SEDIMENT SOURCE ANALYSIS FOR THE BIG RIVER WATERSHED, MENDOCINO COUNTY, CA

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INTRODUCTION

The Big River watershed in Mendocino County (Figure 1) has been listed as a sediment impaired waterbody in California's 1995 CWA 303(d) list, adopted by the State of California North Coast Regional Water Quality Control Board (NCRWQCB). This sediment impairment has resulted in non-attainment of designated beneficial uses, primarily salmonid habitat.

In October 1999, Graham Matthews & Associates was requested by the U.S. Environmental Protection Agency (EPA) and Tetra Tech, Inc., to prepare a sediment source analysis and preliminary sediment budget for the Big River watershed. The purpose of the sediment source analysis and preliminary sediment budget is to assist the EPA in establishing a Total Maximum Daily Load (TMDL) for sediment in the Big River watershed.

The Big River watershed has been divided into five planning areas with a total of 18 sub-watersheds for general planning purposes for this TMDL (Figure 1). For each of these sub-watersheds, past sediment production and delivery, by erosional process, will be determined.

The purpose of this report is to compile, summarize, and analyze sediment production data for the Big River watershed that could be used for TMDL development. The sediment production data is then integrated with other geomorphic information to develop a preliminary sediment budget for the Big River watershed. This study is primarily based on analysis of aerial photographs and analysis of GIS coverages, with limited field reconnaissance surveys, although considerable streamflow and sediment transport data collection occurred during the study period.

Previous Work

As a result of the study methods and timing, existing information from a variety of sources was used to supplement our remotely gathered data. Jackson Demonstration State Forest (JDSF) has been in the process of preparing a watershed assessment for several years in support of their HCP/SYP application process. Selected draft information is available from that effort that provides considerable background information on the JDSF portion of the watershed and its resources. Mendocino Redwoods Company is currently preparing a Watershed Assessment (WA) for their lands within the Big River Watershed, and certain information (substrate quality) has been made available in advance of the draft WA for this analysis. Georgia-Pacific Corporation prepared a Sustained Yield Plan for their ownership in Mendocino County in 1997 (Jones & Stokes 1997).
Similar sediment source analyses have been completed by Graham Matthews & Associates

for the following nearby watersheds: Noyo River (1999), Ten Mile River (2000) and Albion River (2001). Hydrology and sediment transport relationships developed for those reports have been modified for use in the Big River watershed as data from the Noyo Watershed provides the best available information, due to similar hydrologic conditions.

STUDY AREA

Sub-Watershed Areas

The Big River watershed has been subdivided into 5 planning watersheds (PW): Big River Headwaters, North Fork Big River, South Fork Big River, Middle Big River, and the Lower Big River. These planning watersheds encompass drainage areas of 32.78, 43.49, 54.46, 17.85, and 32.47 square miles (mi^2), respectively. The five planning watersheds have been divided again into a total of 18 Sub-Watersheds (SW). The five planning watersheds follow the CALWAA divisions. Table 1 presents the Planning Watersheds and Sub-Watersheds along with their drainage areas, while these areas are shown graphically in Figure 1.

Watershed Characteristics and Overview

The Big River drains a 181.05 mi^2 watershed located in the northern California Coast Range in western Mendocino County (Figures 1 and 2), entering the Pacific Ocean at the town of Mendocino, about 10 miles south of Fort Bragg, the nearest significant population center. Other than the town of Mendocino, there is relatively little human occupation in the watershed, with only scattered ranches and residences. Highway 20 traverses portions of the northern edge of the watershed as it runs from Fort Bragg inland to Willits. Elevations within the Big River watershed range from sea level at the basin outlet to 1566 feet. Much of the basin is remote, moderately to extremely rugged, and mostly (79%) owned by only four property owners.

Annual precipitation averages 38 inches near Fort Bragg, south of the watershed, to over 50 inches at Willits, to the southeast of the watershed. Analysis of precipitation maps indicates that the mean annual rainfall for the entire watershed is 55.5 inches, with portions receiving in excess of 65 inches at the higher elevations in the northern and eastern portions of the watershed. Mean annual precipitation has been calculated for all of the Planning Watersheds and Sub-Watersheds and is contained in Table 1. Snowfall occurs occasionally the higher elevations of the watershed, and rarely accumulates and typically melts within a short period. Snow is not considered to have any appreciable effect on the watershed hydrology. Large flood events are thus generally associated with intense periods of rainfall rather rain-on-snow events. Only limited stream gauging records exist for the Big River watershed, having been collected by the US Geological Survey from 1961 to 1971 and only on the South Fork Big River.

History

The history of the Big River watershed is dominated by timber harvest. The following brief history has been compiled from Carranco and Labbe (1975), Andrews (1985, 1994), and Mendocino County Historical Society (1996). Logging began in the lower basin about 1852 around the time that the first mill was built in what was then known as Mendocino City. The mill was sited on the bluffs and an apron chute to load finished wood onto ships was constructed at the mill. Logs were kept in an enclosure at the mouth of the river, but this facility was continually being damaged by high river flows.

In 1854, a new mill was built on the flat east of the present state highway, and a railroad was ultimately built to haul lumber to the loading point on the bluffs. This mill, with various capacities and configurations and ownerships, continued from 1855 to 1937 when the mill was shut down. This mill was the largest producer of lumber in Mendocino County between 1852 and 1879 with some 225,000,000 board feet cut (MCHS 1996). By 1905, when the company was sold to Mortenson, Union Lumber Co., and Caspar Lumber Co., E.C. Williams said that the mill had cut some 7,150,000,000 board feet from their 36,000 acres in the Big River watershed.

All logs were delivered to this mill by way of the river. The Mendocino Lumber Company used “river drives” of logs more extensively than any other timber operation on the North Coast, probably due to the ruggedness of the watershed. Some 27 splash dams have been documented (Jackson 1991) that were used in the Big River watershed for transport of logs to the downstream mill. The first dams were built between 1860 and 1870, while the last dam was constructed in 1924. Dams varied in size and construction methods, but ranged to as tall as 40 feet. Many of the dams were designed to operate in a synchronized fashion to maximize the flow of water in downstream reaches, and communications were established via a telegraph to allow for such operations. Known travel times for water releases, accurate to the minute, were developed for the larger dams. The last operation of these dams occurred in 1937.

Logging operations in the watershed proceeded generally from the lower reaches in the early years, up as far as the Little North Fork and Two Log Creek by the 1870s, gradually into the headwaters over a period of 40-80 years. Logging in the South Fork began about 1888 (Jackson 1991).

A short railroad was constructed in the lower reaches of the Big River by the Mendocino Lumber Company that extended from the log dump, several miles upstream of the mill on the estuary, to the Little North Fork. The railroad operated from 1883 to 1936, although from 1883 to about 1900 it was operated only as a tramway, rather than for hauling logs. In 1936, the railroad was shut-down and replaced by truck transport. Logs were hauled by the railroad to the “log dump”, where they were dumped into the estuary, to be floated from there downstream to the millpond. The log dump operated from 1901 to 1936. Log rafts were formed and moved on the outgoing tide by raft-tenders and rowboats. Beginning in 1902 a steam driven scow was used to haul the logs to the mill. Pilings were placed almost continuously between the piers and the mill pond to assist in the transport of the logs.
The Caspar Lumber Company acquired ownership of extensive tracts of old growth timber in the northern portions of the Big River watershed in 1893, although logging in the area did

not begin for many years (Wurm 1986). Their railroad was extended into the South Fork Noyo watershed via a tunnel from Hare Creek. From there, several remote logging areas in the Big River watershed were connected to the railroad with a series of inclines. The first incline into the Little North Fork of the Big River was built in 1915. In the late 1930s, the railroad was extended over a low pass from the South Fork Noyo into the North Fork Big River watershed. A branch of the railroad into Two Log Creek was built in 1937, and in 1939, Camp 20 near the Dunlap Ranch at Chamberlain Creek opened. The area around Chamberlain Creek was harvested between 1940 and 1946, when the railroad was finally shut down. After harvesting much of the old growth, Caspar Logging Company sold 47,500 acres of their lands to the State of California in the late 1940s to create Jackson Demonstration State Forest. Portions of the railroad grade were converted into Highway 20.

After 1940, tractor yarding and the construction of roads, skid trails and landings were the primary types of logging practices. Until the Forest Practices Act was passed in 1973, logging practices were unregulated. This Act required road construction and timber harvesting practices intended to protect aquatic habitat and watershed resources. During the past twenty years the use of cable yarding on steeper slopes has increased substantially, and tractor logging is generally restricted to gentler slopes. These most recent changes in practice create far less ground disturbance than tractor yarding, although tractor yarding is still responsible for a significant amount of the harvest, depending upon ownership.

Ownership

Detailed ownership maps for the entire watershed were obtained from Mendocino County in a GIS-based format. There are 1162 parcels in the 181.05 mi^2 watershed, owned by 374 different individuals or companies (Figure 3). Mendocino Redwood Company, LLC owns 212 parcels or 34,114 acres (29.4%) of the watershed, Jackson State Forest owns 76 parcels or 22,714 acres (19.6%), Pioneer Resources owns 135 parcels or 17,850 acres (15.4%), and Hawthorne Timber Company owns 63 parcels of 17,088 acres (14.7%). Another 14.2% is held by 31 property owners with property size varying from 160 to 3760 acres. This includes smaller industrial timberland owners, a several ranches, Montgomery Woods State Reserve, portions of Mendocino Headlands and Russian Gulch State Parks, the Leonard Lake Reserve, Mendocino Woodlands Camp Association, and other property owners. Numerous small parcels, often private residences, make up the balance. No other property owner owns more than 5% of the watershed. The five largest property owners are shown in Figure 3 and combined, they own 528 parcels or 82.5% of the watershed. There are 403 parcels owned by 320 persons that are less than 100 acres in size. Combined, these parcels comprise only 4.4% of the total watershed area. There are 211 parcels (0.4% of the watershed) less than 10 acres, of which 169 are less than 5 acres (0.23% of the watershed), and 60 are less than 1 acre (0.02% of the watershed).

Topography

The topographic setting of the Big River watershed is quite diverse along the length of the watershed. The terrain varies from flat estuarine environments and uplifted marine terraces to rugged mountainous topography with high relief (Figures 2 and 4). Elevations range from sea level to 2725 feet within the watershed. The rugged watershed is characterized by narrow ridgelines separated by deeply incised inner gorges of the major river channels and streams draining the watershed.

The western end of the Big River is distinguished by a drowned and filled estuary occupying a relatively narrow inner gorge characterized by steep slopes that extend up to the flat coastal terraces. Tidal influence extends over six miles upstream of the mouth. Narrow floodplains become mudflats as one moves downstream from the Little North Fork into and through the estuary.

Slope Analysis

A slope analysis of the watershed was conducted using GIS data provided by the California Department of Forestry and Fire Protection, Coast-Cascade GIS Department (CDF). Figure 4 graphically presents the results of this analysis by color-coded slope class. Table 2 summarizes the areas of the various planning and sub-watersheds by slope class. The differences between the Lower Big, and to a lesser extent, the Middle Big, which both contain a higher percentage of area of lower relief, and the other planning watersheds are readily apparent. 32.6% and 35.4%, of the Lower Big and Middle Big Planning Watersheds (PW), respectively, have slopes of less than 30%, while only about 20-25% of the South Fork, North Fork, and Headwaters PW fall into this category. For the steeper slope classes, 31.6%-37.7% of the NF, SF, and Headwaters PW have slopes exceeding 50%, while the Middle Big has 25.5% and the Lower Big has 14.9%. The Upper Mainstem Big SW has noticeably steeper slopes than the other sub-watersheds, with 49.1% of its slopes exceeding 50%, and 17.5% exceeding 70%. The Chamberlain Creek, Upper NF Big, Martin Creek Daugherty Creek, and Middle South Fork SW all have 36-40% of their slopes in excess of 50%.

The low gradient valley floors and the small fragments of marine terraces in the Lower Big stand out visually in Figure 5, with the light gray color coding of the GIS slope classes. Similarly, the red color coding for slopes exceeding 70% is visible in the upper watershed areas of each Planning Watershed, as well as the Lower South Fork SW, and at inner gorge locations along the narrow, incised drainages.

It is also useful to note that by far the majority of the small parcels (Figure 3) in the watershed are found in the areas of low relief, such as the marine terrace remnants near the town of Mendocino.

Geology

The geology of the watershed is represented by the bedrock and overlying surficial deposits. The watershed bedrock geology is dominated by rocks of the Franciscan complex, while lesser amounts of Tertiary marine rocks are also present. This portion of the Franciscan

Complex is relatively stable compared to the mélange terrane of the Central Belt, which is found only in the upper parts of the watershed. These bedrock units are in turn overlain locally by a veneer of a variety of surficial materials and deposits, including soil and colluvium, estuarine sediments, marine terrace deposits, dune sand, landslide debris, or alluvium. The following descriptions are derived from Blake and others (1985), Jayko and others (1989), Jennings (1977), Kilbourne (1982; 1983a, b, and 1984a, b, c), Kilbourne and Mata-Sol (1983), and Manson, (1984a).

Bedrock

The entire watershed is underlain by rocks of the Franciscan Complex except for a Tertiary age sandstone in the Greenough Ridge – Montgomery Woods State Park area. Within the watershed, the Franciscan occurs as two distinct bedrock units: the relatively coherent (stable) Tertiary to Cretaceous age Coastal Belt terrane and the relatively incoherent (easily eroded) Tertiary to Jurassic age Central Belt terrane.

Coastal Belt Terrane

Rocks of the Franciscan Coastal Belt terrane underlie the entire watershed except for the central eastern margin and a small area in the southwest of the watershed. These rocks are characterized by sandstone and interbedded siltstone and shale, with locally minor amounts of conglomerate present. Elsewhere chert, limestone, and greenstone are found. Coastal Belt rocks have been deformed by past tectonic activity. This has created a body of rock that has been broken up into coherent bedrock blocks of varying size (up to city blocks or larger) separated by shear zones and faulting; locally the bedrock is tightly folded.

Central Belt Terrane

Central Belt rocks crop out in the central area of the eastern margin of the watershed. They underlie the subdued topography in portions of that area.

The Central Belt is a mélange characterized by block of bedrock, varying in size from fist size pieces to blocks up to city blocks or larger in size, in a highly sheared, mashed, and mangled clayey matrix. The blocks of bedrock can include sandstone, conglomerate, chert, greenstone, blueschist, limestone, eclogite, serpentine, amphibole, and ultramafic rocks. The subdued nature of the hillside topography overlying the central belt is a result of the weak nature of the sheared mélange matrix.

Tertiary Sandstone

These rocks crop out in the southeastern area of the Big River Watershed. They are mapped to underlie Greenough Ridge and on to the southeast into Montgomery Woods State Park. These sandstones are well consolidated and interbedded with minor amounts of conglomerate and limestone. They are described as gently folded and thick bedded.

Time Period of Analysis

The time period for the sediment source analysis includes an 80-year period extending from 1921 to 2000. The period was dictated by available aerial photography coverage in the years 1936, 1952, 1965, 1978, 1988, and 2000. We assumed that features observed in the 1936 photographs covered a +/- 16-year period generally similar to the length of the subsequent 1936-1952 study period. Therefore, we assigned 1921 as the beginning of the sediment budget period.

Sediment source data have been developed for all six of these time intervals, although the 1936 photography only covered the western half of the watershed. These intervals capture different periods of sediment-producing events, including both large storms (the 1938, 1956, 1965, 1966, 1974, 1993 water years contained notable high flows) and changes in timber harvest practices. Thus, a combination of changing harvest and road building techniques, together with most of the largest storms this century, provide the framework for evaluating changes in sediment production and delivery within the watershed.

METHODS

Available Data

Existing data were compiled from a variety of sources, including the Jackson Demonstration State Forest *Watershed Assessment* (in preparation), Mendocino Redwoods Company, LLC *Big River Watershed Analysis* (in preparation), and TMDL and/or sediment source analyses for similar basins such as the Noyo (GMA 1999), Ten Mile (GMA 2000), Albion (GMA 2001), the Navarro (Entrix et al. 1998), and the Garcia Rivers (PWA 1997). GIS data were obtained from California-Department of Forestry Coast-Cascade GIS and Mendocino County (ownership).

Hydrology

Existing precipitation data were collected from the National Weather Service NCDC database on CD-ROM and from James Goodridge, former state climatologist and now consultant to the California Department of Water Resources. The limited streamflow records available were obtained from the USGS Internet site. A correlation process was used to extend the short streamflow record available on the Big River with the much longer record available from the adjacent Noyo River watershed. These data were analyzed for magnitude, frequency, and duration.

Stream Flow

Monitoring stations were established at various sites throughout the watershed based on access permission and access availability (all-weather roads) during storm events. Stage was generally measured by fenceposts driven into the streambed at most sites. During sampling, river stage was measured from the water surface to the top of the fence post using a pocket surveyor's tape. A few sites had standard staff plates installed in the streambed. Stage was measured directly off the staff plate at these locations. Most stage locations were surveyed to a locally established benchmark using an auto level in the case that the sites are disturbed (by vandalism or high flows) and the stage measurement location needs to be reestablished.

Flow measurements were taken at all sites using standard or modified USGS methods. Most measurements were performed by wading at the location, although bridge measurements were obtained for the Big above SF Big. Wading stream flow equipment included a 4ft top-set wading rod, JBS Instruments AquaCalc 5000-Advanced Stream Flow Computer, and either a Price AA or Pygmy current meter. Bridge measurements were made with a bridge board, A- or B-reel, Aquacalc 5000, a 50# sounding weight, and a Price AA meter.

Due to the large number of study sites and short period of time for the study, it was necessary to modify some standard stream flow methods. The Price AA current meter was used where stream flow velocities were over 3.0 ft/s and at measurement locations where surging flow or poor hydraulics were encountered. The Price AA meter typically performs better in sections with surging flows or poor hydraulics due to its added weight. Typically, the Price AA meter is not used in depths below 1.5 ft, but due to poor hydraulics and the steep gradient of many locations, the Price AA current meter was used in depths as shallow as 0.3 ft.

The maximum discharge per vertical was set as 10% instead of the more standard 5% in order to streamline the time required to complete flow measurements. Fewer verticals were also used in discharge measurements in order to reduce field time associated with a single measurement, thus allowing for more measurements per person-day of field work, or to limit the measurement to a smaller potion of the often rapidly changing storm hydrograph. Most discharge measurements contained 15-25 verticals, and were typically collected on the falling limb of storm hydrographs due to lesser amounts of floating organic debris and less rapid changes in stage. Efforts were made to obtain at least one measurement near the peak of a large storm, although no major storms occurred during the study period. Typically 3-5 discharge measurements were obtained at each site over a range of flows.

Turbidity and Suspended Sediment Sampling

Depth-integrated turbidity and suspended sediment sampling was performed at most locations. Sampling was performed using a US DH-48 Depth-Integrating Suspended Sediment Sampler, with handles of different length depending on the flow depth, or when bridge access was available during high flows, using a rope-deployed US DH-59 sampler. Sampling locations were located at or near stage locations. Standard methods were used for sampling, although velocity criteria for DH-59 sampler were occasionally exceeded.

Due to the number of sites being sampled, a tag line was not always set during sampling; instead, the distance between verticals was estimated. For each sample the location, time, stage, number of verticals, distance between verticals, and bottle # was recorded. At locations where it was not possible to get a true depth integrated sample, grab samples or modified depth integrated samples were taken, and this information was recorded.

Data Analysis

Stage/discharge relationships were developed for each site by plotting stage versus discharge. Generally, a power equation of the form Q = a*(stage^b) was then fit to the rating points in order to determine the stage/discharge relationship. However, in some cases, the power equations poorly matched the stage-discharge data and the relationships were instead developed by eye-fitting curves to the observed data. From these relationships, rating tables were constructed.

Turbidity and suspended sediment data were analyzed in several ways. Turbidity versus Suspended Sediment Concentration (SSC), Turbidity versus discharge, SSC versus discharge, and Suspended Sediment Load (SSL) versus discharge relationships were developed for all sites. In addition, because lab sample analysis in WY2000 had used TSS (EPA 180.1 method), we collected two samples at many of the Big River sites and processed one for SSC (ASTM D-3977) and one for Total Suspended Solids (TSS) (EPA 180.1 method) in order to evaluate the relationship between these tests of sediment concentration. Both WY2001 samples were analyzed for turbidity and the values averaged.

Dataloggers

Only manual stations were operated in WY2000 with periodic measurements of stage-discharge at 9 sites, while in WY2001 continuous dataloggers were installed at 4 sites (SF Big, Big above SF Big, NF Big, and North Fork Big above Chamberlain Creek). All of these sites used Global WL-14 dataloggers. In addition, during WY2001, the California Department of Water Resources and the USGS re-installed a gauging station at the former SF Big River near Comptche site. Records from our dataloggers were periodically downloaded by laptop and then analyzed using Western Hydrologic Systems *Surface Water* computer program to compute discharge records. Continuous records of suspended sediment transport were computed by linking the 15-minute discharge values with the appropriate sediment rating curve. Hydrographs for stations monitored in WY2001 which did not have dataloggers installed were synthetically derived by scaling our other continuous records by watershed area and adjusting, as necessary, to match our observed gage heights during sampling periods.

Geomorphology

Historic aerial photographs were used to evaluate changes in sediment storage. Historic records of timber harvest, railroad construction, and early photographs from a variety of sources were examined to provide a glimpse of conditions in the watershed from 1850-1936.

Bulk Sample Data Collection

Mendocino Redwoods Company has collected bulk samples at five sites on their lands in the Big River watershed. We used similar methods (12” McNeil, but only 2 samples per site and gravimetric sample analysis) at eleven sites throughout the watershed.

Once a site was selected, a cross section was established using 5/8" rebar on each bank as endpins. A measuring tape was strung between endpins with station 0 on the left bank pin and all further sampling at the site was referenced to the tape.

At each site, two bulk samples were taken along the cross section in undisturbed locations that matched the spawning characteristics of the area. The 12" McNeil type cylinders were worked down into the gravel bed, removing the bed material into buckets until the hole was excavated to a depth of about 1.0'. The top surface layer, defined as the depth of the largest surface particle was kept separate from the subsurface. Once removed, samples were placed into sampling bags and buckets for transport to our lab.

At the lab, the entire sample was thoroughly oven-dried and sieved through 2mm using a Gilson TS-1 Testing Screen. This high-volume testing screen allows up to one cubic foot of sample to be sieved in 3-5 minutes. For materials finer than 2 mm, a total weight was first obtained, and then the sample was split into quarters. A random split was selected and run through 8" sieves with a Gilson SS-15 Sieve Shaker. For several samples, multiple splits were independently sieved to verify that each split was truly representative of the entire fine fraction of the sample.

Sediment Source Analysis

Landslide Mapping

Landslide mapping of the watershed was accomplished by review of sequential years of vertical stereoscopic aerial photographs. The methodology was modified from Washington TFW protocols, CDMG landslide mapping methods, and nomenclature put forth by Cruden and Varnes (1998). An Abrams 2- and 4-power Model CB-1 stereoscope was used to review aerial photographs.

The air photos were examined sequentially from oldest to youngest to facilitate consistency and efficiency in the analysis. The order of review was, from initial set of photos to the last set reviewed: 1936, 1952, 1965, 1978, 1988, and 2000. The majority of coverage varied from a scale of 1:20,000 to 1:24, 000; although the scale of the 1988 coverage was about 1:31,680. The earliest coverage available (1936) covered only the western half of the watershed, with most areas above the confluence of the North Fork Big River lacking. These photos may be available at National Archives, but our analysis was limited to those 1936 photos in the collection of the UC Berkeley Geology Map Library. Other years had complete coverage of the watershed.

Landslides observed on the aerial photographs were plotted on acetate overlays placed on 7½ -minute topographic maps. They were classified as rotational/translational, earthflow, debris slide, or debris torrent. Rotational/translational and earthflow slides are characterized as relatively deep-seated, slow-moving or static slides, and it is generally assumed that such failures are contributing little sediment except that derived from sheetwash or gullying processes. Debris slides, however, are judged to be short-term active failures that contribute relatively modest to large volumes of sediment to the drainage. However, over time they revegetate and eventually heal so that, in many cases, sediment input is reduced to similar levels as adjacent undisturbed areas. Debris flows/torrents are fast-moving and relatively shallow (in most, but not all) failures. For this study, cutslope and fillslope failures and rock avalanches are also included in this classification.

In an attempt to maintain uniformity in the size of failures mapped from photo set to photo set, only those failures with estimated dimensions of about 75 to 100 feet or more in width or length were mapped. This included almost all failures observed.

As mapping progressed, slides mapped from earlier photos were searched for in later photos. If they were observed, it was appropriately recorded. Unfortunately, some slides that were observed over a long period of time were not noted on all sequences of photos. This may have been due to being overlooked during review, camera angle, shadows, partial revegetation, or the slide may have healed and failed again. It was noted if a slide occurred along a road, skid road or railroad, on a cutslope or fillslope. Other aspects also noted included if a slide occurred in a forested area or a partial cut or clear-cut. An attempt was also made to relate occurrence to historic harvest activity. A judgment call was made in re-vegetating areas as to whether a slide occurred in an area harvested in the past 20 years or if the historic harvest appeared to be more than 20 years old.

A four-category system of sediment delivery (1-3%, 3-33%, 34%-66%, and 66-100% delivery) was assigned to estimate the amount of sediment delivered to a watercourse. If the feature occurred in an inner gorge, this was also recorded. Certainty of identification was noted as definite, probable, or questionable.

Large, deep-seated landslides were identified as either active, dormant, or relic. Those considered dormant are judged to be relatively stable but could be partially or wholly reactivated under current climatic environmental conditions. Relic means it was judged unlikely to become reactivated under current climatic/environmental conditions. Very few deep-seated landslides were identified as active.

Surface Erosion

Surface erosion from roads was estimated by developing a road construction history, stratifying by location (riparian, mid-slope, and ridge) and applying use and sediment delivery factors. Slope positions were assigned using the following methodology. To determine the location of Riparian roads, all Class I and Class II streams were buffered by 200 feet on either side. All roads segments within this buffer were considered Riparian. To determine the location of Ridge roads, ridgelines were identified by creating watershed boundaries from the 10-meter DEM with a minimum area of approximately 75 acres. Next all Class I streams were buffered by 500 feet to clip the watershed boundaries away from the riparian zone. The resulting ridgeline coverage was then buffered by 100 feet on either side. All roads segments within this buffer were considered Ridge roads. All the roads segments that didn't fall into the 200 foot riparian buffer or the 100 foot ridge buffer were considered to be Mid-Slope.

Surface erosion from skid trails was based on a harvest history including mapping of areas that were harvested with either a low, medium, or high density of skid trails and then application of loading rates. Prior to 1988, the history was developed primarily from interpretation of aerial photography. From 1988 to present, road and harvest history was obtained from CDF GIS coverage's which had been developed by directly inputting information provided as part of submitted Timber Harvest Plans (THPs). Data from the pre-1988 mapping efforts were shown on overlays and simply record road or harvest activity during the period between years of photographs reviewed. For roads, only main roads or haul roads were generally mapped. Because of revegetation over time, probably not all haul roads were mapped. Furthermore, their importance could be misinterpreted because of lack of use, being overgrown, or being incorporated into harvest units and lost in a maze of skid trails. In tractor-logged harvest units, road and skid trail density was characterized as low, moderate, or high. Data from the overlays was digitized into the GIS database for subsequent mapping and analysis.

HYDROLOGY

Precipitation

Precipitation in the Big Watershed, as is typical of California, is highly seasonal, with 90 percent falling between October and April. A small portion of the annual precipitation falls as snow at the higher elevations, although it rarely remains long, and snowmelt or even rain-on-snow events are not hydrologically significant. Long-term annual precipitation records in the vicinity range from about 38 inches in Fort Bragg to over 50 inches in Willits, northeast of the watershed. Mean annual precipitation for the watershed is about 55 inches (Table 1), based on an areal weighting of mean annual precipitation that had been obtained as GIS coverages for the entire watershed from CDF. The isohyetal maps for the watershed indicate that although annual precipitation generally increases as one moves towards the higher elevation along the north and east parts of the watershed, there are areas in the South Fork and Lower Headwaters that are considerably drier. On a sub-watershed basis, mean annual precipitation ranges from 45.1 inches in the Big River Estuary SW to 65 inches in the James Creek SW. The North Fork Big PW is noticeably wetter than either the Headwaters or South Fork PW.

There are relatively few long-term precipitation stations near the basin and none located within the watershed. The longest is that of Willits, with a period of record of 1879-1998, although it is sufficiently removed from the basin that it is not used extensively in this analysis. Figure 5 shows the annual precipitation at Fort Bragg along with the computed cumulative departure, while Table 3 presents the annual totals. For Fort Bragg, the wettest year contained in its record (1896-1998, missing 1901) is 1998, when precipitation totals reached 77.31 inches, dramatically wetter than 1983, the next highest, when 62.47 inches were recorded. The driest year at Fort Bragg was 1977, when only 16.56 inches of precipitation were recorded. The mean for the 102-year record is 38.74 inches. Furthermore, much of the watershed averages higher precipitation than either of the two nearby stations, and the accuracy of the available isohyetal maps is unknown.

Cumulative departure from the mean is a measure of the consecutive and cumulative relationship of each year's rainfall to the long-term mean. When the cumulative departure line is descending (left to right), there is a dryer than normal period, while an ascending line denotes wetter then normal. In reviewing the record at Fort Bragg, we see a long, very wet period extending from 1899 through 1916, followed by a prolonged drought period from 1917-1937. 1928-1934 was the worst multi-year drought in the 102-year record, with 7 consecutive years below the long-term average. 1940-1943 was a wet period, followed by a 7-year dry period between 1944 and 1950. 1950 through 1958 was a wet period, as was 1968-1975. 1982-1986 was a slightly wetter than normal period, with a number of wet years alternating with slightly below average years. The 1976-1977 drought was intense, but short-lived. The 1987-1992 drought was not nearly as severe as many other parts of California. 1995 through 1998 was the wettest period on record. Eight years stand out from the perspective of total annual precipitation and thus runoff: 1909, 1915, 1938, 1941, 1958, 1983, 1995, and 1998, with 1998 by far the wettest year on record.

Table 4 shows ranked 1-day (24-hour) precipitation intensities (only the top 75 entries) for both the Willits and Fort Bragg stations. The maximum 1-day precipitation at Willits is 8.8 inches in 1965, while at Fort Bragg it is 4.15 inches in 1953. The differences between storms are even more surprising when daily totals are considered. The Dec 1964 event was the largest at Willits by a significant margin, but only ends up 11th on the ranked list for Fort Bragg. The 1953 event, the largest at Fort Bragg, is far down the list for Willits (#31). In fact, in the top ten for each station, there is only one match, 1938. Other large years based on intensity records at Willits are 1938, 1906, 1914, 1947, 1960 and 1974. Comparison of the 1-day intensities with peak discharge reveals a poor relationship, indicating that 1-day precipitation (at Willits) is not the driving force in Big River peak flows.

Streamflow

Streamflow data collected in the basin by the USGS are limited to a single gage: #11468070, SF Big River nr. Comptche, located on the SF Big River at Orr Springs Road, just downstream from the confluence of the middle SF Big River and Daugherty Creek. The gage measured streamflow from 36.14 mi^2 of the 56.0 mi^2 of that sub-watershed, including the wetter upper watershed areas. It is expected that unit peak discharges (cfs/mi^2) for the entire watershed would decrease from those recorded at the gaging site as a result of precipitation distribution. The period of record for the USGS gage extends from 10/1/60 to 9/30/71, when continuous measurements at the gage were discontinued.

GMA operated four continuous streamflow stations in the watershed as part of this study between November 2000 and April 2001. Due to the relatively short streamflow record on the Big River and the unavailability of continuous streamflow records for much of the watershed, it was necessary to develop synthetic streamflow records for the watershed. Once synthetic data were developed, they were used to perform various hydrologic and sediment transport analyses.

Peak Discharge

The largest recorded peak discharge for the SF Big River occurred in December 1964, when the river crested at 8,200 cubic feet per second (cfs), according to USGS records, as shown in Figure 6. USGS peak discharge records are available for an 11-year period, 1961-1971, and 1974. In addition, synthetic peak discharges for the SF Big River were developed using peak correlation analysis between the Noyo River Watershed and the Big River Watershed in order to extend the record. Peak discharges were forecast back to 1952 and forward to 1999, based on the record available from the Noyo River. In addition, peak discharge for WY2001 was measured at the same site during streamflow data collection. Surprisingly, the January 1974 (WY1974) was not nearly as significant an event in the SF Big compared to watersheds on either side, the Noyo and Albion, in both of which 1974 was the peak of record. No explanation for this disparity is currently available, although it makes one wonder about the accuracy of the available data. The previously described precipitation intensity records for Fort Bragg are also inconsistent with the magnitude of the 1974 peak discharge.

Table 5 lists the annual peaks for the 12-year historic record as well as synthetic data, ranks them and computes recurrence intervals based on the Weibull formula. Significant stormflows (those in excess of 5,000 cfs) in the extended period of record occurred in December 1951(WY1952), December 1955 (WY1956), December 1965 (WY1966), January 1966 (WY1966), January 1974 (WY1974), March 1986 (WY1986), and January 1993 (WY1993).

Peak discharges were also estimated for the entire watershed based on a correlation with the Noyo record adjusted by drainage area and mean annual precipitation ratios. This analysis, based solely on the Noyo records, indicates that the January 1974 flood would have been the largest in the synthetic dataset, followed by December 1964 and January 1993. The estimated peak discharges are shown in Table 6, in both ordered and ranked lists.

Flood Frequency

Flood frequency analysis is a method used to predict the magnitude of a flood that would be expected to occur, on average, in a given number of years (recurrence interval) or to have a specific probability of occurrence in any one year (1% chance event, for example). Typically, the observed annual maximum peak discharges are fitted to the distribution using a generalized or station skew coefficient, although numerous other distributions may also used. When long records are available, the station skew is used exclusively. Although the log-Pearson Type III distribution is the most commonly applied method, we found that it had a very poor fit to the synthetic data, and instead we selected a 3-parameter log-normal distribution for our flood frequency analysis.

The results of the 3-Parameter Log-Normal flood frequency analysis for the synthetic 1952-

1999 period of record for the entire watershed are shown in Figure 7 and summarized in Table 7 below. This analysis indicates that the 1974 (WY 1974) flood would be about a 45-year event, while flows similar to December 1964 would be about a 35-year event. The 2-year event is almost 12,000 cfs for the entire watershed.

TABLE 7
BIG RIVER NR. MENDOCINO
FLOOD FREQUENCY ANALYSIS

Return Period (years)	**Computed Annual Maximum Peak Discharge** (cfs)
2	**11,900**
5	**22,100**
10	**30,100**
20	**38,700**
50	**51,000**
100	**61,300**

--3-Parameter Log-Normal Distribution

A similar analysis for the SF Big near Comptche site only, based on combined historic and synthetic data, indicates that the December 1964 flood would have been just smaller than a 50-year event, while the January 1974 flood would have been only a 10-year event.

Historic Floods

Although the Big River has a relatively short period of streamflow records, the dates of significant floods years are generally known, due to regional data. Known large flood events in the region, many of which would also have occurred in the watershed, have occurred in Water Years 1861, 1881, 1890, 1907, 1914, 1938, 1952, 1956, 1965, 1966, 1974, 1986, and 1993. The largest of these were likely to have been the 1861 and 1890 events, followed by the 1914, 1938, 1965 and 1974 events (not necessarily in that order by magnitude).

Table 8 presents information that may be used to assess the magnitude of storm events and their geomorphic significance, and includes ranked data for annual streamflow, peak discharge, a magnitude-duration product, annual precipitation, and 1-day precipitation intensity. The top 20 events in each type are included. During the period of available synthetic streamflow records, 1974 stands out well above other years, not only because of its high peak flow, but also the duration of these flows. This is similar to adjacent watersheds such as the Noyo, Albion, Ten Mile, and Caspar Creek watersheds, but considerably different from most coastal watersheds further north, and, apparently, the SF Big sub-watershed. In the Big River watershed, the January 1974 event appears to have been the most significant in the past 50, and perhaps 100, years.

Mean Daily Discharge

The USGS publishes mean daily discharge records for each of its gages on an annual basis. These values are typically used to construct annual streamflow hydrographs and perform flow duration analyses. Due to the extremely short period of record for the SF Big River (11 years), modeling was employed to extend or create a mean daily discharge record for each of the major watershed areas, including the entire watershed. Mean daily discharge measurements were scaled from the Noyo Watershed using watershed area and mean annual precipitation as the scaling factors. Figure 8 shows the comparison between historic mean daily flows measured by the USGS, and the synthetic record for a portion of WY1965. High flows during storms are of very short duration, one to two days at most generally, and flows rapidly return to typical winter base flow within one week after the peak. Almost all significant runoff events occur between December and March.

Flow Duration

A flow duration analysis was performed using a combination of historic and mean daily discharge for the USGS gage on the SF Big River. The results are presented in Figure 9. The analysis indicates that the SF Big River only exceeds 162 cfs 10% of the time, or 36 days per year on average, while 50% of the time flows are below 10 cfs. Flows exceed 850 cfs in the SF Big River only 1% of the time, or 3.6 days per year on average. Relatively little sediment transport probably occurs below 400 cfs, thus all of the geomorphic work accomplished by the river occurs in less than 5% of the time, with most concentrated in the top 1% of the flows.

Annual Runoff

Annual runoff was measured in the SF Big River watershed at the USGS streamflow gage for the 11-year period of record. A combined historic and synthetic dataset was developed for the SF Big, while purely synthetic data for mean daily discharge have been developed at other sites throughout the watershed and annual runoff values have been computed from these data. The mean annual runoff for the 1952-1999 period is 268,700 acre-feet for the Big River below Laguna Creek. The annual runoff data are shown in Table 9, and plotted in Figure 10. Large volumes of runoff are often associated with both large flood years and years with high annual precipitation. The two largest annual runoff years were 1983 and 1974, almost 20% larger than the 3rd largest runoff year, 1958. Three particular dry periods stand out of the cumulative departure analysis, 1959-1964, 1976-1981, and 1987-1992.

SEDIMENT TRANSPORT

Regional Relationships and WY2000-2001 Data Collection

No sediment transport data for the Big River watershed prior to this study were located. Sediment transport data were collected in the Big River watershed during the winter of WY2000 and WY2001. The purpose of such data collection was to allow calibration and verification of regional datasets with site-specific sediment transport data. As a result, we have computed sediment transport records based on both regional and Big River Watershed-specific sediment rating curves. Regional relationships had been developed for the Noyo River, Ten Mile, and Albion watersheds (GMA 1999, 2000, 2001) and the similar relationships were utilized to estimate suspended sediment and bedload discharge in the Big River. The following sections describe the general approach, data, analysis and results. In addition, sediment transport data collected in the Big River watershed will be compared to the regional relationships.

General Approach and Data

Regional sediment rating curves were developed from sediment data for various streams located in the North Coast Hydrologic Basin Planning Area, as delineated by the State of California Regional Water Quality Control Board. Two regional sediment transport relationships have previously been developed (GMA 2001) based on a grouping of the data by watershed size. The "medium" watershed size relationship included only sediment data from watersheds ranging in size from 43.9 to 204 mi^2. The "small" watershed size relationship was developed from regional data for watersheds ranging in size from 2.9-30.4 mi^2. Sediment data (discharge, suspended sediment concentration, suspended sediment discharge, and bedload discharge) was collected for 14 streams located in six (6) different hydrologic unit codes (HUC), from the USGS Quality of Water data base for the original regional relationship, while there were only 10 streams in the relationship for smaller watersheds. All 14 stations contained suspended sediment data, which resulted in a large sample size (n=1439) for developing the suspended sediment rating curve (Figure 12). However, only 5 stations contained bedload data, resulting in a smaller sample size (n=57) (Figure 13) for the bedload rating curve.

In addition, unpublished data collected at seven sites throughout the Big River watershed by GMA during the winter of Water Year 2000 (36 samples) and 2001 (69 samples) are also shown. Obviously, data collected in the watershed should be the most representative, but it is useful to compare these two the regional relationships since neither WY2000 nor 2001 had very high flows, and lack of high flow data may bias the dataset. Although these points are within the general scatter of the regional curve data, they mostly plot below the regression line, possibly indicating lower suspended sediment transport rates in coastal areas, at least under present conditions. These results are similar to those from the Albion River Watershed (GMA 2001). However, there were not sufficient data to justify using this relationship exclusively, and the medium regional equation was still used for all computations.

The medium regional suspended sediment rating curve (Figure 12) found a strong correlation between stream discharge and suspended sediment load ($r^2 = 0.91$, $P<0.0001$), with 91% of the observed variation in suspended sediment discharge explained by stream discharge. The small regional relationship (drainage areas of 2.9-30.4 mi^2) exhibited slightly more scatter, but the regression model ($r^2 = 0.87$) was still quite good. The sediment transport data collected in WY2000-2001 in the Big River watershed appears to fit better with the regional curve for medium watersheds. For the original regional bedload rating curve (Figure 13), stream discharge explained 64% of the variation in bedload discharge. The bedload regression model (r^2=0.64, P<0.0001) was determined to be an adequate predictor of bedload discharge. The small watershed size regional bedload regression model ($r^2 = 0.73$) was slightly better.

Regional Analysis and Results

To provide an estimate of average suspended sediment and bedload discharge for the Big River, the regression equations from the regional rating curves (Figure 12 for Suspended Sediment and Figure 13 for bedload) were applied to the entire discharge record (water year 1952-99) for the synthetic data developed for the Big River. Using this streamflow dataset for the main three forks and the entire watershed, the daily sediment rates were then summed to provide an estimate of annual sediment discharge for each water year. Table 10 summarizes the estimated suspended sediment, bedload discharge rates, and sediment yields for the three forks of the Big River. Based on this approach, the average annual sediment discharge rate for the North Fork Big River is between 18,580 and 98,796 tons/yr, which corresponds to a watershed sediment yield of 428 to 2,277 tons/mi^2/year for the 1952-1999 period of synthetic streamflow records. After review of the data developed by the three equations (medium-sized regional watersheds, small regional watersheds, and WY2001 data only) for the North Fork, it was determined that application of the small regional watershed equation was inappropriate, and it was not applied to the other portions of the watershed. The individual calculations by water year are shown in Table 11 using the medium-sized regional watershed equations.

TABLE 10
SUMMARY OF SEDIMENT TRANSPORT COMPUTATIONS

Summary of estimated annual suspended sediment discharge, bedload discharge, sediment discharge, and sediment yield for the main forks of the Big River for Water Year 1952-99 using the regional regression equations and the Big WY2000-2001 data regression equation.

NF Big **Value**	SSD **(ton/yr)**	BD **(ton/yr)**	SD **(ton/yr)**	SY **(ton/mi2/yr)**
Mean (WY 1952-99) using Medium Regional Curve	**25,774**	**5,800**	**31,574**	**726**
Mean (WY 1952-99) using Small Watershed Regional Curve	**80,032**	**18,764**	**98,796**	**2,277**
Mean (WY1952-99) using WY2000-2001 Curve	**12,780**	**5,800**	**18,580**	**428**

Headwaters Big **Value**	SSD **(ton/yr)**	BD **(ton/yr)**	SD **(ton/yr)**	SY **(ton/mi2/yr)**
Mean (WY 1952-99) using Medium Regional Curve	**12,576**	**3,077**	**15,653**	**478**
Mean (WY1952-99) using WY2000-2001 Curve	**3,975**	**3,077**	**7,052**	**215**

SF Big **Value**	SSD **(ton/yr)**	BD **(ton/yr)**	SD **(ton/yr)**	SY **(ton/mi2/yr)**
Mean (WY 1952-99) using Medium Regional Curve	**29,826**	**6,598**	**36,423**	**669**
Mean (WY1952-99) using WY2000-2001 Curve	**28,602**	**6,598**	**35,200**	**646**

SSD = suspended sediment discharge, BD = bedload discharge
SD = total sediment discharge, SY = total sediment yield

WY2000-2001 Sediment Transport Data

The scope and objectives of this data collection effort was to provide reconnaissance level information on the relative current contributions of sediment from major sub-watershed areas in the Big River. The work consisted of collecting field data and developing the following work products for each sampling site:

1. Develop a stage/discharge relationship,
2. Develop a turbidity/suspended sediment concentration (SSC) relationship,
3. Develop a turbidity/discharge relationship,
4. Develop a SSC/discharge relationship,
5. Develop a suspended sediment load (SSL)/discharge relationship
6. Compute Annual SSL for WY2001.

Data were collected at ten sites in WY2000 and WY2001. Continuous dataloggers were installed at 4 sites in WY2001, including the North Fork Big River above Big, SF Big River above Big, Big River above the South Fork, and the North Fork Big River above Chamberlain Creek. Discharge rating curves were established at all sites based on 3-5 streamflow measurements, and where available, historical data. Figure 14 shows the WY2001 hydrographs developed for five study sites in the North Fork Big River above Big, which includes measured and extrapolated hydrographs. Figure 15 shows the WY2001 hydrographs developed from continuous stage measurement data for the three main Planning Watershed stations, including the North Fork Big River above Big, SF Big River above Big, and the Big River above the South Fork. Five storms occurred during WY2001, two small storms in the last week of January and a third small storm in the middle of February, and two somewhat larger (though still fairly small) storms at the end of February and in early March. Overall, based on analysis of a combination of the historic and synthetic peak discharge records at the former USGS gage site on the SF Big River, peak discharges during this water year were the 7th smallest on record (Table 5). Comparison of the individual hydrographs between the different forks over the winter demonstrates that the relative magnitude of the storms can be quite variable, as seen in the case of the South Fork Big, for which the March 4 storm had a considerably larger peak discharge than the other sites, while for the other storms they had been much more comparableat other sites the March 4 storm was larger.

Table 12 summarizes the discharge and sediment transport measurements collected during this study. A total of 118 suspended sediment samples were collected over the two winters of data collection.

TABLE 12

WY2000-2001 Sampling sites for the Big River, Mendocino County, CA

Site Number	Location of Sampling Site	Area Above Sampling Site (mi2)	Number of Discharge Msmts	Number of Turbidity Samples	Number of SSC[1] Samples
1	Big R. ab. N.F. Big R.	8.42	3	20	21
2	Big R. ab. S.F. Big R.	21.07	4	11	11
3	Big R. at Former USGS Gaging Site	14.45	3	21	22
4	Marsh Ck. ab. Big R.	1.83	1	12	12
5	N.F. Big R. ab. Big R.	5.22	4	25	26
6	Nordan Gulch ab. S.F. Big	0.65	0	2	2
7	S.F. Big R. ab. Big R.	9.10	4	12	12
8	S.F. Big R. ab. Nordan Gulch	6.73	0	2	2
9	Tom Bell Gulch ab. Big R.	1.57	2	10	10
	TOTAL MSMTS OR SAMPLES		**21**	**115**	**118**

1) SSC = suspended sediment concentration (mg/l)

All of the collected turbidity and SSC samples are plotted in Figure 16, along with a linear regression equation relating SSC to turbidity. We found turbidity to be a good predictor of suspended sediment concentration as defined by the regression model ($r^2 = 0.94$), with 94% of the observed variation in suspended sediment concentration explained by turbidity. Turbidity values for all of the WY2000-2001 samples are plotted against discharge in Figure 17, producing a relationship with considerable scatter and a low r^2 value of 0.50. Figure 18 examines the relationship between suspended sediment load and discharge, which was found to have a relatively good relationship ($r^2 = 0.80$).

Table 13 presents all of the equations and their respective r^2 values for all of the study sites. The relationships at all sites for SSC vs. T were quite good (r^2 range of 0.83-0.99) using a linear equation. Relationships for T vs. Q, SSC vs. Q, and SSL vs. Q are all based on a log-log transformation, which is described by a power function.

Table 13

WY2000-2001 Regression Equations and r^2 Values by Site

	SSC vs. T		T vs. Q		SSC vs. Q		SSL vs. Q	
Location of Sampling Site	**Equation**	**(r^2)**	**Equation**	**(r^2)**	**Equation**	**(r^2)**	**Equation**	**(r^2)**
James Creek above NF Big	$y = 1.38x - 15.78$	$r^2 = 0.96$	$y = 17.955x^{0.0741}$	$r^2 = 0.08$	$y = 13.071x^{0.0392}$	$r^2 = 0.004$	$y = 0.0353x^{1.0392}$	$r^2 = 0.74$
NF Big River ab. Chamberlain	$y = 1.11x - 0.406$	$r^2 = 0.92$	$y = 0.77x^{0.803}$	$r^2 = 0.83$	$y = 0.899x^{0.7505}$	$r^2 = 0.51$	$y = 0.0024x^{1.751}$	$r^2 = 0.85$
Chamberlain Creek ab. NF Big	$y = 1.69x - 18.23$	$r^2 = 0.93$	$y = 5.113x^{0.398}$	$r^2 = 0.53$	$y = 2.9145x^{0.5066}$	$r^2 = 0.39$	$y = 0.0079x^{1.507}$	$r^2 = 0.85$
East Fork of NF Big ab. NF Big	$y = 1.186x - 6.39$	$r^2 = 0.83$	$y = 3.34x^{0.6538}$	$r^2 = 0.44$	$y = 7.047x^{0.41}$	$r^2 = 0.23$	$y = 0.019x^{1.41}$	$r^2 = 0.78$
NF Big River ab. Big	$y = 1.65x - 16.57$	$r^2 = 0.91$	$y = 1.954x^{0.522}$	$r^2 = 0.68$	$y = 0.084x^{1.073}$	$r^2 = 0.71$	$y = 0.0002x^{2.073}$	$r^2 = 0.90$
Big River ab. SF Big	$y = 0.78x + 1.391$	$r^2 = 0.99$	$y = 2.229x^{0.596}$	$r^2 = 0.48$	$y = 4.89x^{0.407}$	$r^2 = 0.45$	$y = 0.013x^{1.407}$	$r^2 = 0.91$
SF Big ab. Big	$y = 0.86x - 10.70$	$r^2 = 0.98$	$y = 0.285x^{0.999}$	$r^2 = 0.50$	$y = 1.1984x^{0.692}$	$r^2 = 0.40$	$y = 0.0003x^{2.105}$	$r^2 = 0.86$
SF Big bel. Daugherty	$y = 1.281x - 30.58$	$r^2 = 0.99$	$y = 1.627x^{0.705}$	$r^2 = 0.38$	$y = 0.305x^{0.96}$	$r^2 = 0.45$	$y = 0.0008x^{1.96}$	$r^2 = 0.77$
SF Big ab. Daugherty	$y = 1.072x - 14.64$	$r^2 = 0.95$	$y = 2.363x^{0.692}$	$r^2 = 0.46$	$y = 0.319x^{1.08}$	$r^2 = 0.60$	$y = 0.0009x^{2.08}$	$r^2 = 0.85$
Daugherty Creek ab. SF Big	$y = 0.99x - 7.94$	$r^2 = 0.97$	$y = 0.675x^{1.0075}$	$r^2 = 0.77$	$y = 0.165x^{1.266}$	$r^2 = 0.76$	$y = 0.0008x^{2.104}$	$r^2 = 0.91$

Notes: SSC = suspended sediment concentration (mg/l), T = turbidity (NTU), Q = discharge (cfs), SSL = suspended sediment load (tons/day)

Except for a few sites, the relationships between T vs. Q and SSC vs. Q had relatively little statistical significance. On the other hand, the relationships between SSL and Q, which forms the basis for computing suspended sediment loads, were quite good (r^2 range of 0.77-0.91). The relationships for the NF Big ab. Big, the Big ab. SF Big, and Daugherty Creek were the best for all of the sites.

Although limited by the amount of data, we examined the difference in sediment loads based on hydrograph position (hysteresis) for several sites. Since suspended sediment is primarily supply limited, far lower concentrations are often found on the falling limb, compared to the rising limb, of storm hydrographs. Figure 19 shows such an analysis for the SF Big River below Daugherty Creek (former USGS gage site), which indicates that the WY2001 data found almost an order of magnitude difference between sediment loads on the different portions of the hydrograph.

To examine sediment source relationships between the various sites in the Big River watershed, the individual site data and relationships were combined and plotted on one graph. In Figure 20, the SSL was normalized by dividing by the contributing watershed area and plotted against discharge for the various sampling sites. This analysis shows that for a similar discharge, EF NF Big produces the highest sediment discharge per unit area, while the NF Big above Big produced the smallest. In general, smaller drainage areas produce an equivalent unit suspended load at discharges an order of magnitude smaller than the larger sub-watershed areas. Or viewed another way, for the same discharge, smaller watersheds produce 1 to 2 orders of magnitude more sediment. This relationship is not uncommon, though in some watersheds with large sediment delivery from inner gorge sources, such as the SF Trinity or the Van Duzen, sediment transport unit values actually increase with increasing drainage area.

In Figure 21, we examined suspended sediment load versus discharge per watershed area, which allows the sediment loading from different portions of the watershed to be compared on a unit discharge (cfs/mi^2) basis. This analysis shows that the sites in the South Fork Planning Watershed along with the sites with larger drainage areas tend to produce more sediment per unit discharge than the sites with smaller drainage areas in the NF Planning Watershed.

To examine relationships between these sub-watersheds without a bias towards discharge or area, unit SSL was plotted against unit discharge (Figure 22). This analysis tightens up the dataset considerably, particularly for the regression lines, meaning that most of the watershed area is contributing sediment at a comparable rate for an equivalent discharge. Considerable scatter, about two orders of magnitude, exists over the range of data when individual data points are examined. The outliers still appear to be: (1) the SF Big River sites, which have higher unit sediment loads per unit discharge, and (2) James Creek and other NF Big River sites that appear to have slightly lower unit sediment loads per unit discharge, than the bulk of the sampling sites.

Daily suspended sediment load was computed for the four sites with continuous stage recorders by application of the appropriate discharge rating curve to first obtain 15-minute discharge values, and then by application of the site SSL equation (Table 13). For the six sites without continuous stage recorders (SF Big River above Daugherty Creek, SF Big below Daugherty, Daugherty Creek, Chamberlain Creek, East Fork North Fork Big, and James Creek), synthetic hydrographs were developed by application of a scaling factor based on watershed area to the nearest continuous record of similar drainage area. Thus, data from either the NF Big above Big or NF Big above Chamberlain were used to create hydrographs for the other three sites in that Planning Watershed. Individual stage/discharge observations at these sites were used to cross check the watershed area scaling approach.

Table 13A presents the computed suspended sediment loads in the Big River watershed for WY2001.

TABLE 13A
BIG RIVER SEDIMENT SOURCE ANALYSIS
COMPUTED SUSPENDED SEDIMENT LOADS FOR WY2001

Sub-Watershed	WY2001 SS TRANSPORT (tons)	Unit Area SSL (tons/mi2)
Headwaters Big River	459.3	14.0

Upper North Fork Big River		
James Creek	40.7	5.8
NF Big above Chamberlain	102.3	5.8
Chamberlain Creek	73.9	6.0
East Branch North Fork Big	47.6	6.6
North Fork Big River ab. Big	227.0	5.2
Upper South Fork Big River		
South Fork Big River ab. Daugherty	428.4	22.0
Daugherty Creek	317.8	19.1
South Fork Big below Daugherty	814.4	22.5
South Fork Big River ab. Big	1189.3	21.8

Load calculations are quite sensitive to the slope of the equations used to define sediment transport rates, and given the limited data collected in this study, it is somewhat surprising that all of the rates computed generally agree, in that summing computed loads for upstream sites generally agree with the results at downstream sites, thus validating the sediment transport relationships.

WY2001 turned out to be quite a dry year. According to the synthetic peak discharge calculations, this year was the seventh driest in terms of annual maximum peak discharge in a 48-year record. Suspended sediment loads ranged from 40.7 tons for James Creek to 1189 tons for the South Fork Big River above Big site. Unit area sediment loads (tons/mi^2) indicate that the South Fork Big River Planning Watershed produces by far the largest amount of suspended sediment. The Headwaters Big River is intermediate and the North Fork Big produces considerably less sediment than the other sites. The suspended sediment load in the South Fork during WY2001 is 5.2 times that of the North Fork and 2.6 times the Headwaters. The watershed produced suspended sediment loads in the range of 5-22 tons/mi^2 for this dry year.

GEOMORPHOLOGY

Channel Geometry

Trend monitoring of channel geometry can provide insight into changes to the river channel due to specific events (typically large floods) and to longer-term adjustments and recovery from these flood events. Channel geometry is most often monitored through cross section and profile surveys, both of which are two-dimensional representations of channel shape, with the cross section perpendicular to the flow direction, and the longitudinal profile parallel. The only known cross section and profile survey data were collected by Mendocino Redwood Company as part of their watershed analysis in 1999-2001. Although these data may provide the basis for future trend monitoring, at this point they do not provide any means for evaluating historic changes.

Gaging station records may often be used to develop a stream channel history through computation of mean streambed elevation (MBE) over the period of record of the gage.

Trend analysis for these variables may provide considerable insight into channel changes.

Unfortunately, the short period of record at the former USGS gaging site, makes analysis of gaging station records of little value for trend analysis.

Streambed elevations generally reflect the overall balance of sediment transport at their location. If sediment delivered to the channel is greater than the transport capacity of the channel (which is a combination of flow and channel geometry), then the channel will aggrade or rise in elevation. When sediment loads are less than transport capacity, the channel will degrade or scour as long as suitably sized (i.e. capable of being mobilized) alluvial deposits are present on the channel bed. Dramatic channel adjustments have been observed to occur in watersheds with very high sediment production and delivery, particularly when delivered catastrophically, such as in the December 1964 flood in many northern California basins.

The Big River watershed reflects far less dramatic changes, which is in character with its more stable geology (Franciscan Coastal Belt with only a small amount of mélange of the Central Belt), generally dense vegetation coverage, and lower precipitation rates than most of the watersheds farther north. In general, areas on the Mendocino Coast experienced lesser effects from the December 1964 flood, compared to the unprecedented flood magnitudes experienced in the Eel and Klamath basins (Waananen et. al. 1971), although the Noyo River experienced almost 2 meters of aggradation as a result of the 1964 flood (Lisle 1981).

Historic Changes at the Big River Mouth and Estuary

The Big River has a large estuary with the tidal influence extending up to 8.3 miles upstream during the highest spring tides, making the Big River Estuary the longest estuary in northern California (Warrick and Wilcox 1981). During winter, the estuary extends about 3 miles upstream. The Lower Big River contains numerous freshwater marshes (Seacat et al. 1981). Historically, the estuary was extensively used as a mill pond for the transport and storage of logs delivered either by river transport (via splash dams) or by railroad transport. As a result of this development, significant changes to the estuary likely occurred, although quantitative information does not exist.

The Big River estuary occupies a narrow, steep-sided valley some 400 to 500 feet below the level of adjacent marine terraces (Reneau 1981a). In the lower valley less than a half-mile separates the marine terraces on each side of the valley. Pleistocene sea level fluctuations, combined with uplift of the Big River area, generated landscape features of both emergence and submergence in the Big River estuary providing a classic example of a drowned river valley, eroded by a terrestrial river, and later flooded by a rise in the sea level (Reneau 1981a). Floodplains adjacent to the Big River estuary are characterized by relatively low relief. Wetlands in the lower reaches of tributaries suggest that the estuary may have extended further upstream in the past. In the JDSF assessment area, these wetlands are typically associated with tributary basins dominated by large deep-seated landslides and mass wasting, suggesting that large Holocene deep-seated landslides or tributary debris flows caused deposition of valley fill in which the marshes have developed (CDF 1999).

Deposition of sediment in the estuary has resulted in substantial decreases in the width of the estuary, the filling of tidal sloughs, and the rapid colonization of mudflats by salt marsh vegetation (Reneau 1981a). Since the late 1800s, levees were constructed adjacent to the main channel along two miles of the lower estuary during use of the estuary for millpond operations. These levees have separated the salt marshes/mudflats and the floodplains along much of the lower estuary and have affected the distribution of vegetation in this area (Reneau 1981a).

Reneau (1981b) examined old aerial photographs in an effort to understand the natural and anthropogenic levee creation. He states that the railroad pilings originally "…stood well out from the bank, and the edge of the channel sloped gently into a salt marsh. No levee was present at the time." Aerial photos taken in 1952 and shows a levee near the log dump. Reneau states, "Within a 25-year period prior to 1952, the character of the Big River estuary at the log dump had changed from a channel sloping gently into salt marshes to a channel sharply confined within levees."

The development of levees along the estuary has created a transitional zone, a two-mile stretch distinct from the rest of the estuary in both geomorphic characteristics and vegetation distribution (Reneau 1981b). In this area, rapid ecological change has taken place, with replacement of rushes by alder, willows, and coastal scrub vegetation. Reneau (1981a) concludes that the Big River estuary has experienced major geomorphic changes since the advent of logging in the watershed in 1852 and that the progression of river deposits down the estuary has apparently been greatly accelerated in the last 130 years. Primary indicators of this acceleration are the levees bordering the main channel, which today extend at least two miles farther down the estuary than they did 80 years ago (Reneau 1981a). Sedimentation in the Big River estuary has reduced the area of salt marshes and has reduced tidal flux, resulting in a great decrease in the biological productivity of the estuary (Reneau 1981a).

Influence of Historic Harvest Practices on Channel Geometry

It is generally widely regarded that historic logging practices were highly destructive and have had long-term, pervasive effects on the stream channels of many watersheds (Napolitano 1996). The typical harvest sequence of falling, burning, yarding by bulls or Dolbeer donkey, and railroad transport are all visible in this photograph. However, one of the most damaging logging practices involved the construction and operation of artificial dams to transport logs downstream. The use of artificial dam releases to transport logs downstream was a widely used practice in Mendocino County, particularly where difficult access precluded more reliable transportation methods (railroads), and the practice has been well-documented in the Big River and nearby Albion River and Caspar Creek watersheds. The use of so-called "splash dams," while often effective at transporting logs to downstream mills, is likely to have been highly destructive to the river channel.

During the winter, when the dams and their associated reservoirs were full, the gates were tripped and a flash flood would move downstream, picking up tiers of logs that had been carefully stacked in channels downstream. These "log drives" could occur one or more times per winter, although typically all logs harvested in the previous summer would have been prepared for the first dam release. At a few sites in the Big River, logs were stored in the reservoir itself and released along with the water, but in most places they were stacked in tiers in downstream channels and entrained by the rising waters of the dam release (Jackson 1991).

Before these log drives could be undertaken, however, the entire stream channel between the dam and the estuary had to be cleared of any obstructions (standing trees, fallen logs, and all debris jams) that would interfere with the downstream movement of the logs. Cutting, burning, and blasting of boulders, large rocks, leaning trees, sunken logs or obstructions of any kind were documented activities (Brown 1936). Jams of cut logs during such releases occurred occasionally in the Big River (Jackson 1991), but were removed as quickly as possible. During certain periods and in certain locations, such as the Hellsgate reach of the Lower South Fork, logjams lasted for years, and prevented any of these logs from reaching the mill.

The geomorphic effect of splash dam operation and associated channel clearing on downstream channels must have been immense. To create a frequent series of large, artificial floods, while at the same time removing all of the riparian vegetation and in-channel large woody debris, must have had a significant effect on channel geometry, stream bank stability, and sediment discharge. In nearby Caspar Creek, Napolitano (1996) has documented that the depletion of large woody debris from the stream channel by these activities was so extensive that the streams have not recovered in over 100 years. The greatly increased peak flows, combined with the battering ram effect of transport of thousands of logs, would likely have caused channel erosion and incision. Removal of all in-channel debris jams undoubtedly released a tremendous amount of sediment that had previously been stored behind these jams (Napolitano 1998).

In the Caspar Creek watershed, Napolitano (1996, 1998) assessed the impact of the splash dam operation on channel geometry and concluded that prior to these activities, the channel was only slightly entrenched and had a much higher width-to-depth ratio. Following the log drives and channel incision, the current entrenched condition indicates that valley fills have been converted from long-term sediment sinks (floodplains) to substantial sediment sources (terraces). Napolitano (1998) found this conversion to be a major change of trends in valley sediment storage and a pervasive alteration in the sediment budget for the basin. Furthermore, the channel has not recovered its previous morphology because jams in the channel are now less stable due to the more deeply entrenched geometry that concentrates stream energy. Re-establishment of a functional floodplain would require either streambed aggradation or valley fill erosion through lateral migration. Comparison of second-growth to old-growth channels also shows that pools are much more frequent and their average depth is greater in the old-growth channels (Keller et. al. 1981, Montgomery et. al. 1995).

Although data do not exist to explicitly confirm that a similar sequence of events occurred in the Big River watershed, the current condition certainly resembles that in Caspar Creek: a deeply entrenched stream system, in many places cut down to bed rock, lacking functional floodplains, and substantially depleted in large in-stream woody debris. Lack of instream log jams is allowing sediment delivered to the main channels to move through the system far more quickly, and ultimately reach the estuary in greater quantities, than would have occurred historically, prior to disturbance. The recovery from these historic practices has been further hindered in relatively recent times by log jam removal programs that occurred through much of the channel system in the 1950-1990s period.

CDF (1999) recorded the removal of LWD as fish barriers from streams throughout JDSF in the 1950s, 1980s, and 1990s, including the following streams in the Big River watershed:

- Tramway Gulch;
- Two Log Creek;
- Berry Gulch;
- East Branch Little North Fork Big River;
- Big River Laguna;
- James Creek;
- Chamberlain Creek;
- Water Gulch;
- East Branch North Fork Big River; and,
- North Fork Big River.

Throughout the JDSF assessment area, connection of streams to floodplains and off-channel areas is uncommon; 97% of all stream channels in JDSF are confined (CDF 1999), which is consistent with the effects of channel entrenchment. Surveys by CDF show that channels in the Eastern WWAA (North Fork Big River, East Branch North Fork Big River, Chamberlain Creek, and James Creek) are particularly affected by channel entrenchment and LWD depletion (CDF 1999).

The North Coast Regional Water Quality Control Board (2001) has summarized the impacts to stream channels from pre-logging to present as follows:

"Channel surveys in JDSF in 1997 and a review of the literature that is available for other redwood-forested watersheds in coastal northern California (Keller et al. 1982, Sedell and Luchessa 1982, as cited by CDF 1999) suggest that the following generalizations can be made about channel conditions prior to logging and other land management activities:

- Pools were larger, deeper, and more frequent, with most mid-order channels exhibiting forced pool-riffle and step-pool morphology;
- LWD loading was 3-5 times higher, and LWD formed many of the pools and stored large amounts of sediment;
- Most higher-order channels (reaches with gradients <3%) had smaller cross-sectional areas, and floodplain-channel connectivity was greater;
- The average bed substrate particle size in high-order channels may have been finer than at present, due to lower sediment transport capacity;
- Denser vegetation, including mature redwoods, occurred in most areas along the lower gradient streams throughout what is now JDSF; and,
- Stream shading would have been much higher than what typically occurs today in

managed watersheds with second-growth forests.

Since logging began in the JDSF assessment area in the early 1860s, streams have experienced two major periods of sediment input associated with logging activities: the late 1800s to early 1900s and the 1950s to mid-1970s (CDF 1999). The initial harvesting of old-growth forests in the late 1800s and early 1900s likely resulted in substantial increases in hillslope erosion, particular surface erosion from skid trails and steam donkey yarder roads, and the use of fire. Large inputs of fine sediment likely resulted in filling of pools, siltation of spawning gravels, and filling of substrate interstices used for cover by many aquatic organisms. Abundance and diversity of aquatic invertebrates likely were also reduced. Changes to channel geometry, especially through aggradation and widening, caused large-scale losses of high-quality salmonid rearing habitat such as pools and large substrates. Removal of riparian vegetation for timber or to facilitate timber harvesting had negative impacts on stream shading, inputs of organic matter to the stream, and LWD recruitment potential (CDF 1999).

Splash-dam logging resulted in large-scale destruction or alteration of habitat for aquatic organisms downstream of the dams by causing severe bed and bank erosion. Clearing of LWD and other channel bed and bank obstructions downstream of splash dams to facilitate log transport resulted in reduced channel roughness and habitat complexity (Bauer and Ralph 1999). The subsequent scouring of channels, sometimes to bedrock, eliminated pools, spawning gravel, and much of the fish and other aquatic life (Sedell and Luchessa 1982, as cited by CDF 1999). Entrenchment and reductions in LWD and other roughness elements continue to affect channels where splash damming occurred. As a result, habitat suitability for aquatic organisms, particularly summer rearing and overwintering habitat for juvenile salmonids, has been reduced compared to reference conditions in these channels (CDF 1999).

Entrenchment of stream channels has reduced the interaction between channels and their floodplains and reduced the availability of off-channel habitat, which is important to juvenile salmonids. Access to spawning areas may have been impeded during and after old-growth logging by obstacles such as dams associated with stream log transport, railroad landings constructed in the stream channels, debris jams, and a lack of surface flow caused by aggradation of the channel bed (CDF 1999).

The expansion of tractor logging and road construction following World War II led to removal of riparian vegetation along many streams and significantly increased the road-related mass wasting and surface erosion, resulting in a second pulse of sediment input to channels throughout the assessment area (CDF 1999). Beginning in the 1950s and 1960s, basin-wide removal of LWD, the majority of which occurred in 0-4% gradient channels, reduced the amount of LWD-stored sediment, reduced pool frequency and depth, and caused a conversion from bar-pool to plane-bed channel topography in some reaches (CDF 1999). Increases in sediment transport capacity due to LWD removal and large floods may have caused a relative coarsening of the bed substrates in the larger, lower-gradient channels, potentially reducing spawning gravel availability and shifting macro-invertebrate community structures (CDF 1999). These changes suggest that in the decades following World War II, aquatic and riparian habitats were substantially altered by timber operations, with increased water temperatures, losses of pool and off-channel habitat, and increased fine sediment in bed substrates (CDF 1999)."

Channel Planform Changes

Alluvial valley reaches in river systems often act as "response reaches," since they are areas of temporary (in a time frame of 10s to 100s of years) sediment storage that adjust their storage and the stream channel geometry traversing these areas in response to changes in streamflow and sediment discharge. Thus, episodic events such as large floods may cause the channel location to change, sometimes dramatically, in response to the energy of high flows that exceed the resisting forces of the stream channel banks and riparian vegetation. In a similar manner, large influxes of sediment, whether derived in a single large storm event or delivered chronically over a longer time period, may cause changes in channel form in these response reaches as sediment deposition locally overwhelms the capacity of the channel to transport it. Braided and rapidly laterally migrating channels are often the result.

During the course of this study, we examined sequential aerial photographs for several locations along the lower mainstem Big River between 1936 and 2000. This reach is alluvial, so that there is the possibility of channel change during significant flood events; however, the valley floor is quite narrow, constrained by the inner gorge setting and changes are not readily visible on photos of the scale used in this study. Furthermore, the lower reaches are also affected by tidal influence, which could significantly change the interpretation of various features based on their relative visibility at the time of the aerial photo based on tidal cycles.

There is little change apparent between 1936 and 2000 in the lower reaches of the Big River estuary (Figures 24), at least at the scale available for the air photo comparison. The channel width is similar, although the piling visible in 1936 is no longer visible in 2000. Further upstream, however, changes are visible (Figures 25 and 26) including channel narrowing by encroachment of riparian vegetation onto what were exposed alluvial deposits or into former mud-flat areas.

General Changes Visible from Historic Aerial Photography

We compared 1936 and 2000 aerial photos (and 1952-2000 when 1936 photos were not available) at ten locations randomly distributed throughout the watershed. The watershed locations are shown in Figure 23, and included four sites in the Lower Big PW (Figures 24, 25, 26, and 27), and two each in the North Fork Big PW (Figure 28 and 29), the Headwaters Big PW (Figures 30 and 31), and the South Fork Big PW (Figures 32 and 33).

<u>Lower Big (Figure 24)</u>: Outside of the apparent lack of changes in this portion of the estuary previously described, a few other observations of change over the 65-year time span (1936-2000) can be made: (1) the number of roads has noticeably increased, (2) a modest amount of what appears to be residential development has occurred, particularly along the southern

portion of the watershed, and (3) the overall age and density of the forest stands appear to have increased.

Lower Big (Figure 25): There were very few roads in this area in 1936: one small road was visible in the northwest corner of the photo and the former railroad bed ran along the north side of the river channel. By 2000, the number of roads has increased substantially, and the average width of the roads in noticeably greater along with increased numbers of turnouts and landings to accommodate industrial timberland use. Extensive areas of timber harvest are visible, including a recently harvested area with a high density of skid trails in the northeastern portion of the photoset. The increase in riparian vegetation previously described including the loss of exposed in-channel alluvial features by vegetation encroachment is a noticeable change. Again, except for recently harvested areas, which cover about 1/3rd of the photo, much of the remaining second growth areas appear to have grown considerably since the 1930s.

Lower Big (Figure 26): In this portion of the Lower Big PW in 1936, there were several visible roads including the former railroad grade, while by 2000, a more extensive road network with numerous landings, had been developed. A number of sparsely vegetated areas in 1936, reflecting harvest in this area between 1900 and 1930, have become quite dense by 2000. Although an opening in the canopy still delineates the main road along the Lower Big channel in 2000, the roadbed itself is not visible except for a few short stretches, presumably due to an increase in tree height both in the riparian area adjacent to the channel and in other areas when the roadbed is not immediately adjacent to the channel. Much of the northern half of the photo, which includes the confluence of the Little North Fork Big, shows considerable growth in the forest stand since the 1930s. A number of open gravel bar features are visible in 1936, probably reflecting the higher sediment loads in that period, while by 2000, the number and extent of the features have been substantially reduced, mostly having been colonized by riparian vegetation.

Lower Big (Figure 27): Only one road was visible in this fairly remote portion of the Little North Fork SW (Lower Big PW) in 1952. Most of the area shows historic harvest, probably prior to 1936, except a square portion on the east side that appears to be old growth forest. According to harvest maps, this area was harvested in the 1966-1978 period. The pencil lines in the 1952 photo generally describe the boundary of current ownership by Hawthorne Timber Company. In 2000, landings and cable yarding corridors are the most readily apparent feature. Evidence of extensive recent (last 10 years) harvest is visible over much a considerable amount of the photo.

North Fork Big (Figure 28): In this 1952 view, which includes the confluence of Chamberlain Creek and the former location of Camp 20 of the Caspar Logging Company. In 1952, numerous roads are already present, including former railroad grades, as well as what appears to be a power line corridor. The vast majority of the visible area had been heavily harvested in the 1940s. In 2000, there are a few more roads, but the trees have grown up to the extent that the road surfaces are mostly not visible, but are rather defined by openings in the trees and shadows. Many of the roads seen in the 1952 photo have disappeared into the re-growing forest. Although much of this area has regrown significantly since 1952, is does not yet appear ready for another harvest cycle.

North Fork Big (Figure 29): In this portion of the North Fork Big PW, mostly in the James Creek SW, we see an area that was mostly old growth in 1952, although the highway and power line corridor was under construction. A small amount of harvest to the east of the highway is visible; otherwise no other roads are visible. Our harvest history maps show that this area was harvested in the 1965, 1978, and 1988 periods. Most of the area covered in these photos lies within JDSF, although areas east of the highway are currently owned by Pioneer Resources. By 2000, many more roads are visible. The first road west of the highway lies along the channel of James Creek. Trees have grown up considerably along the highway, obscuring much of the area that was visible in 1952.

Headwaters and South Fork Big (Figure 30): This view of the confluence of the Headwaters Big and the South Fork Big show the effects of a large fire that occurred in 1931, known as the Comptche Fire. A book in 1941, listed the Comptche Fire as the sixth largest fire to have occurred in the United States (Jackson 1991). Areas to the north appear to have been outside of the burn area. As a result of the fire, the channel of the South Fork was extremely visible, with large alluvial features present along most of its length. No roads were visible in 1936. In 2000, a considerable road network has been developed. Much of the area in this photo was harvested during the 1989-2000 period. Far less alluvial features are visible in 2000, probably mostly due to the growth of trees along the edge of the channel, although sediment loading has also been reduced from its peak.

Headwaters Big (Figure 31): This photo set includes the confluence of Martin Creek and the Upper Big River. In 1952, the lower reaches of Martin Creek contained what appears to be old growth timber. Active harvesting was occurring into Martin Creek from the north. Only one road outside the active harvest area shows up on the 1952 photo, following a ridgeline between Martin Creek and the Upper Mainstem Big River SW. The channel of the Big River headwaters was highly visible in 1952, reflecting high sediment yields and likely an accompanying increase in alluvial features. By 2000, the channel is essentially not visible. A large number of roads are evident, as well as extensive skid trails from harvests occurring in the 1978, 1988, and 2000 periods.

South Fork Big (Figure 32): This view of the Daugherty Creek SW shows what appears to be a relatively undisturbed watershed area, with only one road visible. Much of the timber appears to be old growth, although it is possible that it was at least partly harvested in the late 1800s during the splash dam era. The harvest area maps show that this area was harvested in the 1978, 1988, and 2000 periods. In 2000, there are a number of new roads, including a considerable number of skid trails that are disappearing into the forest as it re-grows. The channel of Daugherty Creek is not really visible on either photo.

Upper South Fork Big (Figure 33): In contrast to other photo sets, there are almost no changes between the 1952 and 2000 photos for this area of the watershed. This area includes Montgomery Woods State Reserve, a reserve that contains a considerable amount of old growth forest. The one road visible in both photos is Orr Springs Road, which extends from Comptche to Ukiah. Areas on the east and north portions of the photos have been harvested but are maturing second growth currently. Grassland areas become more widespread in the upper portions of the South Fork, Headwaters, and North Fork Planning Watersheds. These areas do not appear to have changed appreciably in the last 50 years. It is worth noting that the geology of the Montgomery Woods State Reserve is almost exclusively Tertiary Sandstone, which is a relatively stable bedrock terrane.

In conclusion, the comparison of 1936 or 1952 aerial photos with the 2000 photos provides useful qualitative information regarding historical changes in the watershed, including: (1) a substantial increase in the road density between 1936 and 2000, (2) an increase in tree height and thus canopy closure in most riparian areas, although considerable harvest has occurred in 1978, 1988, and 2000, (3) little visible change in channel planform, although the channel is frequently less visible in 2000 compared to either 1936 or 1952 and former alluvial deposits have either been flushed through or stabilized by riparian vegetation, and (4) a general increase in forest density and height from 1936 to 2000.

SEDIMENT SOURCE ANALYSIS

This section describes the process used to evaluate possible sources of sediment within the Big River Watershed and presents the results of these analyses. The sediment source analysis encompasses three primary components: (1) evaluation of the dominant geomorphic processes that deliver sediment to the various stream channels in the Big River watershed through limited field reconnaissance, review of pertinent documents, and discussions with those involved with current studies in the basin or other nearby basins; (2) measurement of various parameters, such as landslide size/type/associated land use, road length, and harvest areas from sequential aerial photography; and (3) selection of factors to complement, modify, and/or extend the photo-based measurements, thus allowing computation of results.

Since the sediment source portion of this analysis is primarily an indirect, office-based approach, data collection was limited to parameters discernible on aerial photography, thus eliminating identification or mapping of many small-scale features (such as gullies, streamside landsliding, and bank erosion, all of which would be generally hidden beneath the canopy). Given the scale of the photography that was available for this analysis and given the need for consistency between photo sets of differing scales and print qualities, only mass movement features with dimensions (length and width) exceeding 75 feet, or approximately 5000 square feet in area, could be identified. Various studies have shown that for many areas of Northern California, sediment delivery to channels is dominated by the contributions of the largest slides (Pitlick 1995, Kelsey et al. 1995, Raines 1998, PWA 1998), although recent sediment source analyses in Mendocino County (GMA 2000, 2001) suggest that smaller slides are an important component of the sediment budget.

Sources of sediment in the Big watershed include landsliding (deep-seated landslides, shallow-seated landslides or debris slides, and debris flows or torrents), surface erosion (hillslope erosion and road erosion), and fluvial erosion (gullying and streambank erosion). This sediment source investigation included photo-based measurements to estimate landsliding and surface erosion, without field verification surveys of these features. Estimates of fluvial erosion were based on published values and results from similar, nearby watersheds.

Landsliding

Six sets of aerial photographs were examined in this investigation. Unfortunately, the earliest set (1936) did not contain coverage for the eastern half of the basin; thus measured values for this year represent minimum rates, and “zero” values that show up for certain sub-watersheds reflect the lack of coverage for that area rather than an absence of slides.

A total of 3488 features (slides) were mapped during this study, which includes some slides mapped in different time periods due to continuing delivery, reactivation, or expansion. There were 3000 unique landsliding features mapped and 488 judged to be delivering in more than one time period. Slides which were observed to have healed with vegetation were not counted as delivering sediment in future time periods. Features were given a certainty rating of definite, probable, or questionable. The first screening of the project database eliminated all questionable features from further consideration, and resulted in a database of 2872 definite or probable unique landslide features with a total (including repeats) of 3350 slides. The distribution of landslides by type for each period is shown in Table 14.

The second screening step involved separation of landslide features into two categories based on assessment of sediment delivery: either delivering or non-delivering. Delivering slides are those whose sediment directly enters a watercourse. Non-delivering slides are those whose sediment generation only reaches a watercourse at a rate comparable to background hillslope creep. Features mapped as non-delivering were eliminated from all future analyses. Determination of sediment delivery status is based on the judgment of the geologist performing the mapping and takes into account slide position relative to the adjacent watercourse, slope at terminus of slide or run-out area, and other factors. The watershed distribution of delivering slides only is shown in Appendix A for the 5 Planning watersheds using output from the GIS digital files. After the delivery screening, 2191 unique features remained, with a total of 2669, including slides mapped as delivering in multiple periods. This screening step eliminated many of the large, apparently inactive older landslides that were found on the CDMG base maps and also mapped in this study, since these were judged to not be delivering sediment in excess of background creep rates. This included almost all deep-seated rotational/translational slides (only 10 out of 393 were mapped as delivering sediment) throughout the watershed, and all very slow-moving earthflows (only 95 out of 279 were mapped as delivering sediment in the watershed).

The remaining dataset was queried by landslide type, year, number of slides and area, and the locations were separated into sub-watershed areas for evaluation at that level. Summary tables for the Planning Watersheds and each sub-watershed were prepared for use in interpreting the data and performing volume calculations.

Of the 2,669 slides mapped over the 80-year period (1936-2000), 2220 or 83.2 % were debris slides, 344 or 12.9 % were debris flows/torrents, 10 or 0.04 % were rotational/translational slides, and 95 or 3.6 % were earthflows. The 2669 slides give a watershed-averaged rate of 14.74 delivering slides/mi^2 for the entire period. Landslide frequencies were highest in the 1952 photo year, followed by the 1965 and 1936 years. The actual number of slides in 1936 was undoubtedly much higher, as previously discussed, since we did not have photo coverage for the eastern half of the watershed. Not surprisingly, these three periods, with the largest number of slides, included several of the largest storm events, in terms of peak discharge (Dec 1937, Dec 1951, Dec 1955, and Dec 1964). Interestingly, perhaps the two largest floods this century (Jan 1974 and Jan 1993) occurred in periods with very low slide frequencies. Three of seven highest 1-day precipitation intensities at Fort Bragg (1937, 1938, and 1939) in a 102-year record occurred in the 1952 period. The number of slides from the 1936 photo set seems anomalously high when it is realized that only about one-half the watershed was mapped. The absence of large floods in the 1921-1936 period would indicate a mild period geomorphically, and the comparatively large number of slides must be attributed to the high level of disturbance in that or perhaps previous periods.

There is a distinct trend of substantially decreasing numbers of slides since the peak number in the first photo year of 1936. Only 28.7 % of the slides that were mapped occurred in the

1965-1978, 1979-1988, and 1989-2000 periods, combined, and only 10.2 % of the slides occurred in the 1989-2000 period. Higher slide frequency appears to correlate well with known periods of relatively intense land use activity, primarily in the form of extensive harvest and road construction, while far fewer slides were found in recent times, when both harvest quantities had been reduced and new forest management practices were implemented.

Landslide Distribution by Sub-Watershed

Review of landslide distribution within the various planning watersheds (PW) and sub-watersheds (SW) (Table 15) show considerable variability for the entire period, ranging from 38 slides in the Two Log Creek SW to 336 slides in the Daugherty Creek SW. The highest numbers were found in the Daugherty Creek, Lower South Fork Big, Upper Mainstem Big, and Middle Big SW, with 336, 313, 289, and 281 slides respectively. Notable areas with fewer slides include most of the sub-watersheds in the Lower Big River PW (except Little North Fork SW) and the Two Log Creek SW.

When individual periods are examined, the South Fork PW is the dominant producer of landslides in the entire study period, with 35.7 % of the slides in the entire watershed occurring in that one PW. When just the most recent period is examined, the South Fork Big PW is even more significant, producing almost 40% of all the slides mapped in the entire watershed. The Headwaters and North Fork PW were similar in the range of 18-19% of the total slides in the 1989-2000 period, while the Middle and Lower Big PW were almost identical at 11%.

Landform Association with Landsliding

In contrast to many other studies in California's north coast, but similar to the recent Sediment Source Analyses on the Noyo, Ten Mile, and Albion Rivers (GMA 1999, 2000, 2001), inner gorge slopes are not the most common origin for landslides at most locations in the Big Watershed. Elsewhere, inner gorge slides have often been recognized to be of particular importance because of their high delivery rate, often directly into the stream channel. Overall, 607, or 27.7 %, of the 2191 unique slides mapped were found to be inner gorge slides (Table 16), with the determination of inner gorge status based on the judgment of the analyst. 478 of 607 or 78.7% of the inner gorge slides occurred prior to 1965. Relatively few inner gorge slides were found in recent years, although more were found in the most recent period than in the 1966-1978 or 1979-1988 periods, perhaps suggesting the impact of wet years in the mid to late 1990s.

Inner gorge slides are most frequently found along the main incised channels of the Lower South Fork Big River, where 164 or 27.0 % of those judged to be inner gorge landslides were located. The Middle Big River SW with 129 or 21.3 % and the Lower NF Big River SW with 81 or 13.3 % are other SW with large numbers of inner gorge slides over the entire study period. Thus, some 61.7 % of the inner gorge slides in the entire watershed occurred in these three SW, reflecting the dominance of these geomorphic landforms in the main channels of the Big River watershed. Not a single inner gorge slide was identified in the Upper South Fork Big River SW for the entire study period.

Land Use Associations with Landsliding

The inventory of landsliding included a land use parameter. This parameter distributed the observed features into a number of categories based on associated land use interpreted from the aerial photography. The categories included occurrence in harvested areas, occurrence judged to be related to roads, or in areas of brush/grassland. Features mapped in harvest units were further subdivided into clear cuts, partial cuts, harvested areas less than 20 years old with method uncertain, harvested areas more than 20 years old with method uncertain, and skid trails. Features mapped as road-related were further subdivided into cut or fill failures. Although some areas were unharvested by the time of the first aerial photography in 1936, and even some in 1952, very few landslides were seen (less than 1% of the slides).

Table 17 presents the distribution of land use types for all mapped features in the debris torrents and slides categories, which encompassed all but one of the delivering landslides. Of the mapped debris torrents, 34.6% occurred in areas judged to have been harvested over 20 years previously, while 28.2% were found in harvested areas less than 20 years old. Only 15.0% of the debris torrents were judged to be road-related, while 16.4% of the debris torrents were found in areas of brush or grassland. Generally similar percentages were found for shallow debris slides, although the road-related category increased substantially to 27.1%, while the brush/grassland-related decreased to 7.8%.

Table 18 divides the number of delivering slides by land use type by Planning Watershed (PW) and sub-watershed. A number of interesting observations can be made, including:

- Slides related to roads are most common in terms of absolute numbers in Daugherty Creek, James Creek and the Lower Mainstem Big SW, with 69, 64, and 62 slides, respectively. In terms of percentages, the James Creek, Lower Mainstem Big, and Two Log Creek SW were the highest. The Lower South Fork Big, Middle South Fork Big, and Upper Mainstem Big SW had the lowest percentages.
- Numbers of slides related to skid trails (included in harvest land use category) were generally quite low, except in the Chamberlain Creek, Middle South Fork, Daugherty Creek, and James Creek SW.
- 63.3% of the slides in the entire watershed were judged harvest-related, while 24.3% were judged road-related, 10.7% were found in brush/grassland areas, and 0.3% occurred in forested (unharvested) areas.
- Slides related to road fills are about 5 times more common than those related to road cuts.
- 69.6% of the slides in the James Creek SW are related to roads, while 36% of the slides in the Middle South Fork Big SW were found in areas occupied by grasslands.

Landslide Volume

Although comparisons between the number of slides is useful at one level, it is the comparison between delivered sediment volumes by type, period, and watershed location that are of primary importance in evaluating both high risk areas for certain slide types and also changes in sediment delivery over time. The first step in determining slides volumes was to query slide areas from the database. Since each slide had been digitized into the database as a polygon in the GIS coverage, geometric characteristics are easily determined. There was no need to measure average slide width and length, and compute area in that manner; instead, the true area as mapped is defined. This provides an improved estimate of area compared to other methods, although the accuracy of such mapping areas should be subject to field verification.

Determining Slide Thickness

To compute sediment delivery from slide area requires the application of a slide thickness and a delivery ratio, and then conversion of volume (yd^3) to tons. We relied on average values determined by MRC (1999) during their Albion River watershed analysis as the best available information in the vicinity. The MRC mean thicknesses were based entirely on their sample of field-verified slides. MRC was able to verify 44% of the slides they mapped. MRC found that road-related slides had a mean thickness of 5.5 feet, while non-road related slides had an average thickness of only 4.0 feet. These values are similar but somewhat larger than those found by MRC in the Noyo (MRC 1999), and used by GMA in the Noyo and Ten Mile Sediment Source Analyses (GMA 1999, 2000). Stillwater Sciences (1999) used 1.3 m (4 feet) for shallow landsliding in the South Fork Eel Basin, based on average thicknesses from Kelsey et al. (1995) in the Redwood Creek Basin, and Kelsey (1977) from the Van Duzen basin. Exactly the reverse of the Albion landslide depths was found in the Garcia River watershed, where data from surveys conducted by Louisiana-Pacific Landslides showed that landslides averaged a depth of 5.5 feet while road fill failures averaged 4.0 feet in depth. Earthflows were assigned a thickness of 10 feet, while rotational/translational slides was assigned a thickness of 25 feet.

Sediment Delivery Ratios and Volume-to-Weight Conversions

Sediment delivery factors vary considerably in the literature, from 40-100% depending upon slide type and position. Based on their investigations in the Albion watershed, MRC developed a mean delivery ratio of 88% for deliverable slides (un-verified) in close proximity to a watercourse. All field-verified landslides had specific delivery factors based on field observations. Other studies have used 80% for riparian roads and 50% for shallow landslides (Cafferata/Stillwater Sciences, pers. comm. 1999). PWA selected 40% for both road and hillslope landslides in the North Fork Elk River watershed. In this study, delivering slides were placed into four categories based on estimated percent delivery: <3%, 3-33%, 33%-66%, and >66%. Volume calculations used the midpoint of each of these percent delivery classes (0.02, .18, .50, and .83, respectively) as factors to adjust slide volumes. We converted volumes (area x thickness, in yd^3) to weight using a factor of 110 pounds/ft^3, or 1.48 tons/yd^3. Further adjustments to the earthflow and rotational slide volumes were made reflect the slower rate of sediment delivery.

Results of Volume Analysis

Review of the data from the aerial photograph analysis can provide insights to particular sub-watersheds that are producing and delivering sediment volumes at greater or lesser rates then the mean. In addition, time trends of sub-watershed response can be attributed to either susceptibility to a given type of failure location or the effects of the various land management practices. For example, the relative sediment contributions from different Planning Watersheds or sub-watersheds during the various study periods are significantly different. Table 19 shows the computed delivered sediment from all types of slides by PW and SW for the study period in both tons and as a percent of the entire watershed delivery. Notable findings include:

- 43% of the sediment delivery in the 1921-1936 period occurred in the Middle Big PW, which is in line with the extent of disturbance in that PW during that period or the immediately preceding period, though this finding is tempered by the lack of aerial photography coverage of the eastern portions of the watershed in this time period. 99% of the entire amount from the PW came from the Middle Big SW, while Two Log Creek produced almost nothing.
- In the 1937-1952 period, the South Fork and North Fork PW were the major contributors. Lesser amounts came from the Headwaters and Lower PW. The Middle Big produced very little in this period.
- 47% of the total volume of sediment for the study period (1921-2000) is computed to have occurred in the 1937-1952 period, while 26% was computed in the 1953-1965 period. This diminished to 4% in 1966-1978 period, despite several large storm events. In the 35 years since 1966, only 17% of the overall landslide sediment delivery has occurred.
- In the 1937-1952 period, the Chamberlain Creek SW and the Upper South Fork Big each produced over 20% of the total for the period.
- The South Fork PW continued to be the largest sediment producer in the 1953-1965, the 1966-1978, and 1979-1988 periods.
- The 1978 period produced only 4% of the 1921-2000 period total, despite one of the larger storms (1974) in the period. Of the 4%, 13% was from the Lower South Fork Big SW, while Martin Creek produced 12%.
- By 2000, the volume of slides had been reduced to only 6% of the 1921-2000 period total, apparently reflecting the cumulative effect of improved practices in the last 25 years, and perhaps the sediment delivery savings from improvement works on roads, etc., performed by industrial timberland owners during the 1990s. On the other hand, this reduction could simply reflect the relatively low rates of harvest until recent years and a potential lag effect before increased sediment delivery levels are seen in the watershed. The Headwaters PW became the largest sediment contributor in this period, with 32% of the total.
- Significant SW contributors in the 1989-1999 period include the Daugherty Creek SW (16%) and the Middle Big SW (10.7%). In 1989-2000, this had shifted to Upper Mainstem Big SW (13.5%) and the Lower South Fork Big SW (11.8%).

There is a trend toward significantly reduced volumes of sediment delivered from landslide sources during the last decade compared to historical periods, in spite of the fact that the middle 1990s have been one of the wetter periods this century, with significant events occurring in 1993, 1995, 1997, and 1998. The percentage of volume reduction is even a little greater than that previously discussed for the number of slides during the study period. This is a result of a reduction in both the average size and average delivery percentage as we approach the present. Table 20 computes the average volume per slide for the various time periods. A noticeable downward trend has occurred since a peak in 1952, although the small numbers of delivering slides in the last 3 study periods may mask the actual slide volumes.

TABLE 20
NUMBER, TOTAL VOLUME, AND AVERAGE VOLUME OF SLIDES BY PERIOD

	1921-1936		1937-1952		1953-1965		1966-1978		1979-1988		1989-2000		TOTAL
Category	(#)	(%)	(#)	(%)	(#)	(%)	(#)	(%)	(#)	(%)	(#)	(%)	
Number of Slides	285	10.7%	871	33%	748	28.0%	229	8.6%	264	9.9%	272	10.2%	2,669
Total Volume (tons)	829,769	10%	3,983,692	47%	2,215,207	26.0%	348,398	4%	550,359	7%	481,109	6%	8,408,533
Average Volume (tons)	2,911		4,573		2,962		1521		2,085		1,769		3,150

<u>Volume by Land Use Type</u>
Table 21 presents slide volume data by land use type and sub-watershed lumped for the entire study period, thus providing the ability to evaluate the relative contributions of various types of sources within the PW and SW. Table 22 presents these same values as percentages of total sediment delivery. Overall, 59.3% of the sediment delivery from landsliding occurred in areas affected by timber harvest (including skid trails), while 31.3% was related to roads and 9.3% occurred in brush/grassland areas, which are a combination of grazing impacts, geology, vegetation, and perhaps some simply from land clearing.

There are considerable differences between the Planning Watersheds in terms of sediment delivery by land use type. Harvest-related volumes range from 38.8% to 68.5% for the four PW, with the North Fork PW being the only low value, and the other PW's are all in the range of 62.6-68.5%. Road-related volumes by PW range from 15.8% (South Fork Big PW) to 60.7% (North Fork Big PW), with the watershed wide average of 31.3%. Brush/grassland-related volumes range from 0% to 20.5%.

Within the harvest-related land use type, the majority of landsliding occurs in harvest units greater than 20 years old, which overall represented 31.3% of the total sediment delivery from the watershed, while harvest units less than 20 years old produced only 22.1% of the total. Skid trails-related landsliding was locally significant (22.5% in the Middle South Fork Big PW), but only 4.8% overall.

Review of the sediment delivery volumes by land use type on a PW and SW basis (Table 21) produced the following highlights:

- Road-related sediment is most significant in terms of overall volumes from the North Fork Big PW, with more than twice the volume of the next PW, the South Fork Big. Road-related sediment was least significant in the Middle Big PW and Lower Big PW. The South Fork Big PW and the Headwaters Big PW had almost identical amounts of road-related sediment.
- Harvest-related sediment volumes are dominated by delivery from the South Fork Big PW, almost 2 times larger than the Headwaters Big PW. The other three PW had very similar amounts of harvest-related sediment delivery.
- Brush/grassland-related sediment volumes were significant in the South Fork Big PW, and top a lesser degree in the Headwaters Big PW. Essentially no grassland-related sediment delivery was found in the North Fork Big, Middle Big, or Lower Big PW.
- Small amounts of landslide volumes were found in undisturbed Forest areas in the South Fork, North Fork, and Middle Big PW. Additional landslides would have been found if the aerial coverage had extended to the entire watershed.
- Skid trail-related landslide sediment volumes are most significant (though relatively small compared to harvest-related volumes) in the South Fork Big PW and North Fork Big PW. Very little skid-trail related landslides were observed in the Lower Big PW. On a sub-watershed basis, most of the skid trail-related landslides are found in the Middle South Fork Big, Chamberlain Creek, and James Creek SW.

As a percentage of the total sediment volumes delivered by landsliding within each PW or SW by land use (Table 22), the following observations are made:

- Road-related sediment delivery, as a function of the total delivery within that SW, is most significant in the James Creek (76.3%), Chamberlain Creek (56.5%), and Upper North Fork Big (56.2%) sub-watersheds.
- The lowest percentages of road-related landslide sediment delivery are found in Upper South Fork SW (1.1%), Lower South Fork Big (10.3%), and Middle South Fork Big (14.2%).
- Brush/grassland-related landslide sediment delivery was found in two of the five PW (South Fork Big was 20.5%), but really only in 4 SW: Daugherty Creek (27.3%), Upper South Fork Big (24.7%), Middle South Fork Big (23.5%), Martin Creek (13.9%). These percentages are in relation to the total sediment delivery from the respective SW over the study period.
- Harvest-related sediment delivery as a percentage of SW total for the entire period was found to be most significant in the all of the PW except the North Fork Big. The SW with the smallest amounts were James Creek (23.7%) and Daugherty Creek (32.6%).
- Within the harvest-related land use type, skid road-related landsliding was only found to be significant in the Middle South Fork Big River (22.5%) and James Creek (13.8%). For the other SW, skid trails were very minor sediment producers, typically 6% or less.

- Only the Big River Estuary (10.2%) and the Middle South Fork Big (8.1%) were found to produce considerable sediment from clear cut harvesting, which was only 1.1% of the total sediment delivery for the entire watershed for the entire study period.

The percentage values by land use are expressed as a function of the total sediment delivered by each SW or PW. For example, road-related sediment delivery from landsliding in the Daugherty Creek SW was found to be 39.6% of the total landslide sediment volume delivered by that SW only; so road-related landsliding is an important component within that SW. Overall, compared to other SW it may be a small volume, but within that SW it was significant.

Trends in Landsliding Delivery by Land Use over Time

Table 23 presents landslide volumes by land use by study period for each sub-watershed. This enables trends in sediment production by land use within a given sub-watershed to be evaluated. The following sections describe this trend analysis for each sub-watershed.

Big River Headwaters PW

Upper Mainstem Big SW: Harvest-related sediment production dominates this sub-watershed, with a large peak (2 times the next largest year) in the 1937-1952 period. Sediment production from landsliding in brush/grassland areas was also found to peak in 1952, and has been observed in only very small amounts since 1978. Road-related landsliding peaked in the 1965 period, and then declined by over 90% in the 1978 period. In the 2000 period, 74% was road-related. Interestingly, similar amounts of skid trail landslides were found in the 1965 and 2000 periods, perhaps suggesting that in certain instances, the regulatory changes resulting from the Forest Practice Act may not always result in substantially smaller amounts of sediment delivery, although this does not take into account the amount of harvest in each period.

Martin Creek SW: Sediment delivery from this sub-watershed peaked in the 1965 period, with delivery during each of the next three periods at about 25% of the peak level. Major harvesting in Martin Creek occurred in the 1952, 1978, 1988, and 2000 periods (Appendix C-1), so the high landslide sediment production in 1965, was probably related to the harvesting in the previous period. Road-related landslides also peaked in the 1965 period, with quite small amounts since then. Brush and grassland-related landslides peaked in the 2000 period, with just over 50% of the volume coming from those areas in the current period.

Lower Mainstem Big SW: Harvest-related sediment delivery from landslides peaked in this SW in the 1952 period, and declined sharply thereafter. Road-related landslide sediment has increased in importance over time, and is now 67% of the total sub-watershed sediment delivery.

North Fork Big PW

Upper North Fork Big SW: Two peaks in sediment production occurred in this SW, with harvest-related landslides providing most of the volume in the 1952 period, and road related landslides providing most of the volume in 1988. Harvest-related volumes have been quite low since the 1952 period. Sediment production from landslides is currently fairly low

James Creek SW: Sediment production from landslides peaked in this sub-watershed in the 1952 period, but remained high through the 1965 period. This production appears to correlate well with harvest and road construction activities and the occurrence of large storms. Current sediment production from landslides is very low in the sub-watershed.

Chamberlain Creek SW: This SW generated an enormous amount of sediment in the 1952 period, with 57% coming from road-related landslides, with the balance from harvest related landslides. 75% of the total sediment production for the entire period was found to occur in the 1952 period. Extensive harvest in this watershed did not begin until the establishment of Camp 20 in 1939, so the delivery of large sediment volumes in 1952 correlates well with intensive harvesting in the early part of that period. Sediment production from landslides since 1978 has been small and consistent, with slightly more in the current period. The current rates are less than 2% of the peak sediment production from landslides in thew 1952 period.

East Branch North Fork Big SW: Sediment production from this sub-watershed also peaked in the 1952 period, with 54% being road-related. Levels have declined significantly since then, although recent values are significantly larger than all other SW in the North Fork Big PW. Overall, harvest and road-related landslides have produced roughly similar volumes of sediment from this SW over the entire study period.

Lower North Fork Big SW: This SW is the second largest sediment producer from landslides over the entire study period behind Chamberlain Creek. Volumes peaked in the 1952 period, and were judged to be entirely related to harvest activities, with many occurring on the steep, inner gorge slopes of this SW. Sediment production from landslides since 1965 has been quite low.

Middle Big PW

Middle Big SW: This SW was harvested intensively earlier than those in the North Fork or Headwaters PW, and with aerial coverage in 1936, extensive landslide production related to these harvest activities was found. Little road-related landslides were observed in this early period, but that changed dramatically in the 1965 period, when 76% of the slides were road-related. Sediment production from landslides in this SW since 1965 has been generally low: greater than most of the North Fork, while less than the Headwaters.

Two Log Creek: Sediment production from landslides in this small SW has been generally low, with what landslides there were, primarily found in the 1952 and 1965 periods. No landslides were found in this SW in the 1988 period. In the current period, 56% were harvest related, while 44% were road-related.

South Fork Big PW

Upper South Fork Big SW: Due to its geology and vegetation, 25% of the entire sediment production from landslides from this SW was found to occur in brush and grassland areas, and these have been found throughout the study period, with by far the largest amounts in the 1952 period. Harvest-related landslide volumes were very large in the 1952 period, while sharply declining thereafter. Road-related sediment production from landslides was only found in this SW in the 1952 period, with none since then.

Middle South Fork SW: Sediment delivery from landslides peaked in this SW in the 1965 period, and has steadily declined since then. Sediment production in the current (2000) period included 53% from harvest-related slides, 33% from road-related slides, and 14% from slides in brush/grassland areas.

Daugherty Creek SW: This sub-watershed has produced the third largest total volume of sediment (after Chamberlain Creek and the Upper South Fork Big) over the entire study period. Rates of sediment delivery from slides were very high in both the 1952 and 1965 periods. Volumes have declined since then, but this SW remains one of the larger producers in the watershed. The three land use associations (brush/grassland, harvest-related, and road-related) have produced sediment at roughly equivalent rates when viewed over the entire study period. In the current period, brush/grassland delivered 44%, harvest-related were 36%, and road-related were 20%.

Lower South Fork Big SW: In contrast to the Upper SF Big, Middle SF Big, and Daugherty Creek, very little sediment production from landslides in brush/grassland areas was found in this SW. The 1936 aerials covered this SW, and found a considerable amount of sediment production from landslides. Slide volumes were slightly higher in the 1952 period compared to the 1936 period, and have diminished since then, although this SW remains one of the largest sediment producers from slides currently (#2 in the entire watershed after the Upper Mainstem Big SW in the Headwaters PW). Road-related sediment delivery from slides is currently quite low (6%), with most landslide delivery associated with harvest activities (94%). No brush/grassland slides were found since 1965.

Lower Big PW

Lower Big River SW: Sediment production from slides in this SW peaked in the 1952 period, was very low in the 1978 and 1988 periods, and currently is at a moderate level. 69% of the current slide volumes are related to harvest activities, while 31% are road-related. Overall sediment production from slides in this SW has been fairly small compared to other parts of the watershed.

Little North Fork SW: This SW produced a large amount of sediment from landslides in the 1952 period (68% of it total production) and moderate levels consistently since then. Historically, harvest-related slides accounted for the majority of the sediment volumes (71%), although currently, road-related slides account for the majority (80%).

Laguna Creek SW: Overall sediment delivery from slides in the SW has been low, with the largest amount (60%) coming in the 1952 period. A small amount of sediment delivery from slides was seen in the 1936 period. Very little slide volume was found in the 1965 or 1978 periods; however, rates have increased in the two most recent periods. Road-related slides were the dominant sediment producer in the 1988 period (93%), but were found to be less significant in the 2000 period (30%) compared to harvest-related slides (70%).

Big River Estuary SW: Modest levels of sediment production from landslides were found in this SW, with two peaks observed in the 1965 and 2000 periods. Overall, harvest-related and road-related sediment production from landslides are approximately equal for the entire study period, although more harvest-related slides were found in the early periods, while much more road-related slides were found in recent periods. In the 2000 period, 84% of the delivered slide volume was road-related.

Conclusions: In general, there appears to be a consistent pattern between road construction, harvest disturbance, and resulting sediment production from landslides. Sometimes there appears to be a lag of one study period (10-15 years). Sediment production after the 1965 period has been dramatically lower, which is attributed to a combination of lesser amounts of harvest in certain periods (such as 1978), with substantially improved harvest implementation following the 1973 change in the Forest Practice Rules.

Unfortunately, no explanation is currently available for the significant amounts of grassland-associated sediment production from landslides in certain SW in certain time periods. An unknown amount of grazing occurs in the watershed, but it is more likely that this delivery is related instead to both landform adjustments in cleared areas and the underlying geology. Virtually all brush/grassland slides are found in the upper portions of the Headwaters and South Fork PW, which is primarily underlain by the Central Belt, or mélange terrain of the Franciscan Formation. It is also possible that more landslides were seen in grassland areas, simply because they could be found much easier on the aerial photographs, as there was not any canopy coverage to preclude visibility. Road-related landsliding was found to account for about 31% of the total delivered slide volume, while harvest-related slides provided that majority of slide volume with 60%. These values are similar to those documented in the Noyo, Ten Mile, and other coastal watersheds.

Average Annual Unit Area Volumes

Landslide sediment production data were also evaluated by calculation of average annual unit area volumes by study period. These data are shown in Table 24 and are simply unit area rates divided by the number of years in each study period. Although we know that most sediment production from mass wasting actually occurs during years with a combination of high annual precipitation and intense storms, we have no quantitative way to assign volumes to a specific year, and it is useful from a planning perspective to look at average annual rates within the selected study periods.

The overall sediment delivery from landsliding for the period of 1921-2000 is estimated at 580 tons/mi^2/yr, with individual periods ranging from 1,375 tons/mi^2/yr (1952) to 148 tons/mi^2/yr (1978). For the entire watershed, the highest delivery is surprisingly found in the 1952 period, which is not associated with any of what were probably the 5 largest storms (Water Years 1974, 1965, 1993, 1956, and 1966) during the study period. It is possible that storms in Water Years 1938 and 1952 were more significant in the Big than in other nearby watersheds, but data are not available to document this. We only know, as noted previously, that three of seven highest 1-day precipitation intensities at Fort Bragg (1937, 1938, and 1939) in a 102-year record occurred in the 1937-1952 period. Landslide sediment delivery was also quite high in the 1965 period, which included the 1956, 1965, and 1966 storms. Following the 1965 period, there has been a sharp decline in landslide sediment delivery in recent times, probably largely the result of a combination of lower harvest intensities and improved management practices.

The highest average annual rates for individual SW in a study period were found to be Upper South Fork Big River in the 1937-1952 period at 6,224 tons/mi^2/yr, followed by the Chamberlain Creek at 4,093 tons/mi^2/yr and the Upper Mainstem Big at 2,009 tons/mi^2/yr. By the 1989-2000 period, the Upper South Fork Big was only delivering sediment from landsliding at a rate of 164 tons/mi^2/yr, Chamberlain Creek at 83 tons/mi^2/yr, and the Upper Mainstem Big at 432 tons/mi^2/yr.

Consideration Of Landslide Volume Adjustment Factors for the Albion River 1979-1988 and 1989-2000 Periods

The recent completion (1999) by Mendocino Redwood Company, LLC of a Level 2 Watershed Analysis for their lands within the Albion River watershed provided an unusual opportunity to compare landslide volumes developed using larger scale 1:12,000 and considerable field verification (MRC) vs. 1:20,000 to 1:31,680 (GMA). GMA (2001) found that the number and volume of landslides between these two datasets was quite different. Less so in 1988, probably as a result of a drier period and greater difficulty for MRC to field verify slides that were a minimum of 12 years old. In the 2000 dataset, MRC mapped 13-16 times as many landslides as did GMA, and the volume difference ranged from 9-36 times greater. The GMA analysis suggested that the differences were primarily related to the scale of the photography used and thus the minimum size of the feature that could be resolved. Secondarily, we would expect significant improvements in the dataset from field verification, and possibly the identification of considerably more slides that are road-related during the road inventory portion of the MRC watershed analysis. We had previously stated in the methods section that the minimum size of a feature that could be reliably resolved at the scale of photography used by GMA would be roughly 5000 square feet. MRC found many smaller landslides than did the GMA mapping. This confirms the critical role of field verification in the mapping process, and that in the Albion River watershed, at least, small landslides were cumulatively important contributors.

Unfortunately, similar datasets that would allow the determination of landslide adjustment factors in the Big River are not currently available. There is little doubt that analyses based on solely on aerial photograph interpretation suffer in comparison to field-based studies. Based on the Albion River Sediment Source Analysis, the volumes reported in this study may be low by a factor of 10-30 times. However, it is expected that the relative percentages between years and perhaps types, would remain relatively consistent, and may thus form the basis for loading reductions expressed as percentages only, rather than in tons.

Limitations of Landslide Analysis

Although few datasets are available to compare the difference between field-based and aerial photography-based landslide analyses, a recent study by the Oregon Department of Forestry (1999) following the 1996 storms provides additional confirmation of the challenges facing aerial photo-based landslide interpretations. Prior to the ODF study, relatively little was known about potential biases in air photo inventories of landslides. Certainly, forest canopy may make detection of landslides more difficult, and it seems reasonable to suspect that a higher percentage of landslides in a recently harvested area may be visible compared to that visible in a mature forest.

ODF found that air-photo surveys detected a greater percentage of landslides in recently clearcut stands versus uncut or mature stands as compared to the ground survey results for the same age class. At one site (Mapleton), 59% (17 of 29) of landslides observed on the ground were visible in air photos at 1:6,000 scale for forest stands clearcut within the last nine years. However, for landslides found in stands over 100 years old, only 5% (2 of 38) of landslides observed on the ground were visible in the 1:6,000 scale photos.

This bias towards detecting more landslides within younger forest stands using air photos may significantly affect the ratio of landslide densities and erosion volume per acre for recently clearcut stands compared to mature stands. ODF (1999) found that if one were comparing landslide density using 1:6,000 air photo analysis, the ratio of landslides in the clearcut stands versus those in mature forest stands is about 21:1, while for ground-based measurements that ratio is about 2:1. For 1:24,000 scale air photo analysis, the clearcut to mature forests ratio of landslide density is 17:1.

ODF found that use of aerial photographs for identification of shallow landslides will likely result in biased and incomplete landslide inventories. This bias significantly underestimates the landslide frequency and erosion volume across all forest stand age classes. At two sites, for example, 72 percent of all landslides identified from the ground-based survey were not detected using even 1:6,000 aerial photographs. The majority (72 to 98 percent) of shallow-rapid landslides were not visible on aerial photographs of any scale. In terms of erosion volume, the landslides that were not identified from aerial photographs accounted for 53 percent and 41 percent of the total landslide related sediment volume delivered to stream channels. Landslide identification is most problematic in areas with mature or semi-mature timber. For instance, roughly 50 percent of the landslides can be detected in recently harvested areas (0-9 years old) but less than 5 percent of the landslides can be detected in mature stands (older than 100 years).

Based on the foregoing discussion, the landsliding analysis presented here most likely underestimates the role of mass wasting in sediment delivery due to lack of data regarding small slides which were smaller than the resolution of the aerial photographs used, as well as the lack of comprehensive field verification. The ODF study confirms that small slides not seen beneath the canopy in old growth or mature forest areas could also substantially increase the background or non-management related landslide volumes. The next section describes a field investigation by GMA to evaluate landslide rates in one of the few remaining “old growth” stands in the Big River watershed.

Comparison to mass wasting rates developed in other north coast California watersheds with similar geology suggests that the results of this study are reasonable. Recent work within the adjacent Noyo and Albion watersheds provides the best basis for comparison. MRC (1999a), in their Level 2 Watershed Analysis, estimated rates of mass wasting for their holdings in the Noyo River watershed at between 67-611 tons/mi^2/yr for a 40-year period between 1958 and 1998. In the Albion River, MRC (1999b) found rates of mass wasting at between 132 and 698 tons/mi^2/yr for a 20-year period between 1978 and 1998.

The Noyo results were averages that included much higher rates for the pre-1978 period reflecting differing forest practice rules. The 1978-1998 rates in the Noyo watershed developed by MRC were from 47-310 tons/mi^2/yr. Studies underway in the Jackson Demonstration State Forest (JDSF) in support of their HCP/SYP Watershed Assessment indicate a rate of delivered sediment to stream channels from landsliding of 265 tons/mi^2/yr (Cafferata/Stillwater Sciences, pers. comm. 1999).

Numerous other studies from north coastal California have developed mass wasting yields of between 192 tons/mi^2/yr (OCEI, 1997) for portions of the Garcia River watershed to 566 tons/mi^2/yr in the Navarro River watershed (Entrix et al., 1998), to 2400 tons/mi^2/yr in Redwood Creek (Madej et al., 1999). Revisions to the Garcia River rates based on new information developed in a Level 2 Watershed Assessment by Louisiana Pacific increased the rate to 462 tons/mi^2/yr (PWA, 1997).

Evaluation of Background Landsliding Rates

Relatively small portions of the watershed were both unharvested in 1952, the year of the first complete aerial photo coverage of the watershed to which we were able to obtain access during the period of our study. A reasonable amount of additional watershed area would have been unharvested in 1936, but was outside the photo coverage available. Thus, there were only relatively small areas of old growth in which we could examine the frequency of landslides in unmanaged lands. Where old growth remained, we found very few landslides in our aerial photo analysis, specifically 7 slides in the forest category. This is similar to the GMA findings (2000) in the Ten Mile watershed. There is little doubt that an unknown amount of small landslides probably were present under the extensive canopy, unfortunately, there is little way to estimate this.

One of the few locations with remaining old growth in the watershed is Montgomery Woods State Reserve, located in the South Fork Big PW. Figure 33 depicts changes to this area between 1952 and 2000, and as noted previously, is the only one of the ten photo comparisons that shows relatively little change. Since public access was available to the state reserve, we determined that field reconnaissance of the unmanaged forest stand could provide some useful information on background rates. Field observations were conducted by a hydrologist in order to understand the nature of mass wasting, surface erosion and stream bank erosion in an undisturbed old growth redwood setting. Majority of the area was inventoried by walking, using direct field observations to attempt to quantify any disturbances in three major hillslope locations. The three locations are ridge-top, mid-slope, and streamside.

Montgomery Woods State Reserve is located in upper portions of the Middle South Fork Big PW. The reserve is accessed by way of the Comptche-Ukiah Road. The majority of the reserve is located with in the Montgomery Creek basin, a tributary to the South Fork of the Big River. The basin is primarily made up of inner gorge slopes (>60%) with a wide alluvial flat adjacent to the stream channel. The size and age of the old growth on this flat shows that the alluvial flat has been relatively undisturbed for the past 200-300 years. On the lower hillsides, old-growth redwood is present, though the size and density decreases with elevation. As the hillslope approaches the ridge-top, old-growth redwood starts to decrease and old-growth Douglas Fir begins to be the dominant conifer species. It should be stated that Montgomery Woods is not completely undisturbed, which is evident by large old-growth stumps in the flat and on the lower hillsides. A road was built into the flat many years ago and some of the larger trees were harvested on both the flat and the lower hillside.

As the channel is followed upstream, the width of the alluvial flat decreases and the channel increases in gradient. At this point, the channel banks and hillsides are mostly inner gorge with few alluvial deposits. The steep slopes and high gradient channel would have made it difficult to access for harvest and therefore, these areas appear to have been completely undisturbed. Most observations and conclusions were based on this area with inner gorge slopes since they tend to be the most susceptible hill slopes to mass wasting and most heavily influenced by harvesting and road building.

<u>Mass Wasting</u>: Mass wasting features normal to the Coast Range are deep-seated landslides, soil creep, and shallow debris slides. In the area inventoried in Montgomery Woods, there were no easily identifiable signs of erosion due to any of the stated mass wasting features, for a period that would extend for at least the past 200 to 300yrs (the time it would have taken for the propagation of an old-growth redwood or Douglas fir). A few of the old growth trees (both redwood and Douglas Fir), and alders show signs of trunk correction (jackstraw) which would indicate there has been some soil movement (creep) or could be a result of weak root

strength, thin soil, and wind throw. The entire hillside has downed trees with uprooted root structures, with the frequency of incident increasing with hillslope elevation (probably due to thinner soils and increased wind velocities). Though this tends to be the most frequent sign of hillslope disturbance, the amount of displaced soil is minimal compared to a typical mass wasting feature. After assessing the undisturbed hillside from streamside to ridge-top it was found that there were no quantifiable mass wasting features.

Surface Erosion: Surface erosion features normal to the Coast range are sheet wash and gullying. Since this area has not been entered, there is no surface erosion associated with disturbance of ground cover or road-related activities. In addition, since there are no mass wasting features, there is not the normal sheet wash and gullying that is associated with bare debris slide scars and the surfaces of earth flows (Lehre 1982). The main stream channel and low order tributaries were carefully walked to assess whether there were gullies delivering to the stream channel. None were found.

Streambank Erosion: The position of the large old-growth trees in relation to the stream channel show that bank erosion and channel migration have been very low or negligible in both the alluvial flat and the steeper inner gorge valley. Large woody debris and old-growth trees influence channel position and stability by dissipating stream flow energy and armoring the banks. Streamside landslides, bank scour and channel incision where absent in the lower reaches as well as the steep headwaters areas. .

Admittedly, evaluation of background landsliding rates from such a small sample as the several hundred acres of Montgomery Woods State Reserve that contain areas of steep slopes could be problematic, however, it is interesting that no signs of recent mass wasting could be located. A complicating factor involves the underlying geology of the area, which is entirely the Tertiary Sandstone described in the geology section. Descriptions indicate that this formation is relatively coherent, thus certainly much more stable than the mélange and possibly more stable than the Coastal Belt of the Franciscan Formation.

SURFACE EROSION

Accelerated surface erosion from land management activities is well recognized. Erosion from road surfaces is often a persistent source of sediment in logged basins due to the large network of dirt roads associated with harvest activities and the increased connectivity of the roads to the stream channels. Numerous studies have documented the role of road construction in increased sediment yields (e.g. Reid and Dunne 1984, Rice et al. 1979). Road-related sediment is a major factor in most North Coast watersheds. The location of roads on basin slopes (near stream, mid-slope, and ridge top) can have major effects on both fluvial and mass wasting processes (Cafferata and Spittler 1998, Jones et al. 2000).

The surface erosion section of the source analysis includes 2 primary components: (1) road surface erosion; and (2) hillslope erosion from skid roads and harvest areas. Given the constraints of the project such that only a small amount of field reconnaissance was possible, the standard procedure emphasizing road evaluation and inventory was not possible. Indirect methods were employed involving development of road and harvest history from aerial photographs, querying of the GIS database, and selection of factors for computation of rates.

Road Surface Erosion

Methods

Road data were developed from various sources and compiled into the project GIS. CDF provided much of the base data, which had originally been obtained from the USGS topographic maps. CDF then amended the USGS data to include data from submitted timber harvest plans since 1988. Unfortunately, the THP data did not include existing roads outside of the harvest area boundaries, and thus new road segments were not always shown to be connected to other roads. In places, road locations were only roughly defined, and we attempted to correct and thus, re-connect, these isolated road segments into the road network.

It should be noted that mapping of roads from aerial photographs with a scale of 1:20,000 or 1:24,000 and significant forest canopy is not always straightforward. We focused on main roads and haul roads, and likely either missed or ignored smaller roads in some years. This likely resulted in an under-estimate of roads for years prior to 2000, and an over-estimate of construction totals for the 1989-2000 period, as the 1989-2000 period estimate was obtained by subtraction of the cumulative total by years through 1988 from the existing GIS total. In addition, road segments that had not been coded as a specific year in the CDF data were also assigned to the 1989-2000 period.

The road construction history for the entire watershed is provided in Table 27. We were unable to determine the extent that unused, "legacy" roads had been abandoned and either put to bed, or simply allowed to revegetate, as is likely the case in parts of the watershed. This process would be most common where very dense road networks were developed in early harvest periods, and many of these roads were subsequently re-worked or totally abandoned. However, unless properly storm-proofed, even abandoned roads may contribute sediment, though likely at a declining rate with time as vegetation coverage develops and potentially unstable cut and fill slopes stabilize. Since virtually all of the early harvest (prior to 1930) was either via railroad or river transport, there was not the same networks of roads specifically constructed for harvest as was seen in portions of the Ten Mile watershed, which were not harvested until the late 1930s or early 1940s, and thus were tractor logged. Portions of the watershed, particularly in the North Fork and Headwaters PW, were logged for the first time after 1930, and thus were tractor logged, but a significant amount of the watershed old growth had probably already been harvested by then. After 1960, most road construction in the Big River watershed appears to be related to access for timber harvest, although a very small amount of road construction for residential development has also occurred.

Current Road Conditions and Types

According to the GIS road coverage developed in this study, there are currently 1242 miles of roads in the Big Watershed, which translates to a basin-wide road density of 6.86 mi/mi^2. Table 25 shows the existing road network distributed by Planning Watershed and sub-watershed. The highest road density in the basin was found in the Middle Big River SW, with a density of 8.85 mi/mi^2, followed by the Lower Big River SW (8.23 mi/mi^2), and the Big River Estuary SW (8.22 mi/mi^2). The various CDF GIS classes were combined into 3 categories for simplicity: paved, rocked, and native. Not surprisingly, native roads were 83% of the total, followed by rocked roads at 13.7%, and paved at 3.2%. A considerable portion of Highway 20 is contained in the watershed. The Middle Big PW has the highest road density (8.64 mi/mi^2) of the 5 planning watersheds. The South Fork Big PW has the largest amount of road miles at 316.6, followed by the North Fork Big PW at 289 miles. Each of the three types was also subdivided by position into riparian, mid-slope, and ridge categories.

Railroads

As previously discussed in the brief history of the watershed, railroads played an important role in the transportation of harvested timber between about 1885 and 1930. Figure 34 shows the extent of the former railroad network based on the 1936 aerial photographs and maps in Wurm (1986). The railroad was not connected to the coast, but rather operated in an isolated area beginning near the middle of the estuary. With no other access, the locomotives were actually barged up the estuary to the beginning of the track at the log dump. From there, the track extended upstream along the mainstem to the Little North Fork, with several branches along the way into smaller tributaries. A spur had also crossed the Big River on a bridge and gone up into the Laguna Creek drainage. Tracks were laid a considerable distance up the Little North Fork. The other area of railroad activity included portions of the Little North Fork, Two Log Creek, and the North Fork Big, accessed by the Caspar Logging Company railroad system from the South Fork Noyo or via inclines. Abandoned railroad grades that have not been converted to roads, are still visible at a few locations in the watershed.

Road Location Characterization and History

All roads within the Big River Watershed were stratified into three categories: riparian, mid-slope, and ridge-top by analysis of the GIS database. Unfortunately, the GIS database for the watershed is not fully crenulated in all locations, as CDF has only updated those areas in recent THP's, and thus road segments adjacent to some drainage features were probably not found in this process.

Table 26 provides the breakout of road miles by the various road positions, as a function of road type, for each Planning Watershed and Sub-Watershed. Interestingly, all of the Planning Watersheds have very similar amounts of road miles in each category. For example, riparian roads are between 20.2% and 28.5% of the total roads in each PW, while mid-slope roads are 54.3% to 61.8% and ridge roads are 17.2% to 21.0%. On a sub-watershed basis, the ranges become much greater. For example, in Chamberlain Creek, riparian roads are 42% of the total roads in that SW. Other interesting data can be seen from this table, including the fact that only 22.7% of the riparian roads are either paved or rocked despite awareness that native riparian roads will contribute much greater amounts of fines directly to the channel than the other types and that this should be a priority for upgrading.

Table 27 presents the results of our mapping of the road network over time based on the sequential aerial photographs. The miles of roads constructed by period for each PW and SW are shown. Of the current total of 1242 miles of roads, 5.5% were existing in 1936, 20.6% were added in the 1937-1952 period, 21% were constructed in the 1953-1965 period, another 16.8% were built in the 1966-1978 period, 11.5% were added in the 1979-1988 period, while 24.7% were created in the most recent 1989-1999 period, although the latter period probably includes some roads that were actually constructed earlier, as discussed previously. The road construction mirrors the progress of second growth timber harvest through the watershed, with lesser amounts of construction in the 1978 and 1988 periods, and then a substantial increase in recent times as more of the watershed reached maturity.

Major road construction in the 1952 period occurred in the Daugherty Creek SW (33.8 miles) and the Chamberlain Creek SW (27.5 miles). In the 1965 period, most road construction occurred in the Middle Big SW (30.9 miles), the Upper Mainstem Big SW (26.7 miles), and the Daugherty Creek SW (26.4 miles). Major road construction occurred in the Lower South Fork Big SW (43.0 miles) and the East Branch North Fork SW (26.6 miles) in the 1978 period.

Major road construction occurred in the Lower Mainstem Big SW (24.3 miles), the Middle Big River SW (16.4 miles), and the Lower South Fork Big SW (15.0 miles) in the 1988 period. Widespread construction (44-72 miles each) in the five PW occurred in the 1989-2000 period, as harvest rates rose considerably.

As noted earlier, some of the roads attributed to 2000 probably were constructed in prior periods, mainly in 1979-1988, but it is still evident that many miles of roads were recently built. 69.4 miles or 29.7% of the total in the Big River Headwaters PW were considered built in the 2000 period, while the North Fork Big PW had 15.3%, the Middle Big had 34.5%, the South Fork Big had 21.5%, and the Lower Big had 28.9%. Despite the significant increase in road density, the advantage of recently constructed roads over earlier roads is that construction standards have markedly improved in the past 25 years, thereby reducing the relative impact of these features. In addition, many of these recent roads are ridge-top roads, providing access for cable-yarding harvest techniques. Ridge-top roads generally deliver substantially less sediment to watercourses than roads near stream courses (riparian roads) or mid-slope roads.

The method used to estimate sediment production from roads after stratification by location is based on characterization of road use (application of a use function) and then calculation of road sediment production by such use (application of a sediment delivery function). Any other method would require detailed information on road characteristics and use that can only be developed through a detailed road inventory. This procedure was developed by Reid (1981) based on studies of industrial timber roads and associated use and sediment production in the Clearwater basin (Washington State). The results of the road sediment production by use analysis were then modified by road surfacing factors (0.2, 0.5, and 1.0 for paved, rocked, and native surfaces, respectively), and by location delivery factors (0.8 for riparian roads, 0.2 for mid-slope roads, while ridge-top roads were assumed to be non-delivering). Similar applications of this method have been recently undertaken on the Navarro River, Noyo River, Ten Mile, and Albion watersheds. The current analysis is improved over those previous used in the Noyo and Ten Mile watersheds because road location is taken into account.

The first step involves converting the observed road mileage by year into cumulative road miles by period to allow for road surface erosion calculations (Table 28). The total road mileage in a given sub-watershed is then stratified into use categories by application of a "use function" which proportions the road miles into four use categories (high, moderate, low, none) based on fixed percentages (high use: 5%, moderate use: 5%, low use: 40%, and no use: 50%). These percentages are based on the patterns of log-truck usage observed by Reid (1981), with the percentages rounded to the nearest 5 or 10% to simplify computation (high from 6% to 5%, low from 39% to 40%). The next step involves application of the sediment production rates for each use class. Reid (1981) found that sediment production rates for each use class in the Clearwater Basin declined by approximately an order of magnitude (i.e., 800 tons/mi for high, 80 tons/mi for moderate, 8 tons/mi for low, and 0.8 tons/mi for no use). The product of each use class by the applicable sediment rate gives annual sediment yield by class. The yields in the various classes are then summed to obtain sub-watershed production from roads. This procedure was followed for all years with road mileage data. The road surfacing and location delivery factors were then applied based on the road type and road location analysis. Table 29 shows the results of this method for estimating road surface erosion for the Big River watershed.

The analysis indicates that sediment production from roads has increased significantly over the study period, tracking cumulative road construction. Existing conditions are estimated to produce an overall watershed average yield of 92.7 tons/mi^2/yr from road surface erosion, which is estimated to be about a 15-time increase over 1936 rates. Current road surface erosion rates are computed to range between 53.6 tons/mi^2/yr for the Upper South Fork Big SW to 117 tons/mi^2/yr for the Lower Big SW. At a Planning Watershed level, computed existing road surface erosion ranged from 76.6 tons/mi^2/yr in the South Fork Big PW to 106.9 tons/mi^2/yr in the Middle Big PW.

Limitations of Roads Analysis and Development of Final Values

The method of characterizing sediment delivery from roads used in this sediment source analysis has a number of limitations, and is only considered an approximation based on the presently available information. Substantial refinement of these values could and should occur during implementation phases when detailed road inventories are developed. As noted previously, we had no way of quantifying the extent of abandoned roads, although we estimate that this is probably less than 10% of the existing total miles. This study lacked precise information on actual type of roads, actual use rates, and typical sediment loading and we were forced to rely on previously published factors. Although we did stratify the roads by location, we were not able to quantitatively determine the actual percentage of road segments by type and location that delivered to a stream channel, and simply relied on delivery factors.

We assumed that any road still visible probably still delivered some sediment, particularly because these older, “legacy” roads were built to far different standards than roads constructed in the last 10-20 years. That older roads often still produce considerable sediment is borne out by findings in the various studies (Toth 1991, Mills 1991, ODF 1999). Toth reported the results of a road damage inventory conducted in Washington that found that roads constructed in the last 15 years survived a landslide-inducing storm with minimal damage, while roads constructed earlier had very high damage rates. Road monitoring in Oregon has documented similar findings (Mills 1991). The recent ODF (1999) study found that although landslides associated with old roads were typically smaller than the landslides associated with actively used roads, they were still several times larger on average than landslides not associated with roads. Of the 506 slides mapped by ODF, 20 were associated with old roads and 37 were associated with active roads, while the erosion volume from old roads was 54,700 yd^3 vs. 65,000 yd^3 for the active roads. Overall, nineteen percent of the sediment volume delivered to stream channels came from landslides associated with old roads. Based on this information, exclusion of old or even abandoned roads from the analysis should not occur without extensive field verification.

Hillslope Erosion (Skid Roads)

There is considerable variation in estimates from the literature in the role of skid roads in sediment production and delivery to stream channels. Since skid roads are generally not linked as directly to stream channels as roads typically are, drainage practices (proper installation of water bars, etc.) are of primary importance in determining whether significant sediment production and delivery will occur. Properly drained skid roads will probably revegetate within 5-10 years (Cafferata/Stillwater Sciences, pers. comm. 1999), leading to relatively minor and short-lived sediment production. In contrast, roads produce sediment every year, even without large storm events. On the other hand, recent research (Ramos 1995, unpublished, cited by Cafferata/Stillwater Sciences, pers. comm. 1999) in Juan Creek, also located in Mendocino County, indicates that skid roads in intensively harvested areas may produce as much sediment as roads. As a result of these site-specific characteristics that control sediment generation, extensive direct field observations would be the only way to obtain reliable information on the role of skid roads.

Given the limitations of this study, evaluation of sediment production and delivery from skid trails has been undertaken using indirect methods. In this case, harvest areas were identified on the historic aerial photographs and given a high, medium, or low rating regarding the density of skid roads. The area of the different types was computed by GIS methods for each sub-watershed. Table 30 summarizes the harvest area by photo date, broken down by PW and SW. According to the mapping, 10% of the watershed was harvested in the 1921-1936 period, 8% in the 1937-1952 period, 14% in the 1953-1965 period, 21% in the 1966-1978 period, 17% in the 1979-1988 period, and 38% in the 1989-2000 period. The total harvest in the watershed for the 80-year period from 1921 to 2000 was 126,141 acres or 109% of the total watershed area, reflecting that a number of areas have been harvested several times. This does not count all harvesting that occurred prior to 1921, which was likely to be extensive. From Table 30, it is possible to track the harvest history of a particular SW, or the relative rates between SW. For example, only 13% of the Upper South Fork Big SW has been harvested (reflecting extensive brush/grassland in this SW), while 188% of the East Branch North Fork has been harvested since 1921.

Table 31 presents the area in acres of harvested areas containing skid roads of high, medium, or low densities based on the mapping from aerial photography using the 1936, 1952, 1965, 1978, 1988, and 2000 photo sets. Virtually all harvest areas seen in the 1936 photos, which only amounted to 12,043 acres or about 10% of the watershed, were considered to have a high density of skid roads, although tractor logging was only just becoming a common practice. Harvest rates have increased steadily since 1952 except for a slight decrease in the 1988 period. In the 1989-2000 period, harvest types obtained from the THP history were primarily partial cuts, with some clear-cutting, and only very small amounts of each tractor logged skid trail density. Some 43,786 acres were harvested in the 1989-2000 period as documented by THP records maintained by CDF. For the 1989-2000 budget period, harvest areas were not mapped, but rather computed from the GIS database based on annual THP's submitted to CDF. The annual values from the database were simply summed to obtain a single value for the 1989-2000 period. The areas are broken down by planning watershed and sub-watershed for use in calculating various parameters based on the area of harvest within each sub-watershed.

To compute surface erosion rates from the harvest acreage data requires selection of a yield or sediment delivery function for each class and selection of a time function to characterize the change in sediment delivery over time, as revegetation occurs and the site stabilizes. Without the benefit of fieldwork, we were limited to the application of use of previously developed yield and time functions developed by Mendocino Redwoods Company (MRC 1999) for their holdings in both the Albion and Noyo River Watersheds. Based on a review of the literature, MRC selected 50 tons/mi^2/yr as a mean rate for skid road sediment production for current management methods. They applied these rates over a 12-year period for each harvest area, with 2 years at the initial high rate, and 10 years thereafter at a reduced, or base rate (MRC 1999). To extrapolate their method to the various density classes that we mapped, we used 300 tons/mi^2/yr for high densities, 200 tons/mi^2/yr for medium densities, and 100 tons/mi^2/yr for low densities. These higher values were estimated to reflect earlier, pre-Forest Practice Rules operations. We used a 10-year period to simplify the calculations, since a 12-year period would have overlapped some of the period lengths, necessitating more complex calculations. The first two years were at the rates listed above, and then reduced to 25% of that rate for the remaining 8 years. For periods 1979-1988 and 1989-1999, rates for clear cutting were set at an average of 100 tons/mi^2/yr, while surface erosion rates for partial cuts were set at 50 tons/mi^2/yr to reflect the combination of improved management practices, the advent of cable skyline yarding, and greatly improved buffering practices. Based on review of preliminary revegetation data on skid roads observed in the JDSF (Cafferata/Stillwater Sciences, pers. comm. 1999), this time function may somewhat underestimate sediment production. They found an average value of only about 75% revegetation cover within 5 years after use ended. Unfortunately, we had no site-specific information on vegetation cover establishment in the Big watershed with which to adjust our calculations, and therefore no adjustments were made.

Table 32 shows the computed surface erosion from skid roads in harvest units for the various sediment budget periods, while these values are totaled and summarized in Table 33. The results suggest a peak in surface erosion coinciding with high harvest rates using high-density tractor logging methods in the 1953-1978 periods. In the most recent period, smaller volumes of surface erosion have been produced by more extensive harvest areas due to a substantial change in harvesting techniques. Overall, however, surface erosion rates from harvest are very small. The computed surface erosion amounts from harvesting in the 1989-2000 period are all in the range of 0-17 tons/mi^2/yr (ranging from no harvesting in Chamberlain Creek SW in the period to the extensive harvesting in the Laguna Creek SW). These numbers are small enough that they are essentially inconsequential in the overall sediment budget.

Fluvial Erosion

Numerous studies have indicated that fluvial erosion, whether from road diversions and washouts, road drainage-induced gullies, natural gullies, bank erosion or small streamside landslides, can be a major component of the watershed sediment sources. Unfortunately, quantification of these components requires considerable field investigation, typically as part of a comprehensive road inventory process, in order to develop reliable information. In this study, we have been limited to using values from previous work in other coastal watersheds with similar geology to develop estimates for bank erosion/small streamside mass wasting.

This approach involved use of unit area values of fluvial erosion rates developed for the Noyo River, which had been extrapolated from preliminary data from Mendocino Redwoods Company (C. Surfleet, pers. comm. 1999) of 0.023 tons/ft/yr for small streamside landsliding along stream channels mapped as Mass Wasting Map Unit 1 (MWMU1), and 0.002 tons/ft/yr for MWMU2, and bank erosion values from USDA (1972) to arrive at a value of 200 tons/mi^2/yr. In the Noyo sediment source analysis, these values were then multiplied by the drainage area and the period length in years to obtain an estimate of the period fluvial erosion total. In this study, however, we computed channel lengths from the GIS database sub-divided into Class 1, 2, and 3 stream types. Since our limited field observations suggested that most of the channels are incised and moderately stable, we averaged the two rates from MRC and rounded down, obtaining 0.01 tons/ft/yr, which was then applied to the Class 1 and 2 channel lengths (Table 34). It was assumed that small streamside failures and bank erosion on Class 3 channels was included in background creep rates.

Changes in Alluvial Storage

Due to the confined nature of most of the main stream channels in the Big River watershed, fluvial-induced change in alluvial storage in these areas is considered a relatively small term in the sediment budget for these portions of the watershed. While this may not be the case for the lower reaches of the mainstem, where somewhat more extensive alluvial deposits are present through the estuary, there were no data to support calculations of changes in alluvial storage. Little change in the position or vegetation characteristics of the lower mainstem were seen between 1936 and 2000, suggesting that such changes may be small. Non-alluvial channel boundaries in the steep valleys, combined with the entrenched channel geometry and bank stabilization by dense streamside forest cover, greatly reduce the opportunity for sediment storage. It appears that much of the sediment that reaches these entrenched channels is flushed through the system into low gradient areas of the lower river in relatively short periods of time.

Evaluation of a Relative Disturbance Index

One parameter of in-channel physical habitat data in the Big watershed that should be directly related to upslope sediment delivery is the percent of fine sediment (%<0.85mm) found in spawning gravel substrate in the various watershed areas. In 1999, MRC collected bulk substrate and permeability samples at 5 sites in their ownership, and in 2001 GMA collected additional bulk samples at 11 sites throughout the watershed. For two of the areas where both GMA and MRC collected bulk samples, the data are in close agreement (East Branch NF and Middle Big), while for two others the data disagree substantially (Daugherty Creek and Lower South Fork Big). We have no explanation for the disparity of these two samples, since the methods used were essentially identical. It may simply reflect inherent variability in substrate measurement at a site level (we did not sample the same tail-outs), implying that a large number of samples would be necessary to obtain much confidence in the statistical significance of the results. In an effort to see how the findings of our primarily office-based approach for this sediment source analysis correspond to measured instream values, we developed a relative disturbance index and compared that to recent instream data.

The relative disturbance index for current conditions was defined as the product of SW road density, the percent of SW area harvested in the 1989-1999 period, and the volume (tons) of landslides mapped in the 1989-1999 period. The simple product of these three variables equally weights all three metrics of potential or actual delivery (Table 35). The results ranged from 0.02 in the Chamberlain Creek SW, due to almost no harvest in the period, to 2,280 for the Martin Creek SW, which combined a high road density with a high percent of harvest, and a high unit area slide volume. Figure 36 shows the relationship between relative disturbance index and substrate quality for 10 of the sites, with Chamberlain Creek being excluded as an obvious outlier. There were no comparable substrate sampling sites for eight of the SW. Measured percentages of fine sediment < 0.85 mm ranged from 3.34-14.54%, all quite low values. Although there is a considerable amount of scatter in this relationship, it is also reasonably apparent that there is a general relationship between the index and the % fines < 0.85mm or 2.0mm. The portions of the watershed with greater relative disturbance values did have somewhat higher percentages of fines in the spawning gravels. It should be noted, however, that the values of percent fine sediment found throughout the watershed are all indicative of good spawning gravels. There is no indication that the presence of fine sediment in spawning gravels is currently a limiting factor to fish populations. The GMA samples were collected in April 2001, shortly (a few weeks) after the last significant storm of the year, and WY 2001 turned out to be a very dry year.

Relative Disturbance and WY2001 Sediment Transport

The computed relative disturbance index was also analyzed in relation to our computations of suspended sediment load for various sites throughout the watershed. As previously described, our field streamflow and sediment transport data allowed computation of total suspended sediment load for WY2001. WY2001 was a very dry year, and is clearly not representative of a typical year (if such exists) in the watershed. However, the data still allow comparison of the relative loads between different sub-watershed areas. It is readily apparent by inspection of Table 35 that no relationship exists between the computed relative disturbance index and unit area WY2001 suspended sediment load (tons/mi^2). There is, however, a rough relationship between substrate data and sediment transport, in that generally the higher percentages of fines are found in the South Fork Big PW, and this Planning Watershed had significantly higher sediment transport rates in WY2001.

SEDIMENT BUDGET

Overview

Typically, a sediment budget quantifies sediment sources (inputs), by each erosional process, as well as changes in the amount of channel-stored sediment, and sediment outputs as measured at a gaging station over a designated time frame or several time periods (Reid and Dunne, 1996). Quantifying sediment sources involves determining the volume of sediment delivered to stream channels by the variety of erosional processes operating within the watershed. For the Big River watershed, these can be divided into four primary processes or sediment delivery mechanisms: 1) mass movement (landslides), 2) fluvial erosion (gullies, road and skid trail crossing failures, and stream bank erosion), 3) surface erosion (rills and sheetwash) and 4) land management activities which directly place sediment in stream channels.

The first three processes can deliver sediment to stream channels both naturally and as a result of land use activities. Sediment production by mass movement processes occurs commonly during large, infrequent storm events, whereas fluvial and surface erosional processes can occur during small storms in virtually every water year or as a result of large storms. Direct sedimentation into stream channels by heavy equipment involved with road/railroad construction and timber harvest was probably commonplace in the Big River watershed prior to 1974. After passage of the California Forest Practices Act in 1973, the practice of yarding logs down stream channels, which resulted in direct sedimentation into stream channels, was prohibited. However, some areas may still be experiencing elevated sediment yields as a legacy of the former practices. The residence time of such introduced sediments is highly variable, but on the order of years to decades and perhaps longer.

Changes in the amount of sediment stored in stream channels is usually measured in the field by analyzing surveyed channel cross sections or by field surveys which estimate the amount of past channel filling and subsequent downcutting that has occurred. Analyzing changes in channel stored sediment can answer questions such as how much of what type of sediment is transported and where is it deposited, how does introduced sediment interact with sediment which was already in storage in the channel, and how does the transport affect overall stream morphology (Reid and Dunne, 1996).

Quantifying sediment outputs requires determining annual transport rates of bedload and suspended sediment past a given point in the watershed, which is typically measured at a gaging station. Few sites have sufficient data to establish a meaningful record, although use of regional values can provide reconnaissance-level information.

Reid and Dunne (1996) discuss the seven steps involved in the construction of a reconnaissance-level sediment budget. Such a budget uses rapid measurements and estimates of physical processes based on air photo analysis, field evidence and published information and should use the following process:

1. Careful definition of the problem,

2. Collection of background information and data,
3. Subdivision of the watershed an project area into uniform or representative sub-areas,
4. Analysis and interpretation of aerial photography,
5. Field inventory, analysis, and calibration,
6. Data analysis,
7. Checking and verification of results through regional comparisons

In this analysis, step 5 could not be undertaken due to time, budget, and access constraints, so data from other studies that incorporated field inventory and verification was used.

The development of a sediment budget for a large watershed area, such as the Big River watershed, can best be accomplished by stratifying the area into sub-watershed units of similar characteristics. A sediment budget would be developed for each sub-watershed and these values are combined to provide an estimate of the overall sediment budget for the watershed. In this reconnaissance-level sediment budget, the Big watershed is considered generally homogeneous in terms of soil, bedrock, vegetation, and topography, and is, as a result, treated as a whole. Land use remains the major variable.

In developing a sediment budget, the magnitude of each major hillslope and channel erosion process operating in the watershed should be evaluated through a combination of (1) field sampling and verification, (2) analysis of aerial photography, (3) GIS-based computer analysis, and (4) an analysis of existing data and literature, generally from regional sources. We accomplished steps 2-4 in developing this preliminary sediment budget for the Big River watershed. Budgetary and timing constraints (most of the work was completed during winter months when roads are often closed to minimize disturbance) precluded any additional field investigations, other than sediment transport data collection and substrate data collection.

Inputs

Background Rates of Sediment Yield

Selection or determination of background rates of sediment yield is both an important component of a sediment source analysis and, at the same time, a fairly speculative endeavor. Few data exist regarding such rates, and no generally accepted method is available to compute or estimate such values. Furthermore, no such information could be developed on background rates during our investigation of the Big River watershed, as the earliest aerial photography is from 1936 and significant human disturbance in the watershed well pre-dates these photographs. Thus, we are limited to using data from other watershed studies with generally similar lithologic, topographic, and climatic conditions and consideration of sediment yields based on our regional sediment transport relationships. Fortunately, there are both estimates of sediment yield from studies underway within portions of the watershed (Jackson Demonstration State Forest (JDSF) by CDF and Stillwater Sciences) and the sediment transport records and sediment yield data available from Caspar Creek.

Cafferata/Stillwater Sciences (pers. comm.. 1999) have estimated background rates in JDSF at 334 tons/mi^2/yr based on a combination of published data and their own analyses. They suspect that the single largest element in that calculation, 248 tons/mi^2/yr for shallow landsliding, may be high since it was computed from their estimated geologic rate of landscape lowering by subtraction of the other budget rates (surface erosion, soil creep, rockfall, and deep-seated landslide components) for which they found either published values or were able to estimate independently.

Sediment transport data from the Caspar Creek watershed in JDSF may be used to estimate background rates and represents the best dataset available for application to the Big River watershed. Sediment yield data are available for both the North Fork and South Forks of Caspar Creek from 1964-1998. The South Fork was logged in the 1970s using tractor yarding, while the North Fork was logged in the mid-1980s primarily using cable yarding methods. Various researchers have evaluated the available data and concluded that the 1986-1998 South Fork Caspar Creek data and the 1978-1989 North Fork Caspar Creek data are most representative of unmanaged sediment yields. The average sediment yield ranges from 212 cubic yards/mi^2/yr to 278 cubic yards/mi^2/tr for the North Fork and South Fork, respectively. Depending upon the bulk density factor selected to convert volume to mass (Stillwater used 1.13 tons/yd^3, MRC used 1.35 tons/yd^3, and GMA used 1.48 tons/yd^3), the range is from 239 to 411 tons/mi^2/yr. These methods produce generally similar results, with the most reasonable values covering the range of about 250 to 325 tons/mi^2/yr. Given this range, our best estimate of long-term unmanaged sediment yields for the Big River watershed is 315 tons/mi^2/yr. We opted for the higher side of the range for the Big River due to its steeper slopes, higher precipitation, and portions of the watershed with more erosive geology (mélange terrain).

It is particularly important to evaluate the hydrologic and geomorphic context of the period under consideration, as sediment yields are known to be highly variable depending on the magnitude of storms in a given year or period, land use changes, and other factors. For example, as cited by Cafferata/Stillwater Sciences (pers. comm. 1999), during the 1964-1975 period, the North Fork Caspar Creek had an average sediment yield of 722 tons/mi^2/yr, while in the 1976-1992 period, the yield was only 124 tons/mi^2/yr. This wide range reflects the large storms in water years 1965, 1966, and 1974, compared to a much drier later period that included a prolonged drought from 1987-1991. Thus, evaluation of current loading rates above background for a given period should include a method for determining a scaling factor that compensates for the hydrologic context of the selected period. For example, in our sediment source analysis, we studied various time periods, with the most recent being the 1989-2000 period. We developed ratios by study period between the long-term sediment transport rate and the average annual rate for each study period and then scaled the background components of the sediment budget by these ratios. For example, using the rate of 315 tons/mi^2/yr which has been selected as the long-term background rate, we then scale background for the 1989-2000 period by applying the ratio value, and the result is (0.89 * 315) or 280 tons/mi^2/yr. Although this current period had several significant storm years (1993, 1997, and 1998), it also contained many very dry years (1989-1992, and 1994 were exceedingly dry), so the mean ends up being less than the long-term rate. So, although MRC (1999a,b) found in their landslide mapping of the Noyo and Albion River watersheds that the storms in 1998 had triggered a number of new debris slides, overall, we would expect lower than average sediment yields in the period. This type of analysis was completed for the various sediment budget periods as shown in the table below.

Period	Ratio to long-term Yield	Period background rate using Ratio	Landslides	Creep	Fluvial erosion
		(tons/mi^2/yr)	(tons/mi^2/yr)	(tons/mi^2/yr)	(tons/mi^2/yr)
1953-1965	1.14	359.1	199.5	85.5	74.1
1966-1978	1.08	340.2	189.0	81.0	70.2
1979-1988	0.73	230.0	127.8	54.8	47.5
1989-1999	0.89	280.4	155.8	66.8	57.9

All three of the components used to define background sediment yields (landslides, creep, and fluvial erosion) were adjusted in a similar fashion by the ratio of each period's mean sediment transport rate compared to the long-term. This type of analysis, which integrates the hydrologic and geomorphic context of a given study period, should provide improved estimates of period sediment yields, and thereby, the degree to which management has altered the basin sediment yields.

Input Analysis Results

Inputs, by process, time period, and sub-watershed were compiled by combining information from several different sources. The source analysis section of this document describes the development of the various input sources. Table 36 summarizes the sediment budget inputs in tons and computes percentages by process, while Table 37 provides average annual unit rates (tons/mi^2/year) by process and by period for the entire watershed.

Total landsliding has ranged from 57-90% of the total inputs, with road inputs (combined landslides and surface erosion) ranging from 2.6-34%, harvest-related surface erosion (skid trails) ranging from 0.5-5.6%, and fluvial erosion from 3.9-12.0%. The general trend has been a decrease in landsliding inputs over time, and an increase in road-related surface erosion sediment delivery over time. Background landsliding is estimated to occur at 175 tons/mi^2/year, which has been adjusted since 1953 to reflect the hydrologic context of each period. Background landsliding is estimated to range from 10-32% of the total inputs. Background landsliding is assumed to mostly reflect small landslides not visible from aerial photographs, and as such, is in addition to management-related landsliding. The landslides found in our mapping were mostly judged to be management-related by the geologist, with the cause of landslides in brush/grassland areas unknown. Since virtually the entire Big River watershed has been disturbed by various levels of harvest-related activities for the last 100 years or more and many areas have been entered several times, it is not unreasonable to believe that most of the larger landslides are management-related. Although a significant percentage of the landslides were found in harvested areas judged to be older than 20 years, it is still likely that most of these are related to the harvest disturbance. For example, in undisturbed old growth areas mapped in the Ten Mile Watershed Sediment Source Analysis (GMA 2000), very, very few slides were seen, only about 2% of the total. While there were likely small slides not visible on the aerials under the canopy of the forest (background slides), the larger slides found appeared to be management-related. In addition, our field investigation of mass wasting in the old-growth areas of Montgomery Woods State Reserve suggest that background rates (in that geology) may be quite low. Management-related landslides are estimated to have ranged from 42-81% of the total inputs during the various study periods.

Surface erosion related to harvest activities has always been a small source, and in recent periods, despite a significant increase in acreage harvested, our analysis approach suggests a reduction in sediment delivery due to a change in technique. Since background creep and fluvial erosion rates are computed based on a simple tons/mi^2/yr value, their relative contribution by period is a function of the number of years in the period, although this has been adjusted by the hydrologic context of each period since 1953, as described in the previous section.

Under current conditions (1989-2000), roads (combined landslides and surface erosion) are estimated to provide 29.8% of the inputs, while fluvial erosion is 9.5% of the total, other landslides are responsible for 20.7%, and skid trails for about 1.2%. Combined management-related sediment sources (management-related landslides, skid trail and road surface erosion) are estimated for the current period at 51.7%, while non management-related comprises the remaining 48.3%. Due to greater levels of disturbance in earlier periods, the overall average for the 80-year period is 66.4% management-related and 33.6% non management-related.

Landslides are currently the dominant sediment source, estimated to be about 63% of the total. Lack of data on several potentially important contributing processes (gullying from stream diversions due to road and skid roads, for example) may result in an underestimation of road sediment delivery. Various other studies have arrived at generally somewhat lower percentages for management-related sediment generation, including the Noyo River at 35% (GMA1999), the Garcia River estimated at 40-60% management-related (PWA 1997), and the Ten Mile River at 56%.

CONCLUSIONS

This study has developed estimates of sediment production and delivery by process for the entire Big River watershed using primarily indirect techniques, involving aerial photo and GIS-based analyses. Streamflow and sediment transport data were collected during WY2001 to evaluate actual transport rates throughout the watershed, although this year has turned out to be a very dry year.

Sources were stratified by time period, land use type, and dominant process, in order to assess management and non-management related sediment sources and their relative contributions. Significant changes through time and by land use were found in the mass wasting category. Improvements in management practices since 1974 have resulted in decreases in road-related mass wasting and harvest-related surface erosion, although sediment delivery from these processes are still well above estimated background rates. Significant construction of new roads has led to increasing sediment yields from road surface erosion, despite improved practices. Under current conditions (1989-1999 period), management-related sediment delivery is estimated to be 51.7% of the total input.

REPORT LIMITATIONS

This report is a reconnaissance-level sediment source analysis. The constraints under which this work was completed have been well described. Graham Matthews & Associates provide their findings, conclusions, and recommendations after preparing such information in a manner consistent with that level of care and skill ordinarily exercised by members of the profession practicing under similar conditions in the fields of hydrology and fluvial geomorphology. John Coyle & Associates provide their mapping products, findings, conclusions, and recommendations after preparing such information in a manner consistent with that level of care and skill ordinarily exercised by members of the profession practicing under similar conditions in the field of geology.

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