of the distance between the bridge bottom and the channel bed at the Howard Heights Bridge with 2000 observations also suggest aggradation of about 0.65 ft. Second, the CDF resurvey of ACE cross-section 3 indicated no change in bed elevation. In addition, data from the lower reach of MS2, which has physical characteristics more like MS3, should be considered. The 1998 CDF re-survey of ACE cross-section 5 (a few hundred ft above Little Freshwater Creek) indicates bed elevation increases of roughly 0.5 to 1.0 ft.

In summary, evidence of local aggradation ranging as high as 3 ft locally in MS2 and as high as 1 ft in MS3 appears possible. This level of aggradation appears to be non-uniform, particularly in CGU MS2. The analysis of flooding due to changes in peak flows and aggradation presented in Section 6.0 evaluates presumed channel bed aggradation of 1.5 to 3 ft at the Langlois site (MS2) and 1 ft at the Hippen's site (MS3). These levels of aggradation are considered to be at the upper end of the range of aggradation for which there is any evidence.

These assumptions regarding bed aggradation provide what we believe are overestimates of predicted increases in flood frequency caused by hypothesized aggradation. Therefore, a margin of error exists that accommodates to some degree the argument that bank accretion may be a significant component of channel sedimentation.

5.1.2.4 Fine Sediment Deposition

It has been suggested that aggradation caused by sand deposits on stream banks is the key sedimentation process in Freshwater (Bair 2000). Bair's analysis also discusses historic factors regarding watershed, floodplain, and channel management. These include the likely initial transformation of the valley from a conifer-dominated riparian zone to a deciduous riparian zone, agricultural conversion, splash dam logging, and efforts by landowners to maintain the channel's alignment since the 1920s. Bair discusses the interaction between riparian vegetation and sediment in transport that could lead to bank accretion, and the likelihood that fine sediment deposition on floodplains has been an ongoing process.

Given the history of management and disturbance in Freshwater, it is difficult to say what "natural" processes may have been. It may well be that lower Freshwater was dominated by conifers, that the channel contained significant woody debris that induced channel avulsions, and that the channel was multi-threaded. Hence, any reference to changes over the past 25 years might bear little relationship to "natural" conditions. If natural conditions are proposed as an explicit or implicit target condition against which cumulative watershed effects are to be assessed, channel conditions in 1975 should not be used to represent "natural" conditions.

Although deposition of fine sediment in some reaches where dense riparian vegetation is present has been observed, this does not appear to be a significant process at either of the sites we analyzed. Sites with abundant recent deposition of fine sediment on stream banks are not uniformly distributed in lower Freshwater. Consideration of the bank accretion hypothesis that fine sediment on banks within the bankfull channel cross-section could reduce channel flow capacity requires consideration of at least two additional geomorphic processes: accretion of natural levees and bank erosion.

First, deposition of this type of sediment on floodplain surfaces is also responsible for development of natural levees (Ritter 1978, p. 262). As sediment-laden flood waters spread onto the floodplain, velocity slows and the coarsest fraction of the suspended load (fine sand and silt) is deposited. These deposits accumulate more rapidly than most floodplain deposits. This process would be enhanced by dense vegetation on the channel margin.

At some 1999 cross-section stations in CGU MS3 downstream of Little Freshwater Creek (the Harper's site, located between Howard Heights bridge and the confluence of Little Freshwater), evidence of natural levee building was seen along a livestock fence bordering a floodplain pasture (Figure 5-4). Significant accumulations of sand and silt amid dense vegetation to the left of the fence were observed in the field. The age of the fence is not know precisely but it is likely about a decade or less; the lower strand of the barbed wire was nearly flush with the ground surface, suggesting at least a few inches of relatively recent deposition. The elevation of this depositional surface above the adjacent floodplain surface is nearly 2 ft, suggesting that channel capacity may increase significantly with increasing deposition of fine sediment on the portion of the floodplain nearest the streambank. Hence, if the effects of fine sediment deposition on streambanks within the bankfull channel were analyzed with respect to flood hazards, deposits that construct natural levees should also be considered.

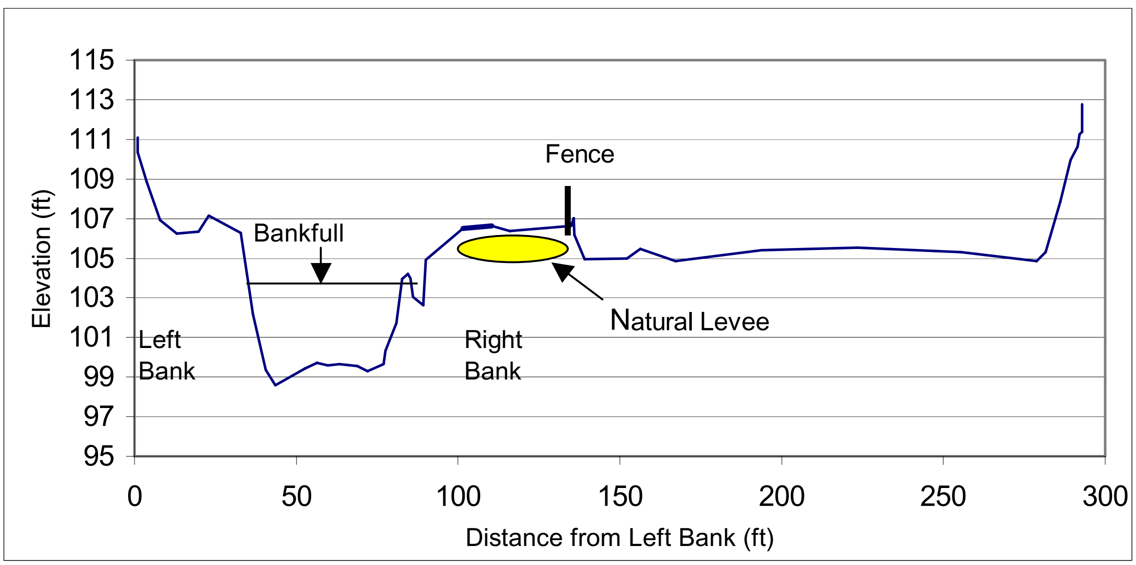


Figure 5-4: Uppermost cross-section in MS3 located about 1,000 ft downstream from the confluence of Little Freshwater and mainstem Freshwater. The bankfull flood surface is the field estimated stream stage representing roughly the 1.2 -year annual recurrence interval flood. The broad surface to the right of the presumed "natural levee" was inundated in the 1997 "New Year's" flood.

In addition, deposition of fine sediment on streambanks or depositional surfaces within the bankfull channel may be balanced by erosion of banks. This is a natural reaction of stream channels driven by the forces of flow and the continuity of mass transport that maintain channel cross-sectional area. Increases in channel cross-section area may be accomplished by both bank retreat and incision of small, secondary channels on depositional surfaces within the bankfull channel (an example of the latter appears in Figure 5-4). These processes are common in alluvial channels and drive exchanges of sediment between the active stream and floodplain deposits. Long-term cross-section surveys and floodplain erosion and deposition surveys would be necessary to determine whether these processes produce net deposition, erosion, or a balance between the two. As described above (Section 5.1.2.1), major shifts in channel position in lower Freshwater are not evident. Hence, smaller scale, local adjustments of the channel cross-section may occur that could compensate losses of channel capacity caused by local bank accretion.

In summary, we believe that observations of fine sediment deposition do not necessarily indicate a reduction in channel capacity. We believe that our hydraulic analysis (Section 6.1) of the effect of aggradation of the active channel bed by gravel and sand adequately represents sedimentation processes as they relate to flood frequency.

5.1.3 Analysis of Sedimentation Status of Stream Channels

Various types of data were analyzed for evidence of response to changes in sediment load, potentially including channel aggradation. As noted above, very few data regarding changes in bed elevation are available. Data regarding sediment storage and indicators of sediment transport are discussed in this section. Many types of data and analysis are used, and not all indicators for a given reach are consistent. Hence, a weight of evidence approach is used to assess conditions in each subbasin or mainstem reach.

Three groups of indicators are evaluated. The first group is based on 1999 channel data. The second group of data includes time trends from monitoring efforts. The last group contains data from the sediment routing model. Each data set is presented and discussed. The indicator data are then summarized, and an interpretation is provided for each subbasin and mainstem reach.

5.1.3.1 1999 Channel Conditions

During the 1999 field season, sampling was completed to analyze the sediment storage depth including pebble counts. The goal of this sampling was to measure the quantity, locations. and sizes of stored sediments. In addition, bulk sediment samples were collected to further quantify sediment size distributions. Hydraulic data collected at survey sites were also used in conjunction with sediment size data to compute an index of the balance between sediment input and sediment transport. The results from these efforts are summarized in this section.

Bulk Sample and Cross Section Methods

Longitudinal profiles and channel cross-sections have been monumented and surveyed in each of the tributary subbasins, and in three reaches of the lower mainstem (see Figure 2-1). Hydraulic data collected include bed slopes and bankfull depths; in combination with data on surface and subsurface sediment size distributions, these data allow computation of the q* index (Dietrich et al. 1989).

The locations of sediment storage surveys and bulk sediment sample sites are also shown in Figure 2-1. Five-gallon bulk sediment samples were collected from typical and accessible gravel bars by excavation of gravel bar material to uniform depth. These samples were processed at the Humboldt State University Geology Department. Pebble count data as well as bulk sample data were used for the computation of q*.

Channel Stored Sediment and Pebble Counts

In-channel surveys of sediment storage in bars, in the streambed, and in deposits upstream of LWD jams were performed in 11 reaches of about 1,000 ft in length distributed throughout the network of Class I streams. The water surface elevation during the low-flow period was used to provide a relatively constant datum for distinguishing between "channel-stored" and "bar-stored" components. The depth of sediment storage in bars was defined by extending this horizontal datum beneath bars; length and width were also measured. Channel-stored sediment was more difficult to estimate because it requires estimation of an average depth of scour, as well as measurements of the average width and length of each channel segment. Adjacent pool depths and/or depth to bedrock defined the scour depth. Sediment stored in upstream of logjams was also measured. Large-scale sketch maps, or "patch maps," were drawn during the survey to keep track of bars, avoid double counting, and provide a means for assessing annual change in future monitoring efforts.

In addition to quantitative estimate of the volume and size distribution of stored sediment stored, channel hydraulic conditions were documented by cross-sections and longitudinal profiles of the channel thalweg. Pebble counts were made on bars to provide reach-scale estimates of the surface sediment size distribution.

The information on size distribution is based on an estimate of the d50 and d84 along each bar or channel unit. During surveys of channel-stored sediment, the distribution of particle sizes was approximated by estimates of the d50 (median diameter) and d84 for discrete patches (e.g., individual gravel bars) of channel bed material. These estimates consisted of visual observation and measurement of a few hand samples of representative particles. Surface and subsurface Wolman pebble counts on some of the bars provide a means of estimating the general bias of the estimates. Estimates for d50 were reasonably accurate; however, d84 was systematically over-estimated. Median grain sizes from subsurface Wolman pebble counts were well correlated with bulk samples.

In addition, observations of typical grain size distributions were made in surveys ("reach characterization") of a broad sample of the channel network used to develop CGUs (data summarized in Table 2-2). These estimates of d50 and d84 were made using the same estimation technique described above at one or two representative locations in each sample reach.

Sediment Storage Results

The sediment storage data are summarized in Figure 5-5. The data are presented in terms of depth of sediment storage per unit channel area to facilitate interpretation. These data are presented in terms of mass in Section 5.2.

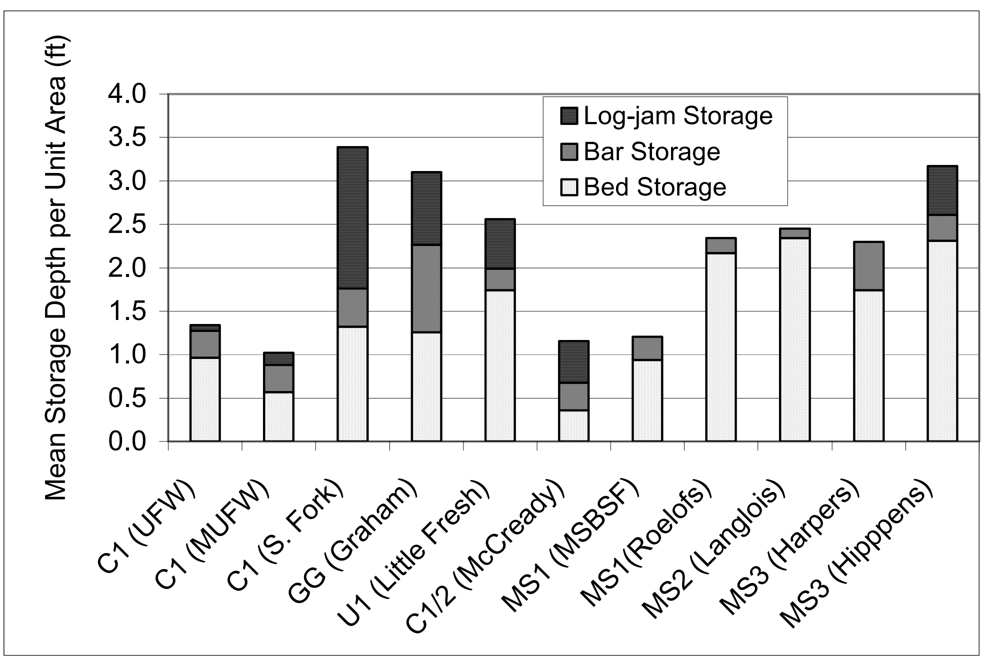


Figure 5-5: Summary results of in-channel sediment storage field surveys. Storage is expressed as average depth of deposits per unit channel area. Note that log-jam storage is minimal in the MS1, MS2, and MS3 sites. The data fall into two groups: those with <1.5 ft of storage and those with >2 ft of storage.

Using this measure, reaches with relatively high sediment storage suggest relatively high potential aggradation. The sites can be grouped in two categories: <1.5 ft and >2 ft. The latter group includes MS2, MS3, South Fork Freshwater, Little Freshwater, Graham Gulch, and lower MS1 (near the Salmon Forever Gage site at Professor Roelof's property). There is no intrinsic significance to these depths of sediment storage. These two groups indicate regions of relatively high and low sediment storage.

Median Grain Size on Bars Results

Potential sedimentation status at the watershed scale may also be evaluated by examining the size distribution of sediment stored in different portions of the channel network. Rivers frequently have smaller sediment sizes farther down the channel network. Such downstream fining is expected; however, streambeds with high sediment supply relative to transport capacity (i.e., aggrading conditions) are also thought to respond by bed fining (Dietrich et al. 1989).

The mean of the median size for all bars for each surveyed reach is shown in Figure 5-6. The data display a trend to finer sizes downstream. Notable deviations include the South Fork, Little Freshwater, and McCready Gulch, which may have finer sediment sizes in part due to the relative abundance of soils derived from the Wildcat Formation in these watersheds.

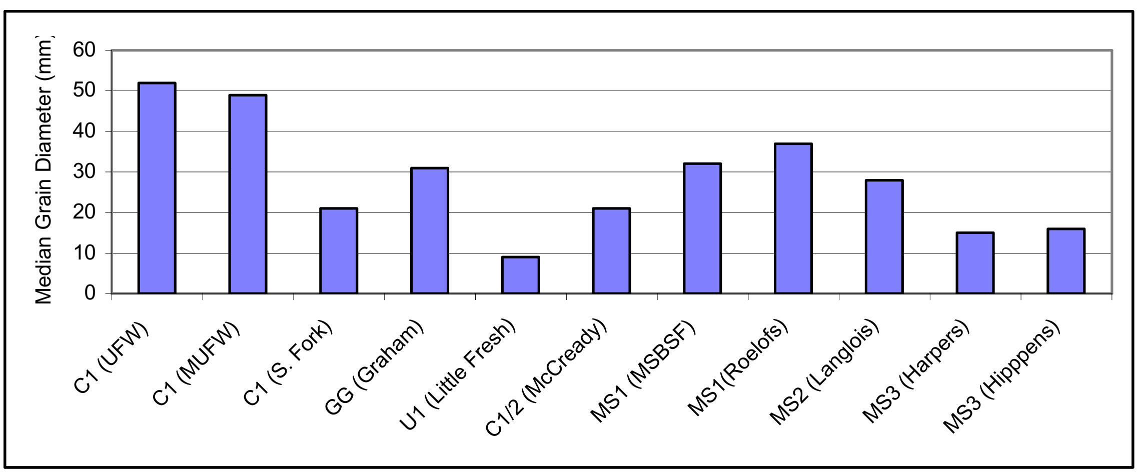


Figure 5-6: Median grain size on bars determined during sediment storage surveys.

This sedimentary formation produces high volumes of sandy material and little gravel. Hence, for these sites, the indication is indeterminate. The upper reaches of Freshwater Creek have grain sizes around 50 mm (with the exception of the South Fork). Grain sizes were 32 and

37 mm in MS1, which is relatively coarse for the watershed. Median grain sizes of 31 mm in Graham Gulch are relatively coarse for a tributary watershed. The median diameter of 28 mm in MS2 is in the middle of the range of values for the watershed, and is intermediate between upstream and downstream reaches. On the other hand, considering the significant decline in channel gradient and confinement in this reach and the confluence of two major tributaries, a stronger tendency to fining might be expected. More substantial bed fining is displayed in MS3 sample reaches, where median grain sizes are about 15 mm, indicative of potential bed fining and aggradation. The low values in MS3 are related both to the sand-rich inputs from Little Freshwater and McCready Gulch, and to depositional/aggradational tendencies in MS3 hypothesized above.

Bulk Sample Results, Percentage of Sediment Finer Than 2 mm

The bulk sediment samples were dried, sieved, and weighed to determine the particle size distribution for each. These data are presented in Figure 5-7.

Percentages of sediment <2 mm diameter from the bulk sediment samples are presented in Figure 5-8 below. The average for these samples is 22%. For purposes of interpretation (Section 5.1.4), the following criteria were applied. Where more than 25% of material <2 mm diameter is present, conditions are considered suggestive of sand aggradation. Where material <2 mm is less than 15%, conditions are considered to contraindicate sand aggradation. For the 15-25% range, conditions are considered indeterminate.

Results at the Upper Freshwater site (5%) suggest conditions that favor transport over deposition. The relatively low value observed at MS2 (12%) also suggests conditions that favor transport over deposition. MS3 had the highest individual value observed (33%), which supports the hypothesized tendency for sediment deposition in this reach.

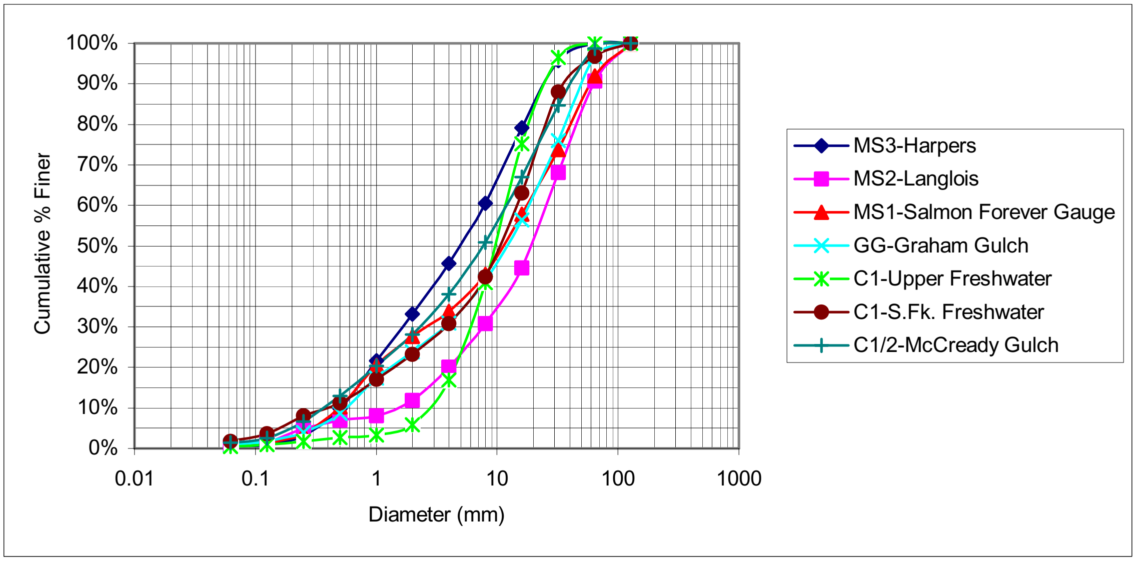


Figure 5-7: Cumulative grain size distribution for bulk sediment samples in Freshwater. Median grain size for a given site can be determined from the intersection of the cumulative distribution to curve as it crosses the 50% line, and matching this point with the diameter on the bottom axis of the graph.

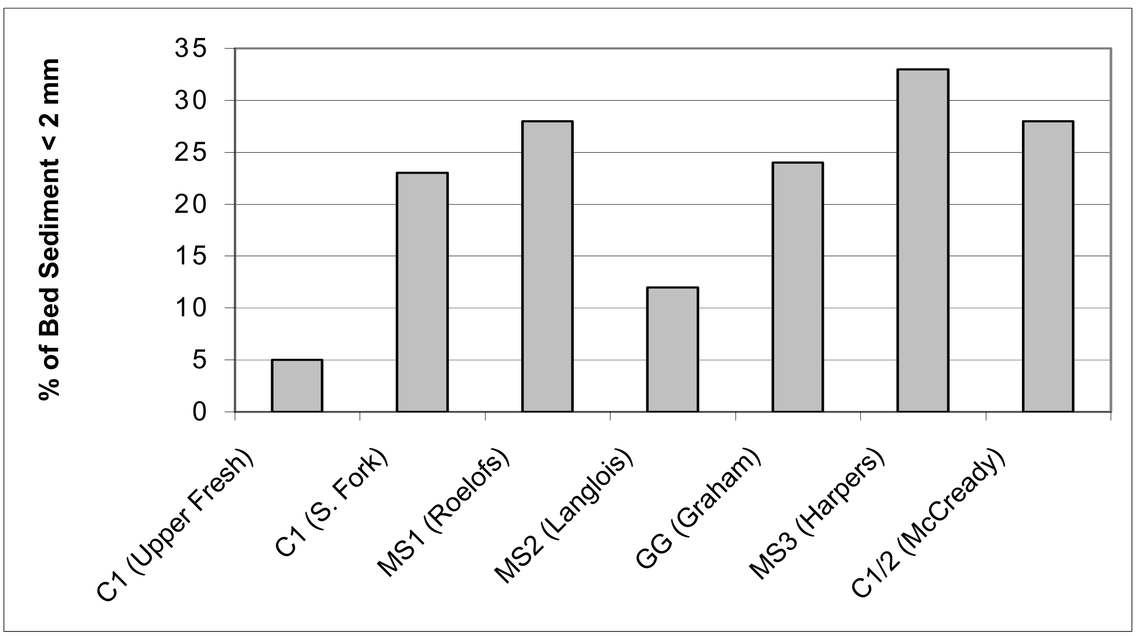


Figure 5-8: Percentage of bed material finer than 2 mm in bulk sediment samples.

Cross Section Results, q_* Index

Estimates of total bed shear stress at bankfull flow and the surface and sub-surface median grain sizes from surveyed cross-sections were used to calculate q*. The dimensionless ratio q_*

provides additional perspective on the balance between sediment supply and sediment transport capacity (Dietrich et al. 1989).

The q_* data are presented in Figure 5-9. The ratio q_* ranges between values of 0 and 1. Values near 0 indicate that sediment transport capacity far exceeds sediment supply and that the streambed surface has developed a coarse armor layer that is rarely entrained. Values near 1 indicate that sediment supply is nearly equal to or exceeds sediment transport capacity, and that there is minimal development of an armor layer on the streambed. This latter condition would be consistent with aggrading bed conditions.

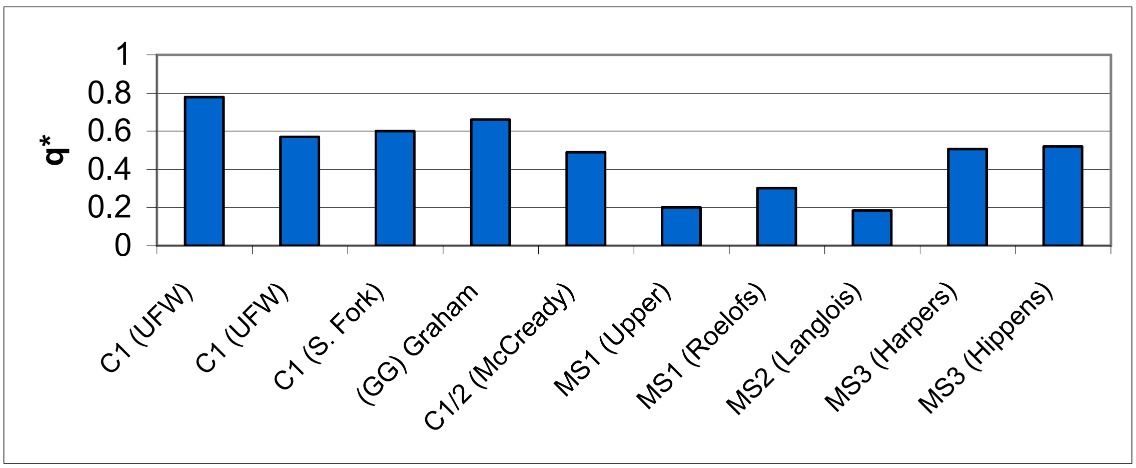


Figure 5-9: q_* values computed for Freshwater sediment storage reaches.

The distribution of q_* values in Freshwater Creek does not indicate that channels in the Class I network are extensively aggraded. The distribution of values can be interpreted to be tri-modal, with characteristic values for tributary subbasins, the upper and middle mainstem (MS1 and MS2), and the lower mainstem (MS3). The mean values for these groups are 0.62, 0.23, and 0.51, respectively. These q_* values are not indicative of severe bed fining, and the values for MS1 and MS2 are more suggestive of bed armoring in response to reduced sediment supply relative to transport capacity.

In addition, these data suggest that the tributary subbasins and the lower mainstem reaches have a relatively rich sediment supply in comparison with transport capacity. In contrast, MS1 and MS2 reaches appear to have relatively low sediment supply in comparison to transport capacity. The tributary channels are near sediment source areas and would be expected to have higher sediment supply. The middle portions of the channel network have lower q* values than the tributaries because the relatively high streamflows (owing to increasing drainage area) increase sediment transport capacity. In addition, the middle mainstem reaches are a greater distance from sediment source areas, indicating that sediment supply would be controlled by fluvial transport from upstream, reducing the likelihood of imbalance between sediment supply and transport. The lower portions of the network (MS3) are expected to have higher q_* values owing to declining channel slope, increasing frequency of overbank flow, and proximity to tide water, all of which reduce sediment transport capacity. The lower reaches also receive sediment inputs from the Freshwater and McCready subbasins, which are expected to generate primarily fine textured sediment.

5.1.3.2 Time Trend Data

The preceding section represented data on channel conditions observed 1999. The data discussed in this section are derived from two different monitoring efforts. Long-term aquatic habitat monitoring conducted by PALCO includes sites where data collection began as early as 1994 at some sites. PWA resurveyed monitoring sites established in 1992 during a prior study where V* (an index of sediment deposition in pools) and the Riffle Armor Stability Index (RASI) were measured. One of the students who conducted the original fieldwork was contracted to perform the field investigation.

PALCO Aquatic Monitoring Methods

Long-term aquatic habitat monitoring conducted by PALCO was initiated in the mid-1990s in connection with Sustained Yield Plan development for the State of California. The long-term monitoring protocol used by PALCO includes a single Wolman pebble count at each site on a riffle located at a pool tail. It should be noted that a single pebble count in a single location may not be representative of reach conditions. With respect to spatial variability, these data are less robust than data presented in Section 5.1.3.1 (patch map pebble counts). However, the PALCO monitoring data do provide a time trend. When measurements are made at a single site, it may be difficult to discriminate between true changes over time and variation in local conditions or selection of slightly different sample sites in different years.

PALCO has also collected bulk sediment samples from riffles considered to be likely spawning sites to monitor the quality of spawning habitat. These samples were processed by the CDFG to determine the percentages <0.85 mm and <4.7 mm diameter sediment.

V* and RASI Methods

Knopp (1993) sampled four indices of cold-water fish habitat in 60 streams in cooperation with the California Department of Forestry and the North Coast Regional Water Quality Control

Board. This study included Graham Gulch (Knopp Reach #54, Pacific Lumber Station 19), South Fork Freshwater Creek (Knopp Reach #55, PALCO Sta. 15), and Upper (a.k.a. North Fork) Freshwater Creek (Knopp Reach #56, PALCO Sta. 34). The indices measured were: (1) V*, (2) RASI, (3) large wood inventory, and (4) pool statistics. In 1993, V* was re-measured at the South Fork and Upper Freshwater Creek sample sites by Bill Lydgate while conducting thesis work. In 1999, V* and RASI were re-measured in all three reaches by Bill Lydgate for PWA. The methods and locations of study sites were repeated as faithfully as possible between years.

V_* Methods

Lisle and Hilton (1992) proposed V_* as a repeatable method of measuring fine bed material accumulated in pools and expressing that volume as a proportion of residual pool volume. The subscript "$_*$" indicates a dimensionless index value, namely the proportion of pool volume occupied by sediment. The reach average V_* weighted by pool volume is known as V^*_w. "V" standing for volume, and "w" standing for weighted. Lisle and Hilton (1999) found a high correlation between V* and annual sediment yield in channels with parent material that produces abundant sandy particles. They also found that V* corresponds with variations in the balance between sediment inputs and water discharge.

V* was measured by probing the thickness of fine sediment mantling the armored pool bed with a steel rod and expressing that volume as a proportion of the residual pool volume. Selected pools had transects established which defined pool morphology and allowed calculation of pool volume. Measurements of residual pool depth and sediment depth were taken systematically across each transect. Residual pool volume was used, so seasonal variation in flow did not affect the results. Hilton and Lisle (1993) clearly illustrate the steps involved in measuring and expressing V*.

Knopp (1993) measured V* in 6 pools in each stream in 1992 and reported the weighted average as V^*_w. Lydgate repeated V* in Upper and South Fork of Freshwater Creek as part of a graduate study in 1993. In 1999, PWA repeated V* in the same three reaches. In cases where pools could not be re-measured, substitute pools were included in the analysis. In some cases, pools measured in 1992 disappeared by 1993 and then reappeared by 1999. In addition to a reach comparison, a pool-to-pool comparison was performed where possible. Whenever possible, the same pools were re-measured to permit a pool-to-pool comparison as well as a reach comparison. Over the three study seasons, 5 of the 18 original pools had to be replaced with substitute pools because they were obscured by woody debris or hydraulic forces had modified the site to no longer meet the definition of a pool. In one case, a pool from 1992 has disappeared by 1993 and reappeared in 1999 (Upper Freshwater, pool 3).

RASI Methods

The Riffle Armor Stability Index (RASI) represents the size of material transported at bankfull flows relative to the surface particle size distribution (Kapasser 1992). RASI is similar to q_* in that it is intended to measure bed fining. RASI is the cumulative percent of the riffle substrate that is less than or equal to the largest surface particle commonly mobile at bankfull. RASI is reported to represent the current dynamics of a channel's sediment transport process since an increase in sediment load will increase the proportion of fines but should not change the nature of particles moved at bankfull (Kapasser 1992).

A 200 point Wolman pebble count was performed on riffles free from structural control (i.e., no forced bends, debris, landslides, etc.). On the proximate bar, a 30 count was performed to estimate the largest commonly mobile particle at bankfull. The following guidelines were used: particles must be as rounded as possible, loose on the bed, free of moss, and in a size class within 20% of the largest sample. If less than 30 particles met these restrictions, it was acceptable to count fewer than 30. The 30 count indicated particles that were mobile at bankfull flows. The 30 count was reduced to a geometric mean, which was compared to the cumulative particle size distribution from the 200 count. A RASI value is determined from the percentage of particles that are equal to or finer than the geometric mean. Kapasser (1992) describes the methods in greater detail. The RASI methodology requires that professional judgment be used to select the 30 particles mobile at bankfull (30 count). Selecting larger particles for the 30 count increases the RASI values and, conversely, a finer 30 count will decrease the RASI value. Measurement bias was minimized over the study period by careful training and consistent interpretation of the methods.

RASI is a product of a 200 point pebble count and a 30 point count of particles mobile at bankfull. These two measurements are also included in the analysis. The d_{50}, or the 50^{th} percentile particle from the 200 count and the geometric mean of the 30 count are also derived from the data collected at each site. Knopp (1993) measured RASI in 3 sites in each stream in 1992. In 1999, PWA repeated RASI in the same locations in all three reaches.

PALCO Aquatic Monitoring Results

The median grain size data as calculated from the Wolman pebble counts are presented in Figure 5-10. The interpretation of these data is simple. At sites where the 1999 observation is coarser than the 1994 observation, bed coarsening or degradation is suggested. At sites where the last 1999 observation is finer than the first observation, bed fining or aggradation is suggested. Median grain sizes have decreased at most monitoring sites. There appears to have been a large decline in median grain sizes after major storm events in 1995, and again at some sites in 1997. The decline after storm events would be expected for two reasons: likely increases in sediment inputs to the stream system and deep scour of the streambed and widespread disruption of surface armoring that would redistribute relative fine sediment stored in the streambed.

With respect to changes over time of the percentage of sediment <4.7 mm, there was no generalized trend. The average percentage change for all sites is a minimal decline of 2% (Table 5-3). There were sizable increases in sediment <4.7 mm at some sites: Little Freshwater, Cloney and Graham Gulch. There were sizable decreases at other sites: Upper Freshwater and McCready Gulch. Small changes occurred at South Fork, the lower reach of Upper Freshwater, and the MS1 reach. The implications of these more notable changes are discussed in Section 5.1.4.

Changes in the percentage of sediment <0.85 mm over time was similarly variable, with an overall average decline of 7% (Table 5-4). Relatively large increases in sediment <0.85 mm occurred at sites in South Fork, Little Freshwater, and Cloney Gulch. Relatively large decreases in sediment <0.85 mm occurred at sites in Upper Freshwater, McCready Gulch, and the MS1 reach. Little or no change occurred in lower Upper Freshwater and in Graham Gulch. The implications of these more notable changes are discussed in Section 5.1.4.

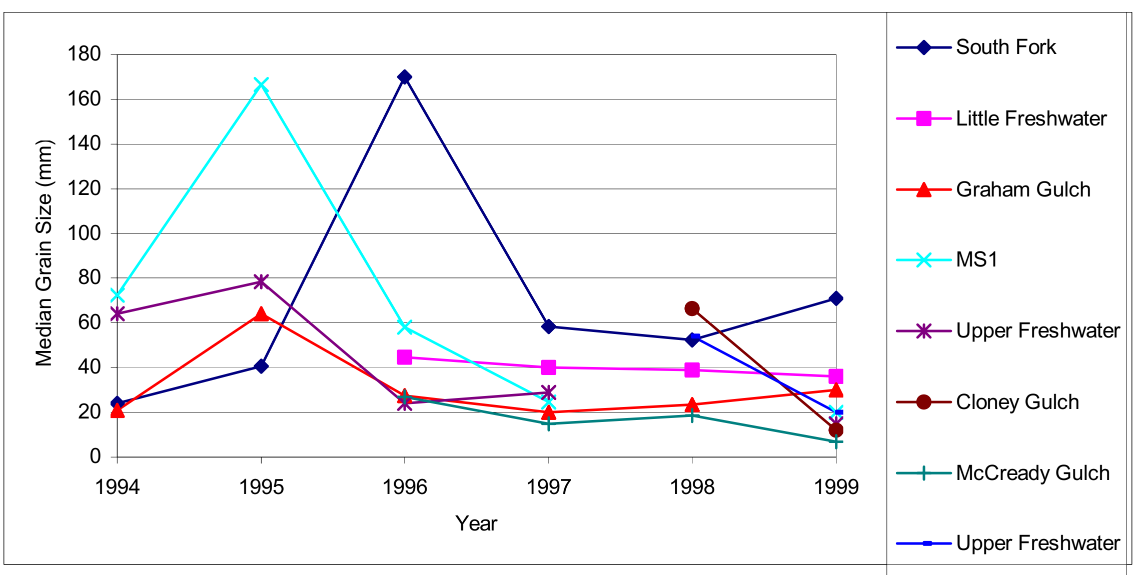


Figure 5-10: Median grain size observations for single riffles at PALCO monitoring sites in Freshwater, 1994-1999.

Table 5-3: Percentage of streambed sediment samples finer than 4.7 mm from PALCO monitoring sites.

PALCO Station #	Location	CGU	1994	1996	1997	1998	1999	Change
15	Lower South Fork	C1	49	43	40	39	46	-6%
34	Lower Upper Fresh	C1	27	32	38	36	29	7%
165	Mid Upper Fresh	C1	-	-	-	32	25	-22%
135	McCready Gulch	C1/2	-	66	60	59	53	-20%
36	Rd. 15 Upper Fresh	C3	49	43	50	38	28	-43%
18	Little Freshwater	U1	-	51	41	55	59	16%
92	Cloney Gulch	CG	-	-	-	37	46	24%
19	Lower Graham G.	GG	36	47	66	56	43	19%
32	Mainstem	MS1	35	28	30	25	36	3%
							Avg.	-2%

Table 5-4: Percentage of streambed sediment finer than 0.85 mm from PALCO monitoring sites.

PALCO Station #	Location	CGU	1994	1996	1997	1998	1999	Change
15	Lower South Fork	C1	23	24	21	24	27	17%
34	Lower Upper Fresh	C1	17	19	17	15	17	0%
165	Mid Upper Fresh	C1	-	-	-	14	11	-21%
135	McCready Gulch	C1/2	-	47	44	39	26	-45%
36	Rd. 15 Upper Fresh	C3	23	22	22	19	11	-52%
18	Little Freshwater	U1	-	36	29	47	47	31%
92	Cloney Gulch	CG	-	-	-	16	25	56%
19	Lower Graham G.	GG	21	27	32	29	20	-5%
32	Mainstem	MS1	23	12	15	12	13	-43%
							Avg.	-7%

V_* and RASI Results

The V_* results are presented in Table 5-5, showing increased sediment storage in pools in Graham Gulch and Upper Freshwater. Small increases in sediment storage in pools were measured in the South Fork.

Table 5-5: V*w in Freshwater Basin.

	V^*_w		
Subbasin (CGU)	**1992**	**1993**	**1999**
Graham Gulch (GG)	0.34	--	0.51
South Fork (C1)	0.52	0.59	0.59
Upper Freshwater (C1)	0.19	0.15	0.46

The RASI value increased between 1992 and 1999 at all sites (Table 5-6), indicating the mean diameter of the largest mobile grains at monitoring sites has increased. The geometric mean diameter also increased by about half in all three reaches. This suggests that RASI and geometric mean diameter are also sensitive to the effects of flood events larger than bankfull. Regional flood events occurred in 1995, 1997, and 1998, and the high flows may be responsible for the measured increase in particle sizes. Consequently, these RASI data exaggerate the effect of bed fining on riffle mobility.

The median grain size (d50) increased somewhat in Upper Freshwater, despite substantial increases in V* that could suggest bed fining. In addition, d50 declined by nearly half at Graham Gulch and South Fork. This is somewhat surprising in that geometric mean diameters decreased by half in these same sites. This apparent discrepancy may be further evidence that recent episodes of high streamflow have played an important role in recent changes in channel sedimentation.

Table 5-6: RASI, d50, and geometric mean of the largest mobile particles at monitoring sites in Freshwater, 1992 and 1999.

	RASI				Geometric Mean (mm)				d50 (mm)			
	1992	1999	Change		1992	1999	Change		1992	1999	Change	
			Value	%			(mm)	%			(mm)	%
Graham Gulch	80.0	95.0	15.0	19%	86	141	54	63%	42	24	-18	-42%
South Fork	84.8	97.4	12.6	15%	90	137	47	52%	33	19	-14	-43%
Upper Freshwater	81.6	89.2	7.6	9%	109	161	52	48%	38	41	3	8%

5.1.3.3 Model Predictions of Change in Sediment Storage

The third type of data used to assess channel sedimentation status is the result of the bedload sediment routing model (Section 4.0). The sediment routing analysis is described in a prior section of this report. The results of this analysis are predictions of change in storage in major tributaries and the mainstem. Data from three time intervals were presented previously (Section 4.2.2). For each time period analyzed, a positive change in sediment storage is taken as suggestive of aggradation, and a negative change in sediment storage is taken as an indication of channel degradation, as summarized in Table 5-7. The indicators are consistent across all time periods with the exception of Graham Gulch and Little Freshwater, suggesting that these subbasins may be more likely to experience significant shifts in the balance between sediment inputs and bedload transport capacity.

5.1.4 Summary of Sedimentation Status of Stream Channels

Table 5-7 summarizes the evidence regarding sedimentation status discussed above for each subbasin and mainstem reach. Reaches or subbasins with indications of high sedimentation may or may not have significantly degraded habitat conditions. Aquatic habitat conditions are evaluated in the Amphibian and Fisheries Assessment Modules. Indications regarding channel conditions developed here are integrated with habitat indicators in the Cumulative Effects Module. A summary discussion and interpretation of sedimentation status are provided for each site.

Table 5-7: Summary of indicators of channel sediment status for Freshwater subbasins and mainstem reaches.

	1999 Channel Condition				Time Trend Data						Model Predictions of Change in Sediment Storage		
Subbasin or Reach	**Sed. Storage Depth**	**Median Surface Grain Size on Bars**	**% <2 mm in Bed Material**	**q_***	**Median Surface Grain Size at Monitoring Sites**	**% <4.7 mm in Bed**	**% <0.85 mm in Bed**	**v_***	**RASI**	**Mean Dia. Largest Mobile Grains**	**1942 to 1997**	**1988 to 1997**	**1975 to 1987**
Up. Fresh.	–	–	–	±	±	±	–	+	+	–	+	+	+
South Fork	+	±	±	±	–	–	+	±	+	–	+	+	+
MS1	±	–	+	–	+	±	–	n.d.	n.d.	n.d.	–	–	–
Graham	+	–	±	±	–	+	±	+	+	–	–	+	–
Cloney	n.d.	n.d.	n.d.	n.d.	+	+	+	n.d.	n.d.	n.d.	–	–	–
MS2	+	±	–	–	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	+*	+*	+*
Little Fresh.	+	±	n.d.	n.d.	+	+	+	n.d.	n.d.	n.d.	–	+	–
McCready	–	±	+	±	+	–	–	n.d.	n.d.	n.d.	+	+	+
MS3	+	+	+	±	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	+*	+*	+*

"+" indicates evidence suggestive of bed fining or aggradation,
"±" indicates no change or indeterminate,
"– " indicates evidence suggestive of bed coarsening or lowering, and
"n.d." indicates no data were available.
"*" indicates that the interpretation of increased sediment storage from model results is derived from the model scenario that combines sediment storage in MS2 and MS3.

Evidence of bed fining in several reaches is consistent with recent sediment inputs and increased sediment transport capacity due to high flows in 1995, 1997, and 1998 after a relatively long period of low storm frequency resulting in lower transport capacity. It is likely that this climatically driven upsurge in sediment transport rates disrupted coarse stream armor on bars and remobilized finer sediment stored in the bed. Additional evidence for this is the large increase (average of 54%) in the geometric mean diameter of the largest mobile particles for the three RASI monitoring sites. Hence, both recent sediment inputs and remobilization of sediment from storage in the channel network are likely significant contributors to apparent bed fining. In other words, not all the apparent sedimentation is attributable to sediment inputs. Recent episodes of high runoff from large events have moved sediment around, and it is difficult to tell which factor is the biggest contributor.

In addition, indices of stream power (functions of channel width, depth, and slope) have been shown to correlate with sediment size distributions (Section 5.3). The fundamental geomorphic character of specific reaches and subbasins must also be considered when assessing channel data for evidence of sedimentation.

Upper Freshwater has a relatively coarse size distribution of bedload in storage, owing in part to the high proportion of Franciscan rocks delivered to the channel and in part to high stream power. Observed sediment storage in the channel is comparable to but less than predicted aggradation, suggesting that perhaps some aggradation has occurred in this subbasin. The magnitude of the predicted increase in bed elevation is relatively small compared to the degree of entrenchment in this subbasin, suggesting that major changes in channel potentially induced by avulsion are unlikely. Evidence of either stable or coarsening streambed sediment (d50, % <0.85 mm, % <4.7 mm) and bed fining (V*) are present. There is not a consistent pattern providing strong evidence of sedimentation. The data are in general consistent with recent sediment inputs and increased sediment transport capacity.

In the South Fork, most indicators suggest aggradation and/or fining. The South Fork has a relatively low drainage area and low stream power, which suggest relatively high sediment storage potential. The high volume of LWD and frequency of debris jams significantly enhance this potential. The high proportion of Wildcat parent material in the watershed suggests that a relatively high proportion of fines would be present in the channel, particularly considering the previously noted conditions. Predicted bed aggradation is less than sediment storage, suggesting that high sediment storage conditions have existed for a relatively long period, possibly related to LWD accumulation in the channel following the first cycle of logging.

MS1 (the upper mainstem below the confluence with the South Fork) has a moderately coarse bed, has relatively high stream power and drainage area, and is deeply entrenched in the valley floor with frequent bedrock exposures. There is limited evidence of aggradation; however, the low q* value is strongly suggestive of transport capacity in excess of sediment supply. The bedload routing model results are consistent with this interpretation. Evidence of bed fining is consistent with recent sediment inputs and increased sediment transport capacity.

Graham Gulch has mixed indications of aggradation and degradation and bed fining. Both long-term and short-term indicators are consistent with episodic direct inputs of sediment by a large, persistent deep-seated landslide and relatively high transport capacity. Graham Gulch has a relatively coarse grain size distribution, in part owing to long-term inputs of relatively persistent gravel from the Franciscan.

Limited data were available for Cloney Gulch. The bedload routing model consistently indicates channel degradation. The evidence of bed fining is consistent with recent sediment inputs and increased sediment transport capacity. These apparently contradictory indications suggest that observations and assessment of habitat conditions in the Fisheries Assessment Module are unusually important and should be used to resolve this uncertainty.

MS2 (the lower mainstem between Graham Gulch and Little Freshwater) has mixed indications of aggradation and fining. The bedload routing model consistently predicts bed aggradation; however, the relatively coarse grain size distribution is inconsistent with bed fining. Conditions in this reach appear to favor selective transport of sand and storage of gravel. The effect of aggradation on flooding in this reach is assessed in Section 6.0.

Little Freshwater has many indicators consistent with aggradation and bed fining. The fine-grained character of sediment inputs in this watershed probably accounts for many of these in that high fine sediment concentration would be expected. The bedload routing model suggests that long-term channel degradation may be interspersed with periods of aggradation in response to increased sediment inputs. Sediment inputs are not expected to persist owing to high attrition rates of coarse sediment derived from Wildcat parent material. Evidence of bed fining is consistent with recent sediment inputs and increased sediment transport capacity.

McCready Gulch has consistent indications suggesting aggradation and fining. Predicted aggradation is consistent with observed sediment storage. However, given the degree of channel entrenchment, this may not have significant effects on channel processes. The fine-grained character of sediment inputs in this watershed partly accounts for indicators of bed fining in that high fine sediment concentrations would be expected. Evidence of bed fining is consistent with recent sediment inputs and increased sediment transport capacity.

MS3, the lower mainstem downstream of Little Freshwater, has consistent indications of aggradation and fining. The low gradient and low confinement of this channel, and many other factors described at the outset of this section, are consistent with these indications. The magnitude of aggradation predicted in this reach is relatively small in comparison to channel depth. The effect of aggradation on flooding in this reach is assessed in Section 6.0.

5.2 STORED SEDIMENTS

With respect to sediment storage and routing, the channel system may be conceptualized to include the active channel and semi-active or inactive floodplain components (see Madej 1995). The degree of activity of these sediment reservoirs is a function of the magnitude of floods required to mobilize the sediment they contain. In Madej's analysis of Redwood Creek, the semi-active reservoirs were conceptualized to be mobile during floods with 5- to 20-year recurrence intervals, and floods in the 20- to 100-year recurrence interval range mobilized the inactive reservoirs. The active reservoir was conceptualized to be mobile during flows with recurrence intervals <5 years. It is generally necessary to distinguish these component sediment reservoirs because they have different residence times. The active reservoir sediment is transported more quickly, on average, than the others. However, sediment from different reservoirs is mixed during flood events as a result of channel erosion and sedimentation processes. In Redwood Creek, a large stream with a wide floodplain, these different reservoirs were readily mapped using aerial photography, and the transition probabilities among different reservoirs were calculated (Kelsey et al. 1987).

In Freshwater Creek, we have focused on active channel deposits, primarily because semi-active and inactive reservoirs are not distinctly identifiable. In the tributary subbasins of Freshwater, channels are typically entrenched, and channel response to erosion and sedimentation processes are not expressed by obvious lateral migration of the channel. This is evident based on review of aerial photography showing no significant shifts in channel position, and on field observations of bank conditions that impose significant constraints on lateral channel movement. Consequently, we adopted a conceptual model of sediment reservoirs similar to that described for North Fork Caspar Creek by Napolitano (1996) which identifies bed, bar, and debris jam sediment reservoirs.

We have estimated channel-stored sediment within each of the longitudinal profile reaches (methods described in Section 5.1.3.1.), located exclusively in Class I (fish-bearing) stream channels. The lateral extent of the active channel storage reservoir is defined by exposed, un-vegetated or sparsely vegetated bed and bar deposits, and by the depth of scour during periods of peak flow. The depth of the channel storage sediment reservoirs is based on observations of thalweg depths and pool depths relative to the low flow water surface. Bedrock is often exposed in pool bottoms, even including some locations in the lower mainstem reaches (CGUs MS2 and

MS3), making estimation of the depth of sediment storage in the active channel relatively clear. In the lower reaches, the estimates for sediment storage may underestimate total storage because bedrock was not always exposed in the pool bottoms, although it was more consistently exposed in the lower banks. The depth of gravel bar sediment reservoir is based on the difference in elevation between bar tops and the low flow water surface, and is typically substantially less than the depth of the channel storage reservoir.

No sediment storage estimates have been made for vegetated bars and terraces that would be considered semi-active sediment reservoirs. Owing to the entrenched character of most channels, such sediment storage features are not widely distributed. If they had been measured, it is likely that they would have represented a relatively small component of total storage. In addition, no quantitative storage estimates have been made for channels in the Class II or Class III channel network. These storage elements are more likely to be substantial. The absence of an estimate for these storage elements reduces the total estimate of fluvial sediment storage in the watershed and thus will necessarily reduce the estimated residence time of bedload in the watershed. During high magnitude floods in these confined channels, it is hypothesized that sediment is removed from storage in the channel system by vertical scour of sediment stored on the streambed. Consequently, the channel bed in conceptualized to contain both active and semi-active sediment reservoirs that are distinguished by the magnitude of scour associated with flows of different magnitude. A graduate student at Humboldt State University (Paul Bigelow) has collected scour data for Freshwater, but these data are as yet unavailable.

5.2.1 Quantity of Stored Sediment

The mean sediment storage depths and volumes from field sites in Class I stream channels in each subbasin were extrapolated to estimate total sediment storage volumes in each reach (Table 5-8).

In most reaches, observations in that reach were used to estimate the total. For Little Freshwater, the sediment storage per unit channel length used to estimate total storage is the average of observations in Little Freshwater and McCready Gulch. Field sites in Little Freshwater were near the mouth of the watershed in CGU U1, and much of the mainstem of Little Freshwater is in CGU C1. The latter channel type is better represented by McCready Gulch. No sediment storage surveys were conducted in Cloney Gulch. The sediment storage per unit channel length used to estimate total storage in Cloney Gulch is the average of observations in Little Freshwater, McCready, Upper Freshwater, and South Fork. These were chosen because they are believed to best represent the range of geology and channel morphology found in Cloney Gulch. This yields a conservative estimate of sediment storage in Cloney Gulch.

Table 5-8: Summary of sediment storage estimates for Freshwater subbasins and mainstem reaches. Cloney Gulch is represented by an estimate based on other subbasin reaches with the most comparable geologic conditions**.**

				Sediment Storage		
Subbasin/Reach	Mean Channel Reservoir Depth (ft)	Mean Bar Reservoir Depth (ft)	Channel Length (ft)	Per Unit Length (yd^3/ft)	Volume (yd^3)	Mass (t)
Upper Freshwater	1.2	1.0	8358	1.51	12600	21158
South Fork	2.1	0.9	10880	2.80	30500	51353
MS1	1.8	0.7	11926	2.21	26300	44300
Graham	2.4	1.3	6391	2.84	18200	30636
Cloney	n.d.	n.d.	11215	1.50	16800	28432
MS2	3.1	0.3	5500	3.63	20000	33600
Little Freshwater	2.2	0.5	13522	0.97	13000	21820
McCready	1.3	0.6	8559	0.66	5600	9477
MS3	2.7	0.9	12307	3.36	41400	69867

Relative amounts of sediment storage between reaches is best summarized by the sediment storage volume per unit channel length (fifth column in Table 5-8). These data show that subbasins underlain primarily by Wildcat rocks (Little Freshwater and McCready Gulch) have the least sediment storage per unit length. This is presumably a consequence of the low gravel production from these rocks. The data also show that the MS2 and MS3 reaches in lower Freshwater have the highest sediment storage per unit channel length. Other subbasins with relatively high storage are South Fork and Graham Gulch.

5.2.2 Bedload Residence Time and Velocity

The stored sediment estimates can be compared with estimated bedload transport rates from the bedload transport model (Section 4.0) to develop an estimate for bedload residence time. This will provide quantitative estimates for the time required to move bedload sediment through different portions of the channel network in Freshwater.

The residence time is calculated as storage divided by rate, yielding units of time. The residence time is interpreted as an approximate time required for the movement of bedload through a sediment reservoir, here considered to be the active storage in the reaches in question. The average bedload velocity can then be calculated by dividing residence time by reach length.

Estimates of residence time and bedload velocity using these methods are of limited accuracy and should be regarded as order of magnitude estimates. This sediment storage and routing analysis does not include Class II or Class III streams; residence time estimates which included sediment inputs from these channels would be expected to increase overall sediment residence time in the watershed.

A critical assumption of the residence time calculation is that the sediment reservoir is "well-mixed." In other words, it is assumed that over a period of a few decades that all of the sediment in the channel bed is eroded from bars or scoured from the bed. The active sediment reservoir must "turn over" during the period of time required to move the material through the reach, approximately equal to the residence time. We believe this is a reasonable assumption considering the depth of sediment reservoirs and streambed dynamics in confined channels over periods of decades. Sediment stored at depth in the bed and bars is excavated during low frequency floods when the bed armor is mobilized allowing deep scour, debris jams fail and release stored sediment, as new LWD and slugs of sediment enter channels and alter the thalweg location. The spatial and temporal frequency of these events is assumed to be sufficient to satisfy the assumption of a well-mixed sediment reservoir.

Residence time calculations are summarized in Table 5-9. The chief conclusion from this analysis is that bedload is transported from the upper reaches of Freshwater Creek and its tributaries to lower Freshwater over a period of decades. Bedload transport through the lower reaches of the mainstem also occurs over a period of decades. Note that these residence time estimates do not distinguish differential transport rates of sand and gravel, which comprise the two size fractions in storage. It is believed that the residence time of sand in these channel reaches is on the order of 10 years. This does not severely skew the residence time estimates presented because sand comprises less than one-third of the bed material, and only averages between one-fourth and one-fifth of total bed material.

Table 5-9: Estimated sediment storage, transport rate and residence time. "MS2 and MS3 Combined" is the scenario where the calculated bedload transport rate at MS2 is regarded as an anomaly.

Subbasin or Reach	1999 Estimated Stored Sediment (tons)	Average Bedload Transport Capacity (tons/yr)	Residence Time (yr)	Average Bedload Velocity (ft/yr)
Upper Freshwater	21,200	860	25	340
South Fork	51,400	200	260	42
Upper Mainstem (CGU MS1)	44,300	1100	40	300
Graham Gulch	30,600	720	43	150
Cloney Gulch	28,400	1290	22	510
Lower Mainstem (CGU MS2: Graham Gulch to Little Freshwater)	33,600	190	180	31
Little Freshwater	21,800	810	27	500
McCready Gulch	9,500	180	53	160
Lower Mainstem (CGU MS3: Below Little Freshwater)	69,900	2620*	27	460
MS2 and MS3 Combined	103,600	2620*	40	450

"*" denotes the MS3 transport rate, which is the average of two stations in the reach.

The bedload velocities calculated for Freshwater Creek subbasins are comparable to values of sediment velocity determined from a wide range of literature sources, shown in Table 5-10. The average bedload velocity calculated from the data above is about 290 ft/yr. Converting the data in Table 5-9 from units of km/yr for "pebbles and cobbles in mountain streams," the mean velocity is about 330 ft/yr, ranging from about 65 to 1600 ft/yr.

Table 5-10: Typical sediment velocities (after NCASI 1999, p. 299).

Particle Size and Stream Type	Range (km/yr)	Mean (km/yr)
Suspended sediment in mountain streams	2-20	10
Sand as the predominant bedload	0.5-5	2
Pebbles and cobbles in mountain streams	0.02-0.5	0.1
Gravels in braided streams	0.02-5	--

The Freshwater data are within this range and the mean values are in close agreement, indicating these estimates are reasonable. Therefore, we believe residence times for coarse sediment in the watershed subbasins upstream indicate that bedload delivery to lower Freshwater has a lag time between input and downstream delivery of a few decades. Consequently, significant reach-scale changes in channel conditions are unlikely to occur in the short-term; residence time for coarse sediment in lower Freshwater is at least on the order of decades. Coarse sediment input to the tributary watersheds from the past few decades will continue to be routed to lower Freshwater; anticipated reductions in coarse sediment inputs will not be immediately reflected in channel conditions.

5.2.2.1 Effect of Changes in Peak Flow on Bedload Residence Time & Velocity

The Hydrologic Change Module developed a set of predictions of peak flow increases and model hydrographs of runoff. Both current conditions and hypothetical undisturbed (hydrologically mature) forest cover conditions were modeled. Total long-term bedload transport capacity increased about 18% on average across all flows for all stations. Tributary watersheds tended to have a higher average increase (about 23%) than mainstem reaches where the increase was about 12%. All bedload routing considerations assume the higher transport rate; hence, the analysis presented is for worst-case conditions with respect to estimated transit time for coarse sediment from the upper watershed to the lower watershed. Under hypothetical baseline hydrologic conditions, bedload transport rates would be reduced by about one-quarter, on average.

5.3 SIZE DISTRIBUTION OF STORED SEDIMENT

The size distribution of stored sediments was analyzed for general patterns of existing sediment sizes throughout the watershed. At the subbasin scale, the size distribution of stored sediment is generally related to the underlying geology of the channel network and of the basin geology upstream of the sampling location. At the reach scale, the size distribution is a function of the local sediment input regime, as well as channel geometry. Much of the data pertaining to sediment size distributions have been presented in Section 5.1. This section focuses on the relationship between indices of stream power and sediment size and demonstrates that fundamental channel characteristics (width, depth, and slope) influence of sediment size distributions.

5.3.1 Grain Size vs. Stream Power Index

Sediment grain size in stream channel networks typically varies with channel slope, drainage area, and watershed geology (weak rocks versus strong rocks). To investigate whether systematic variations in sediment size occur in Freshwater, the median grain diameter of gravel bars (surface d50), the median grain diameter of obviously mobile bed deposits (mobile d50), and the diameter of the 84^{th} percentile of the grain diameter distribution (surface d84) in each CGU was compared to two indices of stream power for each CGU (Table 5-11). In addition to observing grain sizes during reach characterization surveys and cross-section surveys, bankfull channel dimensions were measured at these sample sites. The product of bankfull channel width, bankfull channel depth (in units of ft), and bed slope (%) was computed for each site; this value is called the "stream power index." The "unit stream power index" is the product of depth and slope (equivalent to the stream power index per unit channel width). The average d50 (Figure 2-2, Section 2.2.2) and the average d84 (Figure 5-11) was plotted as a function of the mean stream power index for each CGU (Table 5-11). These plots demonstrate that the stream power index is a useful indicator of grain size distribution and that the CGU groupings reflect distinctive watershed geomorphic characteristics.

Despite typical high variability, it is evident that there is a general correlation between stream size and gradient (as represented by the stream power index), and surface grain size distribution (as represented by the median grains size [d50]). It is also apparent that the Unconsolidated CGUs have generally smaller grain sizes and stream power, while the Consolidated CGUs have generally larger grain sizes and stream power. The Mainstem CGUs have a narrow range of values intermediate between the other CGU groups (Table 5-11).

Table 5-11: Summary of the range of values of d50 and stream power indices for CGU groups.

CGU	SPI	Unit SPI	Mobile D50 (mm)	Surface d50 (mm)	Surface d84 (mm)
C1	125	4.8	10	27	78
C2	134	10	21	70	183
C3(large)	379	25	11	88	165
C3(small)	70	16	8	28	96
C4	139	27	13	54	202
U1(large)	79	3.1	13	24	51
U1(small)	9.4	2.7	1	5.5	69
U2	13	4.6	1	14	63
U3	31	8.3	11	23	53
U4	124	20	1	2	10
GG	153	12	4	40	116
CG	86	3.6	--	39	73
Ms1	95	2.2	16	32	77
Ms2	84	1.7	10	35	70
Ms3	79	1.7	7	22	59

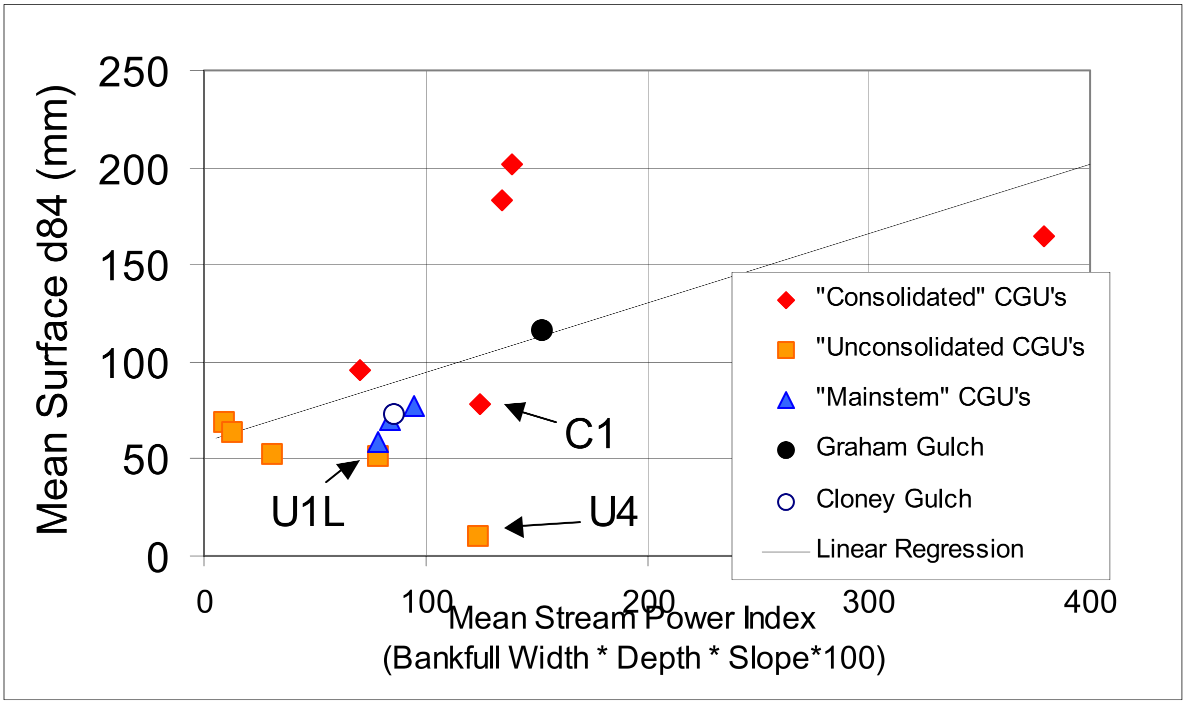


Figure 5-11: Plot of mean surface d84 for Freshwater CGUs versus means stream power index for each CGU.

5.3.2 Fine Sediment Abundance Ranks

In addition to observations of sediment size distribution, the relative abundance of fine sediment (sand) on the channel bed was ranked on an ordinal scale during reach characterization surveys. The ordinal ranking included three categories or relative abundance: sparse, moderate, and abundant. The mean value of fine sediment abundance was plotted against the grain size threshold separating intermittent suspended load and bedload (Figure 5-12). The analysis used to determine this grain size threshold is discussed in Section 3.5.1. This grain size represents the largest grain size expected to be transported in suspension in the given channel type. Channels that transport relatively larger sediment in suspension would be expected to retain little fine sediment on the streambed.

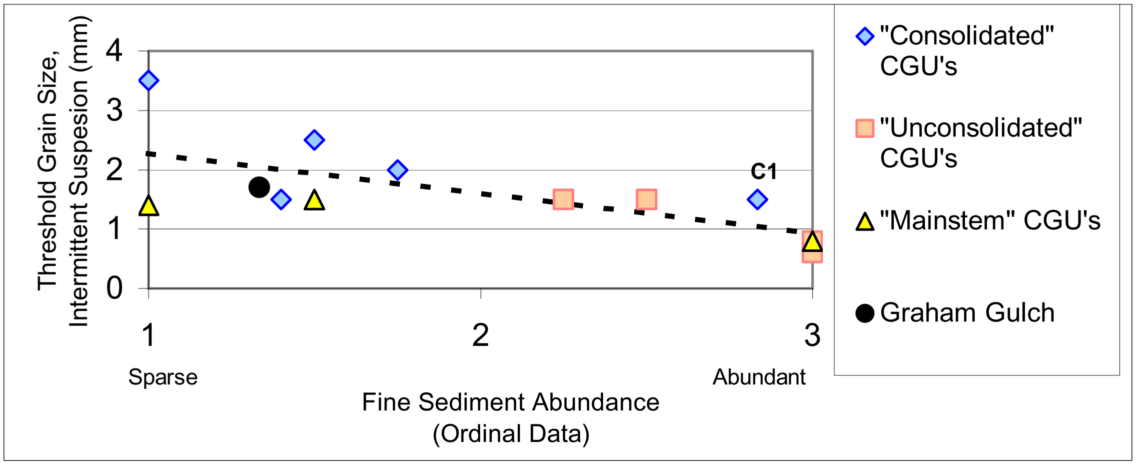


Figure 5-12: Fine sediment abundance versus maximum grain size transported in intermittent suspension.

Fine sediment abundance is greatest in CGUs with grain size thresholds <1 mm, which includes MS3. Fine sediment abundance was also greatest in Unconsolidated CGUs, those with the highest proportions of Wildcat formation in their channel s and watersheds. CGU C1 also has relatively high fine sediment abundance, in part because most C1 channels receive fine sediment inputs from more energetic channels upstream (C2, C3-L, C4) that are less likely to retain sand. MS1 and MS2 have relatively low fine sediment abundance by this measure.

5.4 ATTRITION RATES FOR COARSE SEDIMENT (COBBLES AND GRAVEL)

The attrition process can be defined conceptually as the reduction in size of a gravel particle per unit of downstream transport. This occurs because of abrasion that occurs during transport, and because of weathering of rocks that weakens the outer layers of individual gravel clasts. These weak outer layers disintegrate rapidly when subjected to transport in the bedload.

The significance of the attrition process relates to sediment transport and routing processes. Bedload material (i.e., gravel) is transported relatively slowly. Finer materials such as clay, silt, and sand are transported more quickly. Hence, as bedload material is transported and breaks down through attrition, a fraction of the material is transformed to a size class that can be more rapidly transported through the channel network. Some proportion of gravel-size sediment entering a channel as bedload ultimately is transported out of the watershed as suspended load.

The differences in attrition rates associated with each of the different geologic formations have significant implications for the presence or absence of key habitat elements (coarse substrate, and boulder/cobble cover). In the absence of coarse substrate, spawning and rearing potential is lower, and amphibian habitat is limited.

Much of the channel substrate in the areas underlain by the Wildcat Group is composed primarily of sand, or very soft sandstone. The pebbles and cobbles in the channel do not persist for long in stream channels. Harder rocks, derived from the Yager and Franciscan terranes, provide most of the durable cobble and gravel to the system. In Little Freshwater Creek and McCready Gulch, the channel has incised through the overlying Wildcat sands into the harder underlying rocks. These channel reaches are believed to provide most of the limited coarse substrate (gravel and cobble) found in the lower reaches of these tributaries.

5.4.1 General Observations of Attrition in Freshwater

Attrition rates were qualitatively determined for Freshwater. Field observations indicate that there are two primary attrition rate classes. Attrition classes are a function of bedrock strength. In the Freshwater Creek watershed there are two distinct groups of geologic formations as described for CGUs. One group is comprised of the relatively resistant rocks of the Franciscan formation and members of the Yager formation, collectively referred to as the Consolidated unit. The other group is comprised of the very weak rocks of the Wildcat group, which comprises the Unconsolidated unit.

What little gravel is produced from Wildcat parent material has very high attrition rates. Hand samples of Wildcat gravel found on bars can generally be crushed in one's hand. Based on field observations of the lithologic composition of gravel bars in Freshwater, Wildcat gravels typically do not persist as gravel for more than 100s of ft of transport. Hence, most of the material that enters channels from Wildcat bedrock or soils will be broken down to sand-size particles or finer.

Gravel produced from the Consolidated bedrocks units has a wider range of attrition rates. Chert derived from the Franciscan is relatively resistant to attrition, while sandstones and conglomerates were less resistant than chert but much more resistant than the Wildcat. The proportion of these gravel materials broken down to sand sizes or finer is not known but can be estimated.

5.4.2 Estimated Attrition Rates from Consolidated Geologic Sources

There are relatively few published data on attrition rates for bed material in streams. Potential attrition rates for rocks from the "Consolidated" geomorphic units of the watershed were estimated as shown in Figure 5-13. Collins and Dunne (1989) calculated attrition rates for several types of gravel deposits using a rock tumbling mill and a wet mixture. We selected the equation for the type with the highest attrition rate (upper curve in Figure 5-13). This material was described as weathered basaltic colluvium, which probably has an attrition rate lower than Franciscan sandstones in northern California. In this study, the equation calculated the rate of attrition to <0.5 mm diameter, at which size the material was removed rapidly in suspended load.

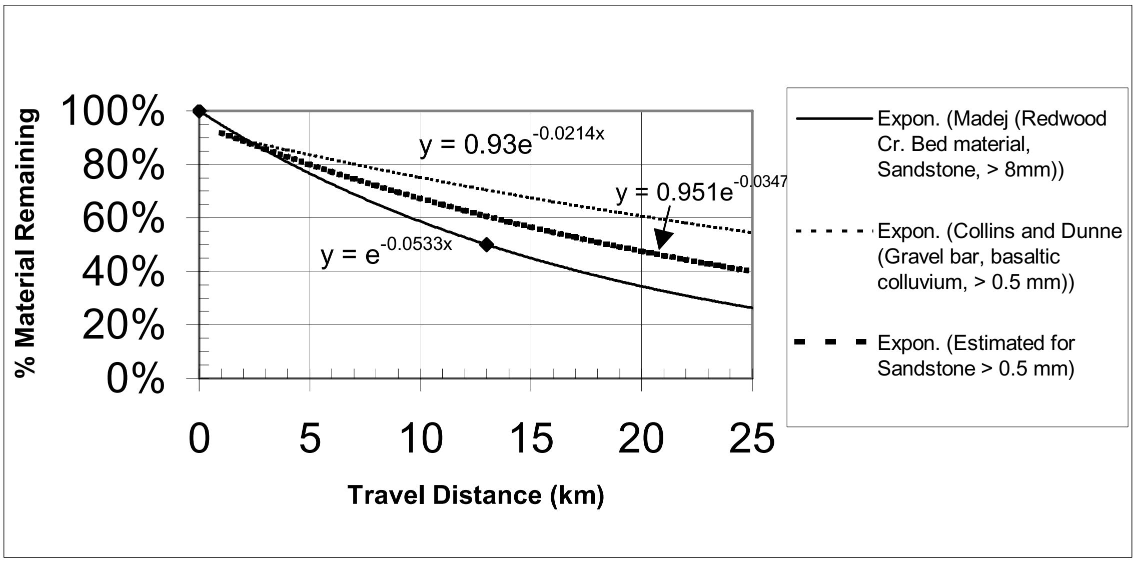


Figure 5-13: Attrition rate estimated from published sources. The middle curve is the average of the upper and lower curves, and represents an estimate for bedload attrition to 2 mm diameter for sandstone.

One published study of attrition rates for northern California sandstone from Redwood Creek used a dry tumbling mill (Madej 1995). This mixture of rocks included schist that weathered much more rapidly; the sandstone was characterized as more durable. The results from this experiment were not presented in the form of an exponential equation, nor were their many data for the sandstone component of the mixture. It was stated that in the two samples, roughly 50% of the material was reduced to <8 mm diameter in 13 km of simulated transport. In Figure 5-13, an exponential curve was fitted to two data points (including 100% at transport distance zero) to represent the results of this experiment. This curve plotted significantly lower than the first mixture.

The two attrition curves described above were combined to provide an estimate of attrition for gravel from Consolidated geologic sources in Freshwater. Neither curve is directly applicable. The first is for a somewhat different material. The Redwood Creek attrition curve estimates attrition to a relatively large diameter (8 mm) that would be transported as bedload in Freshwater. An intermediate curve was created as an average of the two, intended to represent attrition to about 0.5 mm. This roughly represents the middle of the range of sand sizes transported in intermittent suspension. Given the approximate nature of this estimate, this attrition curve is used only to estimate the potential magnitude of attrition of gravel to grain sizes transported in suspension as described below.

5.4.3 Influence of Attrition on Sediment Routing in Freshwater

The estimated attrition rates have not been directly applied to sediment routing analyses for Freshwater. Sediment inputs estimated in the sediment budget predict that about 8% of Unconsolidated inputs and about 23% of Consolidated Inputs are gravel (>2 mm), and an additional 15 to 20% of the inputs are sand. All of these input materials are considered bedload material in the sediment routing analysis. Comparison of modeled bedload transport capacity and sediment inputs were made to estimate aggradation and degradation rates in channels.

By neglecting attrition, the sediment routing analysis overestimates predicted aggradation by bedload material. The quantity of bedload material in any given reach would be reduced if attrition were incorporated in the model. In addition, the quantity of suspended sediment would be increased.

The magnitude of these shifts in sediment size classes and components of the sediment load can be estimate by reference to Figure 5-13. The length of the mainstem Class I channels linking Upper Freshwater and South Fork Freshwater to the bottom of CGU MS1 (i.e., the Salmon Forever gage site) is approximately 6 km. In this distance, approximately 20% of bedload (sand and gravel) would be reduced to suspended load. An additional 6 km of the lower mainstem channel extends through CGU MS3. At this point, approximately 35% of the bedload inputs from the upper watershed will have been reduced to suspended sediment. Hence, attrition processes would be expected to reduce predicted aggradation by bedload of roughly one-fifth to one-third, depending on source area and downstream point of reference. This would increase the long-term suspended load fraction of inputs to about 65-70% from the original input of about 55%.

The foregoing discussion applies only to the more durable rocks in the watershed. As described above, the Wildcat rocks experience extreme attrition. The impact of this attrition in the sediment routing analysis may nevertheless be modest. The Unconsolidated Wildcat formation contains <25% sand and gravel (see Section 3.3); hence, attrition of these materials could increase suspended load by approximately one-third (25% original bedload divided by 75% original suspended load).

Attrition of bedload to suspended load leads to more rapid downstream transport of the sediment. The effect of this on bed aggradation is limited, however. As described above, there will be less bedload material to accumulate in the channel. Moreover, the more rapidly routed material (transported as wash load or intermittent suspended load) in the size fraction approximately <0.5 mm is a small proportion of the material stored in the bed. As shown in cumulative grain size analysis (Figure 5-7), this size fraction represents no more than about 10% of the bed material. This implies that this fine fraction of sediment is either transported out of the system or deposited on the floodplain during periods of overbank flow, and does not contribute directly to channel aggradation. The potential effects of floodplain deposition of suspended sediment are discussed in Section 6.0.

5.5 CHANNEL RESPONSE TO LANDSLIDE SEDIMENT INPUT

Channel response to sediment inputs varies depending on the volume and particle size distribution of the sediment source. With the exception of a few large landslides, most sediment sources in Freshwater have a high proportion of fine sediments, which are readily transported once they reach the channel. Transport potential is limited in low-gradient reaches, especially in areas with frequent LWD accumulations. Some of these areas appear to be significantly impacted by fines (e.g., upper reaches of the South Fork).

5.5.1 Graham Gulch Slide

One of the largest single sediment sources in the Freshwater Creek Watershed is located approximately 2.5 km upstream of the mouth of Graham Gulch. This sediment source consists of two components: a slow-moving earthflow, and a relic landslide dam deposit. Both sediment sources are currently active, especially since the storms of January 1997.

Based on site visits and sequential aerial photo analysis, it appears that the Graham Gulch earthflow was active in the late 1940s. The 1948 aerial photo shows a large hole in the canopy at the location of the slide. There is no bare ground visible in the photo, but one would not necessarily expect much bare ground with this type of deep-seated translational feature. The slide acts more like a slow moving conveyor belt, simply pushing material into the channel.

Much of the volume of material mobilized during the 1997 floods was not from the earthflow, but rather from the remnant landslide dam located opposite the toe of the earthflow.

This landslide dam deposit supports a few redwood trees with >30" diameter, and a handful of large alder trees. It does not seem unreasonable to believe that this dam formed within the past 50 years.

Other sediment sources in the basin are less unique in character and do not tend to dominate channel morphology as dramatically as the Graham Gulch earthflow. Near-stream erosion processes in Graham Gulch are especially active; this is believed to be a manifestation of the downstream effects of this large, concentrated source of coarse sediment.

5.5.2 Streamside Landsliding

Streamside landsliding often introduces both LWD and sediment to the channel network. The grain size distribution of sediments delivered to the stream channel depends on the nature of the material where the slide originates. For example, along portions of the channel network underlain by the Franciscan and Yager terranes, coarse sediment is introduced, which may have a direct influence on proximal downstream reaches. In areas underlain by the Wildcat Group, landslides may consist entirely of sand and have a lesser influence on channel morphology. See Section 3.1 for a complete discussion of the streamside landslide inventory and bank erosion.

Many streamside landslides introduce LWD to the channel which often forms jams downstream of the landslide. These jams accumulate large volumes of bed-material behind them and sometimes provide settling basins for fine sediment accumulations. Gravel bars are often most abundant and store the largest volume of sediment immediately upstream of LWD jams.

Bank erosion was the most abundant type of sediment source (by frequency, but not by volume). Increased bank erosion may be expected in areas where coarse sediment from large inputs is deposited. In regions where competent rocks are more abundant, and in watersheds where very large landslides are more common than in Freshwater, landslide inputs may initiate episodes of channel migration. There were very few cases where downstream bank erosion resulted from coarse sediment inputs. Woody debris is the more evident cause of disturbance.

Zones of fine sediment accumulation were most notable in the middle portions of the South Fork of Freshwater Creek. Many of these accumulations were downstream of small tributary basins that drain hillslopes recently clearcut and burned. Assessment of upslope sediment sources indicated that burned areas generally have a larger proportion of the hillslope in a condition with exposed mineral soil. In the Wildcat formation, this soil is granular and highly detachable. Small alluvial fans were evident at the mouths of some of these tributaries, and fines were notably more abundant than in other portions of the channel network.

6.0 CHANNEL EROSION, STABILITY, & RESPONSE TO HYDROLOGIC CHANGE

This section addresses key cumulative effects issues in the Freshwater Watershed: the effect of erosion and sedimentation on downstream flooding. This issue is analyzed in detail below in Section 6.1. Section 6.2 addresses the effect of predicted changes (increases) in the magnitude and frequency of peak stream flow on streambed scouring events that could damage salmonid redds.

6.1 EFFECT OF EROSION & SEDIMENTATION ON OVERBANK FLOW

The Hydrologic Change Module predicts the magnitude of peak flow increases attributed to forest management in the watershed. In addition to predicted increases in peak flow, aggradation of the streambed would reduce channel capacity, further contributing to potential increases in flood frequency. The effect of peak flow increases and channel aggradation is analyzed at two locations. The first is at the Langlois property located about halfway between Graham Gulch and Little Freshwater Creek in CGU MS2. The second is at the Hippen's property in CGU MS3 located below McCready Gulch about 2,000 ft downstream of the Howard Heights Bridge. These locations were selected because of reports by residents at these locations of increased flood frequency and because flood high water marks were preserved.

This analysis uses predicted peak flow magnitudes generated from the Hydrologic Change Module and maximum levels of local channel bed aggradation that can be reasonably supported based on the aggradation assessment in Section 5.1.2.3, which estimated channel bed aggradation of 1.5 to 3 ft at the Langlois property (MS2) and 1 ft at the Hippen's property (MS3).

6.1.1 Hydraulic Analyses of the Langlois Reach (MS2)

The effects on flood frequency of predicted peak flow increases and possible increased bed elevation (aggradation) are presented in this section. One representative cross-section for the Langlois reach has been the subject of hydraulic analyses in this reach (Figure 6-1). Cross-section hydraulics were analyzed using WinXSPRO software (USDA 1998). The effect of potential aggradation on flood frequency was evaluated by subtracting first 1.5 ft, and then 3 ft of elevation from the channel bottom in the cross-section surveyed in 1999. Flow conditions for the 1999 bed elevation were also considered. The results of these analyses are summarized in Figure 6-2 and Table 6-1.

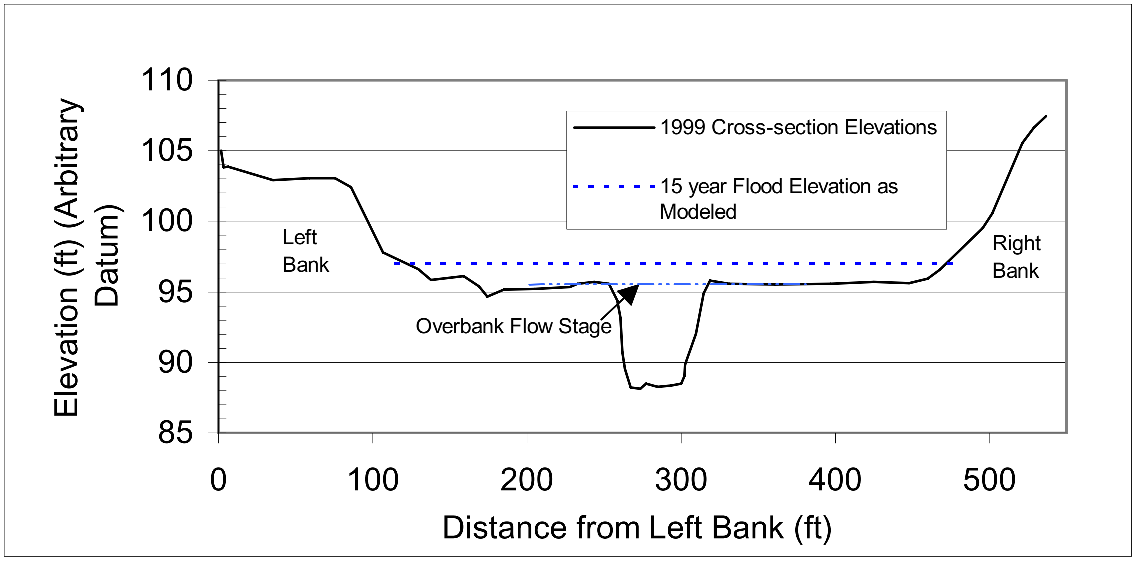


Figure 6-1: Cross-section of Freshwater Creek at Langlois. In addition to overbank flow stage, the predicted water surface elevation associated with a 15-year recurrence interval flow is shown. The 15-year flow elevation is consistent with the elevation of recent high water marks preserved on Langlois' property.

Table 6-1: Flood discharge and frequency for the Langlois cross-section for 1999 channel bed elevations, elevations of 1.5 and 3 ft lower than 1999 elevations conditions, and hypothetical baseline and 1999 runoff conditions.

Scenario	Channel Capacity (cfs)	Recurrence Interval (yrs)	Annual Probability (1/RI)
a – Baseline Flow, Bed Elevation 3 ft Lower	3960	8.3	0.12
a – Peak Flow Increase Only, Bed Elevation 3 ft Lower	3960	7.1	0.14
b – Baseline Flow, 1999 Bed Elevation	2540	2.7	0.37
b – Baseline Flow, Bed Elevation 1.5 ft Lower than 1999	3240	5.0	0.20
c – Peak Flow Increased, 1999 Bed Elevation	2540	2.2	0.45
c – Peak Flow Increased, Bed Elevation 1.5 ft Lower than 1999	3240	4.2	0.24

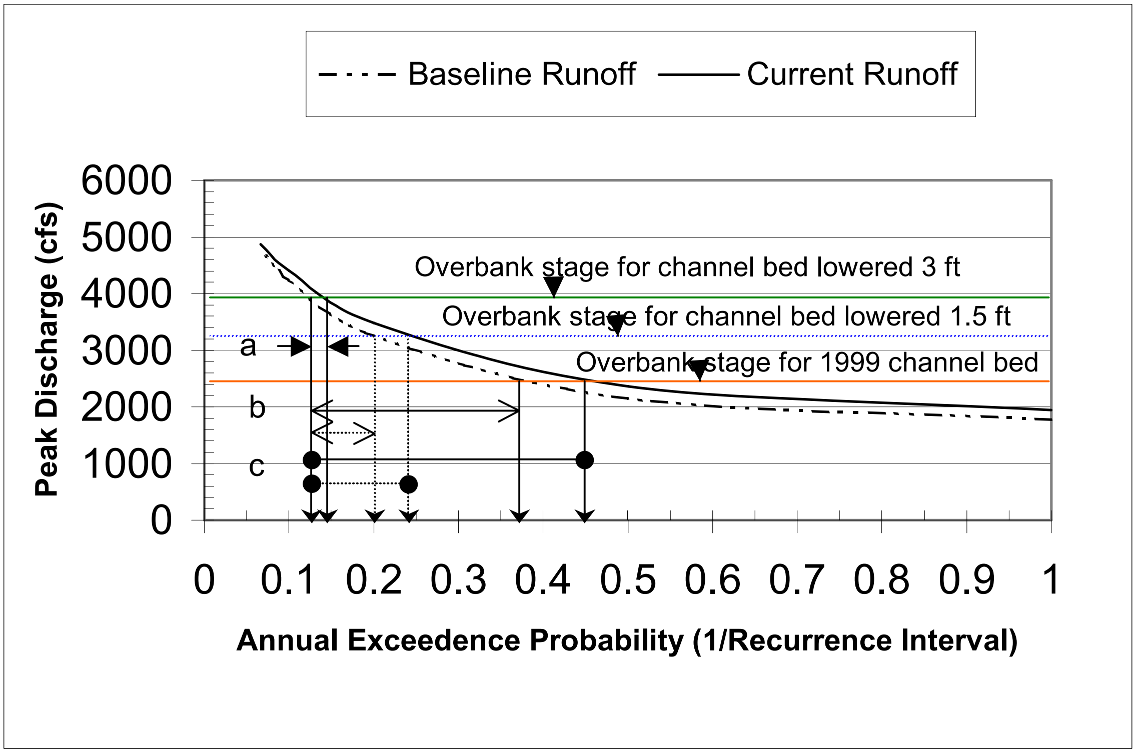


Figure 6-2: Graphical representation of the effect of peak flow increase alone (a-solid arrows), presumed aggradation alone (b-open arrows), and the combined effects of peak flow increase and presumed aggradation (c-solid circles). The dotted lines relate to a hypothetical bed elevation 1.5 ft lower than in 1999; the solid lines farthest to the right relate to the existing channel bed, while those farthest to the left relate to a hypothetical channel bed elevation 3 ft lower than in 1999.

For these three scenarios, Manning's roughness coefficient (n) in the main channel is estimated according to Jarrett's equation (see Section 4.5) as 0.032 to 0.033. Although there are no data to validate this roughness value in this reach, Jarrett's equation was tested against data available from Salmon Forever gage (see Section 4.5) and found to overestimate n by about 25% (predicted value of 0.031 minus observed value of 0.04 divided by observed value). Thus, based on the available data for a flow event near bankfull stage in the watershed, the roughness value used for the model appears to be conservative.

The effect of riparian vegetation on flow resistance is not explicitly included in the equation used to estimate flow resistance; however, we believe it is implicitly accounted for in the approach used. The overbank sections of the channel are analyzed as separate channels with separate hydraulic variables. Jarrett's equation gives an average value of n = 0.046 for sections carrying overbank flow. At this location, floodplain vegetation is comprised of backyard lawns and ornamental plants, which would be expected to offer about half this flow resistance.

Flow resistance in the bankfull channel due to riparian trees, primarily a thin strip of alders, is expected to have a small additive effect on the value of n. Phillips and Ingersoll (1998) developed an empirical equation predicting the additive component of flow resistance as a function of the estimated percentage of flow blocked by vegetation: $n_4 = 0.0008B - 0.0007$, where *B* is the percentage of flow blocked.

Tree trunks and shrubs may block as much as 5 ft (about 10% of the channel width) of the bankfull cross-section at the channel margins at the Langlois cross-section. This would add about 0.007 to n estimated by Jarrett's equation of about 0.033, representing an increase of about 20%. Given the previous indication from the Salmon Forever gage site that Jarrett over-predicts n, we believe that flow resistance is estimated with reasonable accuracy.

The effect of peak flow increases alone on flood frequency is slight if it is assumed that the channel bed elevation was 3 ft lower than in 1999 (see Table 6-1 and Figure 6-2) in which case the annual probability of overbank flow increases from 0.12 (12%) to 0.14. In contrast, assuming 3 ft of channel aggradation (i.e., 1999 channel cross-section), and the predicted peak flow increase, the annual probability of overbank flow is 0.45. If presumed aggradation is reduced by half (1.5 ft), the annual probability of overbank flow is 0.24. In other words, assuming maximum aggradation and flow increases due to forest management, the analysis indicates that overbank flow will occur about four times more often than under estimated background conditions with a channel bed 3 ft lower than observed in 1999.

Overbank flow at this location primarily involves flooding of yards, not of residences. We do not know the elevations of all residences that may be subject to flooding according to this definition of overbank flow; however, it appears that at least one or two residences in the Langlois reach may be at risk under this definition of flooding. Fortunately, it appears that most residences have been built on higher terraces at elevations several feet above flood stage as defined above.

The effects of bed aggradation on less frequent, higher magnitude floods that are more likely to put residences at risk is evaluated in terms of the likely increase in flood stage for a given flood magnitude (Table 6-2). These floods are not evaluated with respect to flood frequency because the hydrologic modeling for Freshwater Creek indicates that very small differences in peak discharge occur for infrequent floods. For 15-year flood events, flood stage is predicted to be in the range of 0.5 to 1 ft higher, presuming that the channel bed is aggraded 3 ft. For the 100-year flood, water surface elevation is predicted to be about 0.5 ft higher with presumed aggradation of 3 ft. The effect of an increase in the flood elevation of this magnitude is believed to affect only those residences constructed on the lower floodplain surface. Detailed surveys of these areas have not been conducted.

Table 6-2: Range of flood elevations for current runoff conditions and three scenarios of hydraulic conditions.

Flow Magnitude		Water Surface Elevation Above Bankfull (ft)		
Recurrence Interval (yr)	Discharge (cfs)	1999 x-sec	1999 x-sec less 1.5 ft	1999 x-sec less 3 ft
15	4800	1.5	1	.5-1
100	7300	2-2.5	2-2.5	1.5-2

6.1.2 Hydraulic Analyses of the Hippen's Reach (MS3)

The effects on flood frequency of predicted peak flow increases and possible increased bed elevation (aggradation) are presented in this section. One representative cross-section located at the Hippen's residence was selected for analysis (Figure 6-3).

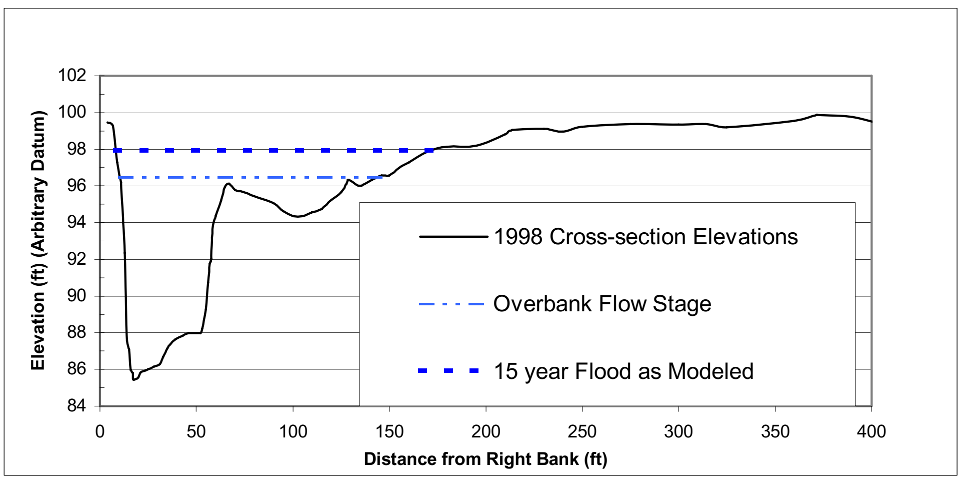


Figure 6-3: Cross-section of Freshwater Creek at Hippen's. In addition to overbank flow stage, the predicted water surface elevation associated with a 15-year recurrence interval flow is shown. The 15-year flow elevation is about 0.5 to 1 ft below flood elevation recorded on the property in 1995.

PWA surveyed a long-profile in this reach. At the cross-section the bed slope was 0.004. The effect of potential aggradation on flood frequency was evaluated by subtracting 1 ft of elevation from the channel bottom in the cross-section surveyed in 1999 for both locations (see Section 5.1.2 for a discussion of how 1 ft of aggradation was estimated). Flow conditions for the 1999 bed elevation were also considered. For these scenarios, n in the main channel (excluding overbank flow) was estimated by Jarrett's equation as about 0.036 at bankfull flow. The results of these analyses are summarized in Table 6-3. Refer to the analysis of the Langlois cross-section (above) for a discussion of vegetation effects on flow resistance. We believe that vegetation effects are implicitly accounted for in the approach used to estimate Manning's n.

Table 6-3: Flood discharge and frequency for the Hippen's cross-section for 1999 channel bed elevations and channel bed elevation of 1 ft lower than 1999 elevations conditions, and hypothetical baseline and 1999 runoff conditions.

Scenario	Channel Capacity (cfs)	Flood Recurrence Interval (yrs)	Annual Probability of Flood (1/RI)
a – Baseline Flow, Bed Elevation 1 ft Lower than 1999	4760	7.1	0.14
a – Peak Flow Increase Only, Bed Elevation 1 ft Lower	4760	5.6	0.18
b – Baseline Flow, 1999 Bed Elevation	4080	4.8	0.21
c – Peak Flow Increased, 1999 Bed Elevation	4080	3.8	0.26

The effect of peak flow increases alone on flood frequency is small if it is assumed that the channel bed elevation was 1 ft lower than in 1999 (see Table 6-3 and Figure 6-4); the annual probability of overbank flow increases from 0.14 (14%) to 0.18. In contrast, assuming 1 ft of channel aggradation (i.e., 1999 channel cross-section), and the predicted peak flow increase, the annual probability of flooding is 0.26. This is roughly a two-fold increase in frequency of overbank flow.

Overbank flow as defined at this location involves primarily flooding of yards or fields, not of residences. We do not know the elevations of all residences that may be subject to flooding according to this definition. However, at this location the Hippen's residence was reportedly flooded at or near the maximum stage for this cross-section in 1995 (see below).

The effects of bed aggradation on less frequent floods that are more likely to put residences at risk is evaluated in terms of the likely increase in flood stage for a given flood magnitude (Table 6-4).

Table 6-4: Range of flood elevations for current runoff conditions and two scenarios of hydraulic conditions (bed elevations). The symbol ">" is necessary in one case owing to a computational problem where the cross-section becomes unconstrained laterally and the 100-year flood discharge cannot be contained in the cross-section.

Flow Magnitude		Water Surface Elevation Above Bankfull (ft)	
Recurrence Interval (yr)	Discharge (cfs)	1999 x-sec	1999 x-sec less 1 ft
15	6140	1.5	1
100	9310	3	>2.5

These floods are not evaluated with respect to flood frequency because the hydrologic modeling for Freshwater Creek indicates that very small differences in peak discharge occur for infrequent floods. In other words, for floods of this magnitude, the effect of runoff changes is very small relative to presumed aggradation effects. For the estimated 15-year flood events, flood stage is predicted to be about 0.5 ft higher presuming that the channel bed is aggraded 1 ft. For the estimated 100-year flood, flood stage is predicted to be less than 0.5 ft higher with presumed aggradation of 1 ft.

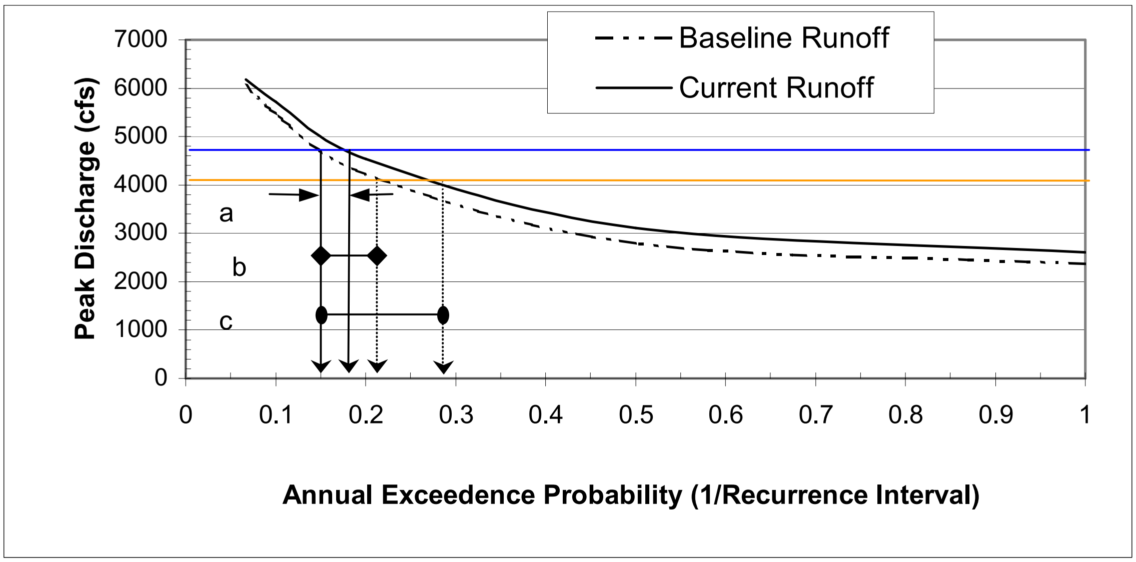


Figure 6-4: Graphical representation of the effect of peak flow increase only (a-closed arrows), presumed aggradation (b-open arrows), and combined effects of peak flow increase and presumed aggradation (c-closed circles). The dotted vertical farthest to the right relate to the existing channel bed, while the solid vertical lines farthest to the left relate to a hypothetical channel bed elevation 1 ft lower than in 1999.

6.1.3 Summary of Overbank Flow Effects

The analysis of sediment storage, routing and effects on flooding in Sections 5.0 and 6.0 are based on a number of assumptions that limit the accuracy of the estimates. Nevertheless, the following conclusions are stated with relative confidence.

- The effect of peak flow increases alone on flooding is relatively small. Assuming aggradation ranging from 1 to 3 ft in the Langlois reach, the hydraulic analysis indicates that the frequency of overbank flow will have increased 2 to 4 fold.
- The reported increase in flood frequency is consistent with gradual channel bed aggradation and the paucity of significant hydrologic events during the period 1975-

1995. There were only two events with recurrence intervals of >2 years at the Little River gage, and these were smaller than 5-year floods. In WY 1996 there was a 5-year and a 10-year event; in WY 1997 there was a >15-year event. In WY 1999 there was an event estimated to be about a 10-year recurrence interval.

- The extent of dense riparian vegetation along the streambanks has increased significantly compared to conditions observed in 1948 aerial photography. Most of the lower Freshwater valley was used as pasture, and in many areas, woody riparian vegetation was absent, presumably the result of grazing. Although there were narrow hardwood forest stands in riparian areas in many locations in 1948, the extent of shrubby understory was much less than is present today. To the extent that such vegetation has encroached on the bankfull channel, flood conveyance may have been reduced gradually over time. This long-term change in land-use patterns in lower Freshwater might also contribute to a gradual increase in flood frequency.

6.2 EFFECTS OF PEAK FLOW CHANGES & BED FINING ON STREAMBED SCOUR

One aspect of increases in peak flow magnitudes is the hypothesis that there may be an increase in the frequency or depth of streambed scour that may affect incubating salmonid eggs deposited in redds. Recent research (Haschenburger 1999) has led to development of a simple predictive model for streambed scour as a function of reach median surface grain diameter and total bed shear stress estimated from the product of channel slope and hydraulic radius for flow magnitudes of interest. The hydraulic modeling performed for the sediment routing analysis allowed us to apply Haschenburger's model to assess potential streambed scour. These calculations are intended to assess the potential effect of peak flow changes on scour to depths that might affect redds. Scour data for Freshwater are as yet unavailable to test the scour depths or frequencies predicted.

The following equations describe the model for streambed scour.

$f(x) = \Theta e^{-\Theta x}$ describes the proportion of the bed scoured to depth x;

x = scour depth in cm.

$\Theta = 3.33 e^{-1.52 t^* / t^*r}$ where t* is Shield's stress and t*r is the reference Shield's stress = 0.045.

$1/\Theta$ gives an estimate of the mean depth of scour or fill in cm.

The median grain size of the bed and the total bed shear stress are incorporated in this model in the term t* (= total shear stress divided by the product of immersed weight of sediment and median grain diameter of the bed).

The Haschenburger model is used to assess streambed scour potential in two ways. First, the estimated average scour or fill depth is calculated as a function of grain size for several stream cross-sections where necessary data are available. Second, the effect of increased frequency and magnitude of peak flows caused by timber harvest are assessed. In both of these assessments, it is assumed that the typical depth of egg pockets in redds of coho and steelhead is 15 cm.

6.2.1 Critical Scour Depth as a Function of Grain Size

Figure 6-5 estimates the critical median grain size (the grain size at which bed scour would average 15 cm) on the surface of the streambed at several stream cross-sections assumed to be representative of channel hydraulic conditions for hydrologic bankfull flow. Bankfull flow in this context is defined as the 1.2-year recurrence interval event on the annual flow series or the 0.5-year recurrence interval on the partial duration series. Flows of this magnitude are on average expected to occur twice per year. The critical median grain sizes range from 22 mm to 53 mm. Curves further to the right in the graph have higher bed shear stress and higher bed slopes. These graphically determined critical grain sizes are discussed further below.

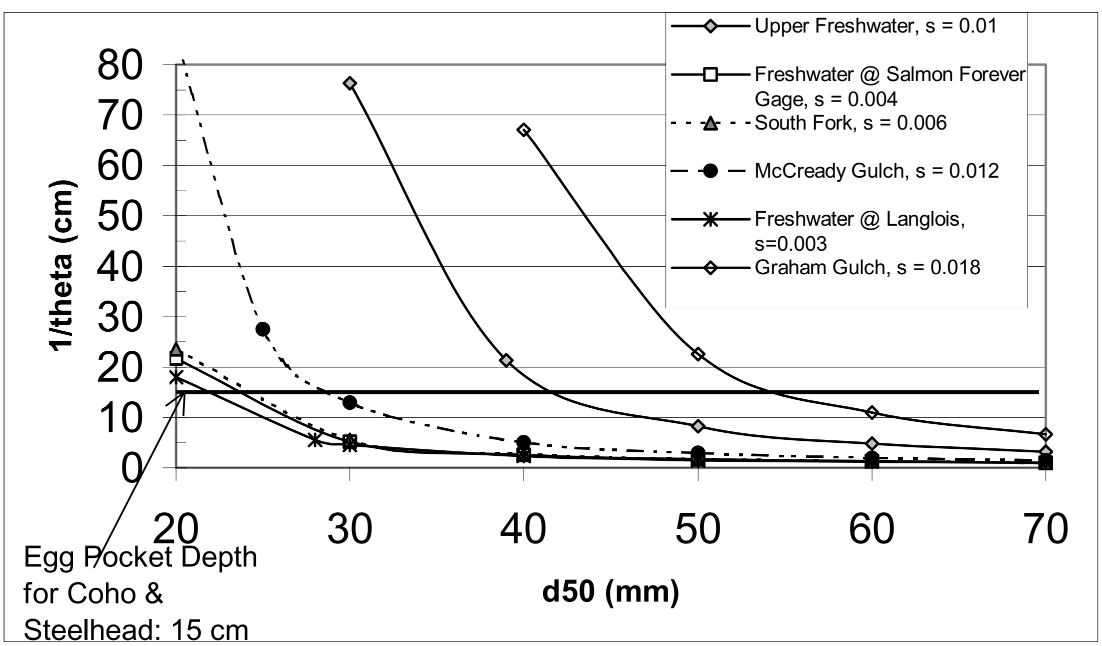


Figure 6-5: Predicted depth of scour and fill as a function of median grain diameter for hydraulic conditions during a 1.2-year recurrence interval flow.

Table 6-5 shows the grain size distribution corresponding to the curves shown in Figure 6-5. The grain size data are of two types: formal Wolman pebble counts (columns two and three), and estimated median grain sizes for gravel bars collected during sediment storage surveys.

Table 6-5: Grain size distributions and proposed "scour hazard index".

CGU (Reach)	Range of d50 and Mean d50 from Pebble Counts (mm)	Range of d84 and Mean d84 from Pebble Counts (mm)	Reach Average d50 for Gravel Bars from Sediment Storage Patch Maps (mm)	Critical d50 for Scour (mm)	Scour Hazard Index (Mean Pebble Count d50/Critical d50 for Scour)	Scour Hazard Index (Gravel Bar d50/Critical d50 for Scour)
C1 (Upper Freshwater)	15-78 / 45	53-164 / 100	49	42	1.07	1.24
C1 (South Fork)	22-70 / 48	38-160 / 97	21	25	1.92	0.88
MS1 (Freshwater at Roelof's)	50	113	37	24	2.08	1.54
GG (Graham Gulch)	27-37 / 31	50-99 / 75	31	55	0.56	0.56
MS2 (Freshwater at Langlois)	41	62	28	22	1.86	1.27
C1/2 (McCready)	19-34 / 28	32-73 / 59	21	29	0.97	0.72

The accuracy of the latter type of data was tested against Wolman pebble counts at many locations and found to be in good agreement. The critical median grain diameter for scour is from Figure 6-5. Finally, a simple index was proposed as a means to evaluate relative scour hazard by forming a ratio of median grain size to critical grain size. When the ratio is greater than 1, the average depth of scour or fill is less than 15 cm. When the ratio is less than 1, the average depth of scour or fill is greater than 15 cm.

The assessment of scour hazard by this means is very sensitive to median grain size of the bed. In addition, the variation in median grain size from location to location is considerable; as seen in column two, the range often includes sizes that would be highly vulnerable to scour and those that would not. Hence, even though the scour hazard index may be near or less than 1 (indicating significant scour potential), there is typically a substantial portion of the bed where conditions are less vulnerable to scour (i.e., there are patches of coarser sediment). In addition, salmonids are known to prefer to spawn in coarser material, 100 – 130 mm (Bjornn and Reiser 1991). Hence, salmonids are less likely to spawn in sites with grain sizes at the critical scour threshold. Considering the inflection points in the curves in the figure above, it appears that selection of coarser grain sizes for spawning by salmonids significantly reduces the likelihood that redds will be scoured during winter peak flow events.

One potential management effect on likelihood of scour is fining of the streambed in response to increased sediment supply (Dietrich et al. 1989). This assessment indicates that fining of the bed in response to increased sediment supply would tend to increase scour potential and suggests that there may be thresholds of median grain size of streambed sediment that may correlate with scour to a critical depth. The sharp inflection points in several of the curves also suggest inflection points of significance.

6.2.2 Effect of Peak Flow Increases on Probability of Critical Scour

The second means of assessing scour potential involves the effect of increased magnitude and frequency of peak flows. The Hydrologic Change Module has computed predicted peak flow increases. Figure 6-6 shows how increased peak flow affects frequency of the 1.2-, 2- and 5-year recurrence interval flows. These frequencies are summarized in Table 6-6.

The frequency distribution for streambed scour predicted by the Haschenburger equation in the survey reach in lower MS1 including the Salmon Forever gage site is shown in Figure 6-7 for three flow recurrence intervals. Curves are fitted to scour depths taken at intervals of 4 cm following the presentation of data and analyses in Haschenburger (1999). Cumulative frequency of scour greater than 12 cm (a conservative value chosen instead of 16 cm in the distribution to estimate scour of 15 cm) was determined for scour to a depth of 28 cm. These cumulative percentages of the bed scoured to 12 cm or greater are summarized in Table 6-6.

In Table 6-6, the annual frequency of flow events under both baseline and present hydrologic conditions and the cumulative frequency of bed scour greater than or equal to 12 cm are given for the selected flow events. The frequency for the 1.2-year event is expressed in terms of the partial duration flow series. These frequencies are multiplied together to determine the estimated probability of scour to a depth of 12 cm or greater, taking into account both spatial and temporal factors.

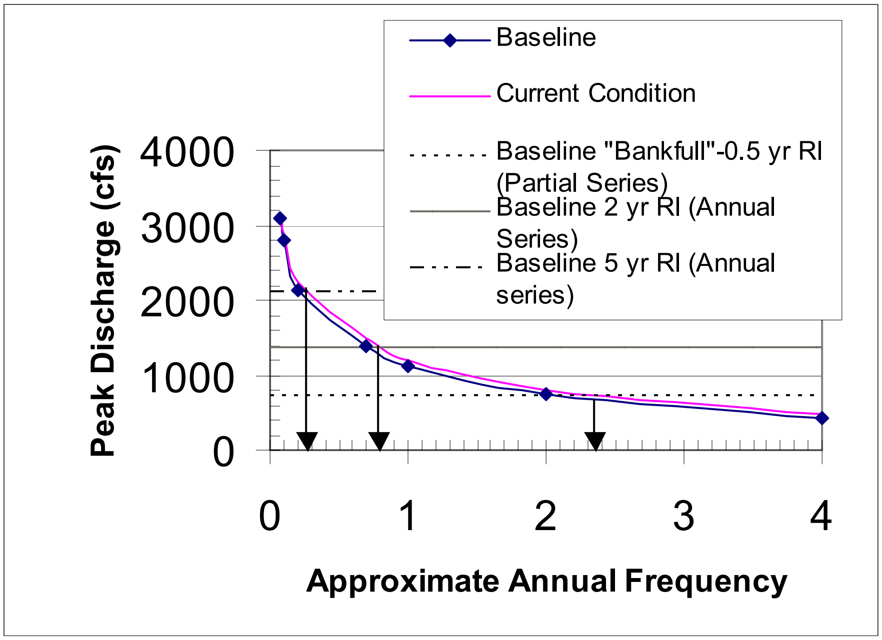


Figure 6-6: Graphical assessment of increased flow frequency caused by increased peak flow.

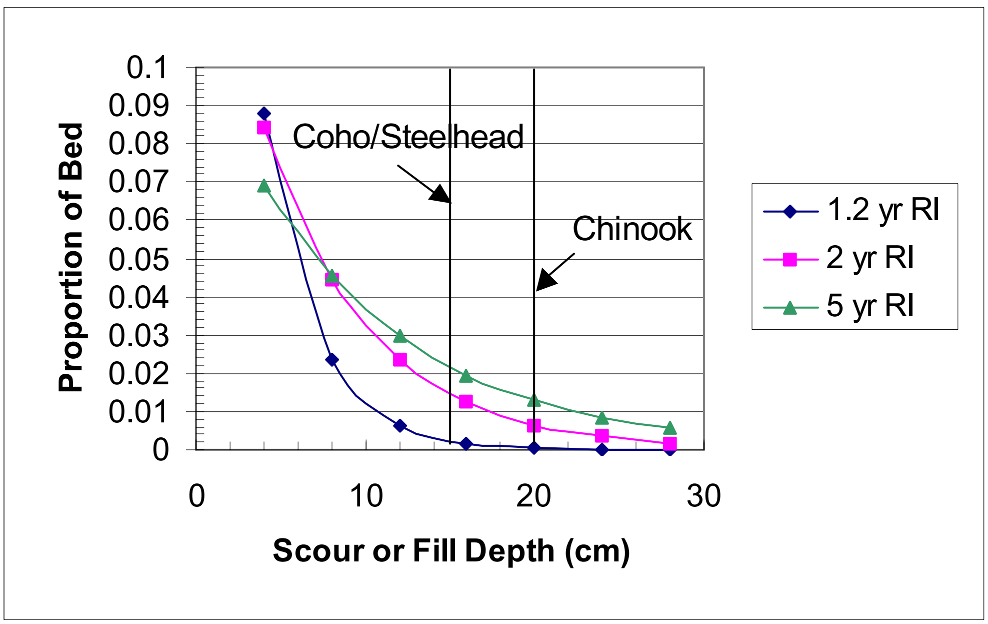


Figure 6-7: Predicted proportion of bed scour or fill in the survey reach containing the Salmon Forever gage site for specified flows under present watershed conditions. The typical depths of egg pockets for different salmonids are also shown.

Table 6-6: Summary of factors used to estimate percentage of bed scoured (or filled) to a depth of at least 12 cm. These calculations pertain to the survey reach containing the Salmon Forever gage site.

Annual RI (yrs)	Approximate Annual Frequency Baseline Hydrologic Conditions	Approximate Annual Frequency Current Hydrologic Conditions	Cumulative Frequency (%) of Bed Scour >12 cm	Percentage of Bed Scoured >12 cm Baseline Hydrologic Conditions	Percentage of Bed Scoured >12 cm Current Hydrologic Conditions
1.2	2	2.35	0.23	0.46	0.54
2	0.5	0.69	2.4	1.7	1.9
5	0.2	0.26	4.9	1.0	1.3

Figure 6-8 displays the probabilities calculated in the last two columns of Table 6-6. This graph suggests that the impact of flow change in this reach is relatively low, and that the greatest potential for scour occurs in the 2-year recurrence interval event. On the basis of these data, it is suggested that the effect of increases in peak flow on scour potential is sufficiently small as to be insignificant.

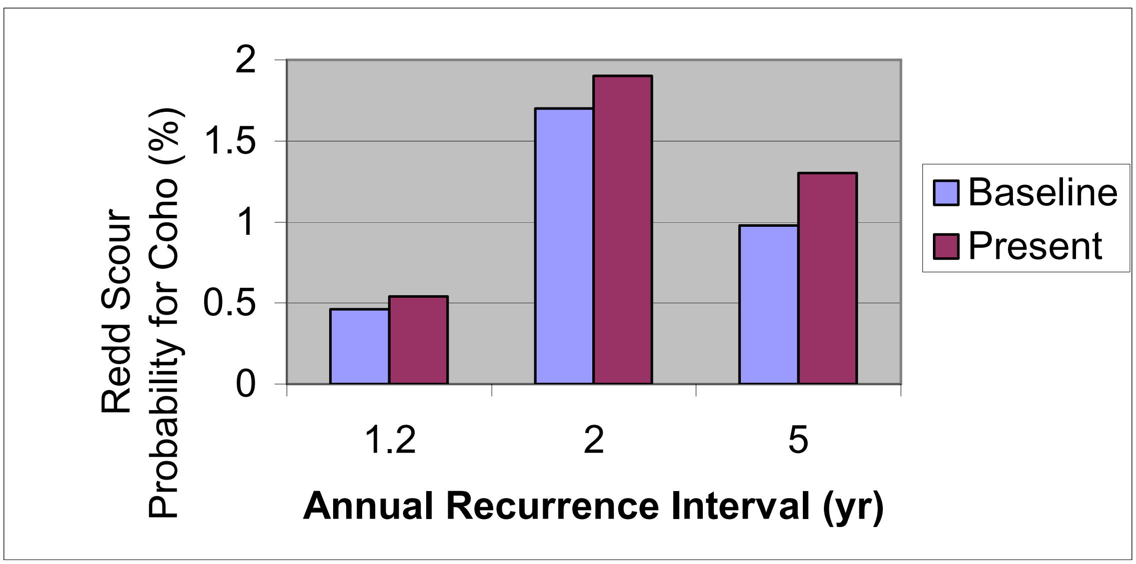


Figure 6-8: Comparison of the probability of critical bed scour under baseline hydrologic conditions and under present managed conditions in the survey reach including the Salmon Forever gage site.

7.0 WOODY DEBRIS & CHANNEL RELATIONSHIPS

LWD size, abundance, and distribution within CGUs is summarized here. Some aspects of LWD function are also analyzed. These include habitat quality with respect to LWD as defined by the NMFS PFC criteria, the role of LWD in pool formation, sediment storage characteristics of LWD, and the role of LWD in bank erosion. In addition, LWD recruitment processes are documented, including observed recruitment distances.

The chief factors relating LWD to habitat features (such as pools, side-channels and other off-channel refugia, and patches of spawning gravel) are addressed in additional detail in the Fisheries Assessment Module and in the discussion of CGU vulnerability in the Cumulative Effects Module.

LWD plays the same role in Freshwater Creek as in any other stream in the region. It is a significant component of aquatic habitat in the generally confined and entrenched channels where there is little off-channel habitat. It contributes to pool formation and overhead cover, which are key components of summer rearing habitat for salmonids. Pools and velocity shelter provided by LWD pieces and jams are key components of winter rearing habitat for salmonids. In large measure, the critical consideration regarding adequacy of LWD with respect to aquatic habitat is LWD abundance. Consequently, much of the following discussion relates to measures of LWD abundance. In addition, the percentage and diameter of LWD associated with pools are discussed.

In portions of the basin underlain by the Wildcat Group, LWD plays a critically important role in sediment sorting, grade control, and provision of habitat complexity. This is due to the general lack of boulder, cobbles, and bedrock outcrops that would normally provide a substantial quantity of channel roughness elements.

7.1 LWD SURVEY METHODS

The distribution and functions of LWD were assessed at three separate scales:

1) Detailed quantitative inventories were conducted at the reach scale as shown (distances of 600 to 1,000 ft, contained within “long profile reaches” in Figure 2-1);
2) Locations of key piece accumulations were mapped at the larger channel scale (distances of 2 to 4 miles in most Class I channels, reaches surveyed for erosion sites as shown in Figure 2-1); and

3) Qualitative assessments of the abundance and function of LWD were recorded during survey sampling for the reach characterization as shown in Figure 2-1. These data were collected in reaches of about 100 to 300 ft, primarily in Class II and III channels.

In addition, sediment storage upstream of LWD jams was surveyed as a component of field measurement of in-channel sediment storage (Section 5). Near-stream erosion attributed to LWD accumulations (i.e., LWD directing flow against banks resulting in bank erosion or small-scale streamside landslides) was quantified in sediment source surveys (Section 3). This latter data set was collected during the same field surveys in which key piece accumulations were mapped. These data are used to assess the role of LWD in erosion and sedimentation processes.

7.1.1 LWD SURVEYS

Detailed LWD surveys were conducted in 23 Class I stream reaches totaling over 17,800 ft (about 3.4 miles) of channel. Seven of these reaches were monitoring sites surveyed by PALCO; PWA surveyed the remaining 16 sites for the Watershed Analysis. These sites are contained within reaches identified as long profile reaches in Figure 2-1.

The LWD inventory method is described in the PALCO Watershed Analysis Methods CD (April 2000 version). This inventory collects information on each piece of wood larger than 0.5 ft in diameter and 6 ft in length. Information is obtained on certain key metrics that have commonly been used to characterize LWD distribution in other areas. The metrics or characteristics observed include the position and orientation of LWD in the channel, whether it is a log or a rootwad, the species of tree if known, the decay class of the LWD, its length and mid point diameter, rootwad dimensions, whether it is associated with a pool, forming a pool, or unrelated to a pool, the mechanism of recruitment to the channel if known, the distance from the bankfull channel from which it was recruited if known, whether it is associated with a debris jam, and whether or not it is judged to be a key piece. Not all of these characteristics have been analyzed here. The subset of data that have been selected to assess LWD abundance and function is discussed in Section 7.2. The level of detail required for these inventories limits the proportion of the channel network that can be covered. Nevertheless, a very large data set containing over 1,400 individual LWD pieces was assembled from a survey sample of perhaps 10% of the Class I channel network.

The minimum diameter of pieces inventoried is 6 inches (15 cm) in most survey plots (those surveyed by Watershed Analysis contractors), and 8 inches (20 cm) in the remainder (those surveyed by PALCO monitoring personnel). Minimum length is 6 ft (2 m) in both surveys. This difference between minimum diameter is considered negligible for purposes of interpretation. Based on comparison to data using minimum diameter of 6 inches, if the minimum diameter used were 8 inches, surveyed LWD volume would be reduced 5% and LWD pieces counted would be reduced by 10%. Hence, for this analysis all pieces counted were included.

7.1.2 Key Piece Accumulations

Key piece accumulations (debris jams) were mapped in the vast majority of the Class I channel network on PALCO ownership during the channel sediment source investigation (described in Section 3.1). These data were not the focal point of the field survey program during which they were collected. Nevertheless, these unique data provide useful perspective on the overall abundance of significant LWD accumulations at the subbasin scale.

7.1.3 LWD Abundance and Function in Class II & III Streams

In intermittent, non-fish-bearing portions of the channel network, LWD was semi-quantitatively surveyed. We collected observations regarding LWD and many other parameters (described in the "Reach Characterization Protocol" of the Methods [PALCO 2000]) in reaches at least 100 ft in length, and generally much longer. LWD abundance was classified in one of three categories: sparse, common, or abundant. This results in an ordinal (i.e., relative) ranking of LWD quantity. Observations were also made with respect to LWD function, which was classified as minimal, normally functional, or dominant. LWD functions include formation of pools, storage of sediment, and flow resistance. The degree of function is often related to abundance, but channel size, LWD size, and LWD position are also considered. Ultimately, the degree of function is a measure of the interaction between LWD and the water column of the stream at bankfull.

7.2 ANALYSIS AND ASSESSMENT OF LWD DATA

As described above, a large and varied data set regarding LWD was collected in Freshwater. The subsets of these data and their analysis and interpretation regarding LWD abundance and function are described below.

7.2.1 Comparison of LWD Data to Regional and PFC Conditions

Quantitative LWD data were analyzed to determine the LWD load (mass or volume of LWD per unit stream channel length) in each sample reach to facilitate comparison to both "old-growth" systems and "second-growth" systems in the region. The quantitative data were also analyzed to facilitate direct comparison of LWD loads in Freshwater CGUs to the NMFS PFC targets for "key pieces" of LWD. PFC targets were developed using a similar survey approach, including comparable or smaller minimum LWD sizes, but were measured in coniferous forest watersheds in western Washington where redwood does not grow.

7.2.2 LWD Recruitment Processes and Distance of Recruited Trees from Streams

Among the data collected during intensive surveys of in-channel LWD was the recruitment process or mechanism and the distance from the channel margin to the source of recruited LWD. These observations can be made for only about 10% of LWD pieces surveyed because most LWD is relatively old, and insufficient evidence remains to infer the origin of the piece. This type of data is the best available means to describe existing LWD recruitment processes. Recruitment processes were categorized as stream undercutting (bank erosion), windthrow, mass wasting, railroad debris, mortality of a standing tree, enhancement structures, no entry (suspended above the channel), and unknown. In cases where the origin of the LWD could be inferred, the shortest slope distance from the origin of the LWD piece to the nearest edge of the bankfull channel was measured or estimated in the field. These data are summarized to document LWD recruitment processes in Freshwater.

7.2.3 LWD and Pools

The association between LWD and pools was noted during quantitative field surveys. Pools were classified as either shallow (<3 ft residual depth) or deep (>3 ft residual depth); only pools with LWD were inventoried in this survey. Complete pool inventory data are presented in the Fisheries Assessment Module. LWD in contact with these pools was classified as either forming the pool or merely associated with the pool. Cases where LWD was judged to form pools were determined on the basis of LWD size and position in relation to pool size and position. The percentage of LWD and the size (diameter and volume) of LWD that forms pools is documented. These data can be used to infer the degree to which LWD recruitment under existing conditions is capable of maintaining pool-forming function.

7.2.4 LWD Function in Class II & III Streams

The semi-quantitative (ordinal) data regarding LWD abundance and function in these stream types (as well as all other CGUs) are summarized. Interpretation of these data focuses on the CGUs that represent the Class II and III channel network.

7.3 LWD ABUNDANCE SURVEY RESULTS

LWD load in the Class I channel network (fish-bearing streams) has been extensively documented in Freshwater Creek. Data include intensive volumetric LWD surveys at sample plots ranging from about 200 to over 1,000 ft, and extensively mapped key LWD accumulations (jams) throughout the entire Class I channel network. These data are summarized below.

7.3.1 LWD Volume – Regional LWD Volumes

A frequency distribution of LWD volume per sample plot has been established using previous quantitative LWD surveys of streams draining redwood-dominated watersheds in northern California (Figure 7-1). These data allow comparison of LWD load in Freshwater Creek to that observed elsewhere in the region. For a given site, the volume of LWD can be compared to the regional curves in Figure 7-1 to determine the percentile rank of the site. For example, a site containing 200 cubic meters of LWD per km of channel length would rank at the 14th percentile of old-growth sites and at the 45th percentile of second-growth sites. Table 7-1 summarizes volumes for percentiles of the distribution that may be of interest.

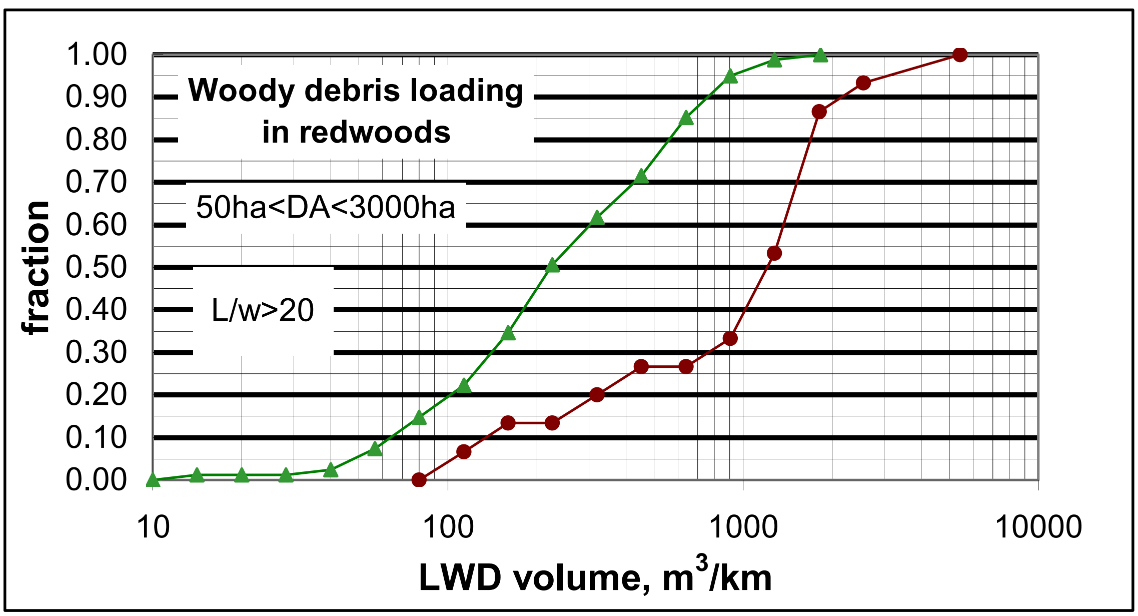


Figure 7-1: Cumulative frequency ("fraction" expressed as decimal quotient) distributions of LWD volume per sample site for old-growth (circles) and second-growth redwood forests (triangles) in northern California. The length of sample sites was greater than or equal to 20 bankfull channel widths; drainage area ranges from 50 to 3,000 ha (130 ac to 7,770 ac). The data for old-growth include sites in Redwood National Park (Harmon et al. 1986, n=11), and sites identified in PALCO's SYP-HCP documents (n=4). The data for second-growth are from Knopp (1993), Caspar Creek, the Garcia River, and the PALCO SYP-HCP, a total of 80 sites.

Table 7-1: Selected percentiles of LWD volume per km stream channel (from Figure 7-1).

Percentile of Distribution	Second-Growth Plots	Old-Growth Plots
15	80	240
50	220	1200
85	630	1800

LWD volumes at survey plots in Freshwater Creek are shown graphically in Figure 7-2. Of the 23 survey plots, 7 (30%) have LWD volumes greater than or equal to the 85th percentile of second-growth plots in the region, and 16 (70%) have LWD volumes greater than or equal to the 50th percentile of second-growth plots. Of the 7 plots with less than the 50th percentile of second-growth LWD, 5 are located in lower Freshwater Creek Watershed outside of PALCO's ownership. Of the 18 plots on PALCO lands, 16 (89%) had LWD volumes greater than the median (50th percentile) for second-growth plots in the region. Of the 18 plots on PALCO lands, two (11%) have LWD volumes greater than the median value for old-growth streams in the region.

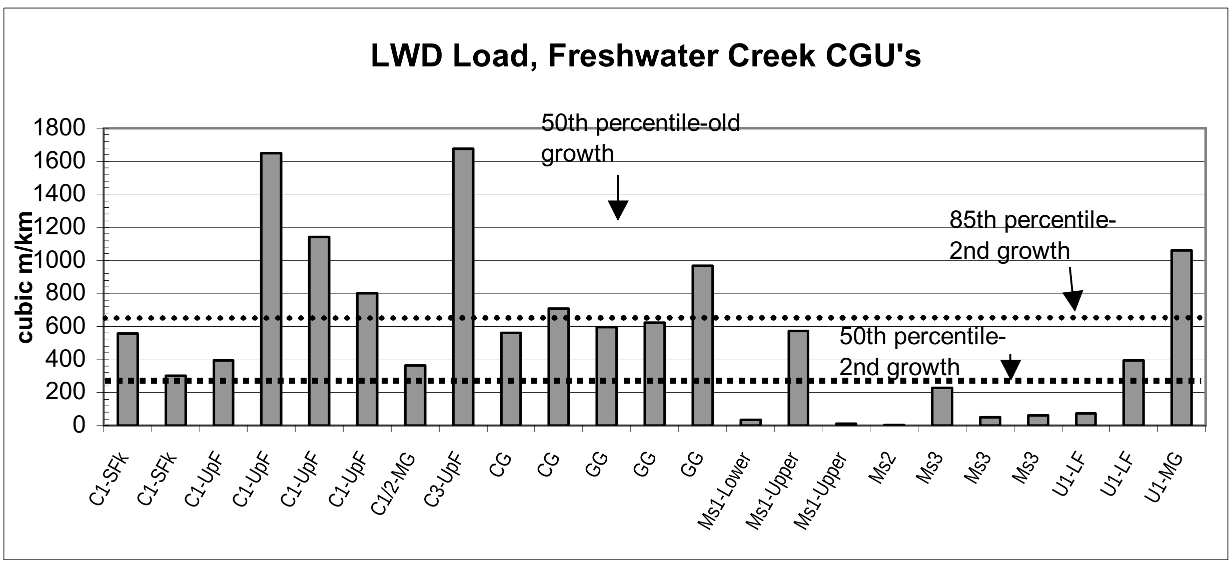


Figure 7-2: LWD volumes measured at Freshwater Creek sample plots. Each bar represents a single sample plot in a specified CGU. MS1-Lower, MS2 and MS3 sites (n=5) are plots outside of PALCO's ownership. The values of other specified percentiles are give in Table 7-1; the 50th percentile for old-growth plots in 1,200 cubic meters per kilometer.

7.3.2 LWD Abundance – NMFS Properly Functioning Conditions

Data from the intensive LWD surveys are also evaluated with respect to the LWD target conditions established in NMFS guidance regarding Properly Functioning Conditions. Note that the channel widths used are those observed at the LWD plot locations and may not in all cases be equal to the overall mean width for each CGU.

The NMFS PFC metric agreed with the SRT is LWD key piece abundance. NMFS criteria for key piece size are defined in the PFC matrix (after Fox). The intensive LWD survey data were used to compare the observed key piece abundance in Freshwater, defined according to NMFS criteria (i.e., minimum diameter as a function of channel width), to the NMFS target abundance (Table 7-2).

Table 7-2: LWD key piece abundance defined by NMFS PFC criteria in sample plots for each CGU. Underlined values in column 5 (observed pieces per 100 ft of channel length) indicate CGUs where the observed abundance is less than the target abundance. Observed key piece volumes are the average of field observations of piece volume for pieces of diameter greater than or equal to PFC key piece diameter. Volume of key pieces both inside and outside the bankfull channel are presented to document that the volume of LWD key pieces in Freshwater are generally greater than the minimum volume under the PFC criteria. Key piece volumes both within and outside the bankfull channel width are presented; relatively small increments of LWD key piece volume are found outside the bankfull channel. * indicates data collected by Fisheries Assessment Module field personnel.

CGU	Plot Average Channel Width (ft)	PFC Key Piece Diameter-Fox (in)	PFC Target (Pieces per 100 ft-Fox)	Observed Key Pieces per 100 ft	PFC Key Piece Average Volume (ft^3)	Observed Key Piece Volume (ft^3 -<u>includes</u> length outside bankfull channel)	Observed Key Piece Volume (ft^3-<u>excludes</u> length outside bankfull channel)
CG	24	22	2-2.5	3.3	88	170	137
GG	31	25	1.4-1.7	5.5	212	166	164
U1	19	16	2.5-3.3	4.1	35	102	92
U2*	11	<16	<3.3	10	<35	148	n.a.
C1	38	25	1.2-1.4	2.3	212	202	190
C2	20	22	2.5	3.6	88	62	62
C3	24	22	2-2.5	8.5	88	212	169
Ms1	28	22	1.7-2.0	<u>0.5</u>	88	314	309
Ms2	45	25	1.1	<u>0.0</u>	212	n.a.	n.a.
Ms3	38	25	1.2-1.4	<u>0.3</u>	212	437	428

There is additional evidence that significant LWD accumulations that function similarly to key pieces are abundant in Freshwater Creek. All LWD accumulations that store sediment or appeared to have significant effects (flow deflection, pool scour, etc.) were mapped throughout the Class I channel network during the sediment source investigation (Section 3.1). Table 7-3 summarizes a data set collected by PWA during its investigation of near-stream sediment sources. The chief CGUs found in each sub-watershed are also listed in Table 7-3. If LWD accumulations are considered equivalent to key pieces, these data also indicate that the abundance of LWD accumulations substantially exceed NMFS PFC target values for key pieces.

Table 7-3. Summary of abundance of key LWD accumulations mapped by PWA during the near-stream sediment source investigation. The data are from surveys of about 17 miles of the Class I channel network on PALCO ownership in Freshwater Creek. PFC targets for key LWD range from 1.1 to 3.3 pieces per 100 ft in Freshwater (Table 7-2); key LWD accumulations per 100 ft exceed this range except in CGU MS1.

Subbasin	CGUs	Key LWD Accumulations per 100 ft
Upper Freshwater	C1&C2	5.2
South Fork	C1&C2	15.1
Graham Gulch	GG	6.2
Cloney Gulch	CG	4.3
Falls Gulch	C1	17.4
McCready Gulch	U1&C1	4.9
Little Freshwater	U1&C1	8.9
Mainstem Below South Fork	MS1	1.6

7.4 LWD RECRUITMENT MECHANISMS AND SOURCE DISTANCES

The dominant recruitment processes for LWD under existing conditions appear to be undercutting (bank erosion) and windthrow (Table 7-4). Together, these processes account for 20% of the pieces observed, and 65% of the pieces for which a recruitment process could be inferred from field evidence. Murphy and Koski (1989) found in Southeast Alaska that these two sources accounted for over 80% of LWD recruitment for those pieces for which a recruitment process could be inferred. The next largest source in Freshwater was mass wasting (about 3%). Enhancement structures are another relatively large category; however, this “source” category is ambiguous with respect to LWD recruitment. While some of this LWD may have been imported to the channel from adjacent banks or hillslopes, these structures typically include significant quantities of LWD that was already in the channel.

Table 7-4: Summary of LWD recruitment mechanisms for Freshwater Creek Watershed.

Input Mechanism	# of Pieces	Percent of Total
Undercutting	104	7.2%
Windthrow	179	12.4%
Mass Wasting	48	3.3%
Railroad	10	0.7%
Mortality	5	0.3%
Structure	77	5.4%
No Entry	10	0.7%
Unknown	1005	69.9%
TOTAL	1438	100.0%

The distance in the riparian zone from which LWD has been recruited is summarized in Figure 7-3. The cumulative percentage of the number of LWD pieces as a function of distance from the edge of the bankfull channel is shown. The average volume of LWD pieces for which a source distance could be determined is somewhat larger than the average volume of all LWD pieces. Hence, if the plot were constructed to show cumulative volume of recruited LWD for which source distances could be determined, the result would show slightly greater percentages for a given distance. As seen in Figure 7-3, over 80% of recent LWD recruitment originated from within 30 ft of the channel. Nearly 100% is recruited from within 60 ft of the channel. The maximum distance from which LWD was recruited was 100 ft. These findings are generally consistent with previous studies in the Pacific Northwest (McDade et al. 1990).

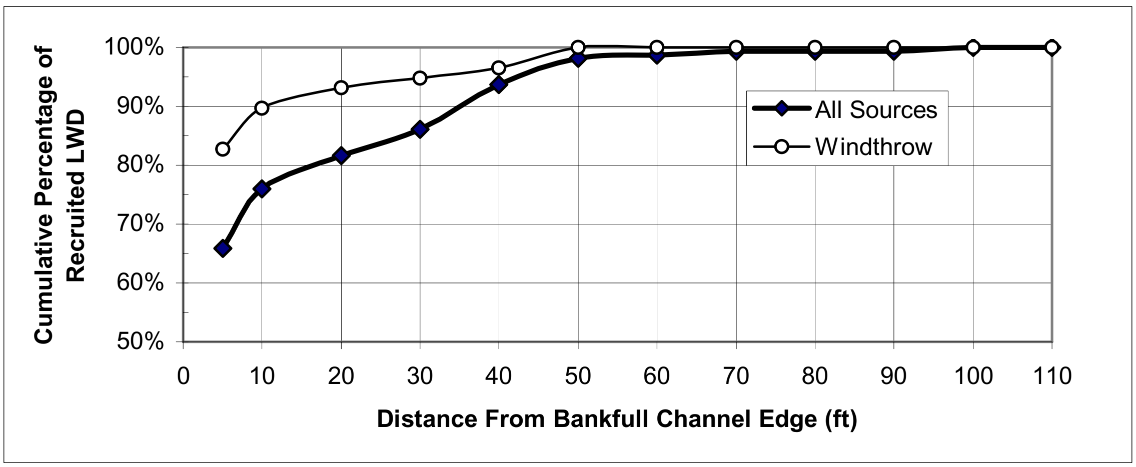


Figure 7-3: Cumulative percentage of LWD pieces recruited as a function of distance from the channel edge. Of the 1,438 LWD pieces surveyed, 158 pieces (11%) could be traced to an origin point from which a recruitment distance could be measured; these are the data shown above. In addition, the source distance curve for LWD recruitment by windthrow is shown.

The LWD pieces for which source distances could be determined were on average somewhat smaller in diameter (about 1.35 ft) than the average for the sample population of LWD (about 1.5 ft). This probably reflects the influence of large diameter old-growth LWD in the sample population, as well as the size of primarily second-growth trees in the riparian zone. The average diameter of LWD for which recruitment distance was observed (about 16 inches) is less than the typical minimum key piece diameter (about 22 inches, Table 7-2); however, about 16% of this LWD is >22 inches diameter. Data regarding the composition of existing riparian stands are provided in the Riparian Function Module. Recruited LWD diameter data may not be entirely consistent with the stocking of riparian stands with trees of different diameter classes. That is, the diameter distribution of recruited LWD may be different than the diameter distribution of riparian stands.

7.5 CHARACTERISTICS OF LWD ASSOCIATED WITH POOLS

Data regarding LWD and pools are evaluated in two ways. First, the total sample population of LWD is considered in relation to pools. The size classes of LWD diameter in each CGU are then compared to size classes of LWD forming pools in each CGU.

7.5.1 LWD Sample Population

Of a total of 1,438 pieces of LWD inventoried, only 4 were forming deep pools and 10 were associated with deep pools. In contrast, 102 and 275 pieces of LWD were forming or associated with shallow pools, respectively. Most of the Class I channel network has relatively entrenched channels with bedrock exposed locally in banks and pool bottoms. The low proportion of deep pools is believed to result from limits imposed by the depth of alluvial channel deposits above bedrock, which rarely exceed 3 ft (see Figure 5-4). Depth of alluvium may thus play a role in determining whether NMFS PFC targets for pool depth are attainable in some streams. In CGU MS3, bedrock exposures are not frequently observed, and there may be greater potential for deeper pools.

Mean diameter of all LWD and pool-associated LWD were essentially identical (Table 7-5). In contrast, the mean diameter of pool-forming LWD was about 1 ft greater (60 to 70%) than the overall mean diameter. This suggests that larger LWD is more likely to form pools, as generally expected. The mean diameter of pool-forming LWD in Freshwater was about 2.5 ft.

Table 7-5: Percentage and mean diameter of LWD associated with pools. The mean diameter of all 1,438 LWD pieces inventoried was 1.53 ft; in the last column, the ratio is formed by dividing the mean diameter in the fourth column by 1.53 ft.

LWD Function	Number of Pieces	% of Total	Mean Diameter (ft)	Ratio of Diameter to Mean Diameter for All LWD
Forming Deep	4	0.3%	2.58	1.7
Associated Deep	10	0.7%	1.68	1.1
Forming Shallow	98	6.8%	2.47	1.6
Associated Shallow	265	18.4%	1.58	1.0

The mean diameter of LWD in old-growth redwood forest streams might be expected to be larger than that found in Freshwater. To assess the extent to which LWD diameter affects formation of pools, we plotted the cumulative frequency of pool-forming LWD by 1 ft-diameter classes (Figure 7-4).

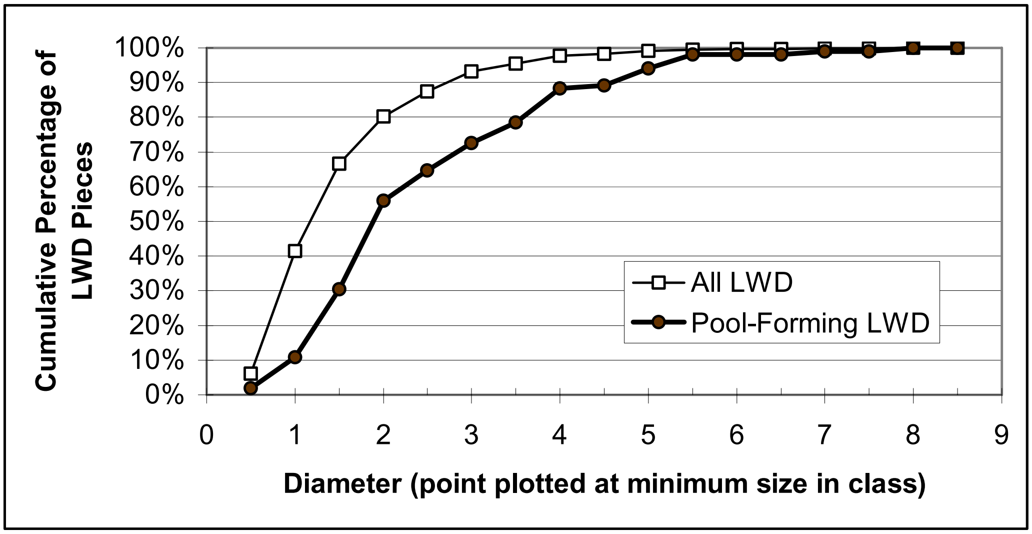


Figure 7-4: Cumulative frequency distribution of LWD and pool-forming LWD by diameter class for Freshwater.

Figure 7-4 shows progressively smaller percentages of pool-forming LWD in larger diameter classes. This reflects the overall distribution of diameter classes in the LWD population in Freshwater. It also demonstrates that over 70% of pool-forming LWD is <3 ft in diameter and that a wide range of LWD diameters are present in Freshwater. Despite the evident effectiveness of LWD <3 ft diameter at forming pools, it is also evident that larger diameter LWD is even more effective. Table 7-6 shows that LWD >3 ft diameter comprises only about 7% of the LWD pieces; however, over 27% of pool-forming LWD are >3 ft diameter. Hence, larger-diameter LWD is more likely to form pools than smaller-diameter LWD, all other factors being equal.

7.5.2 LWD Characteristics and Pool Association in CGUs

LWD survey data were stratified according to CGU to investigate patterns in LWD distribution and function. Table 7-7 summarizes the survey data distribution among CGUs, focusing on LWD diameters. These data indicate that mean LWD diameter (<1 ft) and the proportion of LWD pieces >40 inches diameter (<2%) are both substantially lower in CGUs MS2 and MS3 (see also Table 7-2) than in other CGUs.

Table 7-6: Diameter class distributions for all LWD, pool-forming LWD and pool-associated LWD in Freshwater. N for data set is 1,438 LWD pieces. Percentages are rounded to the nearest 0.1%; only the percentages in column 3 should add to 100%. At a diameter threshold of about 2 ft, LWD is proportionately more likely to form pools. For example, for LWD 1.5 – 2 ft diameter, about 6% of pieces form pools; for LWD 2 – 2.5 ft diameter, about 13% of pieces form pools. Over two-thirds of LWD formed pools are caused by LWD >2 ft diameter. These data are representative of Class I stream only.

Diameter Class (ft)	# of LWD Pieces in Class	% of LWD in Class	# of Pool-forming LWD Pieces in Class	% in Class that is Pool-forming LWD	# of Pool-associated LWD Pieces in Class	% in Class that is Pool-associated LWD
0.5 – 1	87	6.1	2	2.3	12	13.8
1 – 1.5	510	35.5	9	1.8	90	17.6
1.5 – 2	360	25.0	20	5.6	67	18.6
2 – 2.5	197	13.7	26	13.2	43	21.8
2.5 – 3	104	7.2	9	8.7	27	26.0
3 – 3.5	81	5.6	8	9.9	19	23.5
3.5 – 4	34	2.4	6	17.6	6	17.6
4 – 4.5	32	2.2	10	31.3	7	21.9
4.5 – 5	7	0.5	1	14.3	1	14.3
5 – 5.5	13	0.9	5	38.5	3	23.1
5.5 – 6	5	0.4	4	80.0	0	0.0
6 – 6.5	3	0.2	0	0.0	0	0.0
6.5 – 7	0	0	0	n.a.	0	n.a.
7 – 7.5	2	0.1	1	50.0	0	0.0
7.5 – 8	1	0.1	0	0.0	0	0.0
8 – 8.5	1	0.1	1	100.0	0	0.0
>8.5	1	0.1	0	0.0	0	0.0

The function of LWD in pools in each CGU is summarized in Table 7-7. With respect to the influence of LWD diameter on pool formation, these data are consistent with data presented in

Table 7-7: Summary of selected LWD survey data. The >40 inch diameter class (3.33 ft) is presented for comparison with the largest riparian forest diameter class presented in the Riparian Function Module.

CGU	# Reaches	Length Surveyed (ft)	# Pieces	Mean Diameter (ft)	Std. Dev. (ft)	Maximum Diameter (ft)	# >40 inches Diameter	% >40 inches Diameter
CG	2	1115	132	1.65	1.02	5.5	11	8%
GG	3	731	170	1.70	0.86	4.7	10	6%
U1	3	2503	178	1.90	1.17	6.0	10	6%
C1	6	4517	554	1.55	0.98	8.0	29	5%
C2	1	700	102	1.40	0.78	4.2	4	4%
C3	1	200	36	1.89	1.00	4.5	4	11%
Ms1	3	2800	107	1.29	1.15	7.2	5	5%
Ms2	1	1000	3	0.92	0.50	1.5	0	0%
Ms3	3	3550	156	0.95	0.90	9.6	3	2%
MEAN				**1.47**				**5%**

Tables 7-5 and 7-6 pertaining to LWD diameter and pool formation irrespective of CGU. On average, LWD diameters of pool-forming LWD are 40% greater than the mean LWD diameter. Moreover, the diameter of LWD that is merely in contact with pools (i.e., pool associated) is equivalent to the overall mean LWD diameter.

The data in Table 7-8 suggest that LWD function with respect to pools in steeper channels is different than in lower-gradient channels. CGUs C2 and C3 have slopes of 3-6.5% and 6.5% to 20%, respectively. All other CGUs have slopes <3%. As shown in Tables 7-2, LWD key piece abundance in CGUs C2 and C3 (>3% slope) and CGUs CG, GG, U1, and C1 (<3% slope) generally meet NMFS PFC targets. As shown in Table 7-8, a much lower proportion of LWD formed pools in the steeper CGUs. Excluding the CGUs that generally do not meet NMFS PFC targets (MS1, MS2, and MS3), an average of about 11% of LWD in CGUs with slope <3% form pools. In C2 and C3, an average of 3% of LWD forms pools. This suggests that LWD has less effect on pool formation in steeper channels, consistent with other studies (e.g., Montgomery et al. 1995). In the MS CGUs, where LWD is generally below target levels, an average of <2% of LWD forms pools. It is hypothesized that if both larger and more abundant LWD were present in the MS CGUs, a higher percentage of LWD would form pools. In each of the three groups of CGUs discussed above, the average percentage of pool-associated LWD was quite consistent at about 20%.

Table 7-8: Summary of LWD influence on pools stratified by CGU.

	Pool Forming LWD			Pool Associated LWD				Diameter Ratio	
CGU	**# pieces**	**% of Total**	**Mean Diameter (ft)**	**# pieces**	**% of Total**	**Mean Diameter (ft)**	**Total % Forming + Associated**	**Pool Forming to Mean**	**Pool Assoc. to Mean**
CG	13	10%	2.68	30	23%	1.70	33%	1.6	1.0
GG	22	13%	2.00	35	21%	1.64	34%	1.2	1.0
U1	22	12%	2.65	51	29%	1.91	41%	1.4	1.0
C1	38	7%	2.62	63	11%	1.66	18%	1.7	1.1
C2	0	0%	--	35	34%	1.53	34%	--	1.1
C3	2	6%	2.10	4	11%	2.48	17%	1.1	1.3
MS1	4	4%	2.60	23	21%	1.34	25%	2.0	1.0
MS2	0	0%	--	2	67%	0.63	67%	--	0.7
MS3	1	1%	0.60	32	21%	0.93	21%	0.6	1.0
MEAN		**6%**	**2.18**		**26%**	**1.54**	**32%**	**1.4**	**1.0**

Finally, the data in Table 7-8 indicate that on average about 30% of LWD is either pool-forming or pool-associated. This is consistent with a prior study of LWD ecology at North Fork Caspar Creek prior to logging of second-growth redwood stands (O'Connor and Ziemer 1989). In that study, about 30% of the LWD surveyed within the bankfull channel was also found to be either forming of associated with pools. This indicates that data regarding LWD function in relation to pools in Freshwater are comparable to other studies in the region.

7.6 LWD FUNCTION IN CLASS II & III STREAMS

Qualitative and semi-quantitative observational data on LWD abundance and function were collected in Class II and III streams using the Reach Characterization Protocol (Stream Channel Module Appendix A, PALCO 2000) and during the supplemental investigation of small stream channels. Data regarding LWD abundance are summarized in Figure 7-5 using an ordinal scale. Data regarding LWD function on an ordinal scale are summarized in Figure 7-6.

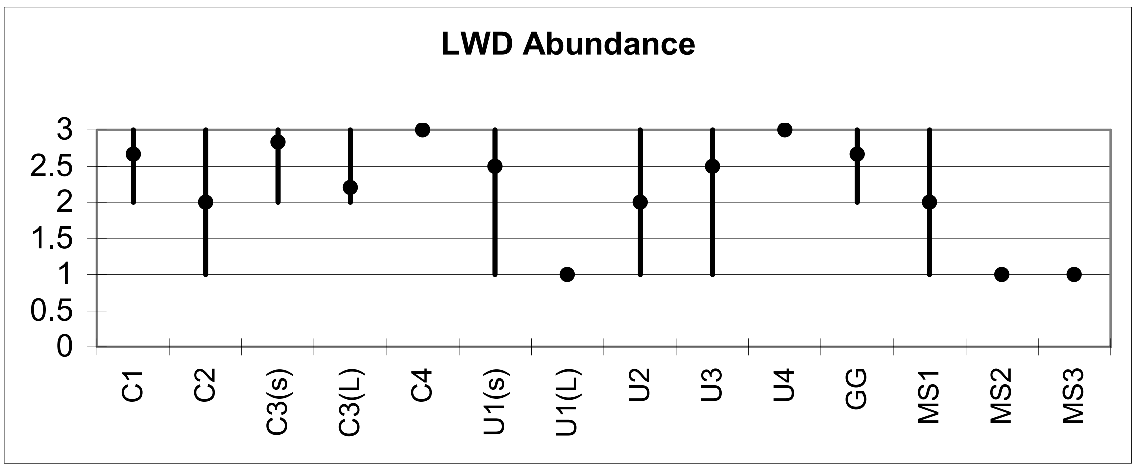


Figure 7-5: LWD abundance in each CGU ranked on an ordinal scale. Descriptors for ordinal values are 0 = "none", 1 = "sparse", 2 = "common", 3 = "abundant". The dot represents the mean value from the data while the bar represents the range of data.

The data indicated that the mean value for LWD abundance is common to abundant in Class II and III streams (CGUs C2, C3, C4, U1(s), U2, U3, and U4). In some sample reaches in C2, U1(s), U2, and U3, LWD abundance was classified as sparse. A similar pattern was observed with respect to LWD function. In these CGUs, the mean of the observations was at least functional, except in U4. In U4, LWD function was minimal. This case is further described in the "small streams investigation" (Section 3.2). In summary, these data illustrate that LWD status in Class II and III channels might be characterized as fair to good in most locations. Function in U4 is believed to be limited by the large size of LWD to the small size of the channel.

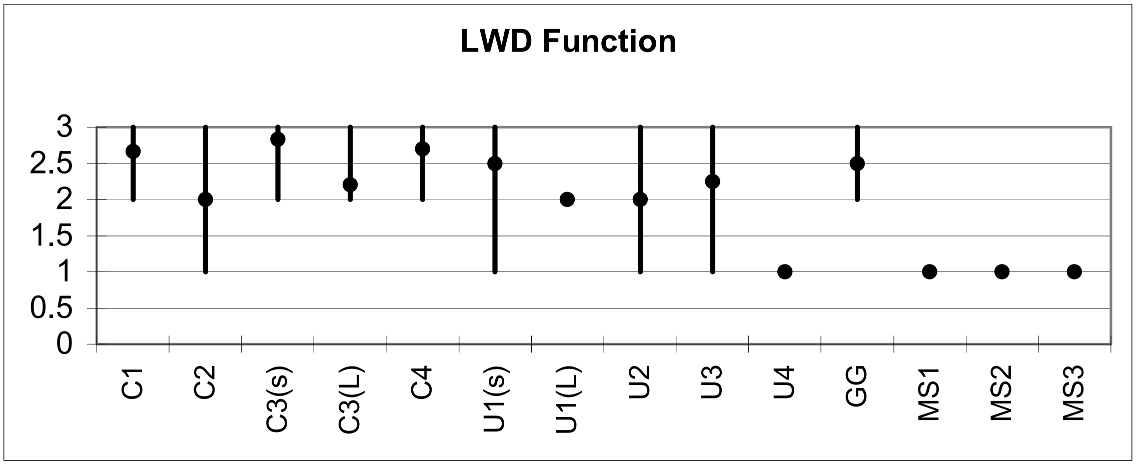


Figure 7-6: LWD function in each CGU ranked on an ordinal scale. Descriptors for ordinal values are 0 = "none", 1 = "minimal", 2 = "normal", 3 = "dominant". The dot represents the mean value from the data while the bar represents the range of data.

7.7 LWD INFLUENCES ON EROSION AND SEDIMENTATION PROCESSES

Insights regarding the influence of LWD on erosion and sedimentation processes are discussed in this section. These influences include development of side channels, sediment storage, and near-stream erosion. These discussions draw on observations and data derived from other elements of the Stream Channel Assessment not focused directly on LWD.

7.7.1 Influence of LWD on Development of Floodplain Side Channels

Channel entrenchment and LWD conditions in most CGUs do not permit development of channel avulsions – that is, locations where the channel becomes congested with LWD and/or sediment and forces the stream to cut a new channel in the floodplain. There is, however, one recent example of this phenomenon, in the MS3 reach between the confluences of Little Freshwater and McCready Gulch. In 1997, a large LWD jam formed in this reach, and flow was forced onto the floodplain on the right (north) bank. Water flowing off the floodplain formed a significant gully in a pasture that was subsequently filled. The LWD jam was also breached and much of the LWD removed in a stream improvement project approved by California Department of Fish & Game. These floodplain management activities suppressed what is probably a natural floodplain process that, left unmanaged, would form significant side channel habitat that is currently extremely limited in Freshwater. In addition, bedload sediment formerly stored upstream of the LWD jam has been remobilized and will be more quickly transported to the vicinity of the Howard Heights Bridge, less than 0.5 mile downstream.

Although conditions in lower Freshwater (MS2 and MS3) prior to European settlement are not well known, it is reasonable to assume that there would have been a more extensive riparian forest with large diameter trees. This contrasts strongly with the current condition, where a narrow riparian gallery forest comprised of willow and alder is present in most locations. These current conditions also represent an improvement in riparian forest conditions relative to the earliest aerial photos available for the area, which showed pastures extending to the edge of the channel in many locations, and generally smaller and less continuous stands of woody riparian vegetation. Prior to the conversion of lower Freshwater to agricultural uses in the late 19th century, it is possible, if not likely, that the Freshwater floodplain would have been traversed by side channels of various age and depth. None are present under current conditions, and the channel pattern has been remarkable stable during since 1942 (see Critical Question 2.3).

7.7.2 In-channel LWD and Sediment Storage

The distribution of LWD accumulation sites in the anadromous reaches of Freshwater Creek is summarized in Table 7-3. LWD accumulations influence sediment storage and routing at scales proportional to the size of the accumulations (i.e., larger jams result in more sediment storage). Large LWD jams exist in each of the major subbasins of Freshwater Creek, but decrease dramatically in the mainstem reaches (CGUs MS1, MS2, and MS3) of Freshwater Creek.

LWD accumulation dynamics vary across the different subbasins of Freshwater Creek, according to the underlying geology. In the channels underlain by the Wildcat Group, LWD provides the only structural resistance to channel incision and, thus, is critical in the formation of complex aquatic habitats and in providing some grade control. In these channels, boulders and other hard roughness elements are practically non-existent due to the sandy nature of most of the Wildcat Group.

In the anadromous channel reaches underlain by the Franciscan Formation, large boulders in the channel often collect LWD, resulting in formation of debris jams and sediment storage reservoirs. The largest streamside landslides (including both debris landslides and deep-seated landslides) occur in the channels underlain by the Franciscan formation. Near-stream erosion features are a source of LWD to channels, and some large debris jams are found directly downstream of the landslide sites.

Sediment storage surveys were conducted in selected reaches of the Class I stream channel network; see Section 5.1.3.1 for a discussions of these results. In addition to estimating the volume of stored sediment in the stream channels, these surveys apportion active channel sediment deposits to log jams, bars, and bed storage. Table 7-9 summarizes these data in terms of percentage of total storage contributed by each type of storage site.

Table 7-9: Sediment storage data summarized as percentage of total storage in each reach.

CGU	Reach	Bed	Bars	Jams
C1	UFW	72%	23%	5%
C1	MUFW	55%	31%	14%
C1	S. Fork	39%	13%	48%
GG	Graham	44%	35%	29%
U1	Little Fresh.	87%	13%	28%
C1/2	McCready	31%	28%	41%
MS1	MSBSF	78%	22%	0%
MS1	Roelof's	93%	7%	0%
MS2	Langlois	96%	4%	0%
MS3	Harper's	76%	24%	0%
MS3	Hippen's	73%	9%	18%
MEAN		**68%**	**19%**	**17%**

The influence of LWD abundance on sediment storage by LWD jams can be assessed by comparing percentages of storage in jams shown in Table 7-9 with NMFS PFC key piece targets summarized in Table 7-3. Key piece targets are met in CGUs CG, GG, U1, C1, C2, and C3; they are not met in MS1, MS2, and MS3. In the former group, the percentage of sediment stored by LWD jams averages about 28% and ranges from 5 to 48%. In the latter group, where there are few key LWD pieces, the percentage of sediment stored by LWD jams averages about 4%. Of these five sites, only one had sediment stored in LWD jams. To the extent that LWD functions to store sediment, it appears that this function is substantial in reaches with relatively high abundance of key pieces (see also Table 7-3). Where key LWD abundance is low, the sediment storage function is quite limited.

LWD function in Class II and III channels was assessed in Section 7.6, using a different type of data. These data indicated that LWD abundance and function, including but not limited to sediment storage, were typically significant (Figures 7-5 and 7-6). Sediment storage in this portion of the stream channel network was not quantified as it was in the Class I channel network. However, the abundance of sediment storage sites (referred to as "bars") in these channels was observed in the field and ranked on an ordinal scale (sparse, common, or abundant). These data for all CGUs are summarized in Figure 7-7 and suggest that under present conditions, sediment storage declines as streams become smaller and steeper, regardless of LWD abundance and function. Thus, the role of LWD in sediment storage generally decreases as one moves from larger Class II channels to smaller Class II and to Class III channels. In all CGUs representing Class II and III channels, except CGU U4, the average LWD function was considered medium to high. The minimal degree of function observed in CGU U4 is attributed to the history of channel incision in these watersheds primarily following first harvest and the tendency for LWD presently in these channels to be too large to function in very small channels. This is discussed further in the small streams investigation (Section 6.1.2).

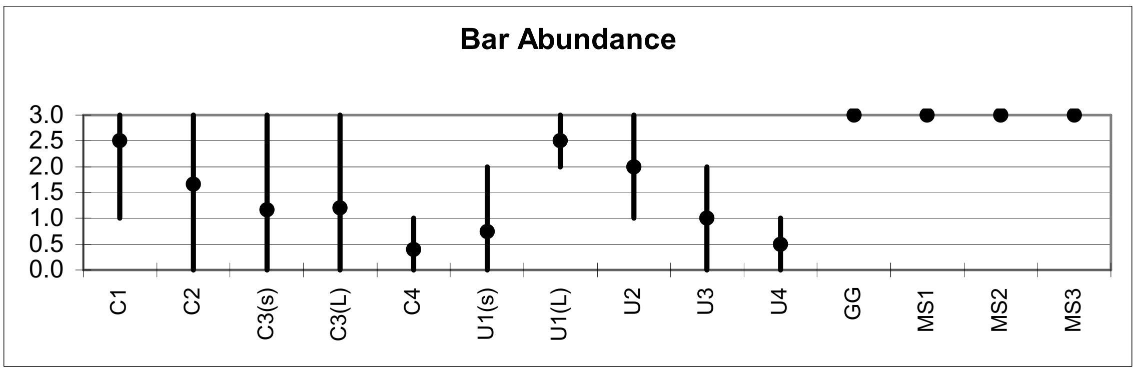


Figure 7-7: Ordinal rank values of gravel bar abundance for each CGU. High abundance = 3, sparse abundance = 1. The dot indicates the mean value; the bar indicates the range of observed values.

7.7.3 Influence of LWD on Bank Erosion and Streamside Landsliding

In addition to storing sediment in channels, LWD is an agent of erosion. As LWD enters streams, or moves in streams to relatively stable positions, the LWD may direct streamflow against banks that results in erosion. The investigation of near-stream sediment sources in the Class I channel network revealed that the most commonly identified agent of erosion was LWD. About 36% of erosion sites were attributed to LWD; the next largest category was erosion in stream bends, which account for about 23% of sites.

The influence of LWD on near stream erosion processes is also expressed by a correlation between the frequency of LWD accumulations and the sediment input rate from near stream sources per unit channel length. Figure 7-8 shows a plot of sediment inputs as a function of LWD frequency. The data plot has considerable scatter but suggests that higher LWD loads tend to induce greater quantities of sediment from bank erosion and streamside landslide processes. Graham Gulch is excluded from this plot as an outlier with high sediment inputs and moderate LWD. The physical rationale for treating Graham Gulch as an outlier is the overwhelming influence of inputs of sediment and LWD from the deep-seated landslide which was reactivated in 1997.

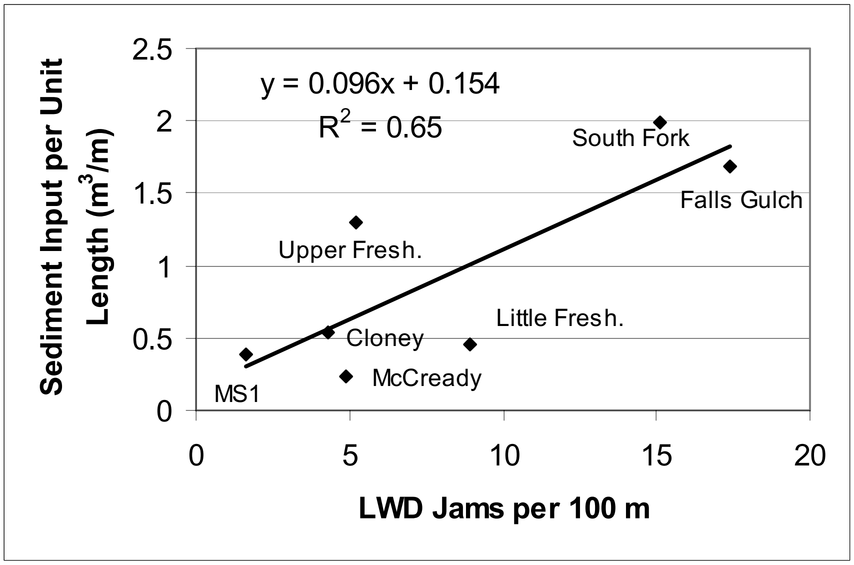


Figure 7-8: Near-stream sediment inputs as a function of LWD jam frequency. The LWD data are from Table 7-3. Sediment data are from the near-stream sediment source inventory.

7.8 CONCLUSIONS ON LWD FUNCTION IN FRESHWATER WATERSHED

With the exception of the largest channels in the watershed, LWD abundance in terms of volume per unit stream length in Class I channels is relatively high when compared to regional values for second-growth redwood forests. Two reaches have LWD volumes comparable to the median for old-growth redwood forest streams. LWD abundance and volume in CGUs MS1, MS2, and MS3 are significantly lower than elsewhere in the watershed. The MS2 and MS3 streams are located in lower Freshwater, outside of PALCO's ownership. Relative to NMFS PFC targets for LWD size and abundance, most CGUs meet the targets. Significant departures from these targets are consistently evident in CGUs MS1, MS2, and MS3. CGU U1-L does not meet the target for total pieces, but does meet key piece targets specified by the NMFS PFC criteria.

8.0 MONITORING RECOMMENDATIONS

A variety of monitoring data pertaining to channel conditions are currently being collected by PALCO. To the extent that additional refinement, validation, or calibration of the existing monitoring data or modeling would be valuable in the development of management prescriptions, consideration should be given to supplementing these data with the following:

- Bedload transport monitoring using gravel tracers and/or bedload transport sampling using a Helley-Smith bedload sampler near the Freshwater gage site. These data would be used to supplement the suspended sediment data collected by Salmon Forever.

- Grain size analysis of suspended sediment samples collected at the Salmon Forever gage. These data would be used to confirm or refine the assessment of transport of sand.

- Observations of stream velocity and stream stage and/or stream discharge at various monitoring stations to confirm or refine the hydraulic model used to predict bedload transport and flood frequency.

- Mapping sediment size distributions within existing monitoring reaches to develop a spatially averaged grain size distribution. This would provide a more robust approach to monitoring surface sediment over time.

- Periodic (not annual) surveys of sites to extend the monitoring record for V* and RASI. This would provide valuable additional medium-term monitoring data that would help assess changes in sedimentation status.

- Observations of streambed scour using scour chains or other devices and/or evaluation of available scour studies pertaining to Freshwater. This would provide a means to assess the scour model used in the assessment.

- Development of a monitoring plan to assess deposition of sand and silt on streambanks in lower Freshwater.

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Appendix F

Freshwater Creek Watershed Analysis

Fisheries Assessment

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EXECUTIVE SUMMARY

This Fisheries Assessment contributes significantly to the understanding of salmonid species distribution, instream habitat conditions, and factors limiting salmonid production within the Freshwater Creek Watershed. To develop this understanding it was necessary to collect and analyze current field and historic data from a variety of sources.

The study's findings show Freshwater Creek basin contains coho and chinook salmon, steelhead and coastal cutthroat trout. Although there is substantial overlap, chinook tend to occupy the mainstem of Freshwater Creek, with steelhead and coho in the larger tributaries and cutthroat in the smaller headwaters. In some cases cutthroat trout are located upstream of natural anadromous migration barriers, which would indicate at least some individuals of this species have residualized into a residential life history. The distribution of juvenile salmonids may be hindered by the presence of county and private road culverts downstream of PALCO land.

An analysis of the in-stream habitat data showed pool area, pool frequency, and water temperatures are at good levels. Limited large woody debris (LWD) inventory data indicated fair to good amounts of in-stream wood. Substrate shovel samples and embeddedness data analysis revealed generally poor to fair spawning habitat conditions in the WAU although there were locations with good quality gravel. The poor habitat tended to be associated with the Wildcat Geologic Formation with the fair substrate in areas influenced by Franciscan rocks. Data analysis also showed evidence of pool filling in sample reaches.

Suspended sediment conditions measured over an extended period in 1999 at the Redwood Sciences Laboratory (RSL) monitoring station in the upper Freshwater Creek mainstem exceeded modeled sublethal, principally behavioral, thresholds for salmonids during some discrete storm events. Suspended sediment conditions did not exceed lethal thresholds in any storm event modeled at this station during the period analyzed. The modeling discussed in this report suggests that suspended sediment conditions during storm events could alter behavior, although paralethal effects on growth were not predicted by the model. Further, since the majority of storm events occur during the late fall to early spring, when salmonids are not actively growing, effects of suspended sediment on feeding behavior are likely minimal.

Substrate conditions represent the primary limiting factor for salmonid production in Freshwater Creek, by affecting spawning and rearing habitat quality. Secondary factors may include the reduced amounts of LWD in some of the larger order reaches both on and off PALCO land.

RECOMMENDATIONS

Fine sediment tends to be the most detrimental fraction in stream substrate affecting salmonid production. Much of this is generated from the skid and haul road system in the watershed. Continuation of the PALCO road erosion control program should reduce the deposition of fines sediment into streams.

Consider placement of unanchored wood in streams reaches shown to be deficient in LWD to enhance that being supplied by riparian zones. These activities could be conducted during logging operations that utilize skyline cable systems, thereby avoiding heavy equipment operations in riparian zones. The Forest Practice Rules may have to be modified to accommodate projects of this type.

Continue the collection of downstream migrant trapping data especially in the mainstem Freshwater Creek to generate a better understanding of chinook spawning and rearing location.

Conduct post-watershed analysis monitoring to ascertain the effectiveness of established and proposed mitigation and enhancement measures. Such monitoring efforts could include: (1) channel cross sections and longitudinal profiles; (2) co-located turbidity and suspended sampling at multiple stations in the watershed to reflect a range in the geological, topographical, and hydrological conditions; (3) large woody debris surveys; and (4) bulk sediment samples.

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1.0 INTRODUCTION

The Fisheries Assessment of the Freshwater Creek Watershed includes the School Forest, McCready Gulch, Cloney Gulch, Graham Gulch, Upper Freshwater, South Fork Freshwater, and Little Freshwater subbasins. This analysis followed the methods and procedures outlined in Version 2 of the Methods to Complete Watershed Analysis on Pacific Lumber Company Lands in Northern California (PALCO 2000a). Some deviation from these procedures occurred where the habitat diagnostic target criteria were not applicable to the types of field data collected and/or were different from the PFC Matrix. In some cases, the PFC Matrix targets were not applicable or appropriate for use in this watershed. Therefore, watershed-specific habitat diagnostic targets that included some PFC Matrix criteria were developed through consultations with the Signatory Review Team (SRT).

The Fisheries Assessment process is designed to identify fish species present in the watershed, summarize the status of the fish populations, identify typical habitats and habitat areas of concern, discuss habitat conditions, and summarize vulnerability of habitat within the channel geomorphic units to changes in inputs that may be the result of forest practices. The following critical questions were developed to address these objectives:

Population Status and Distribution

- What is the distribution and relative abundance of salmonid fish species in the Watershed Analysis Unit (WAU)?
- Is there any evidence of change in distribution or relative abundance from historic conditions?
- What are the location and nature of migration barriers?
- Do non-native salmonids and/or exotic species that may adversely affect native salmonids occur within the watershed?

Habitat

- What are the existing habitat conditions in the WAU?
- Where are the areas of degraded fish habitat in the WAU?
- What are the potential limiting habitat factors for each life phase and each salmonid species in the WAU?
- Where are the existing or potential spawning, rearing, and holding habitat areas in the WAU for each species?

Water Quality Parameters

- Do recorded water temperatures approach or exceed stressful levels for any salmonid species or life stage?
- What information is available on the spatial and temporal distribution of turbidity and/or total suspended solids in the watershed?
- How are salmonids in the watershed likely to respond to increasing levels of turbidity/total suspended solids (TSS)?

The above critical questions that relate to water quality recognized the following assumptions:

- The ability of a waterbody to support all life stages of salmonid fishes is predicated upon water quality parameters that are within the nominal ranges tolerated by each life stage of salmonids within that waterbody.
- Water quality conditions can exhibit high natural variability between and within a watershed on the basis of local geomorphic characteristics, climate, and precipitation.
- Fish native to specific watersheds have evolved to tolerate the natural water quality conditions of the watershed prior to European settlement.

1.1 TOTAL SUSPENDED SOLIDS AND TURBIDITY ASSESSMENT OVERVIEW

One concern expressed during the development of the Watershed Analysis methods for PALCO is the potential for forestry practices to contribute sediment into the stream network above a background rate considered “normal” for the parent geology, topography, and climate within the basin of interest. Aquatic habitat can be indirectly affected by such sediment contributions through the filling of pools, the resultant widening of channel width, and the turbid conditions that may result from the sediment in suspension. Sediment may also cause direct impacts to aquatic biota through a variety of means (e.g., smothering of eggs, impaired feeding, etc.).

Some of the critical questions first posed in the Watershed Analysis Methods Manual (PALCO 2000a) were developed to frame investigations of the potential biological impacts of suspended sediment within the Freshwater Creek Watershed (see previous section). The analysis reported here attempts to address the critical questions related to suspended sediment by characterizing the frequency and magnitude of stressful or lethal suspended sediment conditions to salmonids over the period of record. This preliminary analysis represents a “first look” at the existing conditions within the basin, as measured through approximately one year of data collected by the Redwoods Sciences Lab (RSL), and modeled using a conservative risk assessment model developed initially by Newcomb and McDonald (1991). The Newcomb and McDonald model integrates exposure concentration and duration to calculate a risk number that is reflective of a range of effects endpoints that span the "no effect" to "lethal" range. By considering the annual or seasonal frequency with which suspended sediment conditions in the water column impart a risk number, it may be possible to characterize whether suspended sediment conditions within a basin have the potential to affect fish populations.

Because suspended sediment data available from the RSL monitoring station did not span the entire year for which flow and turbidity measurements were taken by the deadline for this report, the modeling results are temporally limited. As more data undergo complete quality control processing, additional evaluations will be considered. Notwithstanding, the data analyzed provide a thorough assessment of suspended sediment exposure and risk conditions over an 8-month period during hydrologic year (HY) 1999. As such, the analysis represents a significant advancement over all previous watershed analyses conducted that have attempted to address impacts to fish populations from suspended sediment.

Conclusions from the risk modeling exercise can be used to reflect general conditions of suspended sediment in the portion of the watershed where the sampling was conducted only. Although these results may also reflect conditions elsewhere in the watershed, they cannot be extrapolated to reflect the entire range of suspended sediment to which salmonids might be exposed in Freshwater Creek or its tributaries. Further, these results model effects during storms that occurred principally during winter months, when direct negative effects from suspended sediment have been shown to be reduced due to lowered metabolic rates (Sullivan references). No in-situ studies were done to directly examine fish health or behavior during the storm events for which risk endpoints were modeled. Findings of such studies might confirm or refute the findings of this modeling exercise.

Additional evaluations of turbidity were conducted in the watershed to generally characterize the conditions over the entire period of record at the RSL monitoring station. Turbidity data were not specifically used for the quantitative risk assessment, but were considered acceptable to evaluate the general relationships between: (1) turbidity and flow at the RSL monitoring station, and (2) turbidity and total suspended sediment.

2.0 METHODS

2.1 FISH POPULATIONS AND HABITAT

The analysis consisted primarily of compiling and summarizing results of fish and habitat surveys completed within the watershed. Fieldwork consisted of visiting representative reaches throughout the watershed to assess habitat conditions. Intensive habitat data collection was conducted on approximately 2.4 miles of Class I stream. Each intensive survey segment was at least 20 bankfull widths long to capture variability in the channel. Another 5.4 miles was surveyed to determine the upstream extent of fish distribution and had a reduced level of habitat data collection. Field data were entered into an Access database and analyzed by sub-basin and Channel Geomorphic Unit (CGU). A CGU is a reach or number of reaches of stream that have similar geologies and gradients. It is assumed that channels with similar physical characteristics respond similarly to inputs of wood, water, and sediment.

The methods employed for this assessment were those described in PALCO (2000a). The Fisheries Module analyst conducted many of the in-stream habitat surveys with assistance from other qualified fisheries biologist and technicians. Instream surveys typically involved data collection efforts for several assessment modules; thus, data for the habitat parameters described in PALCO (2000a), LWD inventories, barrier locations, and amphibian observations were often collected concurrently. Field data from this module in some cases led to the modification of some stream classifications. The Channel Module analysts also provided LWD inventory, channel substrate characteristics, and geologic information that proved useful during development of the biological vulnerability calls.

2.1.1 Maps

Several maps were produced as part of this analysis including;

- Fish distribution map (Map F-1)
- Stream classification map with modifications (Map F-2)
- Spawning location map (Map F-3)
- Spawning areas of concern (Map F-4)
- Summer and winter rearing areas of concern (Map F-5)
- Sampling location sites (Map F-6)

2.2 SUBSTRATE AND WATER QUALITY PARAMETERS

2.2.1 Substrate Composition

Sediment samples were collected between 1989 and 1999 using three separate methods. These included freeze cores from Barnard (1992), gravel bar samples collected by Pacific Watershed Associates (PWA) for this analysis, and shovel samples amassed as a part of the PALCO monitoring program. The differing sampling methods and locations limits comparisons between the datasets. For example, the freeze cores were sampled only in locations containing known coho redds, while the PWA samples concentrated on gravel bars, and the shovel samples were taken at random pool tails regardless of spawning activity. In addition, there may be biases associated with these sampling techniques. The gravel bar bulk samples may not contain the same substrate composition as those collected at pool tail or redd locations due to different channel hydraulics and depositional patterns. Young et al. (1991) reported that freeze cores over-sampled particles in the 25-50 mm range in their laboratory tests using known substrate compositions. Young et al. (1991) also found that freeze cores, McNeil, and shovel samples tended to under-sample particles 6.3-9.5 mm and less than 0.212 mm in diameter. The authors (Young et al. 1991) found few differences between the McNeil and shovel samples with the McNeil's producing samples that most frequently approximated the true composition. The freeze cores and gravel bar samples are also limited because they were conducted for only a single year each; therefore, trends cannot be ascertained. However, the PALCO shovel samples were conducted for one to five years depending on location, which does enable limited comparisons over a relatively short period of time. See Map F-6 for locations of sampling sites.

2.2.2 Temperature

PALCO recorded water temperatures between 1996 and 1999 at four to six stations in the watershed with automated temperature probes as part of its company-wide monitoring program. Water temperature stations were located in: (1) Upper Freshwater, approximately 8,250 ft upstream of South Fork Freshwater (Station 36); (2) Cloney Gulch, approximately 1,000 ft upstream of the confluence with Freshwater (Station 92); (3) Mainstem Freshwater, approximately 750 ft downstream of South Fork Freshwater (Station 33, no longer in use); (4) Little Freshwater, approximately 500 ft upstream of the confluence with Freshwater (Station 18); (5) Southfork Freshwater, approximately 1,000 ft upstream of the confluence with Freshwater (Station 37, no longer in use); (6) McCready Gulch, approximately 3,750 ft upstream of the confluence with Freshwater (Station 135); and (7) Southfork Freshwater, a Class II watercourse, very high up in drainage in a Class II basin. See Map F-6 for locations of sampling sites.

2.2.3 Turbidity and Total Suspended Sediment Evaluations and Relationships to the Hydrograph

Evaluations of turbidity and TSS for the Fisheries Assessment Module focused on data collected at an RSL continuous monitoring station located on Freshwater Creek at the residence of Dr. Terry Roelofs. This continuous monitoring station is located upstream of the principal tributaries draining into the system and therefore is limited in spatial coverage. Estimates of turbidity and sediment recruited into individual sub-basins are provided in the Stream Channel and Cumulative Effects reports and are not a focus of this report.

Stage/discharge relationships, hydrographs, sedigraphs, and turbidigraphs were produced from the data collected by RSL at the continuous monitoring station. These evaluations considered the period of record for which data were collected by the RSL, including roughly half of hydrologic year (HY) 1999 (January through July 1999), and data from HY 2000 (October through April 2000). Flow, stage, and turbidity measurements were calibrated by RSL for the entire period of record. Suspended sediment data that had undergone full quality control review were available for the HY 1999 data only. Some of these analyses are similar to what has been prepared by the Redwood Sciences Lab (RSL), as available for review on the Freshwater Creek web site (www.rsl.psw.fs.fed.us/projects/water/freshwater).

In addition to the development of hydrographs, sedigraphs, and turbidigraphs, we explored the relationship between rainfall and suspended sediment to ascertain to what extent a given rainfall event (i.e., storm) correlated with a given TSS concentration. For these analyses, we used the median TSS concentration, as done with the subsequent TSS risk assessment procedures (Section 2.2.4). In distributions skewed to the left (positive), such as turbidity and TSS concentrations vs. time (in individual storm events), the median provides a more conservative estimate of the typical concentration to which a fish might be exposed during the course of an entire storm.

Cumulative rainfall was calculated for each "storm" identified from the hydrograph by summing all rainfall over the period under which discharge peaked and returned to a "steady state." The effect of rainfall on streamflow was assumed to be integrated over the basin upstream of the monitoring station, although the monitoring station recorded temporally and spatially discrete rainfall events. To address the effects of rainfall on suspended sediment, it was necessary to combine some adjacent small storms identified in the hydrograph because of the lag in peak discharge following peak rainfall events. Given the highly exploratory nature of this analysis, and the necessity to capture as many data "points" for this analysis, we deviated from the requirement that data used specifically for the TSS risk assessment undergo a quality control check (Section 2.2.4). Thus, for this analysis, we also used the limited suspended sediment data from the 2000 hydrologic year as well as the earlier QA/QC'd 1999 TSS data, although a quality control check on the former data set had not been completed.

2.2.4 TSS Risk Assessment Model Application

To address the potential impacts of TSS to salmonids in the Freshwater Creek basin for this Watershed Analysis, quality controlled and checked suspended sediment data were used for the analysis of risk only (see Section 2.2.4 for full details). This requirement restricted the analysis of TSS risk to storm events that occurred between January and July 1999; suspended sediment data from 2000 HY data were not considered in the calculation of TSS risks.

The Newcomb and Jensen (1996) model, a refinement of the Newcomb and McDonald model (1991), was used to quantify the frequency of TSS exposure events that could impart a "behavioral," "sublethal," or "lethal" risk on the basis of conservative assumptions factored into the model. The model projects risk on a 15-point scale, where each numeric qualifier may be associated with potential effects (Table 2-1). The authors developed six regression equations for use in predicting risk that varied by species and/or life stage. The general equation for each equation was as follows:

$$\text{Effect Severity} = a + b(\log_e x) + c(\log_e y), \qquad [1]$$

Where a, b, and c are constants that vary dependent on the exposure group, x is the exposure duration (ED) in hours, and y is the measured suspended sediment concentration (TSS) in mg/L.

Table 2-1: Salmonid severity of effects rankings from suspended sediment.

Severity Rank	Category	Description of effect
0	Nil effect	No behavioral effects
1	Behavioral effects	Alarm reaction
2	Behavioral effects	Abandonment of cover
3	Behavioral effects	Avoidance response
4	Sublethal effects	Short-term reduction in feeding rates; short-term reduction in feeding success
5	Sublethal effects	Minor physiological stress; increase in rate of coughing; increased respiration rate
6	Sublethal effects	Minor physiological stress
7	Sublethal effects	Minor habitat degradation; impaired homing
8	Sublethal effects	Indications of major physiological stress, long-term reduction in feeding rate and success; poor condition
9	Lethal & paralethal effects	Reduced growth rate; delayed hatching; reduced fish density
10	Lethal & paralethal effects	0-20% mortality; increased predation; moderate to severe habitat degradation
11	Lethal & paralethal effects	>20-40% mortality
12	Lethal & paralethal effects	>40-60% mortality
13	Lethal & paralethal effects	>60-80% mortality
14	Lethal & paralethal effects	>80-100% mortality

We used the equation developed by Newcomb and Jensen for juvenile and adult salmonids only, as these age classes were the relevant endpoints of interest in the Watershed Analysis, and the effects of sediment on spawning habitat, represented by different risk equations, were addressed elsewhere in the Fisheries Module through an evaluation of substrate embeddedness. Other equations developed by Newcomb and Jensen were not relevant to salmonids. The general equation to calculate severity of effect for the juvenile and adult salmonid group ('group 1' in the Newcomb and Jensen model) is as follows:

$$SEV = a + b(\log_e ED) + c(\log_e TSS) \quad [2]$$

$a = 1.0642$

$b = 0.6068$

$c = 0.7384$

The equation for juvenile and adult salmonid risks assumes that sediment grain sizes are between 0.5 and 250 um. The risk summary data presented are based upon estimated TSS concentrations predicted from a "LOESS" regression (LOESS = local regression) regression of actual measured data over the time period. The advantage of using the extrapolated data is that they provide for a measure over the entire data set evaluated. Without the extrapolation, such an analysis would be restricted to the select time periods when TSS measurements were made (i.e., TSS was not measured on every time point that turbidity was analyzed). See Section 5.4 for a discussion of the limitations of this approach.

3.0 SUMMARY DATA

3.1 SALMONID LIFE HISTORY REQUIREMENTS

This Fisheries Assessment focuses on instream habitat conditions influencing the growth and survival of coho (*Oncorhynchus kisutch*) and chinook salmon (*O. tshawytscha*), steelhead/rainbow trout (*O. mykiss*), and coastal cutthroat trout. Other stream-dwelling fish such as speckled dace (*Rhinichthys osculus*), prickly sculpin (*Cottus asper*), riffle sculpin (*Cottus gulosus*), Pacific lamprey (*Lampetra tridentata*), brook lamprey (*Lampetra pacifica*), and three-spine stickleback (*Gasterosteus aculeatus*) are not addressed in this report. No non-native species were observed during the Watershed Analysis or described in any historical report. However, non-native stocks of salmon and steelhead were occasionally planted in Freshwater Creek, with eggs being supplied from hatcheries in northern California, Oregon, and Washington (Higgins 2000). Higgins (2000) also reported evidence of chum salmon (*O. keta*) and summer steelhead (*O. mykiss*) presence in Freshwater Creek as recently as the 1940s. Chum salmon are still occasionally caught and released at the Humboldt Fish Action Council's (HFAC) upstream migrant trap.

Partial barriers for upstream migrating adult salmonids and complete barriers for upstream migrating juvenile salmonids exist along the county road system in the WAU (Map F-1). There are also a number of natural barriers to anadromous migration within the WAU. However, resident rainbow and cutthroat trout have been observed above many of these barriers. Anadromous salmonids have been observed spawning below these barriers. No information regarding fish species presence in the School Forest sub-basin was found in the reference materials. In addition no fish were observed in School Forest during habitat typing, underwater snorkel, or electrofishing surveys conducted during the analysis field work.

3.1.1 Coho Salmon (*Oncorhynchus kisutch*)

Upstream adult spawning migration generally occurs from mid-October to mid-February (HFAC 1999) when water temperatures are 4-14°C (40-58ºF). Coho migrate up and spawn in streams that flow directly into the ocean or tributaries of larger rivers (Moyle et al. 1995). Coho generally spawn in smaller streams than those used by chinook. Coho preferred gravel sizes ranging from 1.3-10.2 cm. Average redd size and recommended gravel area per spawning pair are 2.8 m^2 and 11.7 m^2, respectively (Bjornn and Reiser 1991). Adults die within 10-14 days following spawning. Embryos hatch after 8 to 12 weeks of incubation and emerge from the gravel several weeks later. Studies summarized by Spence et al. (1996) stated that intergravel mortality of coho and steelhead occurs when fine sediments (<0.85 mm.) exceed 13% of the substrate composition. Bjornn and Reiser (1991) reported that emergence rates for swim-up fry declined when the percentage of fines (2-6.4 mm.) exceeded 20%. The PFC Matrix states proper function for embryo survival is attained when fine sediment (<0.85mm) is less than 11-16% of the substrate composition.

After emergence, young fry rear in edgewater habitats and move gradually to deep, well-shaded pools by summer. Highest densities are usually associated with pools ≥1 meter in depth, with plenty of overhead cover, undercut banks, logs, and other woody debris, and water temperatures not exceeding 22-25°C (72-77ºF) for extended periods of time (Moyle et al. 1995). Preferred water temperatures are in the 7.2-16.7°C (45-62ºF) range (Hassler 1987). The PFC Matrix states properly functioning condition should not exceed a maximum weekly average temperature (MWAT) of 16.8ºC (62.2ºF).

The fry/juvenile stages spend 10 to 15 months in stream habitats. Downstream migration to the ocean starts around March when the coho are about one year old. The migration peaks around mid-May and continues until mid-June. Coho then spend two to three years at sea before migrating back to their natal streams to spawn. Readers interested in additional details on coho salmon life history are referred to Weitkamp et al. (1995).

Coho are found in each of the sub-basins, with the possible exception of School Forest, up to the point where either natural barriers or increasing stream gradient limits their distribution. Streams with particularly high use include Cloney Gulch, Upper Freshwater, McCready Gulch, and possibly the mid- to lower mainstem. See Fisheries Map F-1: Fish Distribution.

3.1.2 Steelhead/Rainbow Trout (*Oncorhynchus mykiss*)

Winter run steelhead generally enter the watershed in early December through spring and begin spawning soon after. Preferred water temperatures for spawning migration are 3.9-9.4°C (39-49ºF). Steelhead are capable of repeat spawning. Up to 30% can survive to spawn a second or third time, but in large drainages where fish migrate long distances, the proportion is much lower (Meehan and Bjorn 1991). Steelhead tend to construct redds averaging 4.4 - 5.4 m^2 for egg deposition in gravels ranging in size from 0.6-10.2 cm (Bjornn and Reiser 1991). Egg development is temperature-dependent and usually takes 31 days at 10°C (50ºF) (Flosi et al. 1998). Intergravel mortality of steelhead can occur when fine sediments (<0.85 mm) exceed 13% of the substrate composition (Spence et al. 1996). Upon emerging from gravel, the fry rear in edgewater habitats and move gradually into pools and riffles, as they grow larger. Juvenile steelhead spend 1 to 3 years in fresh water before migrating to the ocean (Busby et al. 1996).

Preferred water temperatures for rearing are reported to be 10-13°C (50-56ºF), with an upper lethal limit of 23.9°C (74ºF) (Bjornn and Reiser 1991). However, juvenile steelhead are known to utilize the lower Mad, Eel, and Van Duzen Rivers in Humboldt County, where summertime maximum daily water temperatures can exceed 24°C (75ºF) for several weeks at a time (Halligan 1998, 1999). Most downstream smolting migration takes place in spring and early summer. The majority of steelhead spend 2 years in the ocean before returning to spawn. Readers interested in additional details on steelhead life history are referred to Busby et al. (1996).

Steelhead are found in each of the sub-basins, with the possible exception of School Forest, up to the point where either natural barriers or increasing stream gradient limits their distribution. Upper Freshwater appears to be the reach with the highest use. See Fisheries Map F-1: Fish Distribution.

3.1.3 Chinook Salmon (*Oncorhynchus tshawytscha*)

Chinook salmon generally leave ocean waters and enter Freshwater Creek in early November through mid-January (HFAC 1999). Spawning usually occurs from November through January when water temperatures are between 5.6-13.9°C (41-57°F) (Bjornn and Reiser 1991). Chinook are riffle spawners and tend to utilize gravel substrate at the head of riffles or pool tails ranging in size from 1.3-15 cm. Average redd size and recommended gravel area per spawning pair are 5.1 m^2 and 20.1 m^2, respectively (Bjornn and Reiser 1991). Chinook die after spawning. The eggs develop in the gravel for 50-60 days before hatching, depending on water temperatures. Embryo survival rates begin to decrease when the amount of substrate smaller than 6.35 mm exceeds 20% (Bjornn and Reiser 1991). Young salmon emerge from gravel after the yolk sac is absorbed 2 to 4 weeks later. Juvenile chinook generally begin their downstream migration soon thereafter. Downstream migration is usually complete by late June, but some fish may remain in estuaries until fall and enter the ocean as yearlings. Chinook will remain in the ocean for 3 to 5 years before returning to freshwater to spawn.

In the Freshwater basin, chinook tend to be found primarily in reaches that contain significant deposits of coarse gravel from the Franciscan formation. These reaches include Upper Freshwater (C1 and C2) and Middle Freshwater (MS1). Their distribution in Upper Freshwater is limited by the presence of natural barriers. See Fisheries Map F-1: Fish Distribution.

3.1.4 Coastal Cutthroat Trout (*Oncorhynchus clarki*)

Resident and anadromous coastal cutthroat trout are known to inhabit the Freshwater Watershed. Some coastal cutthroats may spend their entire lives in freshwater, but most are anadromous, spending the summers in saltwater habitats (Moyle et al. 1995). However, even populations where the vast majority of fish are anadromous may have members that do not migrate to sea every year (Johnson et al. 1999). Their upstream migration usually occurs in the late fall or early winter and, typically, spawning takes place in small streams (Flosi and Reynolds 1994) when water temperatures are between 6.1-17.2°C. They are frequently found above barriers to steelhead migration. They are capable of repeat spawning. Spawning substrate size can range from 0.6-10.2 cm, with smaller fish utilizing smaller substrate (Bjornn and Reiser 1991). The eggs hatch after 6 to 7 weeks with the alevin remaining in the gravel for an additional 1 to 2 weeks while the yolk sac is absorbed. Embryo survival rates decrease fairly rapidly when the amount of substrate <6.35 mm increases. Juveniles rear for two or more years in freshwater before migrating to the estuaries or the sea. Bjornn and Reiser (1991) reported there is a positive correlation between the amount of cover in a stream and standing crops of cutthroat.

Coastal cutthroat trout are found in each of the Freshwater Creek sub-basins, with the possible exception of School Forest. Although present in low numbers in the lower portion of the stream network, they are the dominant species upstream of barriers to steelhead and salmon. It is possible that some of the cutthroat have residualized, that is, reverted from anadromy to resident status. See Fisheries Map F-1: Fish Distribution.

3.2 AVAILABLE FISHERIES INFORMATION

Fish population information has been collected for a number of years by the HFAC, California Department of Fish and Game (CDFG), PALCO, and Humboldt State University (HSU) students. HFAC concentrated primarily on collecting upstream migrant trap counts, carcass/redd surveys, and downstream migrant trapping. PALCO and the CDFG conducted electrofishing on several index reaches throughout the basin. HSU students conducted a number of surveys using varied methodologies including downstream migrant trapping and electrofishing. An inventory of available fisheries information is summarized in Table 3-1.

Table 3-1: Inventory of available fisheries information in Freshwater Creek.

Surveyor	Year	Survey Type/Location	Notes
CDFG	1952-1989	Various ocular stream inventory reports regarding barrier locations, habitat quality, fish species	Spot checks
CDFG	1993-1994	Stream inventory reports for Graham Gulch, Cloney Gulch, Little Freshwater, South Fork Freshwater	Flosi et al. (1991) protocol
CDFG	1993-1999	Index reach electrofishing	Depletion protocol
HFAC	1998	Stream habitat inventory using Flosi et al. (1994) by subbasin	Reports not developed. QA/QC problems suspected
HFAC	1996-2000	Downstream migrant trapping results for Little Freshwater, McCready, Cloney, Graham, Upper Freshwater, South Fork	Trapping effort and locations varied
HFAC	1978-1999	Upstream migrant trapping summaries	Trapping effort varied
HFAC	1988-1990	Spawner/redd surveys	Survey effort varied
HFAC	1994-1999	Spawner/redd surveys	Survey effort varied
HFAC	1987-1996	Various progress reports on trapping, spawner surveys, escapement estimates, stream rehab. Projects	
PALCO	1998-1999	Index reach electrofishing	Depletion protocol
PALCO	1994-1999	Database summaries of macroinvertebrate, sediment, water temperatures, LWD, and thalweg surveys	Survey effort and parameters increased overtime
HSU	1985-1996	Student papers on downstream migration, habitat quality, sediment size distribution, and salmonid abundance and distribution	
NRM (Natural Resources Mngmt. Corp.	1995-1996	Stream survey notes for McCready, Falls, and Cloney Gulches	

3.3 FISH DISTRIBUTION

Map F-1 illustrates the distribution of all salmonid species occurring in the WAU. The distribution map is based on the fish survey work conducted by CDFG, HFAC, PALCO, and watershed analysts.

Coastal cutthroat trout inhabit the entire fish bearing network within the Freshwater Creek basin. However, they are the dominant species in the reaches upstream of anadromous migration barriers. Cutthroat are known to be capable of surmounting barriers that would block upstream steelhead migration. Therefore, it is possible that there are anadromous cutthroat upstream of these barriers. However, this species is also known to residualize above migration barriers and probably have resident populations in the upstream most reaches.

Steelhead trout tend to be found in each subbasin up to the point where upstream migration is no longer possible due to natural barriers. According to downstream migrant trapping data, Upper Freshwater Creek and Cloney Gulch contain the highest populations.

Coho salmon are also found in each subbasin up to natural migration barriers. Based on downstream migrant trapping data, the highest coho production occurs in Upper Freshwater, South Fork Freshwater, and McCready and Cloney Gulches.

Chinook salmon are primarily found within Upper Freshwater and the mainstem downstream of the South Fork confluence. Low numbers have periodically been recorded in Little Freshwater and Graham and Cloney Gulches.

No reference information was found regarding fish presence in School Forest. No fish were observed during streambank, underwater, and electrofishing surveys conducted during the analysis.

A number of watercourses were subject to underwater and streambank observation and limited electrofishing to determine the upstream extent of fish-bearing waters. These surveys filled gaps in fish distribution information and helped groundtruth GIS-generated stream classifications on maps. In some cases, streams that were identified on base maps as non-fish bearing were determined to be fish-bearing and vice-versa. As a result of the surveys, the stream classification layer on the GIS basemap was modified. A number of low gradient watercourses with intermittent flow but no barriers were upgraded from Class II to Class I due to the presence of fish or potential for seasonal utilization during winter runoff periods. By contrast, a number of streams were downgraded from Class I to Class II due to the presence of permanent natural barriers downstream, no fish observed, and steep gradients. In one instance, the reach was considered a Class I watercourse due to the presence of a domestic water supply as required under the California Forest Practice Rules. Table 3-2 summarizes the miles of fish-bearing streams and miles of upgrades and downgrades. Map F-2 illustrates the locations of the classification changes and reaches in need of further investigation.

Table 3-2: Summary of fish-bearing streams and classification modifications

Stream Classification	Miles of Stream
Class I (Total on PALCO) *	22.75
Upgraded from Class II to Class I	1.75
Downgraded from Class I to Class II	2.5
Class I (Outside PALCO) **	9.8
Class I due to domestic water supply ***	0.7

* Includes approximately 1 mile within PALCO ownership above the Road 15 crossing in upper Upper Freshwater and 0.8 mile in School Forest that may be downgraded to Class II pending further investigation.
** Includes approximately 2.4 miles off PALCO land in upper Upper Freshwater that may be downgraded to Class II pending further investigation.
*** Located in McCready Gulch tributary. No fish present.

3.4 FISH POPULATION INFORMATION

There has been a great deal of fisheries population work done in the Freshwater Creek WAU; PALCO, CDFG, HFAC, and HSU have been collecting data for many years. Data collection has been associated with electrofishing index reaches, upstream and downstream migrant trapping, as well as redd, spawner, and carcass surveys. Although many surveys have been conducted over the years, variation in protocols and effort as well as relatively short monitoring duration make trend analysis difficult. In addition, the influences of the 1986-1994 drought, reduced ocean productivity during the late 1980s and 90s, and the recent El Niño may also affect salmonid populations. See Attachment F-1 for summaries of downstream migrant trapping, upstream migrant trapping, index reach electrofishing, and spawner surveys.

Although no hard population data exist, historic newspaper reports and the perceived need to establish the HFAC indicate that salmonid populations in the WAU were once more abundant than they are today. In addition, Higgins (2000) cited newspaper accounts from the late 1940s that reported the presence of chum salmon and summer steelhead in Freshwater Creek. The HFAC upstream migrant trap also collects an occasional chum salmon, although not nearly in the numbers the newspaper accounts suggest. Higgins (2000) stated that the reduction or absence of species that once existed in Freshwater Creek indicates some Pacific salmon diversity has been lost.

3.5 FISH HABITAT FIELD SURVEYS

Fish habitat information has been collected by PALCO, CDFG, HFAC, and HSU students since about 1980. For most of this time, no standardized protocol was used by the investigators. In 1993, the first stream inventories were conducted using a standard protocol (Flosi and Reynolds 1991). In 1998, HFAC repeated the surveys using Flosi et al. (1998), an updated version of the earlier CDFG protocol. The HFAC survey reports have yet to be developed and therefore were not utilized for this Watershed Analysis. Although useful, the CDFG protocols do not provide some data necessary to compare instream conditions to the PFC Matrix targets or Habitat Condition Indices. Therefore, the 1999 survey conducted for this watershed analysis further modified the Flosi et al. (1998) protocol to answer specific questions relating to the module.

Habitat typing is recognized as a relatively poor tool for monitoring activities. Poole et al. (1997) stated

> "Habitat unit classification can be a useful descriptive tool in hierarchical stream classification. However, a critical evaluation reveals that it is applied inappropriately when used to quantify aquatic habitat or channel morphology in an attempt to monitor the response of individual streams to human activities… Stream habitat managers and scientists should only use habitat unit classification to descriptively stratify in-stream conditions. They should not use habitat unit classification as a means of quantifying and monitoring aquatic habitat and channel morphology."

Some of the reasons for the relative weakness of utilizing habitat typing as a trend monitoring tool stem from the variability of habitat calls by different observers, lack of precision and repeatability of the ocular estimates, and transferability of the method. Therefore, if one were to monitor instream habitat conditions it is far better to use quantitative measurement techniques such as V*, surveyed cross sections and long profiles, bulk sediment samples, LWD surveys, and residual pool depths rather than subjective ocular estimates.

Due to the nature of the historical information and variability in habitat condition from year to year, the lead Fisheries Assessment analyst decided to base much of the assessment on data collected specifically for the Watershed Analysis. It was also necessary to use current information to ensure temporal consistency with data collection being conducted by the other modules. The results from substrate bulk samples, V* measurements, and LWD surveys were also used to enhance and cross-check the more subjective habitat evaluation calls. Previously collected quantitative data from the 1994 CDFG habitat surveys (e.g., residual pool depths) were used to "fill out" or further inform the overall assessment. See Attachment F-2 for summaries of habitat parameters by subbasin and CGU.

3.5.1 Habitat Condition Evaluation

The Watershed Analysis requires that comparisons be made between the existing conditions and a table of indices of resource conditions. During the analysis, it was realized that it would be extremely difficult to make comparisons between the existing conditions and all the potential habitat indices contained in the manual. To make the comparisons easier, an abbreviated habitat condition matrix was developed during the Synthesis process with input by the Signatory Review Team. The modified Habitat Conditions Indices are presented in Table 3-3.

Habitat conditions that were quantitatively and qualitatively sampled during the field visit are summarized in Tables 3-4 through 3-9.

Additional information regarding water temperature, substrate composition, and residual pool volume (V*) was reported in Higgins (2000). A synopsis of that information is presented in Section 3.6.4. Aquatic macroinvertebrate information (Lee 1999) and habitat summaries sorted by CGU and subbasin are presented in the attachments.

Table 3-3: Comparisons of percent of pool area, percent pools by stream length, and number of pools >2 feet deep between 1994 and 1999.

Stream Name	% Pool Area 1994 / 1999	% Pool by length 1994 / 1999	Pools >2' deep 1994 / 1999
Little Freshwater	65 / 73	56 / 60	47 / 13
Graham Gulch	34 / 50	23 / 35	40 / 11
South Fork	51 / 72*	38 / 47	33 / 7
Cloney Gulch	51 / 75*	31 / 45	38 / 26

* Intermittent flow may have resulted in elevated 1999 values since % pool area is based upon wetted area and these subbasins contain intermittent reaches.

Pool Condition Evaluation

Based on comparisons with the PFC Matrix, the information presented in Table 3-4 show generally fair to good pool conditions in the sampled channel segments. However, four segments (302, 601, 791, and 1267) had poor ratings in some instances. Segment 601 rated poorly in the pool cover diagnostic since most pools were due to bedrock scour and cover LWD complexity was relatively simple. Segments 302, 791, and 1267 suffered from intermittent flow conditions during the summer, which reduced their pool frequency and surface area. The Habitat Indices (Table 3-3) contain one subjective index relating to the quality and complexity of instream cover since the PFC Matrix did not address it. The analyst felt it necessary to include a cover component due to its importance to summer and winter salmonid habitat.

Comparisons were made between the 1994 stream inventories conducted by the California Conservation Corps in Little Freshwater Creek, Graham Gulch, South Fork Freshwater, and Cloney Gulch and instream habitat data collected for this watershed analysis in 1999 (Table 3-3). The reason for the comparisons was to see if there were changes in quantitative measurements of pool characteristics between the two time periods. There appear to have been increases in pool area and percentage of the stream made up of pools. However, there has been a significant decrease in the number of pools greater than two feet deep from 1994 to 1999. This shallowing of pools was also observed during the V* data collection and analysis as explained in Section 3.6.4 and the Stream Channel Assessment.

Although contained in the PFC Matrix, pool depth (>3 feet deep) was not considered by the SRT as an appropriate habitat diagnostic tool for Freshwater Creek. In many stream systems, a 3-foot deep pool may be the exception rather than the rule even in pristine conditions. As drainage area gets smaller, stream power and channel width naturally decrease and so does pool depth. By contrast, as stream order increases, a three-foot deep pool may be considered too shallow for a reach with that amount of drainage area. In addition, the Stream Channel Assessment reported “Most of the Class I channel network has relatively entrenched channels with bedrock exposed locally in banks and pool bottoms. The low proportion of deep pools is believed to result from limits imposed by the depth of alluvial channel deposits above bedrock, which rarely exceed 3 ft (see Figure 5-4 – Stream Channel Assessment). Depth of alluvium may thus play a role in determining whether NMFS PFC targets for pool depth are attainable in some streams.”

Substrate Condition

An analysis of the data shows that generally poor to fair substrate conditions exist in the sampled channel segments (Table 3-5). The two segments with good ratings (601, 501) also correspond to the reaches with the heaviest spawning utilization. The poorest ratings tended to correspond with the unconsolidated geology and are generally utilized to a lesser degree by spawning salmonids.

Along with criteria approved by the SRT and contained in the PFC Matrix, the Habitat Condition Indices contain two subjective indices that the analyst believed necessary to obtain a better understanding of substrate and habitat conditions. These are “Substrate Quality” and “Gravel Availability,” which were taken from WDNR (1997). The substrate quality parameter relates to the abundance of sand and small gravel filling interstitial spaces in boulder or cobble dominated units, which could affect winter concealment cover. Gravel availability relates to the abundance of spawnable size particles. This gives the analyst and readers an idea of potential spawning gravel abundance. See Section 3.6.3 for a discussion of the percentage of fine sediment within the substrate and a comparison to the PFC Matrix targets.

LWD Loads

Large woody debris data were collected, analyzed, and reported within the Stream Channel Assessment Module. A review of the LWD data and comparison with the Habitat Condition Indices and PFC matrix shows generally fair to good wood loading in the most of the CGUs (Tables 3-6 and 3-7). However, CGUs U1, MS1, MS2, and MS3 did not meet the PFC target criteria for either the number of pieces greater than 10 cm wide and greater than 2 m long and/or key piece abundance.

Summary Table

Table 3-7 represents a consolidation of the sampled channel segment diagnostics to gain a generalized understanding of conditions within each CGU. The information shows that pool and LWD conditions are generally at fair to good levels. The substrate appears to be of generally poor to fair quality throughout the system. It must be emphasized these are generalities, and conditions likely vary within each CGU.

Table 3-4: Indices of habitat conditions.

Habitat Parameters (Source)	Channel Type	**Habitat Quality Ranking**		
LWD		Poor	Fair	Good
Minimum functional size (Synthesis/PFC Matrix)	15-45 ft channels	Length <1 bfw Width <1 ft diameter	Length > 1 bfw Width > 1 ft. diameter	Fox (1994) targets
Debris Pieces per 100' Channel Length, >10 cm diameter and 2 m in length (Bilby and Ward 1989, PFC Matrix)	15-20' wide 20-25' wide 25-30' wide 30-45' wide			12-16 9-12 7-9 5-7
Canopy Closure % within RMZ (Synthesis)	All types	<70%	70-85%	>85%
SUBSTRATES				
Substrate Quality (WDNR 1997)	All types	Sand or small gravel is subdominant in boulder- or cobble-dominant units (i.e., interstices filled absent or infrequent).	Sand is subdominant in some units with cobble or boulder dominant (interstices reduced).	Sand or small gravel is only rarely subdominant in any unit (interstices clear).
% fines <0.85mm (PFC Matrix)	Pool/riffle <3% grade			<11-16%
Gravel Availability (WDNR 1997) (measured at pool tail-outs)	All types	Absent or infrequent.		Frequent spawnable areas
V*	3rd Order, <3% grade			<20%
% Embeddedness / DFG Equivalent Rating (Synthesis)	All types	>40% / >2.5	25-40% / 2-2.5	<25% / 1-2
POOLS				
Pools (PFC Matrix and Synthesis)	<3% 3-6.5%			>25% pool area, >1 pool / 6 cw >20% pool area, > 1 pool / 3 cw
% Pools assoc. with LWD (PFC Matrix)	<3% >3%			50% of pools 90% of pools
Shelter Rating (Flosi et al. 1998)	all			>80

bfw = bankfull width, cw = channel width

Table 3-5: Freshwater pool condition evaluation/diagnostic calls.

Channel Segment	CGU Number	% Pool Wetted Area/ Summer (Winter) Pool Freq. (channel widths/pool)	Summer (Winter) Overall Pool Rating	Pool Cover %pools LWD formed/ %pools assoc/LWD/ pool shelter rating	Overall Cover Rating	Comments
1	U1	76 / 1.9 (1.9)	Good	45 / 91 / 85	Good	
527	U1	60 / 3.7 (3.7)	Good	43 / 100 / 88	Good	Bank erosion
1101	U1	73 / 3 (3)	Good	50 / 100 / 48	Fair	
1110	U1	78 / 3.4 (3.4)	Good	75 / 100 / 91	Good	
18	U2	65 / 3.4 (3.4)	Fair	100 / 100 / 134	Good	McR. Gl. Trib.
1201	U2	94 / 2.8 (2.5)	Good	90 / 100 / 153	Good	Class II
203	U3	75 / 2 (2)	Good	25 / 67 / 81	Fair	High gradient
601	C1	47 / 3.3 (3.3)	Good	0 / 71 / 48	Poor	Bedrock controls
609	C1	70 / 2.3 (2.3)	Good	71 / 93 / 101	Good	
901	C1	75 / 2.5 (2.5)	Good	30 / 70 / 67	Fair	
908	C2	70 / 1.6 (1.6)	Good	87 / 100 / 143	Good	
605	C2	71 / 1.4 (1.4)	Good	20 / 73 / 80	Fair	
980	C2	60 / 5.3 (5.3)	Fair	100 / 100 / 188	Good	Class II
608	C3	63 / 1.7 (1.7)	Good	25 / 75 / 92	Fair	High gradient
791	C3	53 / 8 (4)	Poor (Fair)	67 / 83 / 112	Good	Intermittent
1267	C3	100 / 10.3 (3.4)	Poor (Fair)	33 / 83 / 67	Fair	Dry but for 2 pools
301	GG	50 / 2.8 (2.8)	Good	44 / 100 / 91	Good	LWD structures
302	GG	35 / 10.7 (4.3)	Poor (Fair)	80 / 100 / 54	Good	Intermittent
101	CG	72 / 3 (3)	Good	11 / 78 / 58	Fair	
103	CG	78 / 2.2 (2.2)	Good	33 / 92 / 75	Fair	Intermittent
501	MS1	69 / 3.1 (3.1)	Good	17 / 67 / 61	Fair	
503	MS1	57 / 2.9 (2.9)	Good	50 / 88 / 56	Good	
510	MS3	88 / 3 (3)	Good	29 / 86 / 51	Fair	Resident Reach
511	MS3	90 / 3.3 (3.3)	Good	17 / 83 / 112	Fair	Resident Reach

Table 3-6: Freshwater substrate condition evaluation/diagnostic calls. These ratings are determined by comparing ocular estimates of habitat parameters with the Habitat Condition Indices. The overall rating was determined by averaging the individual ratings.

Channel Segment	CGU Number	Subst. Quality (Dom/Subdom)	Spawning Grav. Available	Embeddedness Number/Rating	Overall Rating	Comments
1	U1	Poor	Poor	2.9 / Poor	Poor	
527	U1	Poor	Poor	3.9 / Poor	Poor	
1101	U1	Poor	Good	3.8 / Poor	Poor	
1110	U1	Poor	Good	3.2 / Poor	Poor	
18	U2	Poor	Poor	3.8 / Poor	Poor	
1201	U2	Poor	Poor	3.6 / Poor	Poor	Class II
203	U3	Fair	Poor	1.9 / Fair	Fair	Class II
601	C1	Fair	Good	1.4 / Good	Good	
609	C1	Good	Fair	2.5 / Poor	Fair	
901	C1	Poor	Good	2.7 / Poor	Fair	Embeddedness good in spots
908	C2	Fair	Fair	2.3 / Fair	Fair	
605	C2	Fair	Fair	2.7 / Poor	Fair	
980	C2	Good	Poor	2.5 / Poor	Poor	Class II
608	C3	Poor	Fair	3.2 / Poor	Poor	
791	C3	Poor	Fair	2.4 / Fair	Fair	Upper F.C. trib.
1267	C3	Good	Poor	2.1 / Fair	Fair	
301	GG	Fair	Good	3.3 / Poor	Fair	
302	GG	Poor	Good	2.5 / Fair	Fair	
101	CG	Fair	Good	2.2 / Fair	Fair	
103	CG	Fair	Good	2.7 / Poor	Fair	
501	MS1	Good	Good	2.1 / Fair	Good	
503	MS1	Poor	Good	3.1 / Poor	Poor	
510	MS3	Poor	Good	2.2 / Fair	Fair	Good in spots
511	MS3	Poor	Good	3.2 / Poor	Poor	

Table 3-7: LWD abundance in sample plots distributed by CGU. Underlined values (pieces per 100 ft of channel length) indicate CGUs where the observed abundance is less than the target abundance. Note that the LWD survey plot widths presented here may not be identical to average channel widths in presented in other width data summaries. Table modified from Stream Channel Assessment Report (Rating added).

CGU	Plot Average Channel Width (ft)	Pieces per 100 ft	PFC Target (Bilby & Ward)	Total # Pieces	Total Length of Plots (ft)	Rating
CG	24	11.8	9-12	132	1115	Good
GG	31	23.3	6-7	170	731	Good
U1	19	<u>7.1</u>	12-16	178	2503	Poor
C1	38	12.3	5-6	554	4517	Good
C2	20	14.6	12	102	700	Good
C3	24	18.0	9-12	36	200	Good
MS1	28	<u>3.8</u>	7-9	107	2800	Poor
MS2	45	<u>0.3</u>	5	3	1000	Poor
MS3	38	4.4	5-6	156	3550	Fair

Table 3-8: Key LWD piece abundance in sample plots distributed by CGU. Underlined values (pieces per 100 ft of channel length) indicate CGUs where the observed abundance is less than the target abundance. Table modified from Stream Channel Assessment Report (Rating and U2 added).

CGU	Plot Average Channel Width (ft)	PFC Key Piece Diameter-Fox (in)	PFC Target (Pieces per 100 ft-Fox)	Observed Key Pieces per 100 ft	PFC Key Piece Average Volume	Observed Key Piece Volume	Rating # Pieces / Volume per piece
CG	24	22	2-2.5	3.3	88	170	Good/Good
GG	31	25	1.4-1.7	5.5	212	166	Good/Fair
U1	19	16	2.5-3.3	4.1	35	102	Good/Good
U2 *	11	<16	<3.3	10	<35	148	Good/Good
C1	38	25	1.2-1.4	2.3	212	202	Good/Good
C2	20	22	2.5	3.6	88	62	Good/Fair
C3	24	22	2-2.5	8.5	88	212	Good/Good
MS1	28	22	1.7-2.0	<u>0.5</u>	88	314	Poor/Good
MS2	45	25	1.1	<u>0.0</u>	212	n.a.	Poor/Poor
MS3	38	25	1.2-1.4	<u>0.3</u>	212	437	Poor/Good

* Key piece LWD data recorded during fisheries field data collection

Table 3-9: Summary channel geomorphic unit fisheries habitat ratings. The intent of this table is to give the analyst and reader a brief review of the various habitat quality ratings based upon the previous comparisons of field data with the Indices of Habitat Condition. The table is also designed to give the reader an understanding of limiting factors to salmonid production at a glance. See Tables 3-4 through 3-7 for numerical/narrative ratings of individual CGU segments.

CGU Number	Pool Rating	Pool Cover Rating	Substrate Rating	Bilby LWD Rating	Fox # LWD Key Piece	Fox LWD Volume/Piece
U1	Good	Good	Poor	Poor	Good	Good
U2	Good	Good	Poor	NA	Good	Good
U3	Good	Fair	Fair	NA	ND	ND
C1	Good	Fair	Fair	Good	Good	Good
C2	Good	Good	Fair	Good	Good	Fair
C-3	Good	Good	Poor	Good	Good	Good
GG	Good	Good	Poor	Good	Good	Fair
CG	Good	Fair	Fair	Good	Good	Good
MS1	Good	Fair	Fair	Poor	Poor	Good
MS2	ND	ND	ND	Poor	Poor	Poor
MS3	Good	Fair	Poor	Fair	Poor	Good

ND=No data collected

3.6 SUBSTRATE AND WATER QUALITY PARAMETERS

3.6.1 Turbidity and Total Suspended Sediment

Hydrograph, Turbidigraph, and Stage/Discharge Relationships

In total, 18 storms were identified during the winter and spring of 1999 where discharge exceeded 100 cubic ft per second (cfs) (Figure 3-1). Noticeably, turbidity and suspended sediment measured earlier in the season at a given flow event were generally reduced later in the season for flows of similar peak discharge. For example, the peak flows measured around 1/16/99, 1/23/99, and 2/10/99 were each approximately 400 cfs (+/-20) (Figure 3-1), yet the measured turbidity of these events peaked at 585, 305 and 330 NTUs, respectively. The flows measured at the latter two dates were decreased by approximately 5 and 10%, respectively, relative to the 1/16/99 event, yet the turbidity reductions per unit flow declined by over 40% (Figure 3-2). Such reductions are generally to be expected as the system flushes proportionately more sediment out early in the hydrographic year relative to later in the cycle. However, significant new inputs of sediment, such as from landslides or road erosion, could lead to spikes in turbidity at a given flow regardless of seasonal timing. The best fit line for discharge relative to stage height conformed uniformly to a first order power equation (Figure 3-3).

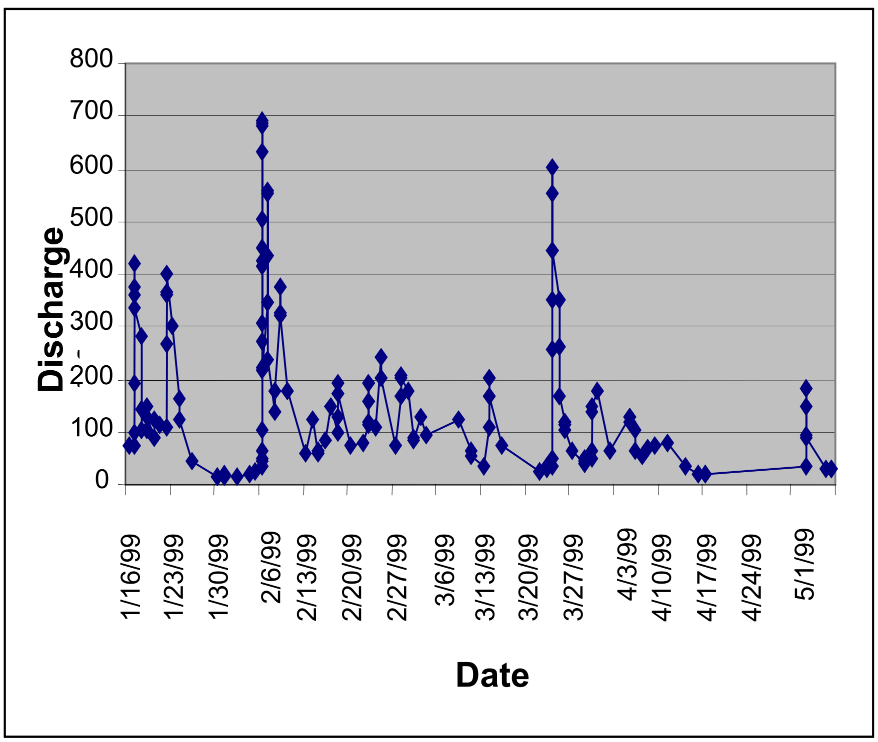

Figure 3-1: Freshwater Creek Discharge, winter and spring 1999.

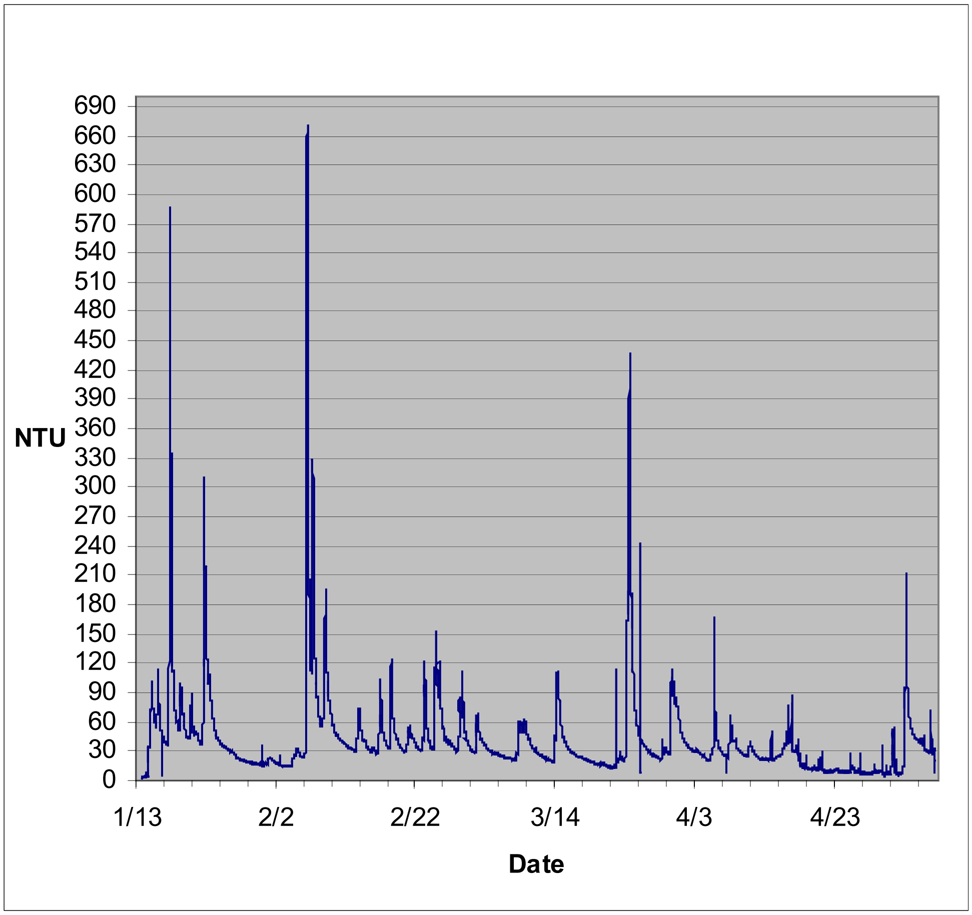

Figure 3-2: Turbidity in Freshwater Creek, winter and spring 1999.

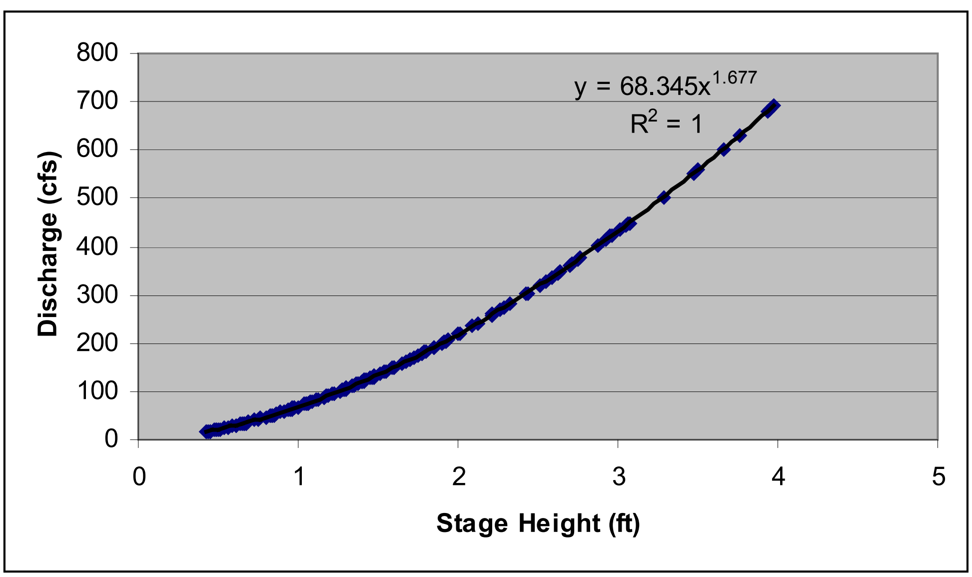

Figure 3-3: Freshwater Creek Stage vs. Discharge, winter and spring 1999.

Relationships Between Discharge, Turbidity, and Suspended Sediment

Flow (i.e., discharge) appears to be a good predictor of turbidity in Freshwater Creek (Figure 3-4), although the predictive power of flow for this measurement endpoint is affected by histeresis. Histerisis is created by disproportionately high turbidity and suspended sediment during the ascending phase of the hydrograph and low turbidity during the descending phase, as measured in discrete storm events. Thus, for a discrete rainfall (storm) event that might peak at a discharge of 220 cfs, the turbidity and suspended sediment concentration measured at 100 cfs during the ascension to this peak will exceed that measured during descension at 100 cfs. These histerisis "loops" appear more pronounced in the fall (Figure 3-5) as opposed to the spring (Figure 3-6). When all data points are considered over the entire period of record (i.e., multiple storm events combined), the effect of histeresis is dampened but is still evident (Figures 3-5 and 3-6). The more pronounced histeresis observed during the fall 2000 monitoring period relative to the spring provides additional evidence of higher sediment transport during the early portion of the annual hydrograph relative to the latter period.

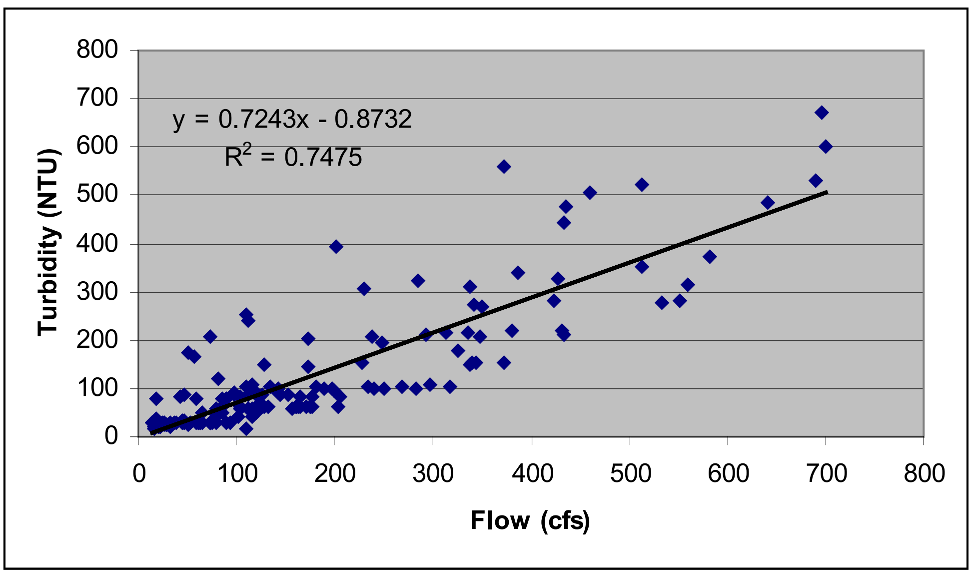

Figure 3-4: Flow (discharge) versus turbidity in Freshwater Creek, 1999.

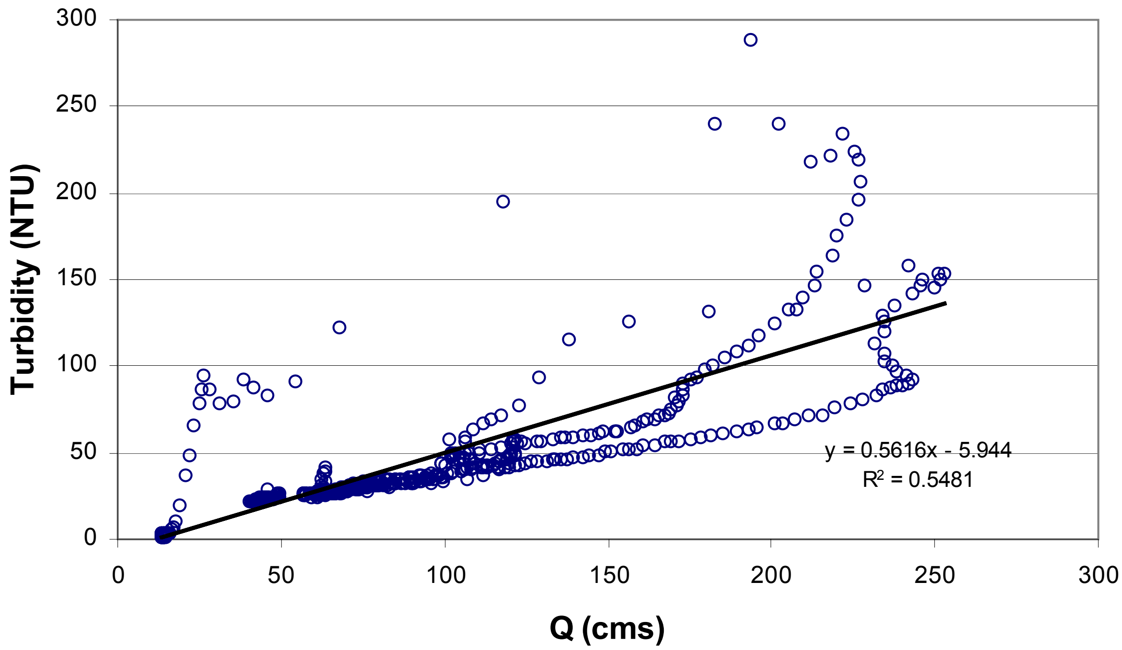

Figure 3-5: Flow (cubic meters/second) versus turbidity, fall 2000.

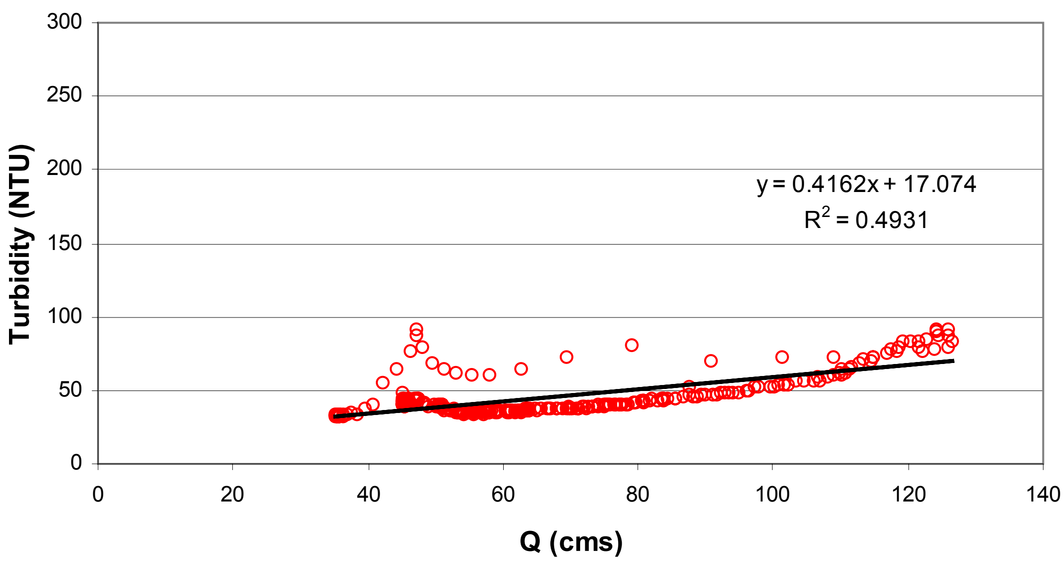

Figure 3-6: Discharge versus turbidity, spring 2000.

The relationship of suspended sediment to flow (Figure 3-7) reflected that of turbidity, with no effective difference in the strength of the relationship ($R^2_{turbidity} = 0.75 = R^2_{TSS}$). In contrast, turbidity was an excellent predictor of suspended sediment concentration (Figure 3-8) in Freshwater Creek, consistent with previous studies by the RSL. Because turbidity is composed of both dissolved and particulate fractions, the relationship is weaker at the lower values of turbidity, as organic acids constitute a disproportionately higher amount of the turbidity reading.

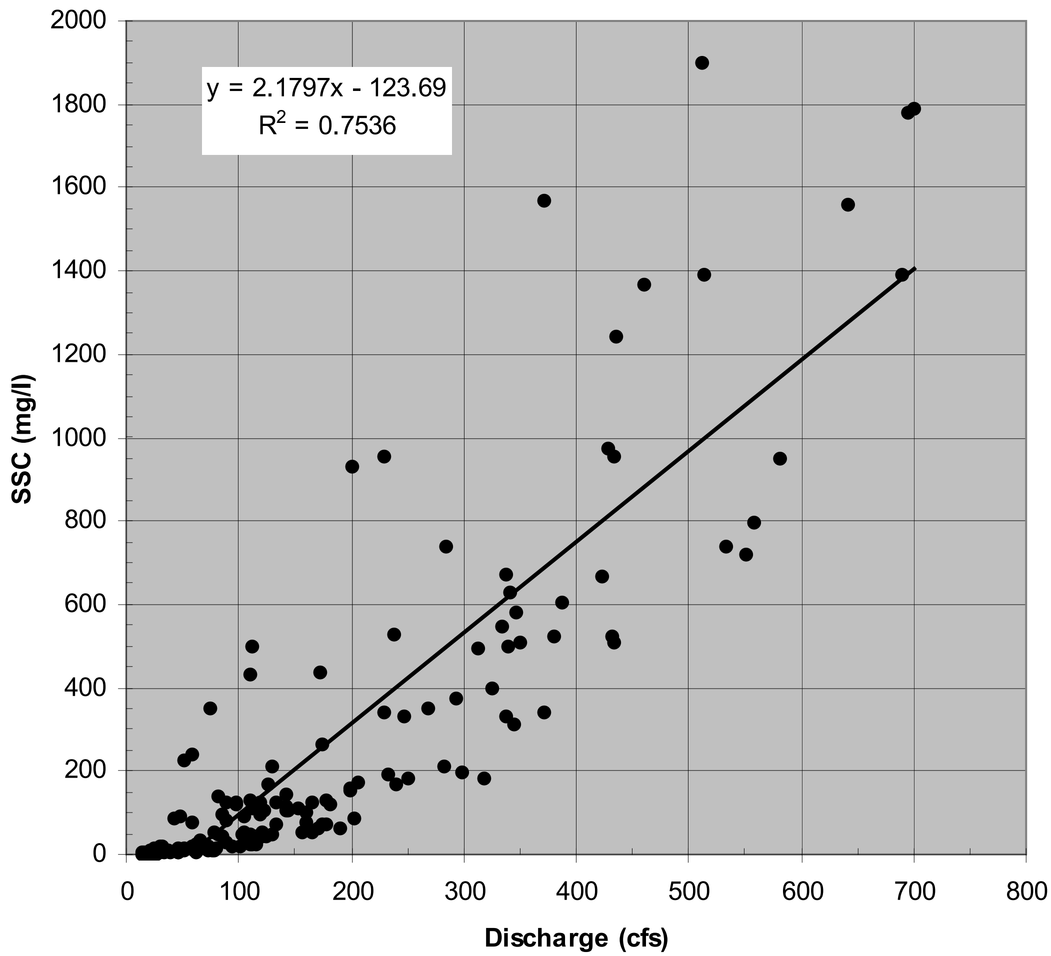

Figure 3-7: Suspended sediment vs discharge, Freshwater Creek, January to August 1999.

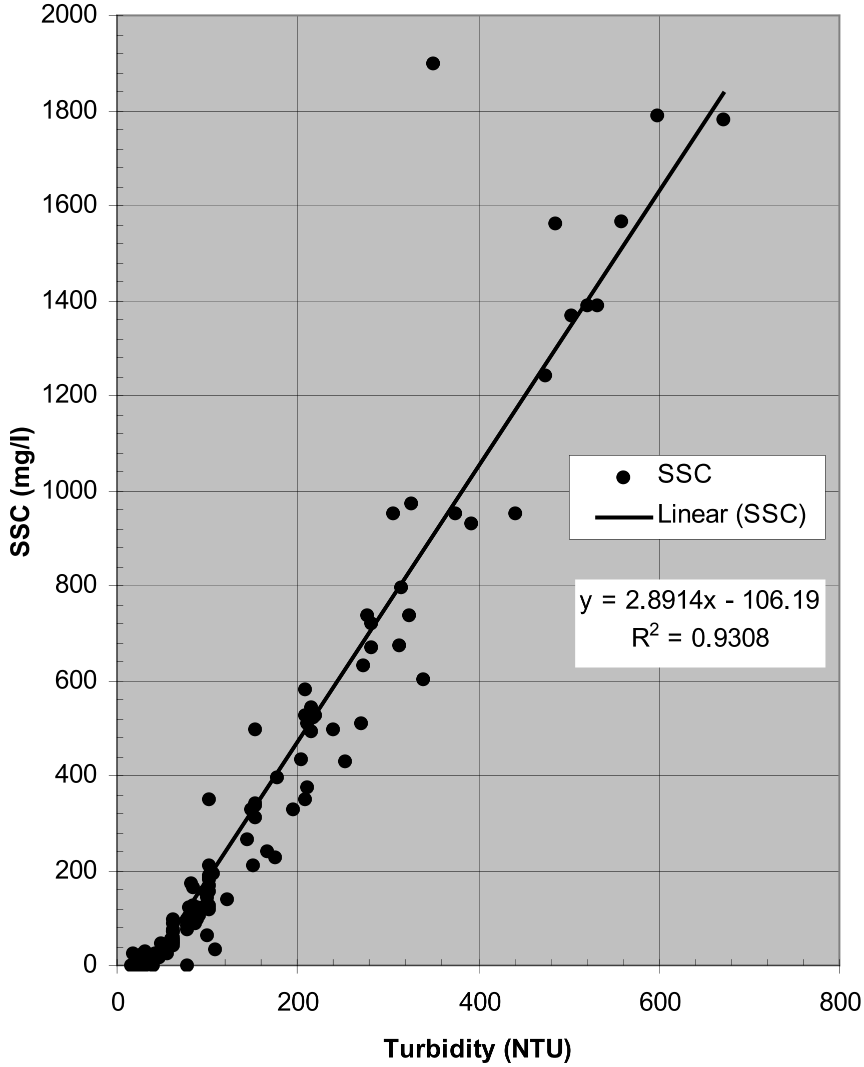

Figure 3-8: Turbidity versus suspended sediment, 1999.

Summary statistics for turbidity and suspended sediment for the entire period of record are provided in Table 3-10. Turbidity and TSS at the 90th percentile were within levels that have caused behavioral changes in fishes as reported in the literature (Attachment F-1). However, the mean, median, or lower quartile values for turbidity and TSS, were generally below risk screening values provided in the published literature (Newcomb and Jensen 1996; Attachment F-1).

Table 3-10: Stage, discharge (flow), and turbidity summary, January 13, 1999 to April 2, 2000. Total suspended sediment concentration calculated from 1/13/99 to 8/2/99 only.

	Stage	Flow (cfs)	Turbidity (NTU)	TSS (mg/l)
Average	0.58	39.6	21.5	24.6
sd	0.54	67.8	49.5	87.8
Median	0.40	4.8	10	2
Mode	0.11	1.0	0	2
25%	0.18	4.0	0	2
75%	0.83	49.9	28	17.6
90%	1.26	100.6	48	49.4

Load Estimation

The total load of suspended sediment delivered past the monitoring station into Freshwater Creek was calculated using the estimated TSS as recorded by the RSL, and integrated over time, between January 13, 1999 and July 31, 1999 (Table 3-11). The additive assessment provided below simply represents the summation of TSS by discharge, over the period of record. The linear and LOESS model estimates were calculated by the RSL. Suspended sediment data from hydroyear 2000 have not undergone complete quality control and are therefore not presented in this report. However, preliminary load estimates for this latter period of record have been addressed in the Surface Erosion Report (Appendix B).

Table 3-11: Estimates of total load of suspended sediments.

Linear Model	LOESS Model	Additive Model
2,845,365 kg	2,800,470 kg	2,804,875 kg
826 kg/ha	813 kg/ha	814 kg/ha
236 ton/sq mi	232 tons/sq mi	282.7 tons/sq mi

Relationship between Rainfall and Suspended Sediment

The response of TSS to rainfall was evaluated to explore the potential for using rainfall to predict sediment loads and risk events. When considered over discrete time points such as the late winter and spring storms of 1999, rainfall was found to represent a reasonably good predictor of suspended sediment (R^2 = 0.883) (Figure 3-9). However, over longer time periods, such as when considering all storm events on record (as identified by peak stream discharge) the relationship was not strong (R^2 = 0.33) (Figure 3-10).

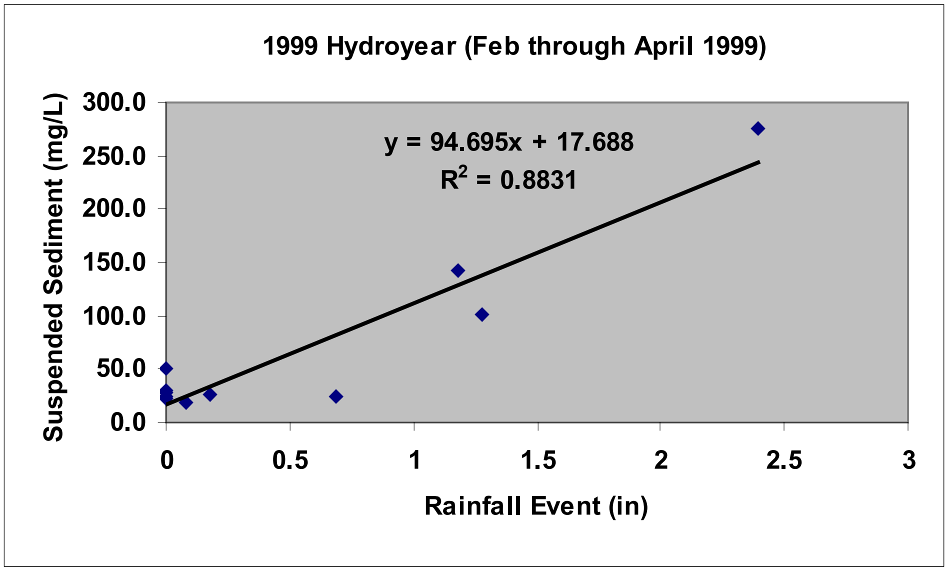

Figure 3-9: Suspended sediment in Freshwater Creek following discrete rainfall events in 1999.

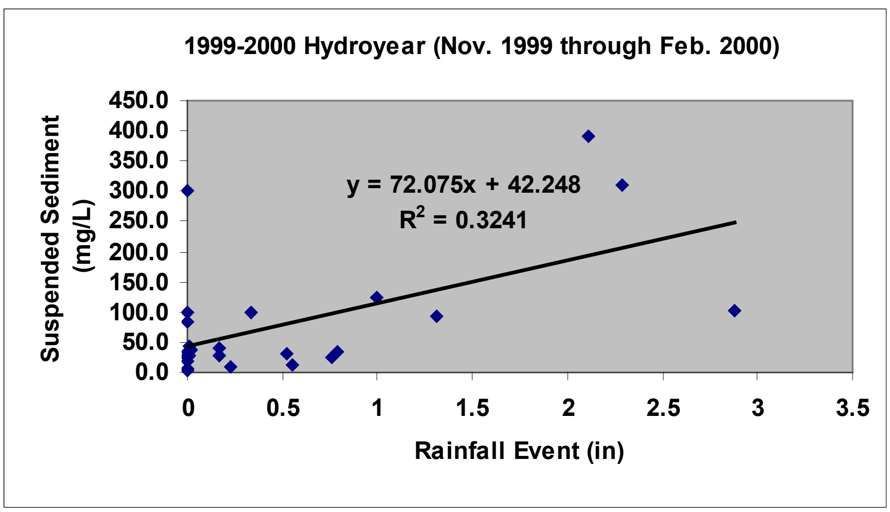

Figure 3-10: Suspended sediment in Freshwater Creek following storm events in hydrologic year 2000.

The strength of the association for all time points was reduced because of the lag time between rainfall in the upper watershed and its measurement at the rain gauge, and because rainfall is not uniform within a watershed. Thus, a single measuring station is equally likely to over- or under-represent total rainfall for specific storm events. The use of rainfall to gauge suspended sediment could therefore be enhanced by rainfall gauging at multiple stations to provide a spatially integrated reading for the watershed; however, this is not currently being done for the Freshwater Creek Watershed. Nevertheless, rainfall measured at only the single station provides a fair-to-good index of potential suspended sediment concentrations realized after a storm, and the potential sediment loading of fines into the watershed. For example, using either of the regressions provided in Figures 3-9 or 3-10, one would estimate a total suspended sediment concentration of (approximately) 113 mg/l following a 1-inch rainfall event. Similarly, a half-inch event would result in a TSS concentration of approximately 65 to 75 mg/l. With further refinement, this type of analysis could be useful for predicting sediment loading into streams from a given rainfall event under existing management practices (e.g., miles of roads in watershed, etc.). Thus, it may be possible to predict sediment loading under different management practices in the future under similar rainfall conditions. Clearly, further refinement of this analysis will be considered.

Risk Characterization of Suspended Sediment Concentrations to Salmonids

Over the entire period of record, no conditions within the basin imparted risk numbers that would be associated with direct mortality, or paralethal effects such as reduced growth, as the highest risk number recorded did not exceed 8 (Figure 3-11).

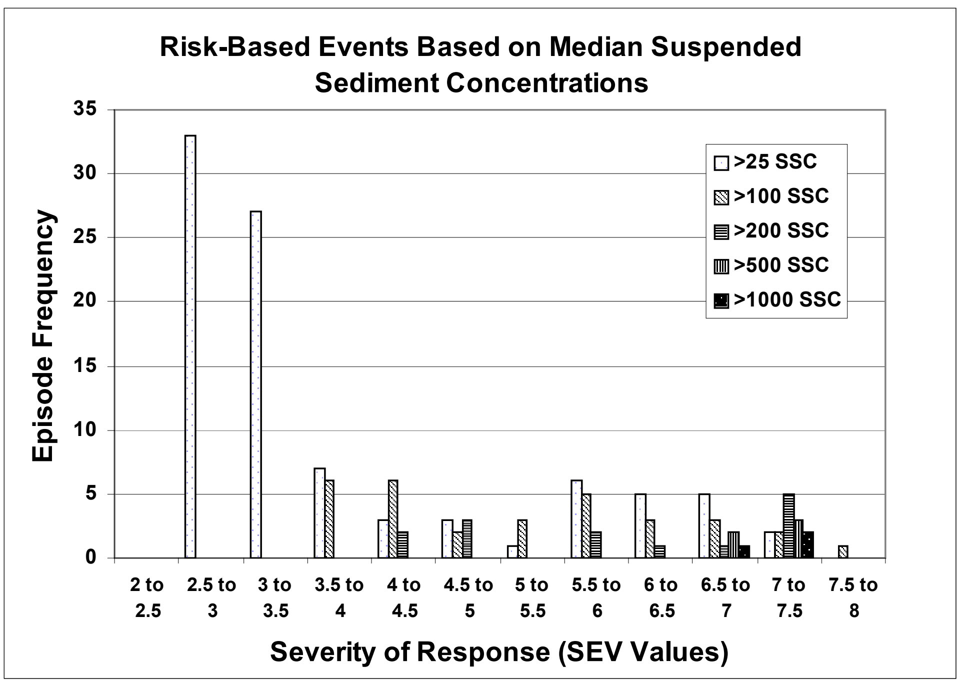

Figure 3-11: Episodic frequency of severity scores for suspended sediment concentration (TSS) induced risks to juvenile and adult salmonids.

The majority of risk numbers were associated with behavioral effects such as alarm and avoidance (SEV scores of 1 to 3), or sublethal effects such as reduced feeding (SEV score of 4), or minor physiological stress (SEV scores of 5 and 6). For comparative purposes, suspended sediment concentrations greater than 25 mg/l were assumed to be influenced by management related sediment inputs; a level of 25 mg/l is also roughly equivalent to the lowest effect level reported in the literature (Sigler 1988). As demonstrated in Figure 3-11, turbidity events >25mg/l but less than 100 mg/l (the next grouping) resulted in the majority of the risk events recorded. Severity of effect scores of 7 and above, associated with habitat degradation, were recorded a total of 15 times (Figure 3-11) and were associated with either very long duration events at low TSS, or brief exposures at very high concentrations.

While the depiction of SEV score frequencies is helpful in understanding conditions of potential effect, it is also worthwhile to examine the frequency that exposure durations at elevated concentrations are actually realized in the basin. Figure 3-12 represents this information, and reflects that most of the exposure conditions that are factored into the SEV frequency analysis (Figure 3-11) are occurring under transient conditions lasting less that 6 hours. Exposure conditions of more than 96 hours occurred only twice, and only at the >25 mg/l exposure category.

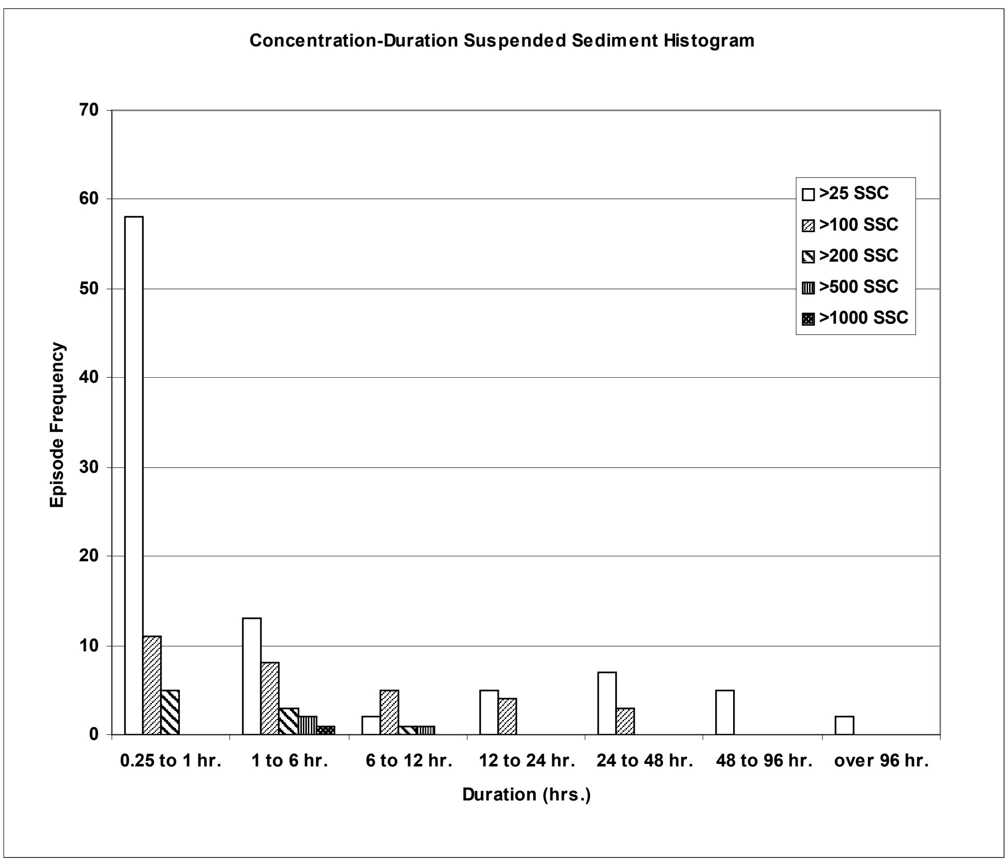

Figure 3-12: Episodic frequency of exposure duration by suspended sediment concentration.

This is potentially important because such short exposures, coupled with lower winter water temperatures that reduce metabolic activity levels in fish, suggests that actual impacts may be significantly lower than those indicated by the Newcombe and Jensen model results. Exposures of 24 to 96 hours, typical for acute bioassay protocols, occurred 15 times, 13 of which were associated with total suspended sediment concentrations in the >25 mg/l category (Figure 3-12).

The frequency of specific storms that achieved an SEV of at least 2 was compared between the mean and median TSS concentration data for those TSS concentrations that exceeded the nominal “background” of 25 mg/L used throughout the analysis. The average of all SEV scores where the median TSS concentration of each storm event was used to calculate the SEV (keeping in mind that each individual storm event will generate an SEV score), exceeded the average SEV score calculated from the mean TSS concentrations over the same storm events. However, the use of the mean TSS to calculate the SEV resulted in substantially more risk events than if the median TSS for each storm event was used to calculate the SEV (e.g., 102 vs. 57 at >25 mg/l, Table 3-12). The median analysis represents a better approximation of the geometric mean, a more conservative measure of the TSS concentration to which fish would be exposed during the course of a storm event.

Table 3-12: Comparison of SEV scores calculated with the mean or median TSS.

SEV Score -->	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8
Median TSS $\leq$ 25 mg/l	1	34	15	15	2	6	15	2	1				
Median TSS > 25 mg/l			16	16	4	4	0	5	7	2	4	0	1
Mean TSS > 25 mg/l		28	21	21	4	4	1	9	7	4	1	3	1
		Median < 25			**Median > 25**				**Mean > 25**				
Average SEV Score		3.50			4.4				3.8				
St. Deviation		1.04			1.4				1.4				
Median		3.02			3.6				3.2				

3.6.2 Water Temperature

The maximum temperatures measured in the Freshwater Watershed ranged from 19.7°C measured in the mainstem of Freshwater in 1997 to 13°C measured in a headwater tributary the same year (Table 3-13). The maximum weekly average temperatures (MWATs) ranged from 12.6°C to 17°C from early July through late October. Average summer water temperatures during all three sampling years ranged from 11.6°C to 16°C.

Table 3-13: Summary of temperature data collected on in the Freshwater Watershed 1996 to 1999.

DATES			Station	Days	Average	Maximum Temperature		MWAT			Data
Yr	From	To	Id		Temp. ºC	Value ºC	Date	Value ºC	From	To	Source
96	06/15	09/30	Sta 92-96 Cloney Gulch	108	14.23	17.81	07/26	16.10	07/25	07/31	PALCO
96	06/15	09/30	Sta 36-96 Upper Freshwater	108	12.00	16.55	07/30	14.27	07/25	07/31	PALCO
96	06/15	09/30	Sta 33-96 Main Freshwater	108	14.43	18.34	07/30	16.19	07/25	07/31	PALCO
97	06/15	09/30	Sta 18-97 Little Freshwater	108	15.74	18.76	08/25	16.67	07/15	07/21	PALCO
97	06/15	09/30	Sta 37-97 SF Freshwater	108	15.44	17.53	07/18	16.19	07/15	07/21	PALCO
97	06/15	09/30	Sta 33-97 Main Freshwater	108	16.02	19.72	08/07	17.00	07/14	07/20	PALCO
97	06/15	09/30	Sta 135-97 McCready Gulch	108	14.45	16.93	09/04	15.45	08/31	09/06	PALCO
97	06/15	09/30	Sta 36-97 Main Freshwater	108	12.58	14.59	08/08	13.41	08/08	08/14	PALCO
97	07/01	09/30	Sta 159-97 SF Freshwater – class II	92	12.12	13.14	08/08	12.57	09/24	09/30	PALCO
98	06/15	09/28	Sta 36-98 Upper Freshwater	106	12.21	15.38	08/14	13.83	09/01	09/07	PALCO
98	06/15	09/28	St 135-98 McCready Gulch	106	13.39	15.57	08/12	14.59	08/11	08/17	PALCO
99	07/01	10/15	Sta 36-99 Upper Freshwater	107	11.56	14.59	07/13	13.32	08/23	08/29	PALCO
99	07/01	10/15	Sta 135-99 McCready Gulch	107	12.58	16.27	08/22	14.62	08/21	08/27	PALCO
99	07/20	10/15	Sta 18-99 Little Freshwater	88	13.06	17.72	08/22	15.49	08/21	08/27	PALCO
99	06/22	10/07	Sta 34-99*	108	14.00	18.79	07/26	14.00	08/21	08/27	Willey
99	1/31	8/2	Roelof's Gauge		10.6						RSL

* Temperature monitored at Pool Tail rather than Riffle

Station 92 Cloney Gulch, approximately 1,000 ft upstream of the confluence with Freshwater.
Station 36 Mainstem Freshwater, approximately 8,250 ft upstream of South Fork Freshwater.
Station 33 Mainstem Freshwater, approximately 750 ft downstream of South Fork Freshwater (no longer in use).
Station 18 Little Freshwater, approximately 500 ft upstream of the confluence with Freshwater
Station 37 South Fork Freshwater, approximately 1,000 ft upstream of the confluence with Freshwater (no longer in use)
Station 135 McCready Gulch, approximately 3,750 ft upstream of the confluence with Freshwater.
Station 159 South Fork Freshwater, Class II watercourse, very high up in drainage. Side tributary, Located approximately 1,500 ft upstream of confluence with Sf Freshwater; put in under or near Road 15 crossing of first Class II tributary closest to Road 15 Bridge over SF Freshwater

3.6.3 Substrate Composition

The bulk sediment sampling data show a general variability in substrate composition over the sampling periods (Tables 3-14 and 3-15, and Figure 3-13). The most recent shovel sampling data found that 11 to 47% of the substrate sampled was composed of fines <0.85 mm, and 25 to 59% of the substrate sampled was composed of fines <4.7 mm. In general, the highest values were associated with streams flowing through Wildcat Formation geology. The majority of recorded values for <0.85 mm exceed 11-16% targets in the PFC matrix. There is no diagnostic criteria in the PFC Matrix or Habitat Condition Indices for the <4.7 mm size fraction. However, Bjornn and Reiser (1991) in a summary of scientific literature reported a 50% decline in salmonid emergence when the percentage of sediment in the 2-6.4 mm range exceeded 24-35%. See Section 5.4 for a discussion of the PFC Matrix targets for fine sediment.

Table 3-14: Percentage of substrate composition less than 0.85 mm from PALCO shovel samples collected during late summer or early fall 1994 - 1999. The PFC target is 11-16%*.

PL Station # / CGU	Location	1994	1996	1997	1998	1999
15 / C1	Lower South Fork	23	24	21	24	27
18 / U1	Little Freshwater	-	36	29	47	47
19 / GG	Lower Graham G.	21	27	32	29	20
20 / GG	Upper Graham G.	24	22	23	-	-
32 / MS1	Mainstem	23	12	15	12	13
33 / MS1	Mainstem	12	13	15	-	
34 / C1	Lower Upper Fresh	17	19	17	15	17
35 / C1	Lower Upper Fresh	20	23	23	-	-
36 / C3	Rd. 15 Upper Fresh	23	22	22	19	11
37 / C1	Lower South Fork	20	23	20	-	-
92 / CG	Cloney Gulch	-	-	-	16	25
135 / U1	McCready Gulch	-	47	44	39	26
165 / C2	Mid Upper Fresh	-	-	-	14	11

*All reported values are averages based on multiple samples

Table 3-15: Percentage of substrate composition less than 4.7 mm from PALCO shovel samples collected during late summer or early fall 1994 - 1999. The <4.7mm size fraction is not represented in the PFC Matrix or Habitat Condition Indices*.

PL Station # / CGU	Location	1994	1996	1997	1998	1999
15 /C1	Lower South Fork	49	43	40	39	46
18 / U1	Little Freshwater	-	51	41	55	59
19 / GG	Lower Graham G.	36	47	66	56	43
20 / GG	Upper Graham G.	39	47	50	-	-
32 / MS1	Mainstem	35	28	30	25	36
33 / MS1	Mainstem	19	27	33	-	-
34 / C1	Lower Upper Fresh	27	32	38	36	29
35 / C1	Lower Upper Fresh	33	48	40	-	-
36 / C3	Rd. 15 Upper Fresh	49	43	50	38	28
37 / C1	Lower South Fork	34	40	39	-	-
92 / CG	Cloney Gulch	-	-	-	37	46
135 / U1	McCready Gulch	-	66	60	59	53
165 / C2	Mid Upper Fresh	-	-	-	32	25

*All reported values are averages based on multiple samples

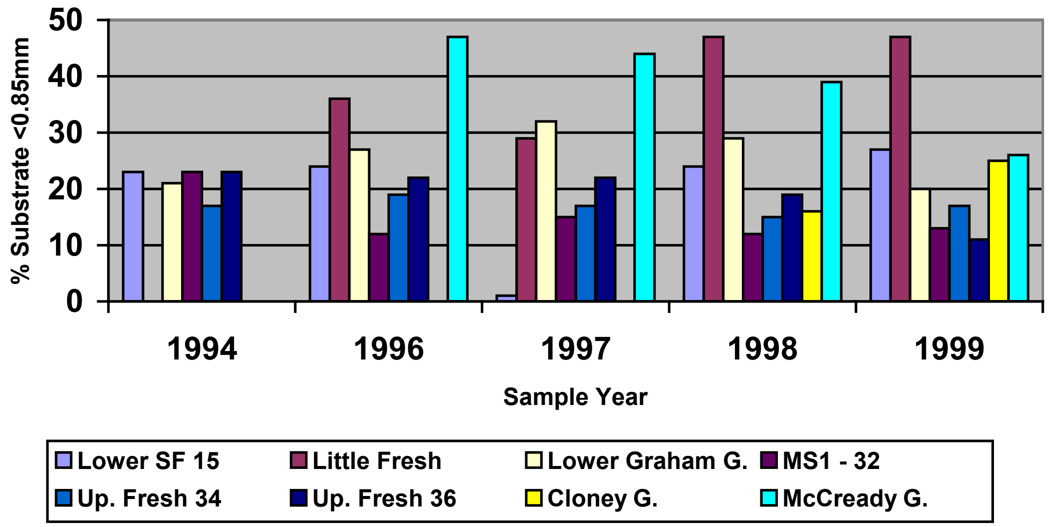

Figure 3-13: Percentage of substrate composition less than 0.85 mm from PALCO shovel samples collected during late summer or early fall 1994 - 1999. The PFC target is 11-16%.

3.6.4 V*

Higgins (2000) reported that Knopp (1993) sampled fine sediment in pools (V*) and streambed particle size distribution in 1992 and 1993 in Graham Gulch, South Fork, and upper Freshwater Creek. V* values represent the proportion of total scoured pool volume that is occupied by fine sediments. The same reaches were re-sampled in 1999. Results from both surveys are shown in Figure 3-14.

V* values for South Fork Freshwater Creek remained fairly constant in all years, with values ranging from 0.52 to 0.59. Graham Gulch showed an increase from 0.35 to 0.51 between 1992 and 1999. The North Fork of Freshwater Creek showed the greatest increase in V*, varying from 0.19 in 1992 to 0.15 in 1993 then rising to 0.46 in 1999. Although this is a limited dataset, the V* information shows a general pool filling trend in the survey reaches. The 1999 V* results exceed the PFC Matrix target of less than 0.2. Please see the Stream Channel Assessment for an expanded discussion of V*.

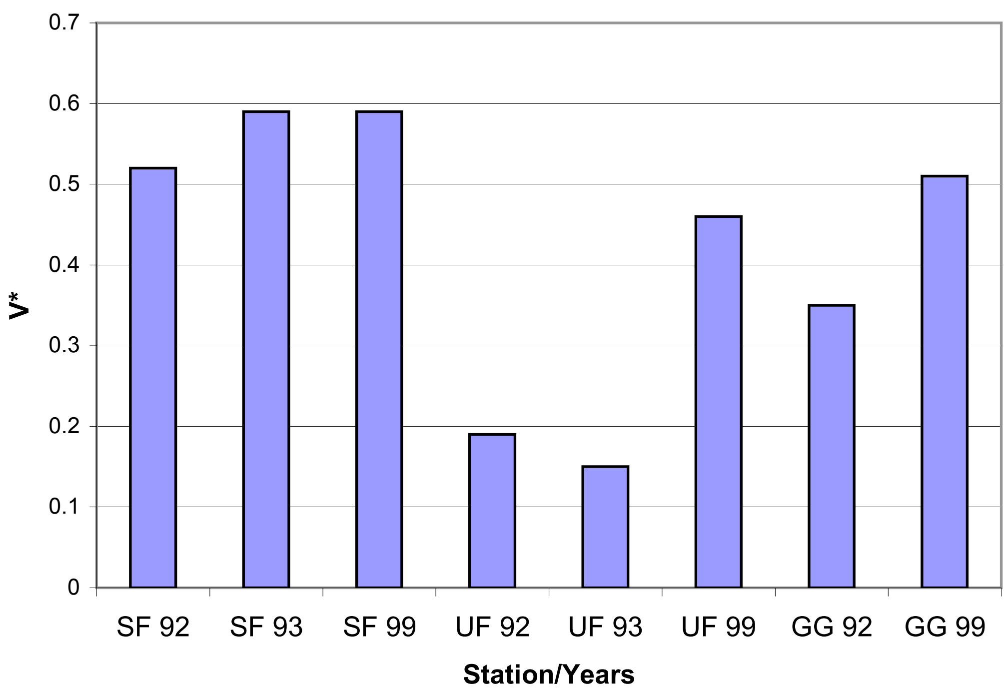

Figure 3-14: V* results from 1992, 1993, and 1999 at three locations in Freshwater Creek: the lower South Fork (SF), Upper Freshwater (UF) above the convergence with the South Fork, and Graham Gulch (GG). Data from Knopp (1993) and PALCO. The PFC target is V* <0.2.

3.7 AREAS OF CONCERN

An "Area of Concern" is an area that has degraded habitat, limited habitat availability, refuge areas, or has high utilization by a particular species or life phase. These areas warrant additional management consideration due to their biological sensitivity and importance. For example, although salmonids spawn throughout the Class I watercourse system, a few reaches have particularly high utilization and importance. These high use reaches (MS1, CG, and C1-Upper Freshwater) are considered spawning areas of concern.

3.7.1 Spawning Areas of Concern

Chinook salmon spawning generally occurs in Upper Freshwater and the mainstem down to the mouth of McCready Gulch (Map F-3). These reaches generally have higher flows and relatively large patches of spawning gravel. Coho salmon and steelhead are known to spawn in every subbasin to the limit of anadromy. They can generally utilize smaller watercourses and smaller patches of gravel than chinook. Coho generally spawn in smaller streams than chinook (Moyle et al. 1995). Coastal cutthroat trout spawn throughout the basin including upstream of salmon and steelhead migration barriers. They can utilize small pockets of gravel in headwater areas.

Generally spawning habitat conditions are poor in the unconsolidated CGUs and the lower reach of MS3. These include McCready Gulch (U1), lower Little Freshwater (U1), School Forest (U2), Graham Gulch (GG), and the resident reach of Freshwater Creek (MS3). The fine-grained nature and general absence of gravels in soils derived from the unconsolidated geologic formations (e.g., Wildcat) may partially explain this observation. The best spawning habitat occurs in MS1 (South Fork to Graham Gulch), C1 (upper Freshwater and lower South Fork), and CG (Cloney Gulch). Good quality spawning habitat also occurs in mid-Little Freshwater, MS2 and upper MS3, although the number of spawning observations are relatively low. Of the 1,054 redds observed by HFAC between 1986 and 1999, 723 (or 68%) were found in MS1, C1, and CG. However, the Substrate Condition Evaluation (Table 3-5) indicates that the presence of sand and fine sediment and relatively high embeddedness levels reduces the quantity and quality of spawning habitat in many reaches throughout the WAU. See Map F-4: Spawning Areas of Concern.

Adult salmonids generally move into the WAU during the fall, winter, and spring and hold in pool habitats prior to spawning. In some cases, adult salmonids may have to hold at the spawning grounds until their gonads mature prior to spawning. These fish typically require deep pools with cover elements during these periods. The CGUs with the greatest percentages of pools deeper than two feet (measured at summer low flow, not the higher winter spawning flows) are C1, CG, MS1, and MS3. With the exception of MS3, these CGUs also correspond to the areas with highest spawning use.

3.7.2 Rearing Areas of Concern

Salmonid rearing habitat is made up of several instream habitat characteristics including cover components (LWD, boulders, undercut banks, rootwads, bubble curtains, etc.), adequate stream-flow, appropriate water temperature, substrate composition, pool depth, pool area, and frequency. Pool area and frequency, LWD function, and habitat complexity information from field surveys were used to determine summer rearing habitat conditions. Downstream migrant trapping records and electrofishing data were also used determine fish utilization. Water temperatures were not used as a diagnostic metric since they are generally within the preferred range for salmonids in the WAU.

Salmonids rear in every accessible reach in the WAU. Based on the 1999 and 2000 downstream migrant trapping data (HFAC 1999), chinook rearing occurs primarily in the mainstem between the South Fork and Graham Gulch (MS1). Coho and steelhead tend to utilize the mainstem (MS1), Upper Freshwater and lower South Fork (CG1), Cloney Gulch (CG), and McCready Gulch (U1). Coastal cutthroat tend to be found throughout the WAU and inhabit reaches upstream of anadromous migration barriers.

The South Fork Freshwater (C1) and Upper Freshwater Creek had the highest densities of juvenile salmonids according to index reach electrofishing summaries. Lowest utilization by juvenile salmonids appears to be in Graham Gulch (GG), where a significant portion of the upper channel reaches have intermittent flow. According to the Pool Condition Evaluation (Table 3-4), every CGU sampled contains fair to good rearing habitat. However, the Substrate Condition Evaluation (Table 3-5) and V* results indicate that the presence of sand and fine sediment in pool and riffle habitat reduces the quality and may reduce the quantity of rearing habitat in many locations in the Freshwater watershed. See Map F-5: Rearing Areas of Concern.

Good winter rearing areas for salmonids contain a number of characteristics including large substrate with interstitial spaces, plentiful LWD, complex pools, and access to floodplains and side channels. Upper Freshwater (C1, C2, C3) appears to provide the best winter rearing habitat in the basin, followed by middle to upper Little Freshwater (U1, U2) and middle McCready Gulch (U2). This is due to abundant instream LWD cover and access to velocity refugia on floodplains. Relatively poor winter rearing conditions exist in Lower Freshwater (MS3) and the School Forest (U2) due to heavily embedded substrates that restrict juvenile salmonids from using interstitial spaces in the streambed as cover, poor access to floodplains, and low LWD complexity. Graham Gulch (GG) provides fair to good winter rearing habitat, but the presence of the county road culvert, which tends to block upstream juvenile migration, restricts the ability of juvenile salmonids to utilize the subbasin. County culverts on McCready and Cloney Gulches also appear to restrict fish movement into these basins (see Section 3.7.3)

3.7.3 Migration Areas of Concern

There are no man-made barriers to salmonid migration on PALCO land within the WAU. However, upstream adult migration ceases when it reaches high gradient reaches, waterfalls, and/or impassable boulder roughs in each of the subbasins.

Three road crossings downstream of PALCO land in the lower reaches of McCready Gulch, Cloney Gulch, and Graham Gulch are either seasonal or permanent migration barriers for salmonids (Taylor 2000). The McCready Gulch crossing is located on an old county road that is outside PALCO land. It is constructed of a perched concrete box culvert with a natural bottom and may be a velocity barrier to juvenile migration at high flows. The Cloney Gulch county road crossing is constructed of a half-arch with a concrete floor. It is a partial barrier for adults and a complete barrier for juveniles due to jump height and outlet flow pattern. The Graham Gulch county road crossing is constructed of a sectional steel pipe. It is a partial barrier to adults and a complete barrier for juveniles due to jump height. See Resource Sensitivity Report – Migration, as well as Map F-1: Salmonid Distribution Map. Intermittent reaches exist in upper Cloney Gulch, Graham Gulch, and South Fork Freshwater Creek. In these areas, low summer flows travel through sediment deposits in the channel bed rather than as overland flow. These reaches create summer season migration barriers for juvenile salmonids. See Map F-5 for migration areas of concern locations.

4.0 RESOURCE VULNERABILITY

Channel segments with similar physical characteristics (stream gradient and geology) and responses are grouped into 12 channel geomorphic units (CGU). The Stream Channel Module (Appendix E) developed the CGU descriptions. Data on habitat conditions and salmonid life history and distribution patterns, obtained from field surveys and historical analysis, were extrapolated to all segments in each CGU and used to determine the potential biological and habitat response to changes in input factors. These inputs are LWD, bank stability, peak flow, coarse sediment, and fine sediment. The potential for biological or habitat response to the input variables is termed the "resource vulnerability." The Fisheries Module analyst has consulted with other module analysts to determine the vulnerability of the fisheries resources to increases or decreases in inputs (Table 4-1). The logic behind how these vulnerability calls were developed for each CGU follows.

Table 4-1: Fish Habitat Vulnerabilities (Low, Medium, High) for each Channel Geomorphic Unit.

CGU		LWD	Bank Stability	Peak Flow	Coarse Sediment *	Fine Sediment *
Consolidated Geology						
C1	0-3%	H+	L	H	H	H
C2	3-6.5%	M+	L	M	M	M
C3	6.5-20%	M+	L	L	L	L [2]
C4**	20+%	L+	L	L	L	H[2]
Unconsolidated Geology						
U1	0-3%	H+	L	H	H+	H
U2	3-6.5%	H+	L	M	H+	M
U3	6.5-20%	L [1]	L	L	M+	L [2]
U4**	20+%	L+	L	L	M	L
Exceptions						
MS[1] (South Fork to Graham Gulch)		H+	L	H	H [3]	H
MS[2] (Graham Gulch to Little Freshwater)		H+	L [4]	H	M	H
Ms[3] (Little Freshwater to 3 Corners)		H+	L [4]	M	M	M
GG (Graham Gulch 0-6.5%)		H+	L	H	H	M
CG (Cloney Gulch 0-3%)		H+	L	H	H+/H	H

* Coarse sediment: >8 mm for fish, >2 mm for channel processes, Fine sediment: 8 mm or less
** Non-fish bearing streams
+ Increase in coarse sediment may have positive effects in this gravel-poor geology
[1] May have been more prior to first harvest
[2] High negative impact to amphibians, low for fish due to scarcity, filling of seeps with fines
[3] Too much coarse sediment can destabilize channel, but moderate increases may be beneficial
[4] Bank erosion could create more complex habitats if residents allowed it to occur

4.1 U1 - UNCONSOLIDATED WILDCAT

Description: Confined, pool-riffle channel with gradients of 0-3%. Substrate is predominantly sand and fines. Wood frequency is high. Pool area (60-76% of wetted channel area) is good.

Pool frequency is good with one pool every 1.9-3.7 channel widths. Most pools in this CGU are formed or associated with LWD. Some pools are formed by scour along bedrock. Bank erosion is present in some of the habitat units. Floods are able to spill over onto narrow floodplains in some locations. This CGU is located in portions of Little Freshwater Creek, McCready Gulch, and Falls Gulch.

Fish Habitat Conditions: The dominance of sand and fines in the substrate, typical of Wildcat geologies, has created poor spawning conditions and adversely affected rearing habitat. Although an average of 8.5% of the channel area contained spawning gravels, the embeddedness level was very high at 3.4. The high percentage of pools and LWD cover provides fair to good conditions for rearing salmonids. The high level of canopy cover provides abundant shade and source areas supplying terrestrial insects to the watercourses. Winter rearing habitat is fair with complex LWD cover in pools and low to moderate access to narrow floodplains. *Anomalous Segments*: NA

Conditions and Response Potential

LWD - Abundant functional LWD that meets the PFC Matrix key piece targets was observed in the surveyed reaches. Unstable banks are significant factors for recruitment of LWD into this channel type. Given the unconsolidated nature of the geology, LWD is an important habitat-forming structure due to its ability to facilitate pool scour and trap sediment. Due to the highly embedded substrates, LWD provides the majority of the rearing cover for juvenile salmonids. LWD also provides an important winter rearing habitat component whether it is in the bankfull channel or on the floodplain. *High Vulnerability +*

Bank Stability - Unstable banks are present in some of the habitat units and in some cases are associated with flow being deflected by LWD. Some of the erosion was the result of high flows scouring the banks. Bank erosion can increase as streambeds aggrade. However, bank erosion is a minor contributor of sediment to the channel when compared to landslides and the road network. *Low Vulnerability*

Peak Flow - Due to the relatively small substrate size, confined nature of the channel, and (when present) narrow floodplains, peak flows have the potential to scour redds. Winter rearing survival of juvenile salmonids is dependent on access to complex LWD and floodplains during high flows. *High Vulnerability*

Coarse Sediment - Coarse sediment accumulations are currently limited in this CGU. The Wildcat Group is composed of mudstones and siltstones that rapidly deteriorate during discharge events that transport bedload and tend to embed those rare coarse sediments that may be present. Therefore, any accumulation of coarse sediment is considered beneficial for fish. *High Vulnerability +*

Fine Sediment - There is an abundance of fine sediment in this CGU that fails to meet the PFC Matrix targets. The fine sediment load is due to natural contributions from the unconsolidated geology and management activities. A reduction in fine sediment input could increase the availability of coarse gravels and provide a significant improvement in spawning habitat quality. Not all fines flush during high flows so pool quality could be moderately affected by increases. *High Vulnerability*

4.2 U2 - UNCONSOLIDATED WILDCAT

Description: Confined, pool-riffle channel with gradients of 3-6.5%. Substrate is predominantly fine sediment. Gravel is subdominant in those reaches downstream of consolidated geologies. Wood frequency is high and meets PFC targets. Pool area and frequency is good and meet the PFC targets. Ninety four percent of the pools in this CGU are formed from LWD. Average wetted and bankfull widths are 2 and 14 ft, respectively. This CGU is located in portions of Little Freshwater Creek, McCready Gulch, and School Forest.

Fish Habitat Conditions: The dominance of fines in the substrate has created poor spawning habitat conditions that fail to meet the PFC Matrix targets. Only 2% of the channel area contained spawning gravels; the embeddedness level in these gravels was very high averaging 3.7. The high percentage of pools and LWD cover provides good to fair conditions for rearing salmonids that would probably be better without the heavy fine sediment load. The high level of canopy cover provides abundant shade and source areas supplying terrestrial insects to the watercourses. Winter rearing habitat is fair with complex LWD cover in pools. *Anomalous Segments*: NA

Conditions and Response Potential

LWD - Abundant functional LWD that meets the PFC Matrix key piece targets was observed in the surveyed reaches. Given the unconsolidated nature of the geology, LWD is an important habitat-forming structure due to its ability to facilitate pool scour and trap sediment. Unstable banks are one of the primary factors for recruitment of LWD into this channel type. Due to the highly embedded substrates, LWD provides the majority of the rearing cover for juvenile salmonids. LWD also provides an important winter rearing habitat component, whether it is in the bankfull channel or on the floodplain. *High Vulnerability +*

Bank Stability - Unstable banks are present in some of the habitat units and in some cases is associated with flow being deflected by LWD. Some of the erosion was the result of high flows scouring the banks. However, bank erosion is a minor contributor of sediment to the channel when compared to landslides and the road network. *Low Vulnerability*

Peak Flow - These segments have low spawning use due to their higher gradient and lack of spawning gravel. Therefore, potential impacts of scour are limited. High volumes of LWD help stabilize channel, reducing the potential for scour *Moderate Vulnerability*

Coarse Sediment - Coarse sediment accumulations are currently limited in this CGU. The Wildcat Group is composed of mudstones and siltstones that rapidly deteriorate during discharge events that transport bedload and tend to embed those rare coarse sediments that may be present. Therefore, any accumulation of coarse sediment is considered beneficial for fish. *High Vulnerability +*

Fine Sediment - There is an abundance of fine sediment in this CGU that fails to meet the PFC targets. The fine sediment load is due to natural contributions from the unconsolidated geology and management activities. The fines have a detrimental impact on spawning habitat quality, although there is limited spawning in these CGUs. Fines tend to flush during high flows so pool development is only moderately affected by increases. *Moderate vulnerability*

4.3 U3 - UNCONSOLIDATED WILDCAT

Description: Confined, step pool/cascade channel with gradients of 6.5-20%. The vast majority of watercourses in this CGU are either Class II or Class III streams with intermittent or ephemeral flow. Substrate is composed of predominantly mudstone and siltstone bedrock with boulders in several reaches from upstream consolidated geologies. Although directed LWD surveys were not conducted in this CGU, instream wood frequency is good. Pool area and frequency are good, meeting PFC targets. Most pools in this CGU are either plunge or bedrock formed. This CGU is located in many of the Little Freshwater, McCready Gulch, School Forest, Upper Freshwater, and South Fork tributaries.

Fish Habitat Conditions: The high gradient and geology type have limited the availability of spawning habitat in this CGU. Only 1.6% of the channel area contains spawning habitat, which has an embeddedness rating of 1.9. In those reaches with perennial flow, the high percentage of pools and boulder cover (provided by upstream Franciscan or Quaternary formations) provides good conditions for rearing salmonids. The high level of canopy cover provides abundant shade and source areas supplying terrestrial insects to the watercourses. Winter rearing habitat is good with boulder and LWD cover in pools. However, the high gradient severely limits utilization by salmonids. As stated above, many of these CGU units are located in Class II or Class III watercourses. Bank erosion is present in some units.

Anomalous Segments: PWA 203 in Falls Gulch has a natural high gradient boulder fish barrier located downstream.

Conditions and Response Potential

LWD - LWD provides for sediment storage and channel stability in this CGU. However, pool formation and salmonid summer and winter rearing cover are provided primarily by bedrock, boulders, and large cobble. *Low Vulnerability*

Bank Stability - Unstable banks are present in some of the habitat units. However, the sediment produced from the erosion would consist of small particles that are easily transported during high flows and do not significantly affect aquatic habitat in this CGU. *Low Vulnerability*

Peak Flow - Due to the confined, high gradient nature of the channel, high flows move with great velocity and create a cascading effect. There are ample locations for juvenile salmonids to take advantage of velocity cover behind or under the LWD, boulders, and cobbles in the Class I reaches during high flows. The high flows have the ability to scour out any redds present in the pool tailouts, although the gradient in many segments may be too high for most spawning salmonids. *Low Vulnerability*

Coarse Sediment - Coarse sediment is limited in this CGU due to the high gradient and poor ability of the Wildcat formation to produce gravel. Any coarse sediment present originates in upstream consolidated geologic formations. The pool habitats are currently composed of plunge and bedrock scour pools. A significant increase in coarse sediment may result in some filling of these habitats and a decrease in rearing potential, but these tend to be poor habitats for fish. An increase in competent gravel could improve amphibian habitat. *Moderate Vulnerability +*

Fine Sediment - Due to the steep gradients and confined channels, fines tend to flush from these reaches during high flows. However, excessive fines could fill in the interstitial spaces in seeps affecting amphibians. *Low Vulnerability for fish, High for amphibians*

4.4 GG - GRAHAM GULCH

Description: Confined, sediment-rich channel with gradients of 0-6.5%. Substrate is predominantly small cobble and gravel. Wood frequency is high, with 57% of the pools being formed by LWD. One hundred percent of the pools are associated with LWD. LWD key piece numbers meet PFC targets, but piece volume is slightly lower than target levels. Much of the LWD, especially in the lower reach, was manually placed during instream habitat enhancement activities. Pool area (50%) and frequency (1 pool every 2.8 channel widths) meet PFC targets in the lower reaches, but fall short in the upstream aggraded area. Surface flow becomes intermittent in the upstream reach. Floods are able to spill over onto narrow floodplains in some locations. A large, deep-seated landslide approximately midway up the drainage contributes large volumes of coarse sediment to the channel, resulting in aggradation. A review of this landslide conducted by the California Division of Mines and Geology (CDMG) staff led them to conclude that this feature occurred in the 1940s or 1950s and is probably of natural origin. There is a culvert under the county road that forms a partial barrier for upstream migrating adult salmonids and a complete barrier for juveniles.

<u>Fish Habitat Conditions</u>: The dominance of coarse substrate has created aggraded conditions and subsequently poor to fair spawning habitat conditions in upstream reaches. Although an average of 14.9% of the channel area contained spawning gravels, the embeddedness level was high (3.0 rating), and the bed may be susceptible to shifting during high flows. Rearing habitat quality is good in the lower reach. Summer rearing habitat quality in the upper reach is poor due to intermittent flow conditions, but becomes good once surface flows commence. The high level of canopy cover provides abundant shade and source areas supplying terrestrial insects to the watercourses. Winter rearing habitat is fair with complex LWD cover in pools and low to moderate access to narrow floodplains. Bank erosion is present in some of the habitat units. The combination of poor quality habitat elements, unstable substrate conditions, and blockage of fish passage by a county road culvert greatly reduces utilization of this CGU by salmonids.

Anomalous Segments: PWA Segment 302 (downstream of deep seated landslide) has intermittent flow, which eliminates summer rearing habitat potential and creates seasonal juvenile migration barriers. This condition may improve once the slide stabilizes and high flows transport excessive bedload from the system.

Conditions and Response Potential

LWD - Functional LWD was observed in many pools in the surveyed reaches. LWD is an important habitat-forming structure due to its ability to facilitate pool scour and trap sediment. This functionality is especially important in this CGU due to the high sediment inputs that aggrade the streambed in many places. LWD also provides an important winter rearing habitat component whether it is in the bankfull channel or on the floodplain. *High Vulnerability +*

Bank Stability - Unstable banks are present in some habitat units and upstream in the vicinity of the earthflow. However, sediment produced from the earthflow significantly exceeds the contribution from bank erosion. *Low Vulnerability*

Peak Flow - Sustained high flows have the potential to transport bedload and aid in pool development. High flows have the potential to mobilize bed and scour redds in this CGU. *High Vulnerability*

Coarse Sediment - Coarse sediment is extremely abundant in this CGU. The landslide contributes large amounts of coarse sediment, which aggrades the channel and degrades spawning and fills in rearing habitats in many places. Therefore, any additional accumulation of coarse sediment is considered detrimental to fish. *High Vulnerability*

Fine Sediment - There is an abundance of sand and fine sediment in the spawning substrate. Embeddedness is very high due to excessive sediment inputs, which results in poor spawning habitat quality. However, should the landslide stabilize and road erosion control work continue, the relatively high gradient (average 3% in fish-bearing reach) and corresponding high water velocities may help flush fines from the subbasin. *Moderate Vulnerability*

4.5 CG - CLONEY - GULCH

Description: Gravel-rich, 1.5–3% gradient pool-riffle channel. Substrate is predominantly small cobble and gravel. The number of pieces and volume of LWD meet or exceed PFC targets, although its contribution to pool formation is lower than ideal with a range of 11–33% of the pools being formed by LWD. Approximately 78–92% of pools are associated with LWD. Much of the LWD is old with limited recruitment of new pieces. Pool area (75% of wetted channel area) is good. Pool frequency is good with one pool for every three channel widths. Some pools are formed by scour along bedrock. Several pools in the lower reach contain man-made LWD structures. Floods are able to spill over onto narrow floodplains in some locations.

Fish Habitat Conditions:

Lower Reach: There is fair quality spawning habitat conditions in the lower reach. An average of 7% of the channel area contained spawning gravels, and the embeddedness level was moderate. The high percentage of pools (51% by length) with 44% greater than 2 ft deep provides good conditions for rearing salmonids. The high level of canopy cover provides abundant shade and source areas supplying terrestrial insects to the watercourses. Winter rearing habitat is poor to fair with limited functional LWD cover in pools and small substrate. Access to floodplains is low. Bank erosion is present in some of the habitat units.

Upper Reach: The dominance of coarse substrate has created aggraded conditions in many locations and subsequently poor to fair spawning and rearing habitat conditions. The aggraded streambed also exhibits intermittent flow conditions during the summer. Coarse sediment may have been delivered by shallow slides originating on the steep inner gorge slopes. Although an average of 10.5% of the channel area contained spawning gravels, the embeddedness level was high. The high canopy cover provides abundant shade and source areas supplying terrestrial insects to the watercourses. Although there is a moderate amount of functional LWD cover in pools winter rearing habitat is of poor to fair quality due to high embeddedness levels and little access to floodplains.

Anomalous Segments: There is a half-arch culvert with a concrete floor downstream at the county road. This creates a partial barrier for upstream migrating adults and a complete barrier for juveniles. Upper Cloney exhibits intermittent flow characteristics in aggraded areas during the summer. This creates a seasonal migration barrier for juvenile salmonids and desiccation of individual fish as portions of the reach dry up.

Conditions and Response Potential

LWD - A low to moderate level of pool-forming LWD was observed in the surveyed reaches. The majority of these LWD pieces were either relatively old or man-made structures. LWD is an important habitat-forming structure due to its ability to facilitate pool scour and trap sediment. Due to the highly embedded substrates, LWD provides the majority of the rearing cover for juvenile salmonids. LWD also provides an important winter rearing habitat component whether it is in the bankfull channel or on the floodplain. *High Vulnerability +*

Bank Stability - Unstable banks are present in some of the habitat units. However, bank erosion is a minor contributor of sediment to the channel when compared to landslides and the road network. Unstable banks are one of the primary factors for recruitment of LWD into this channel type. Approximately 46% of the newly recruited LWD, for which an input mechanism could be determined, came from bank erosion. *Low Vulnerability*

Peak Flow - Due to the relatively confined nature of the channel and narrow floodplains, peak flows have the potential to scour redds. LWD pool formation is relatively low, which could reduce bed stability. *High Vulnerability*

Coarse Sediment - The lower reach is contained in unconsolidated geology, which is composed of mudstones and siltstones that rapidly deteriorate into very fine-grained particles during discharge events large enough to transport bedload. The particles subsequently tend to embed any coarse sediments present. Therefore, accumulation of competent coarse sediment from the upstream consolidated geology could be considered beneficial for fish. *High Vulnerability +*

The upper reach flows through consolidated geology and contains excessive amounts of coarse sediment in many locations. Additional coarse sediment inputs in this area could simplify aquatic habitats, bury redds, and exacerbate intermittent flow conditions. *High Vulnerability*

Fine Sediment - There is an abundance of fine sediment in this CGU. A reduction in fine sediment input would likely increase the availability of coarse gravels and improve in spawning habitat quality. Not all fine sediment flushes during high flows so pool development is moderately affected by increases. However, reductions in LWD could reduce turbulent flow within the channel and result in pools filling with fine sediment. *High Vulnerability*

4.6 C1 - CONSOLIDATED

Description: Confined, 0–3% gradient pool-riffle channel. Substrate is primarily small cobble and gravel. Pool-forming wood frequency is moderate, with 42% of the pools formed by LWD. Pools make up approximately 58% of the channel area, which exceeds the PFC target. A few pools are formed by scour along bedrock. This CGU is located in the lower reaches of Upper Freshwater and South Fork, middle portions of Little Freshwater, and McCready Gulch.

Fish Habitat Conditions: Pools make up approximately 48% and 58% of stream length and area, respectively. However, only 19% have a residual depth greater than 2 ft. Rearing habitat is fair, with an average of 42% pools formed by LWD, 81% associated with LWD, and a shelter rating of 78 (per Flosi et al. 1998). Instream LWD meets or exceeds PFC targets. An average of 7% of the channel area contained spawning gravels with fair (2.3 rating) levels of embeddedness. Heavy spawning utilization in these areas has been observed. The high level of canopy cover (81%) provides abundant shade and source areas supplying terrestrial insects to the watercourses. Winter rearing habitat is composed of a good amount of functional LWD cover, fair substrate embeddedness, and little access to floodplains.

Anomalous Segments: The Lower South Fork contains windthrow that recruited to the stream and a seasonal barrier for salmonids.

Conditions and Response Potential

LWD – Pool-forming LWD was observed in 42% of the pools in the surveyed reaches, with 81% of the pools being associated with LWD. LWD is an important habitat-forming structure due to its ability to facilitate pool scour and trap sediment. There is an average of 2.3 key pieces of

LWD per 100 feet of channel length with an average of volume of 260 ft^3 per piece, which meets PFC targets. These are good levels, but further increases in LWD would likely improve pool formation and summer and winter rearing habitat quality. LWD also provides an important winter rearing habitat component whether it is in the bankfull channel or on the floodplain. A decrease in LWD levels would have an adverse effect on fish habitat. *High Vulnerability +*

Bank Stability - Unstable banks are present in some of the habitat units. However, bank erosion is a relatively minor contributor of sediment to the channel when compared to harvest unit landslides and the road network. Unstable banks are one of the primary factors for recruitment of LWD into this channel type. Approximately 57% of the newly recruited LWD, for which an input mechanism could be determined, came from bank erosion. *Low Vulnerability*

Peak Flow - This CGU is generally heavily utilized by spawning salmonids. An increase in peak flows may put redds at risk of being washed away. The lower reach of Upper Freshwater (PWA Segment 601) may be more susceptible to peak flows due to bedrock outcrops combined with lower levels of LWD that is capable of stabilizing the streambed and storing sediment. *High Vulnerability*

Coarse Sediment - Coarse sediment is plentiful in this CGU due to the higher durability of the consolidated geology. Point bars and meanders develop in areas of deposition. The heavily utilized spawning habitat depends on supply of this material. However, too much coarse sediment could aggrade the channel and fill in pools, reducing rearing habitat. *High Vulnerability*

Fine Sediment - There is a moderate amount of sand and fine sediment in the spawning substrate. Embeddedness averages 30%, which is a fair rating according to the Habitat Condition Indices. The amount of fines in the substrate has a direct effect on spawning habitat quality. V* results, although limited, indicate that some pool filling has occurred, which likely has reduced rearing habitat quality in some locations. *High Vulnerability*

4.7 C2 - CONSOLIDATED

Description: Confined, 3-6.5% gradient step pool channel. Boulder and cobbles dominate the substrate. Pool forming wood frequency is moderate, with 60% of the pools formed by LWD. Pools make up approximately 70% of the channel area, which exceeds the PFC target. A few pools are formed by scour along bedrock and plunges. This CGU is mostly found in the upper reaches of Upper Freshwater and South Fork, with additional portions in each of the other tributary sub-basins.

<u>Fish Habitat Conditions</u>: Pools make up 46% of the stream length, of which 20% have a residual depth greater than 2 ft. Rearing habitat is fair to good with one pool every 1.9 channel widths, shelter rating averaging 123, and LWD levels that approach or exceed PFC targets. An average of 5% of the channel area contains spawning gravels with fair (2.5 rating) levels of embeddedness. The high level of canopy cover provides abundant shade and source areas supplying terrestrial insects to the watercourses. Winter rearing habitat is fair to good being composed of boulder and cobble substrate, high instream cover complexity, and moderate substrate embeddedness.

Anomalous Segments: A series of natural migration barriers are located downstream of the Road 15 bridge in Upper Freshwater Creek (Segment 608). No fish were observed during Watershed Analysis surveys and two years of electrofishing surveys above this point. There are some riffles in the Upper South Fork that become intermittent during summer low flows and create seasonal juvenile migration barriers.

Conditions and Response Potential

LWD - Pool forming LWD was observed in 60% of the pools in the surveyed reaches, and 89% of the pools were associated with LWD. LWD is an important habitat-forming structure due to its ability to facilitate pool scour and trap sediment. There is an average volume of 69 ft^3 per key piece of LWD with 3.6 key pieces of LWD per 100 feet of channel length, which approach or meets PFC targets. However, the higher gradient and confined channel result in pool formation that is not dependent on LWD in many cases. LWD also provides an important winter rearing habitat component, whether it is in the bankfull channel or on the floodplain. However, winter rearing habitat is also provided by the large-sized substrate. *Moderate Vulnerability* +

Bank Stability - Unstable banks are present in some of the habitat units. However, bank erosion is a minor contributor of sediment to the channel when compared to landslides and the road network. Unstable banks are one of the primary factors for recruitment of LWD into this channel type. *Low Vulnerability*

Peak Flow - Sustained high flows have the potential to transport bedload and aid in pool development. However, the large substrate in this CGU is resistant to transport, except at very high flows. *Moderate Vulnerability*

Coarse Sediment - Coarse sediment is currently plentiful in this CGU. Scouring of coarse sediment develops pools by high flows. In these higher gradient reaches, fish are dependent on the larger sized fraction coarse sediment for cover habitat. The smaller size fractions of coarse sediment tend to be flushed out of the system. However, an oversupply of coarse sediment could aggrade the channel and degrade habitat. *Moderate Vulnerability*

Fine Sediment - There is a moderate amount of sand and fine sediment in the spawning substrate. Embeddedness averages >30% (2.5 rating), which is a fair rating according to the Habitat Condition Indices. The amount of fines in the substrate has a direct effect on spawning habitat quality. However, field observations indicate that fines do not tend to accumulate in these higher gradient reaches and fill spawning gravels and pools unless there is an oversupply. *Moderate Vulnerability*

4.8 C3 - CONSOLIDATED

Description: Confined, 6.5-20% gradient step pool-cascade channel. Bedrock and boulders dominate the substrate. Pool-forming wood frequency is moderate, with 38% of the pools being formed by LWD. However, the channel in many locations is choked by LWD exceeding the PFC targets. Pool habitat parameters exceed the PFC targets and make up 62% of the stream area with a frequency of 3.6 channel widths per pool in the summer and 2.5 channel widths per pool in the winter. Due to the high gradient, many pools are naturally formed by scour along bedrock and plunges. Many of these CGUs are located in Class II or Class III watercourses with intermittent or ephemeral flow. This CGU is located in the middle reaches of Upper Freshwater and South Fork.

Fish Habitat Conditions: Pools make up 27% of the stream length, although significant portions or these CGUs exhibit intermittent flow. Only 6% of the pools in this CGU are greater than 2 feet deep, which is to be expected given the narrow channel width and small drainage area. Few habitat units were measured as the channel was filled with LWD. Rearing habitat is poor due to very low or intermittent flows. An average of 4% of the channel area contained spawning gravels, although the steep gradient may restrict spawning activity. The moderate level of canopy cover provides ample shade and source areas supplying terrestrial insects to the watercourses. Winter rearing habitat is of good quality, with a large amount of functional LWD cover in pools and boulder and cobble substrate. *Anomalous Segments*: NA

Conditions and Response Potential

LWD – Pool-forming LWD was observed in 38% of the pools in the surveyed reaches, with 79% of the pools being associated with LWD. LWD is an important habitat-forming structure due to its ability to facilitate pool scour and trap sediment. However, the high gradient and confined channel also result in pool formation that is not dependent on LWD. LWD provides an important winter rearing habitat component, whether it is in the bankfull channel or on the floodplain. *Moderate Vulnerability +*

Bank Stability - Unstable banks are present in some of the habitat units. However, bank erosion is a minor contributor of sediment to the channel when compared to landslides and the road network. Unstable banks are one of the primary factors for recruitment of LWD into this channel type. The relatively high gradient is capable of flushing downstream most of the sediment introduced from unstable banks. *Low Vulnerability*

Peak Flow - Sustained high flows or increases in peak flows have the potential to transport bedload and aid in pool development. However, the large substrate in this CGU is resistant to transport except at very high flows. In addition, the relatively small drainage areas associated with this CGU may not be able to generate the significant peak flow increases necessary to mobilize bedload. Fish respond to these high flows by seeking cover under or behind the substrate and LWD. However, these areas probably have relatively little utilization by fish due to the high gradient. *Low Vulnerability*

Coarse Sediment - Coarse sediment (boulder size, >10 inches) is currently the dominant or subdominant particle size in many of the habitat units in this CGU. Scouring of smaller coarse sediment by high flows develops pools. In these higher gradient reaches, fish are dependent on the larger sized fraction of coarse sediment for cover habitat. The smaller size fractions of coarse sediment tend to be flushed out of the system. A large oversupply of coarse sediment could aggrade the channel and degrade habitat. *Low Vulnerability*

Fine Sediment - There is a relatively small amount of sand and fine sediment in the spawning substrate. Embeddedness averages >40% (2.7 rating), which is a poor rating according to the Habitat Condition Indices. However two of the three stream segment sampled for this analysis had fair embeddedness condition ratings of 2.1 and 2.4. Fines may not accumulate in large quantities in these high gradient reaches and fill pools or aggrade the channel unless stream power was low and there was a significant oversupply. *Low Vulnerability for fish, High vulnerability for amphibians*

4.9 MS1 - SOUTH FORK FRESHWATER TO GRAHAM GULCH

Description: Alluvial transport reach, <1.5% gradient. Substrate is primarily small cobble and gravel with areas of exposed bedrock and large cobble substrate. There are a poor number of LWD pieces (approximately 0.5 key pieces of LWD per 100' of channel length) that fail to meet the PFC targets. However, the average volume of each key piece (313 ft^3) meets the PFC target. Pool-forming wood frequency is low compared to other CGUs, with 36% of the pools being formed by LWD. Bedrock scour and corner pools account of 43% of the pools. This CGU carries high flows, which tend to flush small diameter LWD downstream. Pools make up approximately 63% of the channel area, which exceeds the PFC target. Pool frequency meets PFC targets with one pool every three channel widths.

Fish Habitat Conditions: Pools make up 52% of the stream length, of which 36% have a residual depth greater than 2 ft. Rearing habitat is fair with one pool every three channel widths, shelter rating averaging 58, canopy closure of 76% over the stream, and key LWD that exceeds the per piece volume PFC target but not the number per 100 feet criteria. An average of 10% of the channel area contained spawning gravels with generally fair to poor (2.1 to 3.1 ratings) levels of embeddedness, although several habitat units in the upper segment have low embeddedness levels. This CGU has some of the highest spawning habitat use in the basin. The moderate level of canopy cover provides ample shade and source areas supplying terrestrial insects to the watercourses. Canopy was rated as moderate due to the relatively wide channel. Winter rearing habitat is of poorer quality in the downstream reach of this CGU due to a relatively low amount of complex LWD cover in pools, limited access to floodplains, sand being the dominant or subdominant particle size in some habitat units, and high embeddedness levels. Winter rearing habitat is of better quality in the upper reach of this CGU due to boulder and cobble being dominant or subdominant in many habitat units and lower embeddedness levels.

Anomalous Segments: Man-made LWD structures in the upstream reach trap sediment, creating better spawning habitat than the downstream reach.

Conditions and Response Potential

LWD – Pool-forming LWD was observed in 36% of the pools in the surveyed reaches, with 79% of the pools being associated with LWD. LWD is a secondary habitat-forming parameter because high flows and confined channel conditions in many locations tend to displace all but the largest pieces of LWD. The LWD that is stable traps sediment and small woody debris and provides important spawning and winter rearing habitat components. *High Vulnerability +*

Bank Stability - Unstable banks are present in some of the habitat units. This CGU contains some of the most valuable spawning habitat in the basin and is sensitive to fine sediment inputs. However, bank erosion is a minor contributor of sediment to the channel when compared to landslides and the road network. Unstable banks are one of the primary factors for recruitment of LWD into this channel type. Approximately 85% of the newly recruited LWD, for which an input mechanism could be determined, came from bank erosion. *Low Vulnerability*

Peak Flow - Sustained high flows are the primary habitat-forming parameter in this CGU. The confined nature of the channel and high flows have a direct influence on salmonid winter survivability. Redds are potentially vulnerable to scour in this CGU. The Hydrology Module calculated the increased potential for scour to egg pocket depth (12cm) as being 0.98% at baseline to 1.3% for a storm event with a 5-year return interval. However, due to the importance of this CGU for spawning, any increased scour is undesirable. *High Vulnerability*

Coarse Sediment - Coarse sediment is currently more plentiful in the lower reach of the CGU than the upper reach where bedrock is present in many locations. Scouring of coarse sediment by high flows develops pools. Coarse sediment stability is dependent on the presence of functional LWD. Spawning habitat depends on supply of this material. The upper reach of this CGU is one of the three primary spawning locations in the Freshwater Creek basin and as such is vulnerable to sediment increases, which can destabilize the bed. However, decreases in course sediment supply could reduce spawning habitat availability in this area, especially since many areas have already been scoured to bedrock. *High Vulnerability*

Fine Sediment - There is a moderate amount of sand and fine sediment in the spawning substrate. Embeddedness varies from poor (3.1 rating) in the lower reach to fair (2.1 rating) in the upper reach. There are several habitat units in the upper reach of this CGU that have good (1-2) embeddedness values. This upper reach is a high spawning use area. The amount of fines in the substrate has a direct effect on spawning habitat quality. *High Vulnerability*

4.10 MS2 - GRAHAM GULCH TO LITTLE FRESHWATER

No instream habitat data were collected in this CGU for this watershed analysis. The information presented below in the Description and Fish Habitat Condition section is drawn from 1987 habitat typing information by HSU graduate students.

Description: Alluvial aggradational reach with gradients <1%. Substrate is predominantly gravel with inputs dominated by Graham Gulch contributions. Most pools formed by corner or bedrock scour. Pool area is poor with approximately 20% of channel length in pools. LWD frequency is low due to an absence of large conifer riparian vegetation and LWD removal by residents that live adjacent to the creek in this reach. Few pools formed by LWD. Floods are able to spill over onto floodplains.

Fish Habitat Conditions: The presence of gravel from Graham Gulch has created good spawning habitat conditions in some locations in this CGU, although historic surveys suggest utilization has been low to moderate. Embeddedness levels are fair. Most instream habitat cover is provided by overhanging terrestrial vegetation and small woody debris. The fair level of canopy cover provides moderate shade and source areas supplying terrestrial insects to the watercourses. Winter rearing habitat is poor with low amounts of complex LWD cover in pools and limited access to floodplains until flows overtop the banks. Bank erosion is present in a few locations. *Anomalous Segments*: NA

Conditions and Response Potential

LWD - A low level of functional LWD was observed in the surveyed reaches. Adjacent non-PALCO landowners have significantly modified adjoining riparian forests and reduced LWD levels through active LWD removal. Winter rearing habitat is of low quality in part due to the low level of LWD. LWD is an important habitat-forming structure due to its ability to facilitate pool scour, provide cover, and trap sediment. *High Vulnerability* +

Bank Stability - Unstable banks are present in some of the habitat units. Bank erosion is a minor contributor of sediment to the channel when compared to landslides and the road network. However, the spawning habitat in the CGU may be sensitive to additional sediment inputs. In addition, the narrow strip of riparian vegetation in this CGU may not have the ability to stabilize the bank adequately during high flow events. The human-induced confinement of the channel limits its ability to meander and create higher quality habitats. *Low Vulnerability*

Peak Flow - Due to the relatively entrenched nature of the channel, peak flows have the potential to scour redds, although only limited to moderate spawning occurs here. Winter rearing survival of juvenile salmonids may be affected during high flows due to the lack of complex LWD, large substrate, and velocity refugia. Lack of LWD may also result in less stable substrate, which may scour redds. *High Vulnerability*

Coarse Sediment - Coarse sediment is currently abundant in this CGU, much of which is provided by inputs from Graham Gulch. Coarse sediment contributes to simplification of habitats when there are limited roughness elements that can scour habitat features, such as seen in this CGU. The coarse sediment from Graham Gulch provides some very good spawning habitat although utilization is limited. *Moderate Vulnerability*

Fine Sediment - There is a significant amount of fine sediment in this CGU. An increase in fines could have a detrimental impact on spawning and rearing habitat quality and aquatic insect production. *High Vulnerability*

4.11 MS3 - LITTLE FRESHWATER TO 3 CORNERS

Description: Alluvial aggradational reach with gradients <0.5% and an entrenched channel. Levees confine the channel in the lower reach. The majority of this CGU is influenced by tidal action to some degree depending on streamflow. Substrate is predominantly gravel and sand with small cobble subdominant in the upper reaches. LWD frequency is low and does not meet PFC targets with only 0.3 key pieces per 100 feet of channel length. Pools make up approximately 89% of the channel area, which exceeds the PFC targets. Most pools in this CGU are corner pools. The two longest pools (dammed pools) are formed by sediment plugs at the tailout. Floods are able to spill over onto floodplains. The channel appears to be constricted by encroaching streamside vegetation that, in combination with flooding caused by high tides coincident with high flows, encourages sediment deposition on the banks and further narrowing. The riparian zone is narrow due to agricultural and residential uses which, in turn, significantly limit LWD recruitment. In many places, the extent of riparian vegetation is one tree wide. LWD removal by residents also reduces inchannel LWD levels.

Fish Habitat Conditions: The dominance of small gravel and sand has created poor spawning habitat conditions in the lower reach of this CGU. Embeddedness levels have an average rating of 2.7. The upper segment contains some habitat units with very good quality spawning gravel, although it has relatively low utilization. An average of 5% of the channel area contains spawning gravels that are highly embedded in downstream areas and have low embeddedness in most upstream habitat types. The high percentage of pools and overhanging vegetation provides fair rearing conditions for juvenile salmonids. The instream shelter rating averages 79, which is a fair rating according to the Habitat Condition Indices. However, pools are shallow and the habitat fairly simplified in a large part because of the absence of LWD. The fair level of canopy closure over the stream (66%) provides moderate shade and source areas supplying terrestrial insects to the watercourses. Although the streambank vegetation can provide some velocity refugia, winter rearing habitat is poor with low amounts of complex LWD cover in pools and limited access to floodplains until flows overtop the banks. Bank erosion is present.

Anomalous Segments: The upstream reach contains areas of good spawning habitat although it is has low utilization.

Conditions and Response Potential

LWD - A very low level of pool-forming LWD was observed in the surveyed reaches. In addition, existing riparian conditions are impaired and are unlikely to provide future LWD. LWD is an important habitat-forming structure due to its ability to facilitate pool scour and trap sediment. Nearly all the winter rearing habitat is associated with the encroaching deciduous riparian vegetation and the few pieces of LWD that are present. Removal of LWD by residents diminishes the quality and quantity of fish habitat in this CGU. *High Vulnerability +*

Bank Stability - Unstable banks are present in some of the habitat units. Bank erosion is a minor contributor of sediment to the channel when compared to landslides and the road network of the upstream watershed area. The relatively high quality spawning habitat in the upper reach of the CGU may be sensitive to additional sediment inputs. The human-induced confinement of the channel limits its ability to meander and create more complex habitats. Bank erosion in this CGU could have beneficial effects by developing off-channel habitats, causing channel avulsion, and increasing meander wavelength and amplitude. *Low Vulnerability*

Peak Flow - Due to the relatively entrenched nature of the channel, peak flows have the potential to scour redds, although only limited spawning occurs here. Winter rearing survival of juvenile salmonids may be affected during high flows due to the lack of complex LWD, large substrate, and velocity refugia. However, some velocity refugia is provided by willows and bank vegetation. *Moderate Vulnerability*

Coarse Sediment - Coarse sediment is currently limited in the downstream reaches of this CGU. In part, this is due to increasing contributions to the bed sediment from areas draining Wildcat Group geology. The Wildcat Group is composed of mudstones and siltstones that rapidly deteriorate into fine grain sediments during discharge events that transport bedload. The coarse sediment component of the bedload is reduced as substrate particles undergo attrition as they move into the CGU. There is some Franciscan coarse sediment from Graham Gulch in the upper reach that provides very good spawning habitat. *Moderate Vulnerability*

Fine Sediment - There is an abundance of fine sediment in this CGU due to the unconsolidated geology that contributes bedload, as noted above. In addition, the very low stream gradient and reduced stream power encourages deposition of fine sediment. A reduction in fines would improve spawning habitat quality to some degree. However, spawning habitat quality may have been historically relatively poor in the low gradient downstream depositional reaches that are influenced by tidal action. Being at the downstream end of the watershed, the natural attrition of cobble and gravel particles as they tumble and roll from further up in the watershed during runoff events contributes fines and small substrates. *Moderate Vulnerability*

5.0 CONCLUSIONS

5.1 HABITAT CONDITIONS

Analysis of the data indicates that fair to good conditions exist for summer rearing and holding salmonids in the WAU. Pool area and frequency meet target levels. Pool habitat cover complexity and LWD abundance are at fair to good levels. There is a need for more pool-forming LWD in C1, U1, MS1, MS2, and MS3. Increased complex LWD would improve the summer and winter rearing habitats in these CGUs. Summer water temperatures generally do not exceed MWAT target levels in the PFC Matrix. Substrate conditions are generally poor to fair throughout the watershed. There is evidence of fine sediment accumulating in and shallowing pool habitats. This indicates that salmonid abundance may be limited by sediment inputs that reduce successful spawning through emergence of fry and rearing habitat quality. Substrate quality is not good in CGUs C1, C2, MS1, and CG and it is generally poorer in U1, U2, GG, and MS3. This could be expected since these latter CGUs are either poor gravel production areas and/or have excessive fine sediment bedload. The Mass Wasting, Surface Erosion, and Stream Channel Assessment Modules provide information on sediment sources and the relative contribution from natural and anthropogenic causes.

5.2 TURBIDITY/TOTAL SUSPENDED SEDIMENT

The Watershed Analysis methods developed by PALCO recognize that turbidity and suspended sediment may directly or indirectly affect fish and fish habitat. For the current Freshwater Creek Watershed Analysis, a temporally extensive but spatially limited data set was available to evaluate turbidity and TSS and assess their potential impacts to salmonids. The risk modeling provided in this report demonstrated that behavioral and mild sublethal stressful conditions likely occur in Freshwater Creek during some peak flow conditions; however, no conditions measured in the basin were of adequate duration or concentration to lead to direct mortality or deficits in growth. Exposure durations over the period examined were generally less than 24 hours, and would not result in biological impairment at the concentrations realized. It must be noted, however, that the analyses provided here considered storm events from January through July of 1999 only. Data from the early storms of HY 1999 could not be analyzed because no TSS data were collected during this period. Early storms of HY 2000 were not analyzed because the TSS samples collected had not been completely analyzed and reviewed for quality control.

Analyses of turbidigraphs and hydrographs demonstrated that the conditions of greatest concern may be associated with early season storm events, when sediment loading into the stream will be disproportionately higher for a given rainfall and/or discharge event. Given this evidence it is certainly possible that the severity of effects from storms would be greater earlier in the season than later. Notwithstanding, most exposures to high TSS concentrations occur during periods of low water temperatures, when the metabolic rates of fish are depressed thereby reducing the likelihood of behavioral or physiological impairment (Sullivan 19xx). Furthermore, any interpretation of impact must be made cautiously because the effects reported (e.g., are often difficult to compare due to the inconsistencies in study designs and methods (see Attachment F-1 for general review). No site-specific studies have been completed to validate the effects of turbidity or TSS on salmonids in Freshwater Creek. The possibility that salmonids in Freshwater Creek are more or less sensitive to turbidity or TSS than the modeling results would suggest cannot be discounted at present. The Newcomb and Jensen model is inherently conservative because the source data used to develop the risk equations were largely derived from laboratory studies on fish stocks adapted to waters of naturally low turbidities in more ecologically stable regions.

The analysis of rainfall as the mechanism for sediment recruitment suggests that events of approximately ½ inch of rain could yield suspended sediment concentrations of at least 65 mg/l, which in turn would yield turbidity of approximately 60 NTU. The lowest observable effect concentration for suspended sediment reported in the literature is 20 mg/l, which interfered with home stream preference in Chinook (Sigler 1988); however, numerous other researchers have reported no effects at concentrations over 10 times higher. The variability in the sensitivity of fish to turbidity and suspended sediment highlights the local adaptation of some stocks to naturally turbid waters. Whether salmonids from the Freshwater Creek basin are more tolerant of suspended sediments and/or turbidity because of the relatively erosive geology and naturally high turbidity levels within the basin is not known.

5.3 TEMPERATURE

The Aquatic Properly Functioning Conditions Matrix states that the indicator range for temperatures is 11.6 to 14.5°C. This is consistent with the preferred temperature range of 11.8 to 14.6°C reported in Reiser and Bjorn (1979). The matrix identifies a maximum weekly average temperature (MWAT) of 16.8°C. The MWAT was only exceeded in one case during 1997 at the Mainstem Freshwater site, approximately 750 ft downstream of South Fork Freshwater. The average water temperatures were within the preferred range of temperatures. This indicates there are no chronic temperature problems in the Freshwater watershed.

5.4 INSTREAM FINE SUBSTRATE COMPOSITION

Bjornn and Reiser (1991) consolidated the results of several studies and showed that the success of emergence of swim-up fry (i.e., salmonid fry emerging from the gravel) began to decline when the percentage of fine sediment (smaller than 2-6.4 mm) increased beyond 8 to 23%. McHenry et al. (1994) reported that a threshold conditions exists at >13% of fines <0.85 mm, above which egg to alevin survival drops rapidly. The PFC Matrix recommends a target range of <11-16% for fine sediment <0.85 mm, above which there could be a decrease in embryo survival due to a reduction in gravel permeability. PALCO substrate samples found that 11 to 47% of the substrate sampled was composed of fines <0.85mm, and 25 to 59% of the substrate sampled was composed of fines <4.7 mm. Thus, it appears survival of salmonids from the egg to emergence stages is adversely affected by fine sediment levels in the watershed. This corresponds with the generally poor to fair substrate embeddedness conditions found during the Watershed Analysis field surveys. However, the field surveys also found localized areas of good gravel quality within reaches containing generally poor conditions. This was likely due to localized hydraulic patterns that enabled the flushing of fine sediments from the gravel. Thus, survival of salmonid eggs and fry is likely higher in many sites than the averaged substrate data would suggest.

The PFC Matrix referenced three papers that were used to develop the HCP and subsequently Freshwater Creek Watershed Analysis target of 11-16% fine sediment <0.85 mm. These papers were Chapman (1988), Peterson et al. (1992), and Burns (1970). Chapman (1988) described results from a variety of authors who sampled substrates and analyzed incubation and emergence within active redds and laboratory conditions. Chapman (1988) noted that redds contain a significantly lower proportion of fines than the surrounding substrate due to construction by female salmonids. Peterson et al. (1992) reviewed papers by researchers that looked at substrate composition within streams in Oregon, Washington, British Columbia, and Alaska to come up with their target of 11-16% fine sediment <0.85 mm. Burns (1970) collected multiple samples of spawning substrate (not redds) at riffle crests for three consecutive years. Burns' (1970) unlogged control reaches in Humboldt and Mendocino Counties contained an average of 16.4 to 23.2% fine sediment <0.83 mm for the same soil types found in Freshwater Creek.

It is important to note that of the three papers only Burns (1970) contained information specific to coastal Humboldt County soil types. In addition, the protocol Burns (1970) utilized was very similar to the method recommended by the PFC Matrix, Valentine Protocols (1995), and the substrate sampling protocol used by PALCO. The PALCO protocol did not sample within redds and Valentine (1995) does not recommend it. Redd sampling could also be viewed as a take of listed salmonids. Many of the studies reviewed by Chapman (1988) specifically sampled within redds, which makes those results incompatible with the Valentine protocols and PALCO monitoring program. Peterson et al. (1992) stated “Basin geology can have a significant effect on percent fines and this suggests that a universal target condition applied indiscriminately across geologic boundaries may be inappropriate.” Peterson et al. (1992) targets may be representative of unlogged conditions in the Pacific Northwest and Alaska soil types and geologies, but not those in Humboldt County, California. The PFC Matrix states “Given the natural variation in sediment loading between and within watersheds, a watershed inventory and analysis should determine existing sediment levels and identify reasonable interim targets…” It appears that the Chapman (1988) sampling techniques and the Peterson et al. (1992) fine sediment target (11-16% <0.85 mm) are inappropriate for the Freshwater Creek watershed. Of the three papers, Burns (1970) appears to contain the most representative target criteria (16-23% <0.85 mm) for this and other watersheds containing similar soil types.

6.0 RESOURCE SENSITIVITY REPORT

A Resource Sensitivity Report (RSR) is written for those situations that occur off PALCO property but have an effect on fisheries resources in the watershed. The RSRs are similar to Causal Mechanism Reports but are not used in the Prescription writing process due to the lack of regulatory authority for properties outside PALCO ownership. However, RSRs can be used to identify potential restoration sites or suggest modifications for current downstream land use that could benefit salmonid species.

6.1 FISHERIES ASSESSMENT RESOURCE SENSITIVITY REPORT – MAN-MADE SALMONID MIGRATION BARRIERS

Resource Situation: Three road crossings in the lower reaches of McCready Gulch, Cloney Gulch, and Graham Gulch constitute either seasonal or permanent migration barriers for salmonids (Taylor 2000). The McCready Gulch crossing is located on an abandoned county road within non-PALCO private land. It is constructed of a perched concrete box culvert with a natural bottom and may block upstream juvenile migration. The Cloney Gulch county road crossing is constructed of a half-arch with a concrete floor. It is a partial barrier for adults and a complete barrier for juveniles. The Graham Gulch county road crossing is constructed of a sectional steel pipe. It is a partial barrier to adults and a complete barrier for juveniles. See Map F-1: Salmonid Distribution Map.

Resource Sensitivity: Insufficient or too high of flow through the culverts may result in denial of access to sub-basins for migrating adults and subsequently affect salmonid spawning opportunities. Barriers limit access by juveniles seeking refuge from high mainstem flows, thereby potentially affecting winter survival.

Triggering Mechanisms:

- Road built prior to understanding of salmonid migration needs.
- Crossings targeted for eventual upgrading by the county, which should improve passage.

Delivered Hazard Rating and Vulnerability:

Resource Vulnerability: Moderate

Target Habitat Diagnostics: Any man-made barriers present in the watershed allow upstream and downstream fish passage at all flows (NMFS 1997).

Additional Comments:

- McCready, Cloney, and Graham Gulches have been given upgrade prioritization rankings of 35, 12, and 29 respectively by the Humboldt County Culvert Inventory and Fish Passage Evaluation project.
- Each culvert has either Washington-style baffles or inlet and outlet beams to aid fish migration.
- The migration barriers lie outside of the PALCO lands. Effects are primarily related to non-forestry land uses. No prescriptions to be written.

7.0 CONFIDENCE IN RESULTS

Confidence in the fish species list is good. None of the reviewed reports and surveys recorded observations of exotic species. Confidence in fish distribution is good due to the electrofishing and underwater and bank observation survey efforts during the analysis. However, additional rearing location information for MS1, MS2, and MS3 is desirable. Confidence in spawning locations is moderate due to the difficulties inherent in conducting spawner surveys. Confidence in the habitat calls is moderate since there were areas where data were not collected. Confidence in the area of concern and vulnerability calls is moderate to good due to analysis of field data and correlation with the stream channel and amphibian modules. Confidence in determination of substrate quality as the primary limiting factor to salmonid production in the WAU is high. Confidence in the LWD calls is low to moderate since data were not collected in 13 out of 24 channel segments.

8.0 DEVIATIONS FROM THE STANDARD METHODS

There were no deviations from the standard data collection methodology. However, the Habitat Condition Indices Matrix in the Methods (PALCO 2000a) proved to be too unwieldy, complex, and sometimes contradictory for rating habitat conditions. In addition the PFC Matrix, which is a draft "Work in Progress," contains a target (pools >3 feet deep) that is not applicable for Freshwater due to shallow alluvium over bedrock. The SRT was consulted, and a modified set of Habitat Condition Indices were developed that rated critical habitat parameters. The analyst added three subjective indices (Substrate Quality, Gravel Availability, and Shelter Rating) due to the additional understanding these parameters contributed toward determination of spawning and rearing habitat quality. These modified indices are presented in Table 3-3. The methods worked well and are recommended for future watershed analyses.

9.0 MONITORING SUGGESTIONS

The field validation of the original base map Class I stream classification was conducted during summer low flows. Although the analysts were conservative on their classification calls, field visits should be conducted during timber harvest planning activities to further determine the upstream extent of fish residence. This is particularly true for low gradient intermittent watercourses that may have seasonal utilization by salmonids, particularly coastal cutthroat trout. It is recommended these reaches be visited prior to July 1 (while there is still surface flow) to determine their suitability for cutthroat trout. Surveyors should look for pool tail gravel 2-5 cm in size in patches greater than 0.3 m^2 and no downstream migration barriers, which would suggest spawner utilization. The surveyors should also look for habitats that contain complex LWD, which could indicate use as high winter flow refugia.

Additional surveys (electrofishing) should be conducted in School Forest and upper Upper Freshwater Creek to determine if these reaches warrant classification changes from Class I to Class II (See Map F-2). It is recommended that at least three years of surveys be conducted to determine fish absence (Larry Preston, pers. comm.). Monitoring locations in these reaches were previously electrofished (Upper Freshwater [PL Station 36] in 1998 and 1999, School Forest in 1999) with no fish being captured.

Continuation of PALCO's ongoing stream monitoring program is recommended. Turbidity monitoring is recommended in selected subbasins.

Bulk sediment samples should continue and include analysis of particles <6.5 mm in size to compare with the PFC Matrix. However, PALCO and the agencies need to rectify the PFC Matrix which sets a fine sediment target based on redd substrate composition within redds and the PALCO bulk sampling that samples outside of redds. Redds typically contain less fine sediment due to the construction process than the surrounding substrate.

There is a gap in monitoring data in CGUs MS2 and MS3. Public monitoring efforts should emphasize physical and biological sampling in areas outside PALCO property, such as the residential reaches in the basin.

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ATTACHMENTS – ON DATA CD

ATTACHMENT F-1: SUMMARIES OF DOWNSTREAM MIGRANT TRAPPING, UPSTREAM MIGRANT TRAPPING, INDEX REACH ELECTROFISHING, AND SPAWNER SURVEYS

ATTACHMENT F-2: EFFECTS OF SUSPENDED SEDIMENT & TURBIDITY ON SALMONIDS: AN OVERVIEW OF THE LITERATURE

ATTACHMENT F-3: A MULTIMETRIC ANALYSIS OF BENTHIC MACROINVERTEBRATE DATA COLLECTED FROM THE FRESHWATER CREEK WATERSHED (HUMBOLDT COUNTY, CALIFORNIA) 1994-1998

Appendix G

Freshwater Creek Watershed Analysis

Amphibian and Reptile Habitat Assessment

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December 2003

EXECUTIVE SUMMARY

The Amphibian and Reptile Assessment Module was completed to provide information about the occurrence of amphibian and reptile species of concern, or species identified with conservation status and their available habitats within the watershed. There are five amphibian and reptile species all listed as California species of concern (CSSC) covered under the incidental take permit issued by the U.S. Fish and Wildlife (USFWS), National Marine Fisheries Service (NMFS) and California Department of Fish and Game (CDFG) under the HCP: southern torrent salamander (*Rhyacotriton variegatus*); tailed frog (*Ascaphus truei*); northern red-legged frog (*Rana aurora aurora*); foothill yellow-legged frog (*Rana boylii*); and northwestern pond turtle (*Clemmys marmorata marmorata*).

Habitat and occurrences were identified for the southern torrent salamander and tailed frog in headwater streams through field surveys for this assessment. Upstream distribution of these headwater species was estimated based on drainage areas. The actual upstream extent (Class II/ III breaks) will be field verified as part of the THP process. Seeps and springs provide habitat for the southern torrent salamander, but these small (few square feet) features were not mapped for this analysis. These features are thought to be more commonly located along the interface of the Wildcat and Franciscan geologies. During the THP process, these features should be mapped to see if any patterns in the distribution of seep habitat are discernable.

Potential habitat for the northern red-legged frog and the foothill yellow-legged frog was based on parameters identified through baseline data and literature, as well as consultation with local and regional experts. Specific field surveys were not conducted for these two species; however, both species were observed in the Freshwater Creek Watershed. (Surveys were done concurrent with fish habitat surveys.) Habitat for the northwestern pond turtle is not likely to occur because basking and nest sites are unavailable. This species has not been observed in this watershed.

Data on the aquatic habitat conditions and amphibian and reptile life history and distribution patterns, obtained from field surveys and historical analysis, were extrapolated to all segments in each CGU and used to determine the potential biological and habitat response to changes in certain input factors. These inputs were large woody debris (LWD), bank stability, peak flow, coarse sediment, and fine sediment. Few Channel Geomorphic Units (CGUs) were identified as having high potential for habitat and were vulnerable.

C4 Consolidated >20% Gradient: These are confined reaches with gradients greater than 20%, composed primarily of step-pool habitat. LWD is abundant, and small pieces (<1 m in length) are functional due to the small channel size. Substrates contain low percentages of fines, and cobble/gravel sediments are prevalent. The low fines and high gradient here provide good habitat for tailed frog tadpoles and torrent salamanders, with animals observed at 7 of the 12 survey sites. Good habitat is provided with low embeddedness values through coarse sediments for feeding and cover habitat and high LWD volumes creating numerous small step pools and, in some cases, obscuring the stream. High canopy covers are present over streams (average 89%). Underlying geology influences the stream substrate. The yellow-legged frog, southern torrent salamander, and tailed frog benefit from larger cobbles and other coarse sediment. The CGUs with unconsolidated geology (i.e., Wildcat) produce little or no coarse sediments and high volumes of fine sediments and result in highly embedded substrates. The CGUs with consolidated geologies (i.e., Franciscan) produce more coarse sediments that provide interstitial spaces and are suspected to form better quality habitat for these three species. CGUs in unconsolidated geologic areas are unlikely to provide quality habitat. Fine Sediments parameter provides a high vulnerability call. Currently, percent fine sediment and the percent embeddedness were good and sediments are unlikely to accumulate due to the stream gradient; however, accumulation of fine sediment would reduce habitat quality.

U1 Unconsolidated Wildcat 0-3% gradient: These reaches have confined, pool-riffle channels with gradients of 0-3%. Substrate is predominantly sand and fines. Wood frequency is high. Pool area is good. Most pools in this CGU are formed or associated with LWD. Some pools are formed by scour along bedrock. Floods are able to spill over onto narrow floodplains in some locations. The fine sediments typical of Wildcat geologies provide poor habitat for tailed frog tadpoles, yellow-legged frogs, and torrent salamanders. Red-legged frogs may breed off channel in very low gradient, low flow backwaters and off streams in floodplain pools throughout this geology but not in the main channels. Torrent salamanders were not observed in any surveys within Wildcat geologies, and tailed frog tadpoles were observed at only one atypical survey site. LWD is important in trapping coarse sediments, providing the only available appropriate substrates. One site was notable within this CGU. PWA 1 has greater residual pool depth and higher percentage of pools by length and area than the other verified segments. Tailed frog tadpoles were observed in segment 1101. This segment has good cobble and boulder substrates, which is not consistent with segments surveyed for fish habitat. These substrates may have originated in the adjacent Yager formations.

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1.0 INTRODUCTION

The Amphibian and Reptile Habitat Assessment was completed to provide information for watershed analyses about the occurrence of amphibian and reptile species of concern, or species identified with conservation status and available habitats within the watershed. There are five amphibian and reptile species all listed as California species of concern (CSSC) covered under the incidental take permit issued by the U.S. Fish and Wildlife (USFWS), National Marine Fisheries Service (NMFS) and California Department of Fish and Game (CDFG) under the HCP (PALCO 1999). These species are:

- Southern torrent salamander (*Rhyacotriton variegatus*)
- Tailed frog (*Ascaphus truei*)
- Northern red-legged frog (*Rana aurora aurora*)
- Foothill yellow-legged frog (*Rana boylii*)
- Northwestern pond turtle (*Clemmys marmorata marmorata*)

Four habitat delineations were developed with the tailed frog and southern torrent salamander lumped in this treatment since they utilize similar headwater habitats. The remaining three species have divergent habitats requirements and are considered individually.

1.1 AMPHIBIAN AND REPTILE HABITAT ASSESSMENT OVERVIEW

The goal of the Amphibian and Reptile Habitat Assessment is to locate potential habitat in the watershed for the five species of concern, document locations where species presence has been confirmed, evaluate the condition of existing habitat and identify areas of special concern. The Amphibian and Reptile Habitat Assessment for the Freshwater Creek Watershed was completed with the intent of answering the following critical questions:

Distribution

- Which of the five species potentially occur in the watershed?
- What is the distribution and relative abundance of the five species of concern in the watershed?

Habitat Conditions

- What are the extent, distribution, and condition of occupied and nonoccupied habitats in the watershed?
- Where are areas of degraded habitats in the watershed (by species and life history)?
- Where are areas of high existing or potential habitat use in the watershed (by species and life history)?
- Where are areas of limited habitat availability?
- Where are areas that currently have low potential habitat quality?

Water Temperature

- Do recorded water temperatures approach or exceed stressful levels for covered species?
- Are there reaches where distribution may be limited by water temperatures?

The distribution assessment was completed using field surveys conducted by PALCO crews (1999 unpublished survey data, PALCO), and by identifying potential habitats from existing map and aerial photo information. The habitat assessment was conducted using maps, aerial photography, field survey, and consultation with local and regional amphibian experts. The temperature assessment was completed using stream data (unpublished data 1994-1999, PALCO). These data will be used in the synthesis process in two ways. First, the results of habitat assessments and the descriptions of areas of concern are a key component of making habitat vulnerability calls. Second, the broader descriptions of animal distribution and habitats in the watershed are used to develop a habitat context for Synthesis and for completion of the resource sensitivity calls.

2.0 LIFE HISTORY REQUIREMENTS

This section describes the life history requirements of the covered species based on literature review. These covered species require aquatic habitat with different spatial and seasonal requirements for upland habitat. As identified below, the upland habitat requirements of many of these species are not well-documented, and in some cases primarily anecdotal. In cases where the upland habitat requirements were defined in the literature, they were used in this assessment. Identifying and mapping the seeps and springs used by southern torrent salamanders outside of riparian management zones (RMZs) can be very difficult. The seeps and springs can be ephemeral and are small patch sizes, sometimes measured in a few square feet, while the minimum stream channel-mapping unit is 1,000 ft. In the Freshwater Watershed these seeps and springs are often found at the interface of Franciscan and Wildcat geologies. The locations of seeps and springs are identified in the Timber Harvesting Plan (THP) process and the appropriate RMZ prescriptions are applied.

The life history for each of the Rana species is presented in Figure 2-1. A discussion of the habitat requirements is provided below.

2.1 HEADWATER SPECIES: SOUTHERN TORRENT SALAMANDER & TAILED FROG

The habitat requirements for these species is similar with both often being found in headwater streams (Table 2-1). However, the tailed frog is more widespread in this watershed using streams with cobbles and boulder substrate. Diller and Wallace (1996 and 1999) indicate that overall the distribution of these species overlaps, both species being associated with consolidated geologic formations, which influences the stream substrate. Diller and Wallace (1996 and 1999) provide that the sites with tailed frogs were generally larger in size relative to sites with southern torrent salamander (10s of m and 100s of m of stream length for the salamander and tailed frog, respectively). Data from microhabitat surveys indicate that both species are not likely to be found in areas with a higher level of fine sediments, although the tailed frog larvae are generally associated with larger substrate compared to the salamander (cobble verse gravel) (Diller and Wallace 1999). Although incidental use has been documented, no upland habitat requirements have been documented for either of these species.

Figure 2-1: Annual timing of life history stages for amphibian and reptile species potentially occurring on PALCO lands.

	Jan	Feb	March	April	May	June	July	August	Sept	Oct	Nov	Dec
Red legged frog												
Breeding	BBBBB (1-2 wks)											
Hatch	HHHHHH (35-49 dys)											
Larvae		LLLLLLLL	LLLLLL (11-14 wks)									
Tadpoles			TTTTTTTT	TTTTTTTT	TTTTTTTT	TTTTTTTT	(4-5 mos.)					
Adults					AAAAAAAAAAAAAAAAAAAAA							
Sexual maturity- 3-4 yrs												
Yellow legged frog												
Breeding			BBBBBBBB (2 wks or longer)									
Hatch				HHHHHHHH (5-30 dys)								
Larvae				LLLLLLL (4-5 wks)								
Tadpoles				TTTT	TTTTTTTT	TTTTTTTT	TTTTTTTT	TTTTT (3-4 mos.)				
Adults						AA	AAAAAAAAAAAAA					
Sexual maturity	(6 mos, 2 yrs to adult size)											
Tailed Frog												
Breeding: most active late Aug-Sept				bbbbbbbb	bbbbbbbb	bbbbbbbb	bbbbbbbb	bbbBBBB	BBBBBBB	bbbb		
Hatch									HHHH	HHHHHH		
Larvae	LLLLLL	LLLL (up to 9 mos.)								LLL	LLLLLLLL	LLLLLLLL
Tadpoles: metamorphasis 2-3 yrs			TTTTTTTT	TTTTTTTT	TTTTTTTT	TTTTTTTT	TTTTTTTT	TTTTTTTT	TTTTTTTT	TTTTTTTT	TTTTTTTT	TTTTTTT
Adults							AAAAAA	AAAAAA	AAAAAA	AAAAAA	AAAA	
Sexual maturity	(up to 7 years)											
Southern Torrent Salmander												
Breeding			BBBBBBB	BBBBBBB	BBBBBBB	BBBBBBB						
Hatch	(No distinct hatchling stage, eggs hatch in 7 to 10 months)											
Larvae	(Metamorphose 4 to 5 years)											
Sexual maturity	(6 to 7 years)											
Western Pond Turtle												
Nest (peak in June-mid July)				nnnnn	nnnnnnnn	NNNNNNN	NNNNNnn	nnn				
incubation (80-100 days)							OOOOOO	OOOOOO	OOOOOO	OOOOOO	OOOO	
Hatchlings	HHHHHHH	HHHHHHH	HHHHHHH								HHH	HHHHHH
Adults	(5-8 years to adult size)											
Sexual maturity	(10-14 years)											

The Pacific giant salamander is an opportunistic predator and will prey on both of these species. Field crews noted that a higher density of the Pacific giant salamanders was typically related to low numbers of southern torrent salamanders and tailed frogs.

Southern torrent salamander – This species is usually found within a few meters of seeps, saturated talus, or the splash zones of streams (Nussbaum et al. 1983). They are found in cold seeps and non-fish-bearing headwater streams, with substrates larger than sand (Welsh and Lind 1996). On managed lands, abundance is correlated with high stream gradients and consolidated underlying geology, yielding the coarse substrate they prefer (Diller and Wallace 1996 and 1999). In this watershed they are associated with perennial streams typically less than 2 ft across. During low water they move into the interstitial zones within the stream bed for access to water. They may be found along larger streams, but not found within pools, rather along seeps, springs or splash zones.

Tailed frog – Unique among North America anurans, the frog is highly adapted for life in cold, clear, mountain streams (Nassbaum et al. 1983).The tailed frog is most commonly found in or immediately adjacent to cold, permanent, headwater streams, and prefers streams with unembedded cobble/boulder sediments (Diller and Wallace 1996, 1999, Nussbaum 1983). At night, during wet weather, the tailed frog has been found 20 to 30 m from water feeding on insects and other invertebrates or on objects along the stream (Nussbaum et al. 1983), but is most commonly found in or immediately adjacent to permanent streams.

Table 2-1: Life history requirements for headwater species: southern torrent salamander and tailed frog.

	Torrent Salamander	Tailed Frog
Water Temperature	6.5°C -15°C (Welsh and Lind 1996)	5°C –18.5°C (Brown 1975, Claussen 1973)
Stream Gradient	Mean gradient of 31.8% (Diller and Wallace 1999); in previously logged areas >11% (Corn and Bury 1989)	Mean gradient of 9.1 % (Diller and Wallace 1999)
Stream Substrate	larger than sand but <50% cobble, with some very fine organic sediments (Diller and Wallace 1996, Welsh and Lind 1996)	cobble/boulder >10cm, <18-33% embeddedness with low % sand (Altig and Brodie 1972, Hawkins et al. 1988)
Geology	consolidated geologic areas in managed forests (Diller and Wallace 1996)	consolidated geologic areas in managed forests (Diller and Wallace 1996)
AND:		
Forest Temperature and Humidity Levels	<22°C air temp, <14°C soil temp, >40% relative humidity and low radiation on hottest days and nights (Bury and Corn 1989)	<22°C air temp, <14°C soil temp, >40% relative humidity and low radiation on hottest days and nights (Bury and Corn 1989)
OR:		
Canopy Cover	>80% (Welsh and Lind 1996)	85% canopy closure (Bury and Corn 1989, Welsh et al. 1993)
Riparian Stand Characteristics	22-38 conifers >53cm-DBH/ha. (Welsh and Lind 1996)	old growth/late seral stands present or nearby (Welsh and Ollivier 1998)

2.2 FOOTHILL YELLOW-LEGGED FROG

The foothill yellow-legged frog is a river-dwelling frog typically breeding in shallow, low-velocity habitats adjacent to shallow wide stream reaches, with temperatures below 24 to 27°C in the spring and early summer (Lind et al. 1992, Kupferberg 1996). Breeding requires low-velocity shallows with a cobble and larger substrate. They use cobble and boulders for egg attachment (Hayes and Jennings 1988, Kupferberg 1996), and disperse along the streams outside the breeding period. Low vegetation cover is required within 5 m of the stream to provide escape cover (Kupferberg 1996) (Table 2-2). Introduced macrofauna are predators on this species and limit its distribution (Hayes and Jennings 1988).

This species is typically found in or immediately adjacent to streams. During winter, adults have been found up to 5 m from the streams, possibly hibernating (Nussbaum et al. 1983). No upland habitat requirements have been documented.

2.3 NORTHERN RED-LEGGED FROG

This species prefers a variety of slow-moving water habitats, ranging from lakes, ponds, stream backwaters and sloughs to roadside ditches (Nussbaum et al 1983). Breeding habitat is thought to be the limiting factor. Breeding occurs in ponds, ditches, and very slow-moving streams with emergent vegetation for egg attachment. Northern red-legged frogs have the lowest embryonic temperature requirements of any Ranid species (21°C maximum). Areas used for breeding may be temporary, but must persist at least 4-5 months following the winter rains, from late December through May or June to allow the tadpoles time to metamorphose (Nussbaum et al. 1983) (Table 2-2). This species is expected to occur throughout the watershed in appropriate habitat.

Table 2-2: Breeding requirements for *Rana* species.

	Northern Red-Legged Frog	Foothill Yellow-Legged Frog
Water Temperature	<21°C in late winter/early spring (Licht 1971)	<24-27°C in spring/early summer (Kupferberg 1996)
Stream Gradient and Temporal Status	small, moderately deep (0.7 m) ponds or pools in intermittent streams, low gradient (Hayes and Jennings 1988)	low-velocity shallows, with riffle habitat (Hayes and Jennings 1988)
Stream Substrate	Not specified in the literature	large percent at least cobble sized (Hayes and Jennings 1988, Kupferberg 1996)
Riparian Stand Characteristics	Dense emergent vegetation to the water's edge around breeding areas (Hayes and Jennings 1988)	undisturbed vegetation within 5 m of stream (Kupferberg 1996)

The terrestrial needs of this species are not well understood, although adults have been found 200 to 300 m from water (Nussbaum et al. 1983). Adults require dense riparian vegetation that is in contract with, or close to, deep water (Hayes and Jennings 1988). Vegetation includes cattails (*Typha* spp.), bulrush (*Scirpus* spp.), and willows (*Salix* spp.). The riparian vegetation is important escape cover from predators (i.e., birds and raccoons) and possible also as shading to maintain cool water temperature. Introduced bullfrogs and fishes are additional predators on the red-legged frog. A study at Freshwater Lagoon, California, found that adult males and subadults are not present in the lagoon during the summer, indicating they disperse to upland habitats, but habitat preferences have not been described (Twedt 1993). While they are believed to utilize upland habitats, habitat types used have not been documented.

2.4 NORTHWESTERN POND TURTLE

Northwestern pond turtles utilize a variety of aquatic habitats including streams, rivers, ponds, and marshes, but need basking sites (Bury 1972). Basking sites are sunny spots with logs, boulders, or other structures emerging from the water. In river systems, they prefer areas with low velocities and underwater refugia (Reese and Welsh 1997) (Table 2-3). Both suitable upland nesting and aquatic habitat is required for this species.

The northwestern pond turtle nests in areas with little to no canopy cover. Nesting activity has been documented as much as 500 m from the nearest aquatic habitat (Reese and Welsh 1997). Nesting habitat upslope of the RMZ was considered in the analysis. In addition, this species has been found using a variety of upland habitats for over-wintering cover, but specific habitat requirements for over-wintering have not been determined (Reese and Welsh 1997). They found a mean canopy cover of 63% (median 72.5 %) with a range of 15-90 % for 10 terrestrial overwintering sites. In addition, they indicate mean distances from river's shore at 12 over-wintering sites was 196 m (median 135.5) with a range of 65-200 m.

Table 2-3: Habitat requirements for northwestern pond turtle.

	Northwestern Pond Turtle
Water Temperature	<32°C in late winter/early spring (Licht 1971)
Stream Size	Moderate water depths (> 0.5 m) and stretches of slow water (Bury 1972, Reese 1996)
Large Woody Debris	Large woody debris accumulations in slow water of rivers. (Bury 1972, Holland 1994, Reese 1996)
Riparian Stand Characteristics	=> 50% canopy closure (Reese 1996)
Nesting Habitat	Clearings or unforested areas up to 500 m from suitable aquatic habitat (Rathbun et al. 1992, Reese and Welsh 1997)
Over Wintering Habitat	Mean canopy cover 63 % (median 72.5 %, range 15-90 %) and mean distance to shore 196 m (median 135.5 m, range 65-500) (Reese and Welsh 1997)

3.0 WATERSHED ANALYSIS SURVEYS

The survey goals were primarily to evaluate habitat quality or condition within the watershed and secondarily to verify amphibian and reptile species occurrence and distribution. Watershed Analysis Methods (PALCO 2000) uses species distribution based on habitat distribution and quality, as such; verification of species presence within each reach was not required. Information on the habitat type and quality is based on two categories of surveys:

1) *Amphibian and reptile distribution*. Data was gathered in Class I and Class II streams. Because both red-legged and yellow-legged frogs have been commonly observed in appropriate habitats within the Freshwater Watershed, searching for these species was included in the field protocols for the fisheries habitat parameter surveys for Class I streams. These methods are described in the Fisheries Assessment Module (Appendix F). In Class II streams, reconnaissance level surveys for headwater species, southern torrent salamander and tailed frog where conducted in 1999. Procedures for these Class II surveys are provided in Appendix 6.1. There is only one anecdotal observation of turtles (and these were not verified as northwestern pond turtles) in the watershed and this was in an area of modified habitat. Preliminary analysis of the Freshwater Watershed indicated that habitat suitable for northwestern pond turtle was not present as evidenced by few slow moving pools with sandy beaches. Areas in lower Freshwater Creek with potential pools were deemed too warm or were impacted by domestic uses. The amphibian module group concurred that no field survey for this species was required.

2) *Habitat Parameter Surveys.* Physical stream habitat parameters in Class I streams are based on Flosi (1998) and are described in the Fisheries Assessment Module.

3.1 SURVEY METHODS

Amphibian and reptile survey procedures were not specified in the April 2000 Methods document (PALCO 2000). To gain information on amphibian and reptile distribution in the Freshwater Watershed a reconnaissance level survey was conducted using two different methods. Survey A, commenced in early May 1999, required an intensive search for animals. While this was effective for finding many animals that may be present at the site the crews could only cover a small area and subsequently collected habitat data for short reaches. To increase survey data for habitat parameters the survey was redesigned and the remaining plots were collected using "Survey B". These methods adapted from a draft regional amphibian sampling protocol. This protocol reduced the level of search intensity for individuals in favor of increased data collection on available habitat variables.

Data collected during search for individual amphibians included area searched and species by life stage present. All individuals were released unharmed. Data sheets for these two methods is provided in Attachment A. The habitat variables collected were the same under both methods and are provided below.

General site information:

- extensive location info
- elevation
- distance surveyed (200 m)
- pool lengths/depths
- riffle depths
- bankfull/wetted width

Specific information:

- Habitat type: Stream class, seep, riparian forest or upland forest
- Location
- Length/width/area searched
- Survey start/end time
- Air/water temp
- Overstory/streamside vegetation species
- Stand age and density
- % overstream overstory canopy
- Stream gradient (up and downslope), aspect, elevation
- Substrate: surface embeddedness,
- % in each substrate class (bedrock/boulder/cobble/gravel/sand/silt/organics)
- LWD: inventory of 10 m segment including dimensions
- Habitat indicators: flowing or standing water; presence of inverts/algae/wetland plants or other)

Survey Method A: This survey was designed to develop species presence/absence information and collect data on the available habitat in the analysis area. The survey used 200 m reaches (i.e., sample sites) with consecutive 50 m segments or sample plots. Data collected in the 50 m plots included general site information (e.g., slope, aspect, elevation), habitat quality (e.g., stream width and depth, water temperature), and the plots were searched thoroughly for amphibians with consideration for all life stages. Small nets were used to capture amphibians for identification as the substrate was disturbed in the attempt to locate amphibians. Flashlights were used in areas where the stream was covered with large woody debris.

Survey Method B: This survey was designed with emphasis on habitat characteristics, availability, and extent and distribution. Habitat measurements were simplified through the use of categorical data for selected variables. Amphibian searches were limited to small belts that were the length of specified habitat units and the width of the stream. This differs from the Survey A methodology where sample segments or plots were standardized at 50 m long.

3.2 SURVEY RESULTS

During 1999, headwater amphibian surveys were conducted at 33 sites throughout Freshwater watershed in Class II and Class I streams. Twenty samples were completed using the initial Survey A, and 13 samples were completed using Survey B. Approximately 3.7 miles of stream were surveyed for headwater amphibian habitat, with data collected on key habitat parameters. During these surveys, 7 species of amphibians were observed (Table 3-1). Both survey methods provided a reasonable opportunity locate the tailed frog and southern torrent salamander. The southern torrent salamander was found in 38.9 % of the sites (n=18) surveyed in survey A and in 42.9 % of the sites (n=7) surveyed in survey B (Table 3-2). Of the target species, 43 southern torrent salamanders were found at 10 sites and 93 tailed frogs were found at 13 sites. Other amphibian species located during these surveys included the Pacific giant salamanders, clouded salamander, slender salamander, and ensatina. It is notable that Pacific giant salamanders were found at every site searched; this salamander is known to prey on tailed frogs and southern torrent salamanders.

Table 3-1: Species and total numbers of amphibians observed during headwater surveys, May-August 1999, Freshwater Creek Watershed.

Species	Total number of individuals	Total number of occurrences
Southern torrent salamander	43	10
Tailed frog	93	13
Pacific giant salamander*	1,979	33
Clouded salamander*	2	1
Slender salamander*	4	2
Ensatina*	2	1
Northern red-legged frog*	6	2

*Pacific giant salamander, the terrestrial salamanders and Northern red-legged frog were not targeted in these headwater surveys, these represent incidental observations.

Southern torrent salamanders were found at 10 of twenty-five sites in consolidated geology, and tailed frogs at 12 (Table 3-1). These headwater species are most commonly found in the higher gradient (6.5-20% in C3, greater than 20% in C4) areas with consolidated geology (Table 3-2). Tailed frogs were found at only 1 site in unconsolidated geology, southern torrent salamanders at none (Table 3-2, Figure 3-1), however it is acknowledged that the sample size in this geologic type is small. The site where tailed frogs were observed was classified as occurring in unconsolidated geology, however the site had plentiful coarse sediments, probably from a Yager inclusion in the stream channel.

Table 3-2: Numbers of tailed frogs and southern torrent salamanders observed during the summer of 1999 in Freshwater Creek by Channel Geomorphic Unit (CGU).

Channel Geomorphic Unit (CGU)	# of sites sampled	Tailed Frog		Southern Torrent Salamander	
		# individuals	# Occurrences	# individuals	# Occurrences
C2	**1**	0	0	0	0
C3	**12**	66	7	5	5
C4	**12**	21	5	38	38
U1	**1**	6	1	0	0
U2	**1**	0	0	0	0
U3	**4**	0	0	0	0
U4	**1**	0	0	0	0
GG	**1**	0	0	0	0
Grand Total	**33**	93	13	43	43

3.3 Notable Observations

Most sites surveyed contained less than 10 individuals of any covered species. However, 44 tailed frog tadpoles were observed in segment 608 (C3), classified as a Class I stream. There were no distinctive habitat characteristics that could explain this high number.

Tailed frogs were observed at segment 1101 (U1) a site classified as unconsolidated geology in a Class I stream. Although the segment was classified as unconsolidated, the habitat was more characteristic of consolidated sites, with cobble and boulder substrates. This may have resulted from an inclusion of the Yager formation at the survey site, or from boulders and cobbles washed downstream from a Yager formation inclusion upstream.

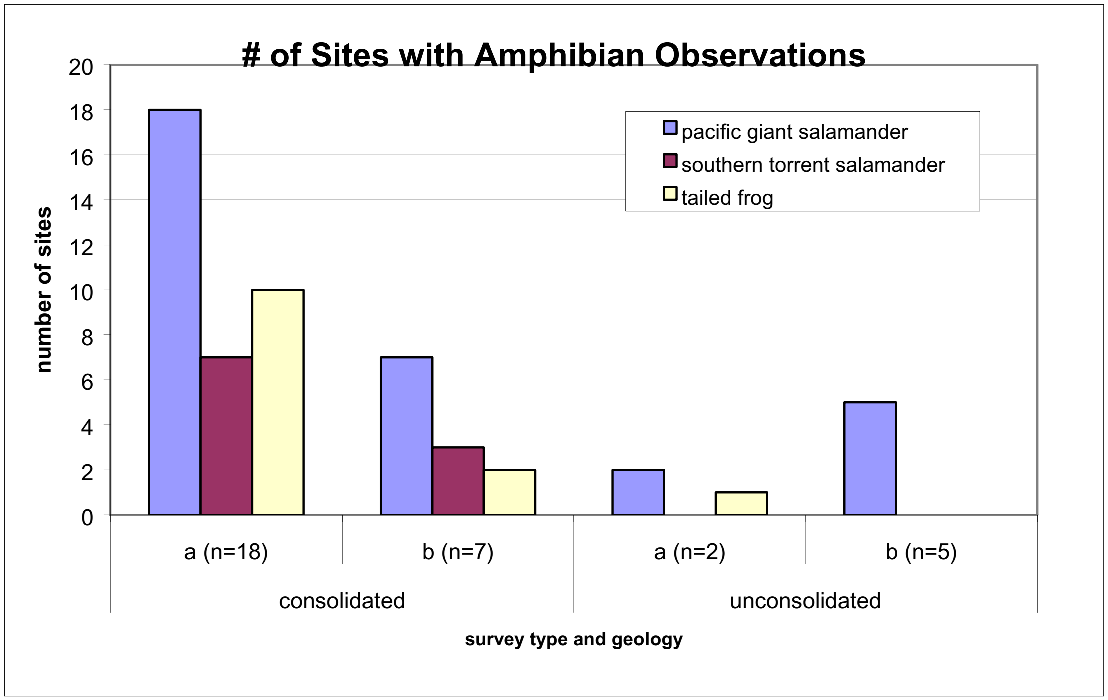

Figure 3-1: Freshwater Creek survey sites with amphibian observations. a= survey method A, b= survey method B. Pacific giant salamanders were found at all sites.

3.3.1 Non-headwater Species

Surveys were not conducted specifically to evaluate the occurrence of the other species. However, fish survey crews did record all frog species during their dive and habitat surveys Refer to the Fisheries Module - Appendix F for a discussion of these surveys methods. Fish surveys were conducted along 2.4 mi of Class I stream using intensive survey efforts. An additional 5.4 mi of Class I streams were surveyed for upstream extent of fish distribution with a reduced level of effort for habitat data collection. As reference, there are 22.75 mi of Class I stream on PALCO property and 9 mi of Class I stream off PALCO property in the Freshwater Watershed Assessment area. The sampling effort was high. These fish surveys include a total of 1,440 ft downstream of PALCO property. Northern red-legged frogs were observed during both headwater and fish habitat surveys. Red-legged frogs were noted as common during fish habitat surveys. Red-legged frog were noted as common in the McCready Creek drainage and all occurrences were not mapped (D. Halligan, personal communications, 2001). This frog was observed both along the stream and on ridgetops in this drainage.

Yellow-legged frogs were not located in the Freshwater Watershed during any surveys. It is expected that this frog would be located below the confluence of the North and South Forks of Freshwater Creek. This species is reported from in this area via incidental observations. Habitat for this species is found in this slower moving water with openings in the canopy providing warmer water desired by this species. Northwestern pond turtles were not observed during headwater amphibian surveys or fish habitat surveys, nor have they been identified through incidental observations in this watershed.

4.0 DISTRIBUTION

4.1 EXISTING INFORMATION

Limited surveys had been conducted prior to the initiation of the Freshwater Creek Watershed analysis. Surveys for the southern torrent salamander and tailed frog using intensive searches were completed in 1988 and 1989 on selected PALCO lands (Wroble and Waters 1989). The Freshwater Creek Watershed was surveyed in January 1988 at four sites in Class I and one site in Class II streams (three on South Fork Freshwater and two on the upper mainstem of Freshwater). No southern torrent salamanders were found at any sites and tailed frogs were found only at the South Fork Freshwater sites.

PALCO fish survey crews reported northern red-legged frog observations throughout the watershed in appropriate habitats, but specific locations were not recorded.

Company personnel have reported no incidental sightings of northwestern pond turtles; however, the McVays, (Freshwater residents) reported sighting turtles (species unknown, possibly northwestern pond turtles) just downstream from Freshwater Park prior to about 1996 (McVay, pers. comm.). At this location residents had added sand to the stream bank to provide a sandy beach. The sand washed away in *(1997)* and the turtles have not been observed since that time.

4.2 AMPHIBIAN DISTRIBUTIONS

Amphibian distribution based on potential habitat for each of the considered species was identified by channel geomorphic unit and based on the existing information, survey results, channel geomorphic conditions, aerial photographs, and other information (Table 4-1). For each of the four amphibian species, the potential for habitat within the CGU is identified as likely or not likely. In addition, the results of the amphibian surveys within each CGU area noted as were found or not found during these surveys.

Table 4-1. Potential amphibian and reptile distributions by Channel Geomorphic Units (CGU).

CGU		Southern Torrent Salamander	Tailed Frog	Foothill Yellow-legged Frog	Northern Red-legged Frog[1]
C	C1		X	X	
	C2		X+		
	C3	X+	X+		
	C4	X+	X+		
U	U1		X+		
	U2		X-		
	U3	X-	X-		
	U4	X-	X-		
Exceptions:	MS1			X	X
	MS2			X	X
	MS3			X	X
	MST			X	X
	CL		X	X	X*
	GG		X	X	

X indicates the CGU has geomorphic conditions which potentially could provide suitable habitat for the indicated species

+ indicates species presence was documented during surveys

- indicates species presence was not documented during amphibian surveys.

[1] Northern red-legged frogs may use ponds, sloughs and other off-channel habitats where there are no fish which are most likely to be present in the indicated CGUs.

U = Unconsolidated; C = Consolidated

4.2.1 Headwater Species

Tailed frogs and southern torrent salamanders have similar habitat requirements although the tailed frog is more widely distributed that the southern torrent salamander because their habitat requirements are broader. Map G-1 illustrates the potential habitat delineated and known locations of these species.

The upstream limit of potential southern torrent salamander and tailed frog habitat was estimated using information from the Fish habitat parameter surveys and Stream Channel Analysis (Appendix E). Based on the field survey work completed by the channel analysts and by the drainage areas of Class II/III breaks from recent THP field reconnaissance the break between Class II and Class III streams typically occurred where the upstream watershed area exceeded 20 acres. This acreage break was plotted using a Geographic Information System (GIS) to identify the potential upstream extent of amphibian habitat throughout the watershed. It is important to note these estimated stream breaks are field checked during THP layout.

4.2.2 Northern Red-legged Frog, Foothill Yellow-legged Frog & Northwestern Pond Turtle

Relative to other species, northern red-legged frogs are habitat generalists, and their breeding habitat consists of a wide variety of water bodies. Breeding habitat can range from flooded meadows, ponds, and backwaters of streams, to man-made water bodies including roadside ditches, settling ponds, and borrow pits. These habitats generally contain some emergent vegetation for egg attachment and persist long enough for metamorphosis to occur. These water bodies may be connected or unconnected to the stream network; because of their small size and occasionally ephemeral nature, they can be hard to identify from maps and aerial photos. For the purposes of this analysis low gradient CGUs and wetlands identified on National Wetland Inventory (NWI) maps and in the PALCO GIS database were mapped as potential habitat (Map G-2). Although it is documented that road side ditches and culverts can be used by the northern red-legged frog, these were not mapped nor included in habitat analysis for this species. This species was found throughout the watershed and it is anticipated that the streams provide higher quality habitat.

Foothill yellow-legged frogs are stream and river-dwelling frogs that typically breed in shallow, low-velocity habitats adjacent to shallow; wide stream reaches (Lind et al. 1992). Because this frog uses a well-defined breeding habitat, we were able to map potential habitat based on CGU locations (Map G-2).

The amphibian working group concurred that the Freshwater watershed is unlikely to provide habitat for the northwestern pond turtle based on review of aerial photography and amphibian and fish habitat surveys and consultation with local experts. The watershed does not contain any aquatic habitat suitable for northwestern pond turtles and no appropriate nesting habitat. Therefore no maps of potential habitat for this species were generated.

5.0 HABITAT CONDITION EVALUATION

The habitat conditions were evaluated using habitat diagnostics to describe conditions in each CGU. The CGU summaries for amphibians and reptiles are integrated into the fish habitat CGU summaries.

5.1 HABITAT DIAGNOSTICS

The analysis methods manual (PALCO 2000) requires that comparisons be made between existing conditions and a table of indices of resource conditions. The index being used is the Properly Functioning Condition Matrix (PFC). This matrix was developed by National Marine Fisheries Service to provide a basis for comparison of existing stream conditions with stream channel conditions in undisturbed streams.

The habitat qualities in the headwater streams surveyed varied with the underlying geology. The relevant PFC matrix values based on the data collected for this analysis are summarized in Table 5-1.

Table 5-1: PFC habitat diagnostics used for amphibian headwater habitat condition evaluation.

		Good	Fair	Poor
Pool Area	**<5% gradient**	>30%	20-30%	<20%
	>5% gradient	>40%	20-40%	<20%
Fine sediments		<12%	12-17%	>17%
Embeddedness		<25%	25-40%	>40%
Large Woody Debris (LWD)		>37.5 m^3/100m	13.8- 37.5 m^3/100m	<13.8 m^3/100m

5.2 HEADWATER HABITAT CONDITIONS

Based on the above diagnostics, habitat in the consolidated CGUs is of higher quality than in than the unconsolidated CGUs. For example, in consolidated CGUs the average percent of fine sediments in the substrate ranges from 43% in C2 to 11% in C4 and averaging 15% (fair) overall. This contrasts with unconsolidated CGUs where the average percent of fine sediments in the substrate ranges 15% to 54%, averaging 42% (poor) overall. Average embeddedness values for consolidated units range from 21% to 25% (good to fair), versus 14% to 56% (good to poor) in the unconsolidated CGUs (Table 5-2).

Table 5-2: Summary of headwater amphibian habitat by Channel Geomorphic Unit (CGU).

		Pool Area		Fines		Embeddedness		LWD	
CGU	# of Sites	Average Value	Rating*	Average Value	Rating*	Average Value	Rating*	Average Value	Rating*
C2	1	95%	Good	43%	Poor	23%	Good	111	Good
C3	12	43%	Good	17%	Fair	21%	Good	90	Good
C4	12	29%	Fair	11%	Good	25%	Fair	116	Good
All Cs	25	38%		15%	Fair	23%	Good	103	Good
GG	1	26%	Fair	27%	Poor	5%	Good	100	Good
U1	1	69%	Good	15%	Fair	17%	Good	22	Fair
U2	1	56%	Good	33%	Poor	56%	Poor	28	Fair
U3	4	58%	Good	54%	Poor	33%	Fair	63	Good
U4	1	47%	Good	31%	Poor	14%	Good	32	Fair
All Us	7	58%	Good	42%	Poor	31%	Fair	47	Good

*The ratings are determined using the PFC matrices.

5.3 CLASS I STREAM HABITAT CONDITIONS

Analysis of the habitat data collected in Class I streams is included in the Fisheries Assessment Module. Please refer to this report for a full discussion of the habitat conditions. Generally in Class I streams pool area and pool frequency met target levels identified in the aquatic properly functioning conditions matrix. Pool habitat cover complexity and LWD abundance were at fair to good levels. There is a need for more functional LWD in C1, U1, MS1, MS2, and MS3. Substrate conditions were generally poor to fair. There is evidence of fine sediment accumulating in pool habitats. This may be reducing available interstitial spaces and impacting tailed frog habitat. While substrate quality was not good in CGUs C1, C2, MS1, and CG, it was worse in U1, U2, GG, and MS3. This could be expected since these latter CGUs are in unconsolidated wildcat geology where there is poor gravel production areas and high fine sediment bedload.

5.4 TEMPERATURE ASSESSMENT

PALCO recorded water temperatures between 1996 and 1999 at two to six stations in the watershed with automated temperature probes as part of its property-wide stream monitoring program (Table 5-3 and Map F-6 – in Fisheries Assessment).

The maximum temperatures measured in the Freshwater watershed ranged from 19.7°C measured in the mainstem of Freshwater in 1997 to 13 °C measured in a headwater tributary the same year. The maximum weekly average temperatures (MWAT) ranged from 12.6°C to 17°C from early July through late October. Average summer water temperatures during all three sampling years ranged from 11.6°C to 16°C.

Table 5-3: Summary of Temperature data collected in the Freshwater Watershed 1996 to 1999.

DATES			Station	Days	Average	Maximum Temperature		MWAT			Data
Yr	From	To	Id		Temp. ºC	Value ºC	Date	Value ºC	From	To	Source
96	06/15	09/30	Sta 92-96 Cloney Gulch	108	14.23	17.81	07/26	16.10	07/25	07/31	PALCO
96	06/15	09/30	Sta 36-96 Upper Freshwater	108	12.00	16.55	07/30	14.27	07/25	07/31	PALCO
96	06/15	09/30	Sta 33-96 Main Freshwater	108	14.43	18.34	07/30	16.19	07/25	07/31	PALCO
97	06/15	09/30	Sta 18-97 Little Freshwater	108	15.74	18.76	08/25	16.67	07/15	07/21	PALCO
97	06/15	09/30	Sta 37-97 SF Freshwater	108	15.44	17.53	07/18	16.19	07/15	07/21	PALCO
97	06/15	09/30	Sta 33-97 Main Freshwater	108	16.02	19.72	08/07	17.00	07/14	07/20	PALCO
97	06/15	09/30	Sta 135-97 McCready Gulch	108	14.45	16.93	09/04	15.45	08/31	09/06	PALCO
97	06/15	09/30	Sta 36-97 Main Freshwater	108	12.58	14.59	08/08	13.41	08/08	08/14	PALCO
97	07/01	09/30	Sta 159-97 SF Freshwater – class II	92	12.12	13.14	08/08	12.57	09/24	09/30	PALCO
98	06/15	09/28	Sta 36-98 Upper Freshwater	106	12.21	15.38	08/14	13.83	09/01	09/07	PALCO
98	06/15	09/28	St 135-98 McCready Gulch	106	13.39	15.57	08/12	14.59	08/11	08/17	PALCO
99	07/01	10/15	Sta 36-99 Upper Freshwater	107	11.56	14.59	07/13	13.32	08/23	08/29	PALCO
99	07/01	10/15	Sta 135-99 McCready Gulch	107	12.58	16.27	08/22	14.62	08/21	08/27	PALCO
99	07/20	10/15	Sta 18-99 Little Freshwater	88	13.06	17.72	08/22	15.49	08/21	08/27	PALCO
99	06/22	10/07	Sta 34-99*	108	14.00	18.79	07/26	14.00	08/21	08/27	Willey

* Temperature monitored at Pool Tail rather than Riffle

Station 92 Cloney Gulch, approximately 1000 ft upstream of the confluence with Freshwater.
Station 36 Mainstem Freshwater, approximately 8250 ft upstream of South Fork Freshwater.
Station 33 Mainstem Freshwater, approximately 750 ft downstream of South Fork Freshwater. (no longer in use)
Station 18 Little Freshwater, approximately 500 ft upstream of the confluence with Freshwater
Station 37 South Fork Freshwater, approximately 1000 ft upstream of the confluence with Freshwater (no longer in use)
Station 135 McCready Gulch, approximately 3750 ft upstream of the confluence with Freshwater.
Station 159 South Fork Freshwater, Class 2 watercourse, very high up in drainage.
Side trib, Located approximately 1500 ft upstream of confluence with SF Freshwater

The PFC matrix states the indicator range for temperatures is 11.6 to 14.5°C. The matrix identifies a maximum weekly average temperature (MWAT) of 16.8°C. The MWAT was only exceeded in one case during 1997 at the Mainstem Freshwater site, approximately 750 ft downstream of South Fork Freshwater. Table 5-4 summarizes the preferred temperature ranges of the amphibian species considered in this analysis. The torrent salamander is the most temperature sensitive of all species considered in the analysis. The torrent salamander also only occurs in Class II tributaries or springs and seeps. There was one sampling location in a Class II tributary that was station 159 that collected data in 1997 (159). The maximum temperature recorded at this site was 13.1°C and the average summer water temperature was 12.1°C, indicating that temperatures in this tributary were within the preferred range of this species. The highest maximum temperature recorded was 19.7°C measured in the mainstem of Freshwater in 1997 and 18.8°C measured in the mainstem of Freshwater in 1999. These maximum temperatures are below the maximum preferred temperatures of the northern red-legged frog, foothill yellow-legged frog and northwestern pond turtle (Table 5-4). They are only slightly greater than the preferred temperature range of the tailed frog. This site is on the main stem of Freshwater and does not have the characteristics of preferred tailed frog habitat, and this species is not likely to occur in this area. The temperatures in tributaries where the tailed frog is most likely to occur were all within the preferred temperature range of the species.

Table 5-4: Preferred temperature ranges of covered species.

Species	Preferred Temperature Range
Southern Torrent Salamander	6.5°C -15°C (Welsh and Lind 1996)
Tailed Frog	5°C –18.5°C (Brown 1975, Claussen 1973)
Northern Red-Legged Frog	<21°C in late winter/early spring (Licht 1971)
Foothill Yellow-Legged Frog	<24-27°C in spring/early summer (Kupferberg 1996)
Northwestern Pond Turtle	<32°C in late winter/early spring (Licht 1971)

6.0 AREAS OF CONCERN

6.1 WILDCAT VS. OTHER GEOLOGIES

Underlying geology influences the stream substrate. The yellow-legged frog (Hayes and Jennings 1988, Kupferberg 1996), southern torrent salamander, and tailed frog (Diller and Wallace 1996 and 1999) benefit from larger cobbles and other coarse sediment. The CGUs with unconsolidated geology (i.e., Wildcat) produce little or no coarse sediments and high volumes of fine sediments and result in highly embedded substrates. This reduces the habitat quality for the headwater species by eliminating available coarse sediments and interstitial spaces. As a result CGUs in unconsolidated geologic areas are unlikely to provide quality habitat. The CGUs with consolidated geologies (i.e., Franciscan) produce more coarse sediments that provide interstitial spaces, and are therefore suspected to form better quality habitat for these three species

The western pond turtle and northern red legged frog do not appear to require coarse substrate.

7.0 CHANNEL GEOMORPHIC UNIT (CGU) VULNERABILITY CALLS

Channel segments with similar physical characteristics (stream gradient and geology) and responses were grouped into 12 channel geomorphic units (CGUs). The Stream Channel module has complete CGU descriptions. Data on the aquatic habitat conditions and amphibian and reptile life history and distribution patterns, obtained from field surveys and historical analysis, were extrapolated to all segments in each CGU and used to determine the potential biological and habitat response to changes in certain input factors. These inputs were LWD, bank stability, peak flow, coarse sediment, and fine sediment. The potential for biological or habitat response to the input variables is called a resource vulnerability. The amphibian and fisheries analysts consulted with other module analysts to determine the vulnerability of the aquatic resources to increases or decreases in inputs of above factors (Table 7-1).

Table 7-1: Fish/Amphibian Habitat Vulnerabilities (Low, Medium, High) for Each Channel Geomorphic Unit (CGU)

Channel Geomorphic Unit		LWD	Bank Stability	Peak Flow	Coarse Sediment *	Fine Sediment *
Consolidated Geology						
C1	**0-3 %**	H	L	H	H	H
C2	**3-6.5 %**	M	L	M	M	M
C3	**6.5-20%**	M	L	L	L	H [2]
C4	**20+%**	L	L	L	L	H [2]
Unconsolidated Geology						
U1	**0-3 %**	H	L	H	H+	H
U2	**3-6.5 %**	H	L	M	H+	M
U3	**6.5-20%**	L [1]	L	L	M+	L [2]
U4	**20+%**	L	L	L	M	L
Exceptions						
MS1 (South Fork to Graham Gulch)		H	L	M	H [3]	H
MS2 (Graham Gulch to Little Freshwater)		H	L [4]	M	M	H
MS3 (Little Freshwater to 3 Corners)		H	L [4]	M	M	M
GG (Graham Gulch 0-6.5%)		H	L	H	H	M
CG (Cloney Gulch 0-3%)		H	L	H	H+/H	H

* Coarse sediment: >8 mm for fish, greater than 2mm for channel processes, Fine sediment: 8 mm or less

+ Increase in coarse sediment may have positive effects in this gravel-poor geology

1 May have been more prior to first harvest

2 High negative impact to amphibians, low for fish due to scarcity, filling of seeps with fines

3 Too much coarse can destabilize channel, but moderate increases may be beneficial

4 Bank erosion could create more complex habitats if residents allowed it to occur

The stream segments are grouped according to geologies and gradients, with a number of reaches grouped as exceptions due to significant differences.

7.1 CONSOLIDATED GEOLOGIES

These CGUs are in predominantly Franciscan and Yager geologic formations, which provide coarse sediments for amphibian habitat. The canopy cover over streams in these units is high, and the percentage of fine sediments and embeddedness varies with gradient. Pond turtles are not expected to occur because high canopy cover (average >80%) over streams with small channel widths (≤25 ft) limits basking sites and because nest sites are unavailable. Red-legged frogs may breed off channel in very low gradient (C1), low flow backwaters and off streams in floodplain pools throughout this geology, but not in the main channels, although they may occasionally be encountered. Yellow-legged frog habitat is unavailable due to high canopy cover over the streams. The stream segment number included in the Amphibian Survey is listed with those segment where southern torrent salamander and tailed frog located noted in bold (The Stream Channel Analysts developed a map breaking the Stream Network into segments – see Channel Module for more information).

C1 Consolidated 0-3% Gradient

Description: Confined, 0 - 3% gradient pool-riffle channel. Substrate is primarily small cobble and gravel. Functional wood frequency is moderate with 50% of the pools being formed by LWD. Pool area is good. A few pools are formed by scour along bedrock.

Amphibian/Reptile Habitat Conditions: The lower gradient reaches (C1, C2, U1, U2) typically provide habitat for foothill yellow-legged frogs, in locations where areas of canopy cover is lower than 80%. The habitats in this CGU consist primarily of low gradient pool-riffles. The small cobble and gravels may provide breeding habitat for yellow-legged frog.

Stream Segments included in Amphibian Survey: none

Conditions and Response Potential : See Fisheries Assessment Module

C2 Consolidated 3-6.5% gradient

Description: Confined, 3-6.5% gradient pool-riffle channel. Boulder and cobble dominate substrate. Functional wood frequency is moderate with 46% of the pools being formed by LWD. Pool area is good. A few pools are formed by scour along bedrock and plunges.

Amphibian Habitat Conditions: The habitats in these gradients consist of primarily of moderate gradient pool-riffles. The high canopy cover and the coarse substrates consisting of boulder, cobble, and gravel provide good habitat for tailed frog tadpoles. While the percent of fine sediment was poor (43%), percent embeddedness was fair to good, and LWD amounts were good.

Stream Segments included in Amphibian Survey : 1201

Conditions and Response Potential : See Fisheries Assessment Module

C3 Consolidated 6.5-20% gradient

Description: Confined, 6.5-20% gradient plunge pool-cascade channel. Bedrock and boulder dominate substrate. Functional wood frequency is high with 50% of the pools being formed, and the channel choked, by LWD. Pool area is good. A few pools are formed by scour along bedrock and plunges.

Amphibian/Reptile Habitat Conditions: The habitats in this gradient class consist of primarily high gradient step-pool and plunge pool-cascades. The high canopy cover (>80%) and the cobble/gravel substrates provide habitat for tailed frog tadpoles throughout, while instream torrent salamander habitat is limited to Class II streams and off-channel seeps. The amounts of coarse sediments available in these streams provide good habitat for headwater amphibians, with covered species observed at 9 of the twelve segments sampled and high numbers (44) of tailed frog tadpoles at one segment. While the percent of fine sediments is fair overall, the embeddedness values are good (<25%), allowing frogs and salamanders to effectively utilize coarse sediments in many places. LWD volumes are high, creating numerous small step pools and in some cases completely covering the stream. The LWD provides cover and refuge, thus providing good amphibian habitat. Streams here have high canopy cover (average 89%) providing good thermal cover. The percent pool area is good, providing another measure of the quality of the habitat. A high percent pool area reflects habitat diversity important.

Stream Segments included in Amphibian Survey: **107**, 133, **204**, 208, **367, 608**, 621, **674, 726, 758, 791,** and **980**
(Notable occurrences: Forty-four tailed frog tadpoles were observed at segment 608. The next highest observations number was 10 animals at segment 910 (C4)).

Conditions and Response Potential: See Fisheries Assessment Module

C4 Consolidated >20% Gradient

Description: These are confined reaches with gradients greater than 20%, composed primarily of step-pool habitat. LWD is abundant, and small pieces (<1 m in length) are functional due to the small channel size. Substrates contain low percentages of fines, and cobble/gravel sediments are prevalent.

Amphibian/Reptile Habitat Conditions: The low fines and high gradient here provide good habitat for tailed frog tadpoles and torrent salamanders, with animals observed at 7 of the twelve survey sites. Embeddedness values are low, allowing amphibians to utilize the available coarse sediments for feeding and cover habitat. LWD volumes are high, creating numerous small step pools and in some cases obscuring the stream, providing good amphibian habitat. High canopy covers over streams (average 89%)

<u>*Stream Segments included in Amphibian Survey:*</u> 129, 215, **331**, 646, **654, 690, 735-736+739, 750+752, 751**, 794, **910-911**, and **914**

Conditions and Response Potential

<u>LWD</u>: Volumes of LWD are high (116 m^3 /100 m) providing cover and creating step pools. Functional pieces in these headwaters may be as small as a few inches in diameter and LWD sometimes forms a cover over the entire stream. While the loss of LWD would have serious consequences for headwater amphibians, the long decay time of redwood and high retention of LWD in this CGU moderate that risk. *Low vulnerability*.

<u>Coarse Sediments</u>: The cobble/gravel/boulder sediments needed by tailed frog tadpoles and for torrent salamanders are currently available and will be maintained by normal stream processes in this gradient and geology. *Low vulnerability*

<u>Fine Sediments</u>: The percent fine sediment and the percent embeddedness were good (11% and 25% respectively). These sediments are unlikely to accumulate due to the stream gradient; however, accumulation of fine sediment would reduce habitat quality. *High vulnerability*

<u>Peak Flow</u>: Increased flows do not result in incised channels in this CGU. Sustained high flows have the potential to transport bedload, but the large substrate in this CGU is resistant to transport except at very high flows. High flows have the potential for improving amphibian habitat quality by flushing fine sediments downstream. *Low vulnerability*

<u>Bank Stability</u>: Bank stability is maintained by the presence of extensive root systems in the headwater channels, and bank erosion is a minor contributor of sediment to the channel when compared to landslides and the road network. The relatively high gradient is capable of flushing most of the sediment introduced from unstable banks downstream, but disturbance of the root system may result in decreased stability. This is unlikely to affect amphibian habitat. *Low vulnerability*

7.2 Wildcat Geologies

The unconsolidated CGUs in Wildcat geologies (U1-U4) have generally high fine sediments and very low amounts of coarse sediments. The sediment quality is a result of the composition of the Wildcat formation; mud and siltstones that decompose to form silt and sand.

Accumulations of coarse sediments in these CGUs are uncommon. Because the Wildcat formations provide poor habitat, any consolidated CGU inclusions within unconsolidated CGU are especially important.

U1 Unconsolidated Wildcat 0-3 % gradient

Description: Confined, pool-riffle channel with gradients of 0-3%. Substrate is predominantly sand and fines. Wood frequency is high. Pool area is good. Most pools in this CGU are formed or associated with LWD. Some pools are formed by scour along bedrock. Floods are able to spill over onto narrow floodplains in some locations.

Amphibian/Reptile Habitat Conditions: The fine sediments typical of Wildcat geologies provide poor habitat for tailed frog tadpoles, yellow-legged frogs and torrent salamanders. Like in the consolidated geologies, the basking needs of pond turtles are not met due to high canopy cover (average> 80%) over streams and because of the lack of nest sites. Red-legged frogs may breed off channel in very low gradient, low flow backwaters and off streams in floodplain pools throughout this geology, but not in the main channels, and they may occasionally be encountered. Torrent salamanders were not observed in any surveys within wildcat geologies, and tailed frog tadpoles were observed at only one atypical survey site. LWD is important in trapping coarse sediments, providing the only available appropriate substrates.

Stream Segments included in Amphibian Survey: **1101**

Anomalous segments: PWA 1 has greater residual pool depth and higher percentage of pools by length and area then the other verified segments. Tailed frog tadpoles were observed in segment 1101. This segment has good cobble and boulder substrates, which is not consistent with segments surveyed for fish habitat. These substrates may have originated in the adjacent Yager formations. In addition, LWD is abundant, covering the stream extensively.

Conditions and Response Potential: See Fisheries Assessment Module

U2 Unconsolidated Wildcat 3-6.5% gradient

Description: Confined, pool-riffle channel with gradients of 3-6.5%. Substrate is predominantly fine sediment. Wood frequency is high. Pool area is good. 90% of the pools in this CGU are formed from LWD. Average wetted and bankfull widths are 2 and 14 feet respectively.

Amphibian Habitat Conditions: These moderate to high gradient units contain high fine sediment values that typically cover surfaces limiting algal growth and burying interstitial spaces which reduces usable amphibian habitat. LWD is important in trapping coarse sediments, providing the only available appropriate substrates. See also U1.

Stream Segments included in Amphibian Survey: 3

Conditions and Response Potential: See Fisheries Assessment Module

U3 Unconsolidated Wildcat 6.5-20% gradient

Description: Confined, pool-riffle channel with gradients 6.5-20%. Substrate is predominantly bedrock and boulders. Wood frequency is good. Pool area is high. Pool frequency is fair to good. Most pools in this CGU are either plunge or bedrock formed.

Amphibian/Reptile Habitat Conditions: High gradient unconsolidated stream segments have very limited capacity to provide the coarse substrates needed for the headwater amphibians nor provide pool formations needed for the western pond turtle nor the yellow-legged frog. Fine sediments are high and coarse sediments are uncommon. See also U1.

Stream Segments included in Amphibian Survey: 563, 930, 1112, and 1255

Conditions and Response Potential: See Fisheries Assessment Module

U4 Unconsolidated Wildcat >20%

Description: These are high gradient reaches with gradients greater than 20%. Substrates are composed of a high percentage of fine sediments with moderate embeddedness values. LWD is fairly common, and small pieces are functional due to the small channel size.

Amphibian/Reptile Habitat Conditions: These very high gradient unconsolidated stream segments have very limited capacity to provide the coarse substrates needed by the amphibians. Fine sediment volumes are high and coarse sediments are uncommon. The headwater species normally found in high gradient reaches (torrent salamander and tailed frog) are unlikely to be found here due to the substrate characteristics. See also U1.

Stream Segments included in Amphibian Survey: 32

Conditions and Response Potential

LWD: LWD volumes are fair in this unit and are important to provide structure and trap sediments. Habitat quality is limited by the sediment characteristics. *Low vulnerability*

Coarse Sediments: Coarse sediments are uncommon in this unit and there is little potential for change due to the source material. *Moderate vulnerability*

Fine Sediments: While the fine sediment percentages in this unit are poor (31%), embeddedness values are good (13%), and there is little potential for change due to the source materials. *Low vulnerability*

Peak Flow: High flows in these high gradient streams act to transport fine sediments. The lack of coarse materials to provide habitat and the small volume of water transported minimize its importance. *Low vulnerability*

Bank Stability: Unstable banks are present in some of the habitat units, but the sediment produced from the erosion would consist of small, easily transported particles during high flow and not significantly affect aquatic habitat. Root structure is also important to maintain stability, but the lack of coarse materials to provide habitat minimizes the importance of bank stability. *Low vulnerability*

7.3 CGU Exceptions: Mainstem Freshwater

The segments composing CGUs MS1-MS3 are low gradient (<1.5%) segments, with average stream canopy cover of 65-76%. Substrates are variable, ranging from bedrock to cobble to sand.

MS1 South Freshwater to Graham Gulch

Description: Alluvial transport reach, <1.5% gradient. Substrate is primarily small cobble and gravel with areas of exposed bedrock and large cobble substrate. Functional wood frequency is relatively low with 36% of the pools being formed by LWD. This CGU carries high flows, which tend to flush small diameter LWD downstream. Pool area is good. 1/3 of the pools are formed by scour along bedrock.

Amphibian/Reptile Habitat Conditions: These low gradient segments with moderate canopy cover over the stream (average 76%) provide better habitat for yellow-legged frogs but poorer habitat for tailed frog. While the lower canopy cover is better for pond turtles, there is limited LWD for basking sites and a lack of nest sites. Red-legged frogs may breed in off-channel ponds on the floodplain. No amphibian surveys were conducted in Mainstem Freshwater CGUs, other than as done with the fish habitat surveys.

Stream Segments included in Amphibian Survey: None

Anomalous Segments: Man-made LWD structures are in place in the upstream reach, which trap sediment. Spawning habitat is better upstream than downstream.

Conditions and Response Potential: See Fisheries Assessment Module

MS2

Description: Alluvial aggradational reach with gradients <1.5%. Substrate is predominantly gravel with inputs dominated by Graham Gulch contributions. LWD frequency is low. Few pools formed by LWD. Most pools formed by corner or bedrock scour. Pool area is poor with approximately 20% of channel length in pools. Floods are able to spill over onto floodplains

Amphibian/Reptile Habitat Conditions: This CGU with moderate canopy cover over the stream and abundant coarse sediments provides good foraging and shelter habitat for yellow-legged frog tadpoles. It does not provide good habitat for tailed frogs (prefer high gradient streams) or pond turtles. While the lower canopy cover is better for pond turtles, limited LWD for basking sites and lack of nest sites limit distribution.

Stream Segments included in Amphibian Survey: None

Conditions and Response Potential: See Fisheries Assessment Module

MS3 Little Freshwater to 3 Corners

Description: Alluvial aggradational reach with gradients <1.5%. Substrate is predominantly gravel and sand with small cobble subdominant in the upper reaches. LWD frequency is low. Pool area is good. Most pools in this CGU are corner pools. The two longest pools are formed by sediment plugs. Floods are able to spill over onto floodplains. The channel appears to be constricted by encroaching vegetation that encourages sediment deposition and further narrowing.

Amphibian/Reptile Habitat Conditions: The low gradient segments with moderate canopy cover over the stream do not provide good habitat for any of the considered amphibians. While the low stream canopy cover (66%) is better for pond turtle basking, very limited LWD for basking sites may limit distribution. This CGU is the most likely to provide turtle nesting sites, but the high degree of human disturbance may prevent utilization of appropriate sites.

Stream Segments included in Amphibian Survey: None

Conditions and Response Potential: See Fisheries Assessment Module

7.4 CGU Exceptions: Graham Gulch and Cloney Gulch

GG Graham Gulch

Description: Confined, sediment-rich channel with gradients of 0-6.5%. Substrate is predominantly small cobble and gravel. Wood frequency is high with 57% of the pools being formed by LWD. 100% of the pools are associated with LWD. However, much of the LWD especially in the lower reach was manually placed during instream habitat enhancement activities. Pool area and frequency are fair. Creek becomes intermittent in the upstream reach. Floods are able to spill over onto narrow floodplains in some locations.

Amphibian/Reptile Habitat Conditions: The gradient in this CGU varies from 0-6.5%, stream canopy cover averages 83%, and embeddedness values are high, containing abundant fine sediments. These characteristics yield poor habitat for the all the considered species, with too much canopy cover for yellow-legged frogs and pond turtles, and too much fine sediments for tailed frog tadpoles and torrent salamanders.

Stream Segments included in Amphibian Survey: 303

Anomalous Segments: 302 has intermittent flow which eliminates summer rearing habitat potential and creates seasonal juvenile migration barriers. A large landslide contributes large volumes of coarse sediment to the channel resulting in aggradation.

Conditions and Response Potential: See Fisheries Assessment Module

CG Cloney Gulch

Description: Gravel-rich, 1.5 - 3% gradient pool-riffle channel. Substrate is predominantly small cobble and gravel. Functional wood frequency is low with a range of 11 - 33% of the pools being formed by LWD. Pool area is good. Pool frequency is fair with one pool for every three channel widths. Some pools are formed by scour along bedrock. Several pools in the lower reach contain man-made LWD structures. Floods are able to spill over onto narrow floodplains in some locations.

Amphibian/Reptile Habitat Conditions: The gradient in this CGU varies from 0-3%, stream canopy cover averages 81%, and embeddedness values are high. These characteristics yield poor habitat for the all the considered species, with too much canopy cover for yellow-legged frogs and pond turtles, and too much fine sediments for tailed frog tadpoles and torrent salamanders.

Stream Segments included in Amphibian Survey: None

Conditions and Response Potential: See Fisheries Assessment Module

8.0 CONFIDENCE IN ANALYSIS

All species on the covered species list, except northwestern pond turtles, were encountered either incidentally or in surveys conducted for this analysis or previous surveys conducted. Other amphibian species were located during the reconnaissance surveys for amphibians and reptiles, but none are listed as a species of concern. The confidence in the species list identified above is high. No other species of special concern were identified in the watershed and no others were indicated for survey through contacts with agency personnel or local experts. Confidence in habitat quality and distribution evaluation is high for the southern torrent salamander and tailed frogs. Confidence in habitat quality and distribution evaluation is moderate for all other species, as surveys were not specifically aimed at these species. Habitat evaluations for these species were made based on fish habitat parameter data.

8.1 ADDRESSES CRITICAL QUESTIONS?

The assessment was able to qualitatively address all critical questions.

9.0 MONITORING RECOMMENDATIONS

This assessment focused on identifying the general patterns of distribution and verifying presence of the key amphibian and reptile species in the watershed. The specific distributions, microhabitat associations and status of amphibian and reptile populations are not well understood or documented. Ongoing sampling and monitoring regionally should help provide additional information on the habitat associations of these species and their population status. This information will ultimately increase the confidence in the findings of watershed analyses. The conservative approach used in identifying potential habitat for these species will result in conservative prescriptions. More specific information identifying specific habitat conditions and species distributions may allow for less conservative prescriptions in areas that do not provide suitable habitat.

9.1 HEADWATER SPECIES: SOUTHERN TORRENT SALAMANDER AND TAILED FROG

The upstream distribution of headwater species (torrent salamanders and tailed frogs) was estimated based on drainage areas as part of this assessment. The actual upstream extent (class II/ III breaks) will be field verified as part of the THP process. As additional data on the actual locations of the stream breaks becomes available the relationship between drainage area and stream class break should be double checked to verify its accuracy.

Southern torrent salamanders tend to associate with seeps and springs as well as streams. This analysis did not attempt to identify any seep habitat areas. These seeps would be identified during field verification performed in the THP process. The Stream Channel analysts noted an increased frequency in seeps along the interface of the Wildcat and Franciscan geologies. However no data was collected to verify this observation. As additional data on locations and distributions of seeps becomes available through the THP process these features should be mapped to see if any patterns in the distribution of seep habitat are discernable.

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Attachment G-1: Amphibian Survey Methods – On Data CD