ANALYSIS OF CHANNEL GEOMORPHOLOGY AND HABITAT FORMING PROCESSES FOR FEASABILITY ASSESSMENT OF RIP-RAP REMOVAL, MUIR WOODS NATIONAL MONUMENT MILL VALLEY, CALIFORNIA

Final Report

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And the
Golden Gate National Recreation Area

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EXECUTIVE SUMMARY

Purpose

The National Park Service (NPS) is considering a pilot project to remove some sections of riprap armoring the banks of Redwood Creek in Muir Woods National Monument to restore fluvial processes and ultimately improve salmonid habitat. The pilot approach aims to try riprap removal on a small scale to evaluate the benefits of removal, removal methods, and effects of removal to evaluate the potential for riprap removal on a larger scale. Riprap currently armors about 30% 0f the length of streambank on outside meander bends and some straight reaches in the reach through Muir Woods. The purpose of this research was to provide a basic understanding of the geomorphic and related ecological processes creating and maintaining habitats in Redwood Creek, to analyze the effects of the existing riprap on channel form and aquatic habitat, to document former channel conditions and historical changes, and to assess probable effects of riprap removal at pilot sites based on existing channel conditions.

Methods

To study the effects of the riprap on the creek's geomorphology and aquatic habitat, and to develop baseline data for future monitoring, we surveyed long profiles and cross sections at riprapped sites inside Muir Woods and in unriprapped upstream and downstream sections and sampled aquatic insects from riprapped and natural banks to determine family diversity and abundance in the two habitats. We also analyzed salmonid survey data for redd and fish abundance and distribution in Muir Woods and in the upstream and downstream sections.

Riprap Effects

Literature Review

Riprap restricts natural channel movements, reducing channel complexity and habitat diversity (Brookes, 1988), leading to: loss of riparian vegetation and in-stream cover, altered riffle-pool sequences and bed substrate composition, decreased sinuosity, increased velocity, increased bank erosion, higher suspended sediment concentrations, and higher stream temperatures (Crandall et al., 1984).

Effects on Redwood Creek

Pool-to-length ratios were higher in the unriprapped reaches (downstream: 1 pool per 92 ft of stream length, upstream: 1 pool per 130 ft) than in the reach through Muir Woods with riprap (1 pool per 169 ft of stream length). Analysis of habitat typing data provided by the NPS showed the non-riprapped reach immediately downstream of Muir Woods had pool coverage of 59% and riffle coverage of 28%. The Muir Woods reach had pool coverage of 39% and riffle coverage of 48%. Fish sampling data provided by the NPS showed higher spawning in the Muir Woods reach, which would be expected due to the higher riffle coverage. However, the main limiting factor on salmonid populations in Redwood Creek has been identified as poor juvenile summer and winter rearing habitat (Darren Fong, pers. comm. 2002). Juvenile salmonid biomass was higher in a non-riprapped reach with placed LWD than in a reach with riprap.

Aquatic insects are the major link in the aquatic food web between the primary producers and larger predators such as fish. We sampled aquatic insects in three strata (natural banks, riprap, and the bed) at five different sites within Muir Woods to determine what effects the riprap has on aquatic insect habitat and if any insect habitat would be lost by removing the riprap. Among all samples, we found a total of 38 insect families. The natural bank samples contained 32 of those families while the riprap samples only had 18 different families. Also, the natural bank samples had 18 families that did not appear in riprap samples. The riprap samples only had four families that were not in natural bank samples, one of which was found in greater abundance in bed samples and another was a margin dweller, rather than truly aquatic. Natural banks had both higher aquatic insect diversity and higher numbers of individuals. Replacement of riprap with natural banks is likely to improve aquatic insect diversity and abundance.

Project Alternatives

Of the four project alternatives analyzed, no action, LWD installation, riprap removal, and riprap removal plus addition of LWD, the latter best fits with the stated NPS goals because it would restore natural stream processes by allowing the channel to migrate and erode its banks, with initial additions of LWD providing some bank protection, diverting flow to induce meandering, providing cover for salmonids, and reducing velocities.

Conclusions

Because of the large rock size used for the riprap, and the relative lack of rock movement over the last 70 years, the channel is unlikely to restore itself by incorporating the rock into the bedload and moving it downstream. Removing the rock from the channel on a pilot basis would allow the channel to migrate and create complex habitat. Two pilot removal areas that best fit the NPS criteria for pilot removal were selected and characterized. Removal of the riprap combined with placement of LWD would meet the NPS goals for restoring natural processes and sustaining aquatic habitat and forest ecology. Merely placing LWD in the channel would likely lead to increased juvenile rearing habitat, however the life of the LWD would be limited and so not sustainable. Because LWD can act to reduce flow velocities, protect banks, direct flow, trap sediment, and provide habitat value, we recommend that any riprap removal be combined with LWD placement.

I. INTRODUCTION AND SCOPE

The watershed of Redwood Creek in Muir Woods National Monument is relatively undisturbed, especially given its proximity to a major metropolitan area. This is largely due to the early designation of the Muir Woods grove as a national monument. Ironically the channel of Redwood Creek through Muir Woods was subjected to a massive bank protection project in the 1930s installed by the Civilian Conservation Corps (CCC). At that time, bank erosion was viewed as detrimental, and the dynamic nature of channels was not well understood. Seventy years after the installation of riprap to stabilize the banks, the importance of dynamic channels for creating habitat complexity and healthy ecosystems is better understood. Coast wide declines in abundance and subsequent listing under the Endangered Species Act of coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Oncorhynchus mykiss*) prompted the National Park Service (NPS) to begin a system-wide effort to improve the conditions for these federally threatened species.

As an important element in the program to enhance habitat for juvenile coho and steelhead, the NPS has proposed to remove selected, pilot sections of the riprap to restore natural stream processes that can then sustainably create and maintain channel complexity and valuable salmonid habitat such as pool-riffle sequences and undercut banks. Sustainable is defined as "to keep up or keep going, as an action or process" (Flexner, 1988 p. 1324). In the case of Redwood Creek, we use the term sustainable to mean taking restoration actions that will result in habitat improvements that are self-perpetuating. This implies restoring the fluvial processes that create habitats in Redwood Creek.

Redwood Creek supports sustainable populations of two federally threatened species, coho salmon and steelhead trout. Although their numbers are greatly reduced from historical population levels, this population represents the southernmost yearly run of coho salmon on the west coast. Juvenile coho and steelhead are the dominant aquatic predators in these coastal streams and are good indicators of the health of aquatic ecosystems. However, lack of good juvenile rearing habitats such as deep pools with undercut banks are considered a main limiting factor to increasing salmonid populations in Redwood Creek (Darren Fong, pers. comm., 2001). Restoration of particular habitats has been the common approach in stream restoration projects. Current research promotes a process-based approach, focusing on restoring the ecological functions, which can then create the habitats in a self-maintaining cycle (Ward et al. 2001). Thus addressing limiting factors and restoring natural processes that create and maintain salmonid habitats is a priority for the NPS (Carolyn Shoulders, pers. comm., 2001). Because the

Redwood Creek watershed is protected for natural resource values and the natural processes are mostly unaltered, the creek is a good candidate for experimenting with riprap removal.

Large woody debris (LWD) had been cleared from the channel up until 1981 as routine maintenance to improve hydraulic efficiency (Mia Monroe, pers. comm. 2002). However, recent research has demonstrated the importance of LWD for salmonid habitat (Cederholm et al., 1997; Connolly and Hall, 1999; Crispin et al., 1993; Giannico, 2000; Roni, 2001). As bank erosion is an important mechanism for recruiting LWD to the channel, increased loading of LWD is expected as a benefit of riprap removal and increased channel migration.

The purpose of this study was to provide a basic understanding of the geomorphic and related ecological processes creating and maintaining habitats in Redwood Creek (notably the role of channel migration and LWD recruitment), to analyze the effects of the existing riprap on channel form and aquatic habitat, to document (to the extent possible) former channel conditions and historical changes, to assess probable effects of riprap removal at pilot sites based on existing channel conditions, to provide guidance for the appropriate extent of pilot riprap removal and subsequent bank treatment, and to recommend related management actions such as additions (size and location) of LWD. This study presents background data on geomorphic processes and their relation to habitat formation, site maps showing recommendations for approximate extent of riprap removal, and an adaptive management plan for monitoring and reacting to the actual channel responses to riprap removal, such as pool formation, channel movement, LWD recruitment and effects on park infrastructure.

We characterized two potential sites for pilot riprap removal projects based on their geomorphology, potential to improve salmonid habitat, potential constraints such as park infrastructure or heritage redwood trees, and their visibility to the visiting public. We then assessed the feasibility of riprap removal by analyzing channel geomorphology and habitat forming processes. This feasibility study combined with concurrent studies by the NPS that evaluate the cultural value of the CCC riprap and potential removal methods for the riprap provide a comprehensive basis on which the NPS can evaluate the potential for riprap removal.

II. SITE CONTEXT

Description of Site

Muir Woods National Monument is located about 13 mi (20 km) north of San Francisco, in Marin County, California (Figure 1). Known for its large stands of old-growth redwood trees (Sequoia sempervirens), the land was donated to the U.S. government by William Kent to protect the groves from development pressures. Muir Woods became a National Monument in 1908 and receives an average of about 1 million visitors each year. The Monument contains a coastal redwood forest with bays, alders, oaks, and maples. The upper watershed is drier with more oaks than redwoods. Vegetation on the valley floor along the margins of the creek in Muir Woods is limited due to shading and effects of heavy visitor use over the years; however revegetation programs by the NPS are in place.

Redwood Creek drains 3.65 mi^2 flowing from the slopes of Mt. Tamalpais to the Pacific Ocean. Entering from Mt. Tamalpais State Park, Redwood Creek flows for one mile through Muir Woods National Monument, with the Fern Creek confluence just downstream of the monument boundary. Channel width ranges from about 25-40 ft (8-12 m) and bed substrate consists mostly of cobble with some areas of gravels and sand and a few large boulders, mostly adjacent to riprapped banks, as some pieces of riprap have fallen into the channel.

The CCC worked in Muir Woods from 1933 to 1938, constructing a stream bank stabilization project. They installed 26 sections of riprap on the banks of the main channel and two sections on Fern Creek. No riprap was installed in Mt. Tamalpais State Park upstream.

Redwood Creek supports two federally threatened fish, coho salmon and steelhead trout. The NPS is working to restore habitat conditions for these fish, as well as other aquatic life.

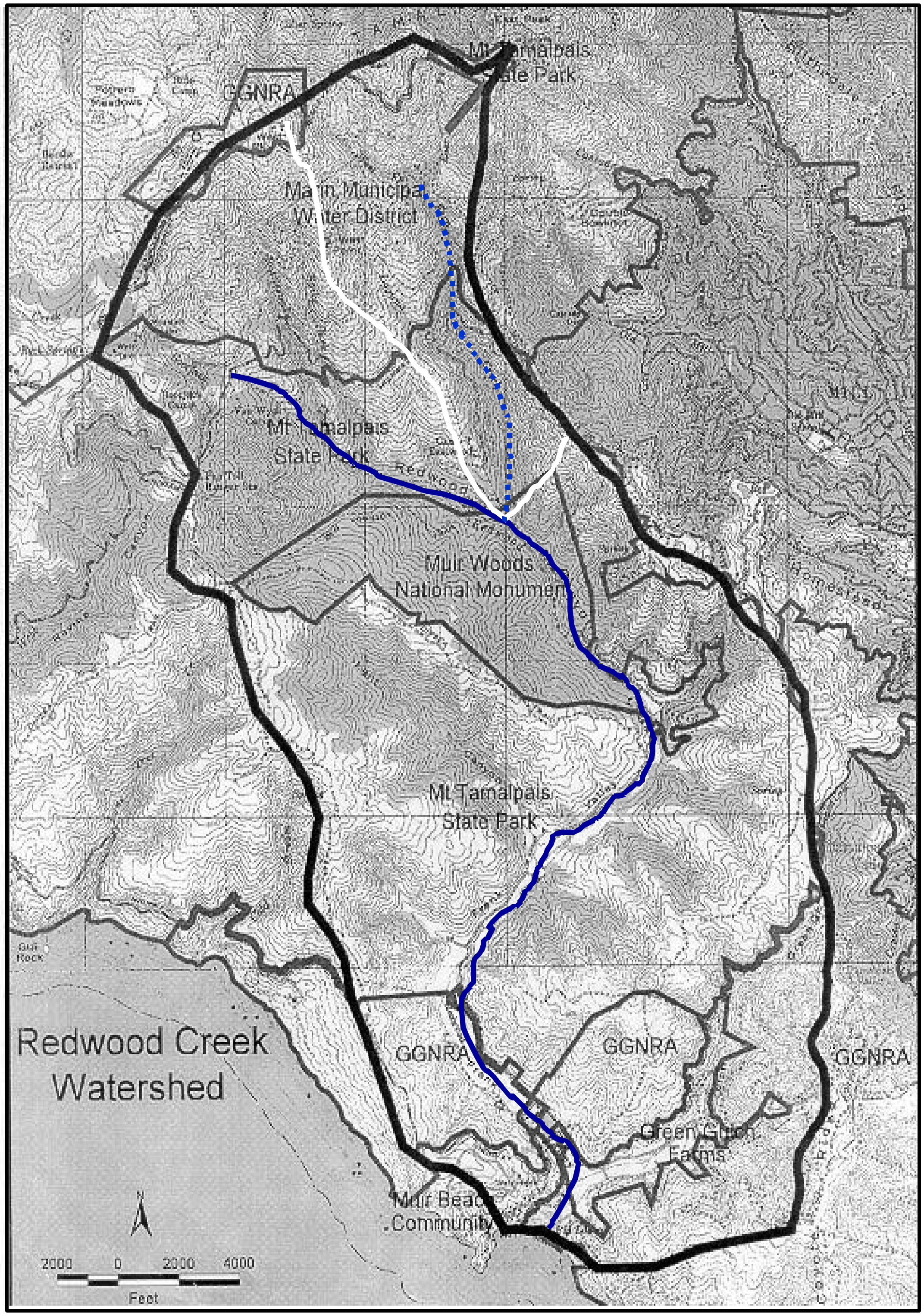

Figure 1. Redwood Creek watershed map showing the Muir Woods National Monument boundary, Redwood Creek watershed boundary (thick black line), and Redwood Creek (blue line) (Courtesy of the NPS). Note the Fern Creek watershed outlined in white, fern creek in dashed blue, and the confluence at the upstream Monument boundary.

NPS Objectives

Muir Woods National Monument Goals

Muir Woods National Monument was established with the mission “to protect the primeval character of the woods” (Carolyn Shoulders, pers. comm., 2001). The definition of “protection” continues to change, and with it, so do the management practices for Muir Woods. Long-term management goals for Muir Woods are to restore natural processes that achieve a healthy, dynamic ecosystem sustaining habitat and forest ecology (Carolyn Shoulders, pers. comm., 2002). Scientific research continues to reveal effects of various land management techniques on the natural ecologic processes of the woods.

Pilot Project Goals

Riprap removal in sections of Redwood Creek in Muir Woods National Monument has been identified by the NPS as a potential salmonid habitat restoration technique. The goal of such a project would be to remove riprap at selected sites on a pilot basis to restore the channel processes to a state where channel complexity and salmonid habitat (especially for juveniles) would be created in a self-maintaining system. Through a pilot project, the NPS hopes to test whether riprap can be successfully removed, natural creek processes can be restored, and some salmonid habitat characteristics can be regained without negative effects.

A successful project would reintroduce the dynamic nature of the channel and allow it to meander, undercut its banks, and recruit LWD to increase habitat value and overall creek ecosystem health and restore natural processes to the creek. The project also aims to improve overall forest health with the potential for floodplain reconnection, thereby recruiting nutrients to the forest floor and aiding redwood seedling establishment.

Research Objectives

The objectives of this research were to:

1. Document effects of riprap and channelization on channel form and aquatic habitats.
2. Assess current channel conditions and evaluate habitat quality in relation to inferred effects of channelization and riprap. These data were used as a basis for evaluating potential ecological effects of riprap removal and subsequent channel change.
3. Review archival data and field data on historical conditions to document the extent of the CCC riprap installation project and watershed and channel changes.
4. Apply basic fluvial geomorphic principles to assess potential geomorphic effects of removing riprap.
5. Develop conceptual plans for riprap removal pilot projects at two sites in Muir Woods. Site selection was based on the following criteria as set out by NPS[1]:
    - Historical channel course
    - Potential to improve juvenile salmonid habitat
    - Relative accessibility for removal of the rock
    - Lack of likely threats to park infrastructure such as bridges and trails
    - Cultural resource designations
    - Visibility for visitor education about stream dynamics and habitat
6. Develop conceptual plans for additional juvenile salmonid habitat improvements based on data analysis such as installation of LWD (size, placement).

[1] Site selection was made by NPS, based on input from this study.

7. Identify potential impacts of riprap removal on channel change and juvenile salmonid habitat and prescribe mitigation for any negative impacts.

Effects of Riprap Cited in Literature

Introduction

Riprap (large cobble or boulders) is installed for a variety of reasons, including flood control, erosion control, or stream bank stabilization. Riprap installation continues in many channels, although current scientific literature concludes that riprap has negative effects on stream channel processes and aquatic habitat (as discussed below). Knowledge of the effects of riprap on stream processes and habitat is important for those planning to install riprap as well as for those working with riprapped streams. Understanding riprap's effects can inform planning for mitigation of riprap, the use of alternative bank protection methods, or the removal of existing riprap. Our objective for the literature review was to review current scientific literature to determine the effects of riprap and bank stabilization activities on stream processes and aquatic habitat.

We reviewed current scientific journals and unpublished reports for literature on riprap effects on stream processes and fish habitat. We have also included literature discussing the effects of stream channelization, as riprap installation is a type of channelization and effects of riprap were often included in studies on channelization. We reviewed reports on riprap removal projects to learn the reasons for and the perceived benefits of riprap removal. NPS staff provided information about the potential riprap removal project in Muir Woods National Monument and an ongoing riprap removal project in Zion National Park.

Riprap Effects on Fish Biomass

Schmetterling et al. (2001) reviewed literature on the effects of riprap bank reinforcement on salmonid habitat and populations. Effects of riprap and resulting channel changes are summarized in Table 1.

Table 1. Effects of riprap on channel form and resultant changes in channel complexity and habitat, summarized from Schmetterling et al. (2001).	
Effect of Riprap	Response
Loss of Riparian Vegetation	Decreased aquatic habitat complexity, decreased LWD availability, less input of CPOM, less overhanging vegetation, less insect habitat, warmer water temperatures
Channel Confinement	Halted lateral migration, less LWD recruitment, less riparian plant regeneration, halted point bar evolution, reduced habitat complexity, less gravel retention, decreased channel dynamics
Fewer Undercut Banks and Pools	Less cover for fish, less refugia from high flows, less habitat during summer low flows
Increased Velocities	Increased scour on downstream banks opposite riprap
Unnatural Bedload Size	Fewer interstitial spaces, difficult for spawning, altered hydrology

Studies in their review aimed to quantify effects of riprap on fish populations. The review concluded that riprap had negative effects and its use on rivers and streams should be discontinued in favor of soft techniques. Riprap does not supply the variety of habitats required by different age classes of salmonids and it alters the natural erosion and sedimentation cycle in streams, therefore altering recruitment of suitable bed substrate composition and preventing the formation of salmonid habitat. Riprap also prevents the channel from being maintained in a dynamic steady state.

Knudsen and Dilly (1987) studied five sites on four streams in western Washington and compared effects on juvenile salmonids shortly after riprap installation. Total biomass of salmonids decreased in small stream (<$3m^3$/s) test sections after installing riprap, while biomass increased in control sections. Juvenile steelhead biomass decreased in test sections but increased in control sections. These results indicate a negative effect of riprap on salmonid biomass in small streams. The authors cite loss of pool habitat and streamside cover as the most significant factors affecting salmonid biomass. Graham (1975) found a 50% reduction in trout biomass on the Ruby River, Montana following installation of riprap bank stabilization. Areas of the river where the bed was also reshaped by bulldozers had further reductions in trout biomass.

Hortle and Lake (1983) studied the distribution and abundance of fish in channelized and unchannelized sections of the Bunyip River, Victoria. Number of fish species, total biomass of fish, and total numbers of fish were significantly higher in unchannelized sections than in channelized sections. One of the sampled channelized sections had a weir just downstream, which was believed to mitigate some effects of channelization by lowering velocities, providing some cover with a retaining wall and limited vegetation, and providing a range of depths. This site had significantly higher numbers of fish species than other channelized sites. Hortle and Lake (1983) found that effects of channelization were loss of fish habitat (woody debris, bank vegetation, pools) and a change in channel form from relatively shallow and wide with low velocities to narrow and deep with higher velocities.

Through examining salmonid habitat and biomass in 24 stream sections affected by channelization and livestock use and their respective controls in western Washington, Chapman and Knudsen (1980) found significant decreases in salmonid habitat: sinuosity decreased by 10%, wetted stream area decreased by 20%, and overhead cover decreased by

89%. Bank vegetation changed from woody vegetation dominated to grass dominated. However, the volume of pools and glide areas, the percentage of riffle areas and fine sediments remained constant. The authors attributed most of these reductions to channelization rather than the livestock impacts. In early summer sampling, biomasses of coho salmon and 0-age cutthroat and steelhead trout were not significantly reduced in channelized sections, however cutthroat trout mean and total biomasses were reduced by 52% and 41% respectively. Coho salmon biomass was reduced in the ten moderately to heavily affected sections. Two areas were resampled during winter to compare seasonal differences. Wetted stream area decreased 20% from the control reaches. Coho salmon total biomass decreased 81% and total biomass of all salmonids combined decreased 23%, suggesting greater impacts of channelization on winter habitat. Higher salmonid biomasses were found in some channelized sections in summer, and thought to be a result of higher light levels in these areas. In other channelized sections, lower biomasses were found as well as higher numbers of warmer water fishes such as three-spined sticklebacks (*Gasterosteus aculeatus*).

Riprap Effects on Meandering and Bank Scour

Meandering of a channel creates complex habitats such as pools, undercut banks, gravel point bars, and supplies LWD. Creation of these complex habitats is limited or eliminated when the channel is stabilized. When a channel meanders, pools form on the outside of the bends and point bars form on the inside (Kondolf, 1996). As the channel erodes the outside bank, it also creates an overhanging bank that coho salmon and other species use for cover. Many stream projects have used channelization and stabilization of stream banks to inhibit lateral or vertical channel migration. Stream bank armoring (i.e. installation of riprap, large rock used to stabilize or halt erosion of stream banks) restricts natural channel movements, thereby restricting ecological processes. Riprap installation can lead to the following adverse impacts: loss of riparian vegetation and in-stream cover, altered riffle-pool sequences and bed substrate composition, decreased sinuosity, increased velocity, increased bank erosion, higher suspended sediment concentrations, and higher stream temperatures (Crandall et al., 1984). Loss of channel complexity (pools and riffles) results from armoring channel beds or banks and leads to loss of habitat diversity (Brookes, 1988).

The Washington State Department of Fisheries (WSDF) reviewed literature on effects of bank armoring projects on habitat creation processes related to the Newaukum River basin. The authors cite natural geomorphic processes (bed and bank scour, deposition of sediments, and bed load sorting by grain size) as important for creating physical fish habitat. Channel characteristics formed by geomorphic processes include channel pattern, riffle-pool sequence, gravel bar characteristics, channel dimensions, channel slope, and floodplain characteristics (WSDF, 1984). WSDF noted that when geomorphic processes are limited by riprap, these channel characteristics also become limited.

Stream energy dissipation is affected by bank armoring. In natural channels, scouring and transporting of bank material help dissipate water velocity. If stream banks are hardened, scour cannot occur. Stream energy will then be channeled downstream, resulting in increased erosion of downstream banks (WSDF, 1984; Schmetterling et al., 2001). WSDF described increased flow velocities resulting from bank armoring because stream energy was not dissipated in scouring banks but instead was transferred downstream (WSDF, 1984).

Riprap Effects on LWD Recruitment

Recruitment of LWD has been cited as important for salmonid habitat creation, shaping pools and bars, providing cover, and acting as substrate for microorganisms and invertebrates (Cederholm et al., 1997; Connolly and Hall, 1999; Giannico, 2000; Roni, 2001). LWD can also create slack water areas (Cherry and Beschta, 1989), which provide valuable salmonid spawning and rearing habitats and refugia during high flows. Riprap precludes growth of bank vegetation, which provides cover for fish and acts to cool water (WSDF, 1984). WSDF cites bank armoring as reducing growing area for riparian vegetation, which can lead to reduced LWD recruitment.

LWD has been shown to enhance salmonid habitat and stream ecosystems (Connolly and Hall, 1999). Channel meandering recruits LWD to the channel as trees are undercut and fall into the channel. Potential for LWD recruitment and bank undercutting is reduced as the armored banks impede lateral channel migration (Schmetterling et al., 2001). The resulting channel straightening and shortening can lead to increased channel slope.

Channelization Effects Associated with Riprap

Channelization refers to alterations in a river channel including: widening and deepening, straightening, levee construction, bank stabilization, and vegetation clearing (Brookes, 1988). The effects of riprap on a channel are similar to those of channelization. However, not all effects of channelization can be attributed to riprap. For example, severe modifications such as cutting a trapezoidal channel or channel deepening are commonly seen in channelization activities but may not include riprap installation. Therefore we only included the channelization activities in reviewed literature relevant to riprap (bank stabilization, channel straightening through constricted meandering) in this review.

As summarized by Brookes (1988) channel straightening leads to increased channel slope, resulting in increased velocities, bed and bank erosion, increased sediment loads, increased flooding, downstream sedimentation, and decreased water quality. Loss of instream and bank vegetation during riprap construction leads to increased water temperatures, loss of cover, loss of food inputs, and decreased water quality. Lowering of the water table can also result from incision caused by channelization, harming floodplain vegetation and wildlife. Riprap and channelization effects ultimately lead to adverse biological consequences especially for fish, benthic invertebrates, and aquatic vegetation.

In Zion National Park, the North Fork of the Virgin River was deepened and confined to the western portion of the floodplain by a 4-mile (6.5 km) levee in the 1920s and 1930s to reduce flood risk to the Zion Lodge (Anon., 2001). The river has since eroded the upstream portion of the levee, but the portion nearest the lodge remains and is armored with rock gabion baskets. The NPS has found that channelization has altered the river's natural flooding and meandering processes, resulting in severely limited reproduction of the once dominant native riparian Fremont cottonwood (*Populus fremontii*). Riparian forest composition has changed and is now co-dominated by Box elder (*Acer negundo*) and Velvet ash (*Fraxinus velutina*) (Anon., 2001).

The NPS plans to remove the levee and bank protection, and possibly to reconstruct historical channel form (Anon., 2001). A new road, which is at a higher elevation than the levee and farther from the channel, currently provides flood protection, so levee removal would not result in flooding of the Lodge. By removing the channelized river section, the NPS hopes to restore the natural fluvial processes of flooding and channel migration, which will improve Fremont cottonwood seedling recruitment and maturation (Anon., 2001).

Conclusions From the Literature Pertinent to Redwood Creek

The majority of recent scientific research concludes riprap and channelization have negative effects on stream processes and habitats, especially in smaller streams such as Redwood Creek. Studies also concluded negative effects of riprap or bank stabilization on fish biomass, citing decreased fish populations resulting from lost habitat. Thus, the presence of riprap reduces habitat for fish. It is therefore likely that removal of riprap would improve aquatic habitat through restoring natural channel processes, and ultimately leading to healthier salmonid populations.

This literature review focused on smaller streams which could be related to Redwood Creek, however the findings of Knudsen and Dilly (1987) of slightly higher biomass of two salmonid species in riprapped sections of larger streams shows the importance of considering the scale of a stream when planning potential projects. Riprap in larger streams, such as the Sacramento River, requires regular maintenance to keep it from being completely washed out. Thus riprap removal is not necessarily as important for larger rivers because they have the stream power to restore themselves, if riprap is not maintained, by rearranging the rock in a more natural way or carrying it downstream.

Smaller streams typically do not have the stream power to erode riprap even in the long term as demonstrated by the riprap in Redwood Creek in Muir Woods, which has had little maintenance in 70 years yet remains mostly intact. Here, physical removal of the riprap would be necessary for restoration. Removing riprap to restore a stream is a method that is not presently documented in the literature. Future research could document the effects of removing riprap on stream processes and aquatic habitats. Studying current projects by the NPS in Muir Woods and Zion National Park will add to the current knowledge of restoration efforts. Detailed plans for monitoring should be implemented with these projects, allowing for collection of baseline data and post-removal monitoring.

III. METHODS

We used standard research and data collection methods for ease of replication. This study included the one-mile (1.6 km) reach of Redwood Creek and its banks through Muir Woods as well as non-riprapped reaches upstream and downstream in the adjacent Mt. Tamalpais State Park for reference.

Historical Analysis Methods

Knowledge of the historical conditions of a channel and its watershed is important to give context to channel change and current conditions and to guide potential restoration efforts (Kondolf and Larson, 1995). In the case of Redwood Creek, a historical study can also provide an understanding of the context in which the channel banks were seen as highly erodable and in need of stabilization. Specific questions addressed in this study to gain an understanding of natural (pre-alteration) watershed and channel conditions were: did land use changes lead to alterations in the watershed that required the installation of riprap, who requested the project and why did they see the need for the project, and to what extent were the banks and/or riverbed stabilized?

We obtained preliminary historical information about Muir Woods and the CCC work through conversations with NPS staff. We found further details and photographs of the CCC work in superintendents' reports held in the National Archives in Bethesda, MD and in the History Room of the Mill Valley Public Library, which were used to determine the purpose, extent, and methods of riprap construction. Books documenting the history of the CCC on Mount Tamalpais provided further information about the extent of their work in Muir Woods and about the overall background and feeling of the CCC. We found further relevant information in reports on the natural history of the land that is now Muir Woods and of people influential in protecting the land and establishing the monument such as William Kent.

We obtained historical land use information from reports provided by the NPS and from books and documents held in the History Room at the Mill Valley Public Library. We used this information to determine what, if any, watershed disturbance could have led to creek conditions that would require bank stabilization. We also used the information in estimating potential future conditions with and without riprap.

Geomorphic Analysis Methods

Basic Geomorphic Process Analysis

We studied geomorphic conditions to understand current stream processes and limits and to provide background data for long-term monitoring and future projects. We used this analysis to create a basis for determining if riprap removal is feasible at this site or if other measures need to be taken (e.g. adding LWD to induce pool formation or as bank stabilization or installing grade control structures to prevent channel downcutting).

We field-checked a GIS-based map generated by the NPS showing Redwood Creek, the trails, riprap sections, pools, riffles, and monument tags for accuracy. We adjusted features based on their relationship to the creek, pools, riffles, and riprap sections. We then updated the GIS file with new data layers and locations of data and sampling points, which are noted on the base map (Appendix 1).

Hydrologic Calculation Methods

We participated in a preliminary hydrologic study (Barth and Kimball, 2001) that calculated rainfall-runoff relationships using a variety of methods and used a HEC-RAS model to calculate stage-discharge relationships (water surface elevation at a given discharge) for the 2 and 100-year recurrence interval storms. We determined water surface elevations in the channel and when flows would overtop the banks. We measured watershed area from a USGS topographic map using a planimeter and a map wheel and channel length and slope from long profile data provided by the NPS. We surveyed six cross-sections for use in the study using a Topcon AT-G6 Auto Level mounted on a tripod and a 25 ft rod.

Long Profile Survey Method

The NPS surveyed a long profile of the Redwood Creek channel in Muir Woods in 2000, which we used with their permission. For reference use, we continued the long profile upstream into Tamalpais State Park, where the banks have not been stabilized. The long profile ended where the channel became so steep that it was no longer comparable to the reach through Muir Woods, at approximately station 0172+56 (Monument Tag 0172 + 56 meters). We compared the spacing, length, and depth of pools and riffles shown on the long profiles between the riprapped and non-riprapped reaches. For all surveys (by the NPS and myself), elevations were calculated based on the elevation of a PSOMAS benchmark in the Muir Woods parking lot of 138.87 ft (42.33 m) above sea level. We surveyed an additional fourteen cross-sections[2] across the creek bed and banks of the proposed riprap removal sites, three at each section of riprap: upstream, center, and downstream. We used these to characterize the channel and also serve as baseline data in future monitoring.

Pebble Count Method

We used the pebble count method (Kondolf, 1997; Wolman, 1954) to determine channel bed particle size. We conducted the pebble counts along the creek from the downstream Muir Woods boundary at approximately station 0153 upstream to the State Park boundary at station 0169. We conducted a pebble count on every third exposed gravel bar where feasible. In some cases, we skipped a bar so as not to disturb extensive vegetation growing on the bar and noted this in the data. We randomly sampled approximately one hundred particles per bar according to the methods described by Kondolf (1997) and Wolman (1954). We compiled pebble count data to obtain mean particle size and to determine differences in size varying with distance downstream.

Suspended Sediment Sampling Method

Suspended sediment samples from Redwood Creek were collected during storm flows to support a sediment budget for the watershed and to put estimated sediment influxes from riprap removal and post-removal bank erosion into perspective. We collected four suspended sediment samples during heavy rains on February 19, 2002 according to the method described in (Beschta, 1996). We lowered a DH48 (Depth-integrated Handheld) suspended sediment sampler from the upstream side of Bridge 2 (Figures 2 and 3) moving across the

[2] All cross sections are marked on the base map in relation to the Monument Tags. In the field, the cross sections are marked with a rebar stake and a metal tag noting number and compass reading of the cross section line on the creek side of the trail.

flow from the left bank to the right bank. We lowered and raised the sampler in even motions so it was in contact with the water for the same amount of time at each spot. We repeated this at intervals of about two feet moving across the creek. Samples will be analyzed by NPS and the data used in decision making about riprap removal.

Figures 2 and 3. Suspended sediment sampling. Lowering and raising a DH-48 sampler into the flow across the channel and a temporary gage on left bank.

Ecological Analysis Methods

Existing Ecological Conditions Analysis Methods

We analyzed current ecological conditions to determine what effects, if any, the riprap has had on habitat value. Our analysis also provided information that may indicate what actions would be most effective at improving salmonid habitat in the long-term. Field discussions with project managers, fish biologists, and geomorphologists helped us identify limitations on stream processes and salmonid habitat and areas likely to benefit most from riprap removal. These discussions also provided preliminary information on areas of the creek that have been heavily used by salmonids.

Salmonid Habitat Analysis Methods

Using NPS spawning survey data from 1998 and 1999, we compared habitats preferred and most used by the salmonids with their proximity to riprap. We compared the number of "definite" redds per unit length of stream in the riprapped versus non-riprapped reaches upstream and downstream of the Monument. We did not count redds classified as indefinite by NPS because of lack of confidence. Also from these data, we calculated the ratio of live adult salmonids sighted by NPS staff to length of stream for the three study areas.

We used NPS juvenile salmonid sampling data to analyze the distribution of juveniles in relation to riprap. Coho and steelhead biomass data from a reach in Muir Woods at the Upper Boardwalk site were compared with a reach without riprap at the downstream Monument boundary.

Aquatic Insects Sampling Methods

We collected samples of aquatic insects at five sites on Redwood Creek in Muir Woods by using a modified Hess sampler (Figure 4). The mouth of the sampler had a 0.5 ft^2 (0.046 m^2) opening area, which we placed over the substrate to achieve a known sampling area. We taped a nylon stocking around the hole in the side of the bucket to act as a sieve and catch the sample. For each site, we took samples from three strata: the surface of riprap in water, a natural bank in water, and the bed (Figure 5). We placed the sampler over three areas per sample and disturbed the substrate to put any insects into the water column and then into the collection net. For example, at one riprap site, we sampled three different 0.5 ft^2 (0.046 m^2) areas for one minute each, giving a total sampling time of three minutes and a total sampling area of 1.5 ft^2 (0.14 m^2) for one riprap site. This method allowed for a more representative sample to be collected from each site. We repeated the process for a natural bank and a bed area within 100 feet to achieve somewhat constant conditions.

Figure 4. Hess-like sampler used to sample aquatic insects in Redwood Creek. A plastic garbage can with a 0.5 ft opening and a nylon stocking to catch the sample.


Natural Bank Strata Example


Riprap Strata Example


Bed Strata Example

Figure 5. Examples of the three strata samples for aquatic insect abundance and diversity.

At the time of sampling in late fall, water depth was very low, especially along the natural banks. This made sampling difficult because the water was too low to carry the disturbed sample particles into the net. The net was therefore scooped through the water to pick up the disturbed sediments. We then emptied samples into jars and preserved them with 75% ethanol. In the lab, we sieved each sample with a 0.0319-inch (0.8 mm) sieve to reduce the fine sediment content. We then sorted samples under a microscope and identified the insects to family level using keys in Merritt and Cummins (1996).

We used a univariate approach, analyzing individual metrics, for analysis because the study was focused on family richness between two different strata: riprapped banks and natural banks. Also, because NPS will use results from this study, our use of the more widely accepted univariate approach will allow them to repeat the study for monitoring purposes. We compared family diversity and abundance of families and individuals found in riprap areas with those of natural bank areas to determine if the riprap provided unique habitat for any aquatic insect families. We calculated our sampling precision for each stratum to gauge accuracy of the samples in representing the aquatic insect population. We also used the precision to advise if more samples should be collected in the future to improve population representation.

IV. RESULTS: HISTORICAL AND GEOMORPHIC

Historical Study

The goal of the historical study was to identify the influences that led to riprap installation, and to gauge the extent to which those influences have been repaired. Results of historical research include a history of watershed land use and change, historical channel conditions, and the specifics of the CCC project: what was done, why was the riprap installed and how that may have affected stream geomorphology and ecology.

Historical Watershed Conditions

Land Use and Disturbance

Assessing the degree of watershed disturbance is important for understanding the context in which the channel banks were seen as unstable. Activities in a watershed greatly influence the rivers and streams that flow out of them. Reduction in watershed vegetation can lead to increased runoff, higher flows and therefore increased channel erosion, increased sedimentation, higher peak flows, and lower, more prolonged summer base flows (NRC, 1992).

With the arrival of the Spanish in the early 1800s came cattle and a more intense land use than practiced by the coast Miwok, who visited the Redwood Creek watershed but with little impact. Cattle of the Spanish settlers might have been grazed in the Redwood Creek watershed as they were free to roam the hillsides (Jebens, 2001), however the area in and above Muir Woods is steep and therefore relatively inaccessible so may not have been affected. In 1838, William Antonio Richardson received a Mexican Land Grant that included the Redwood Creek watershed and he continued to graze cattle until he sold the land to Samuel Reading Throckmorton in 1855. Throckmorton began dairy farming on the lower watershed lands and leased plots to immigrant farmers (Jebens, 2001).

After purchasing the land from Throckmorton, the Tamalpais Land and Water Company created more plots for ranching. However, the land in the Muir Woods area and above was not contained in any of the plots, rather in an area of 'Unsurveyed Lands' (Tamalpais Land and Water Company Map No. 3, 1892 from Jebens, 2001), presumably too steep for ranching. One of these leased dairy ranches reportedly grazed cattle as far up in the watershed as the Dipsea Trail (Spitz, 1997), which lies just downstream of the Muir Woods boundary. However, there is no record of grazing within the Muir Woods area or, more importantly, in the upper watershed. Therefore it is unlikely that the watershed of Redwood Creek in the Muir Woods area and above was affected by grazing.

The property that is now Muir Woods was purchased by William Kent from the North Coast Water Company in 1906. After threats of logging the last grove of old growth redwoods and filling the canyon as a reservoir Kent donated the land to the Federal government under the Antiquities Act, which served to preserve the land and the redwoods. Muir Woods officially became a national monument on January 6, 1908. The land in the upper watershed was acquired from the North Coast Water Company by the State as part of Tamalpais State Park, while the Marin Municipal Water District owns the uppermost portion (Jebens, 2001).

The upper watershed, Muir Woods and above, has been protected from wildfires by the California state park system. The last major fire in the upper Redwood Creek watershed burned in 1859. This event could have affected runoff and erosion rates in the watershed, however, the flood that prompted riprap installation was not until 1925, 66 years later. It is likely that the watershed would have recovered from the effects of the fire by that time. Recent fires in the watershed above Muir Woods have been small, either prescribed burns or extinguished quickly before burning out of control (Jebens, 2001). These recent fires were presumably not on a scale large enough to cause major watershed disturbance and occurred after bank erosion and creek incision in 1925. In fact, lack of recent fire is shown by a dangerous buildup of fuel in the watershed (McBride, 1978; Jebens, 2001).

Historical Channel Conditions and Change

Analysis of the historical geomorphic conditions showed changes in the channel and resulting effects on current channel conditions.

Historical Geomorphic and Hydrologic Conditions

On February 11, 1925, the heaviest rainstorm recorded to date fell in Marin County (Hildreth, 1966). Resulting high flows washed out two foot bridges in the Monument and one road bridge. Bank erosion was reportedly “severe” (Hildreth, 1966) and coupled with incision (Figure 6). William Kent began a campaign to have bank revetments constructed in Muir Woods to prevent further erosion from such high flows. In February of 1928 and continuing for six years, brush pile revetments were installed at the banks that had severe erosion (Hildreth, 1966). In 1930, further stream works included construction of gabion-style revetments (wire baskets filled with rock) at several sites and the placement of a log dam. After the flood of 1925, William Kent thought that the erosion had also acted to lower the water table and wanted to build check dams to raise it (Hildreth, 1966). Therefore Kent had a log dam built in an attempt to raise the elevation of the creek bed and the elevation of the water table. I found no record of the result of this project.

Figure 6. CCC workers in the Redwood Creek channel. Note the height of the bank in relation to the men and the roots exposed from scour (from NPS Archives).

Historical Ecologic Conditions

Human use and therefore impact on the land in Muir Woods has increased with increasing numbers of visitors. In the early years of the Monument, visitors had higher ecological impact, however in recent years, steps have been taken to minimize this impact. For example, in the late 1930s, approximately 16 footbridges crossed Redwood Creek in the monument (Hildreth, 1966). This meant that 32 trails led to the creek, causing compaction, soil erosion, and trampling of vegetation. By 1961 however, the NPS had significantly reduced the number of crossings to four.

Plants growing on the valley floor such as ferns and rhododendrons were dug up and taken to the home gardens of many visitors. These activities greatly added to the reduction of creek side vegetation in Muir Woods and could have led to increased bank erosion. Fewer roots were then available to hold the soil together and the vegetative buffer along the creek was reduced which could have allowed more runoff directly to the creek. Destabilization of the banks due to loss of riparian vegetation could have altered the channel's response to natural flows, resulting in the severe erosion during the 1925 flood. As it was the highest recorded rain thus far, people had no context in which to gauge the channel shaping resulting from such a high flow in this system. So again, the channel could have been reacting naturally, to natural processes and the bank stabilization works might not have served to protect Redwood Creek and Muir Woods from unnatural destruction, rather they might have stopped natural channel forming processes and storm recovery based on the perception that flooding, erosion, and channel movement are detrimental to stream ecosystems.

Automobiles were allowed inside Muir Woods in the early days, adding to soil compaction, erosion, and vegetation loss. A wagon road was improved in 1908-1909 to bring tourists from the Muir Woods Inn to the forest floor and cars were allowed to park in the forest (Hildreth, 1966). This human impact to the ecosystem likely caused much soil compaction and vegetation loss, which would have destabilized the stream banks. Autos were finally banned in 1923 and camping inside the monument in 1924 (Hildreth, 1966).

Original CCC Project

Overview of CCC Project

The CCC camped in and worked on Mt. Tamalpais from 1933-1942 performing two main projects: construction of the Mountain Theatre and work in Muir Woods (Fairley, 1983). The work in Muir Woods consisted of firebreaks, trail construction, riprap and check dam installation, and bridge construction. The firebreaks on Mt. Tamalpais and trails in Muir Woods would have reduced vegetative cover in the upper watershed and could have increased runoff from the hills and contributed more sediment to the creek.

According to reports by the project superintendent at the time, installation of bank revetments was a high priority for the CCC to protect the creek banks and bed, trails, and bridges from being washed away during high flows (Haynes, 1936).

The CCC project officially began on November 21, 1933 and on the 15th of December of that year, William Kent was recorded to have stated a preference for installation of brush revetments, however rock was used instead (Hildreth, 1966), as is evident today. The large rock was quarried from Kent's land (Figure 7) about ¾ mile from the monument at a cost of $ 0.10/y^3 (Hildreth, 1966).

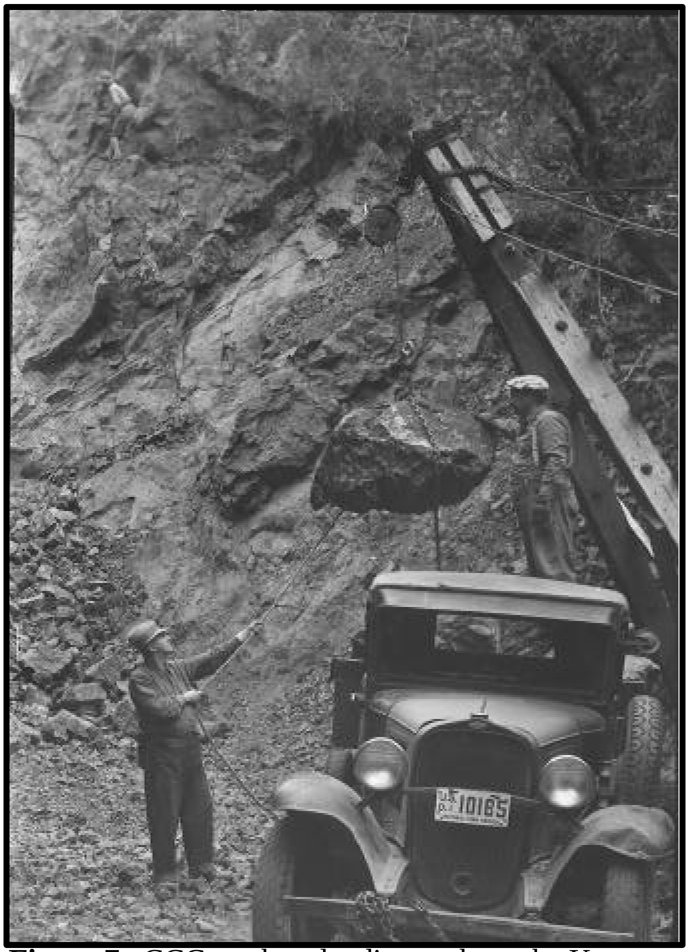

Figure 7. CCC workers loading rocks at the Kent quarry for riprap in Muir Woods ca. 1934 (from NPS Archives).

CCC Project Particulars

Following the initial attempts at stream bank revetments and the concern over what were seen as unstable banks, the CCC installed 26 sections of boulder riprap on the banks of Redwood Creek and 2 sections on Fern Creek (a tributary) from 1933-1938. Length of the riprap sections ranged from 13-540 ft (4-165 m) and rock size ranged from about 1-3 ft (0.3-1 m) in diameter (Figure 8).

The CCC consulted with landscape architects and NPS engineers about particulars of the riprap project and decided to blend the rock in with the banks and to protect only areas in danger of erosion during storms (Haynes, 1936b). Bank vegetation was removed in order to construct the riprap walls (Fairley, 1983) (Figure 9). The riprap itself consisted of large boulders placed so that flow hitting the walls would be directed away and into the channel (Fairley, 1983). Gabion-style revetments (wire mesh holding small cobbles) were also used (Haynes 1936a) but are no longer visible (the wire mesh typically disintegrates and the creek carries the rocks downstream).

Figure 8. CCC workers placing large boulders on Redwood Creek in Muir Woods ca. 1934 (from NPS Archives).

Figure 9. CCC workers installing rock riprap along the banks of Redwood Creek. Note the lack of bank vegetation and the truck on the bank, showing bank disturbance, also the machinery in the creek. ca. 1934 (from NPS Archives).

Trucks and heavy equipment were driven in the creek bed to excavate parts of the bed for the riprap and check dam installations (Figures 10,11) (Haynes, 1936), however it is not clear whether the bed was excavated and then filled in after rock placement, or if the material was moved elsewhere, leaving the bed wider or lower than previously, or even if the channel was straightened as part of the project[3] (Figure 12).

Three check dams were constructed with the goal of raising the bed level and halting vertical erosion (Fairley, 1983). These dams consisted of a redwood log anchored into the bank with large rock (Fairley, 1983) one is still visible today at station 0159+about 25 m)

Figure 10. Equipment working in streambed during CCC riprap construction ca. 1937, note the bed and bank disturbance (from NPS Archives).

[3] Specific details of the CCC riprap project such as construction diagrams or narratives have yet to be found, if they even exist. Superintendent's reports reviewed contained brief progress narratives of all projects in the area.

Figure 11. CCC workers with equipment in the streambed placing rock ca. 1936 (from NPS Archives).

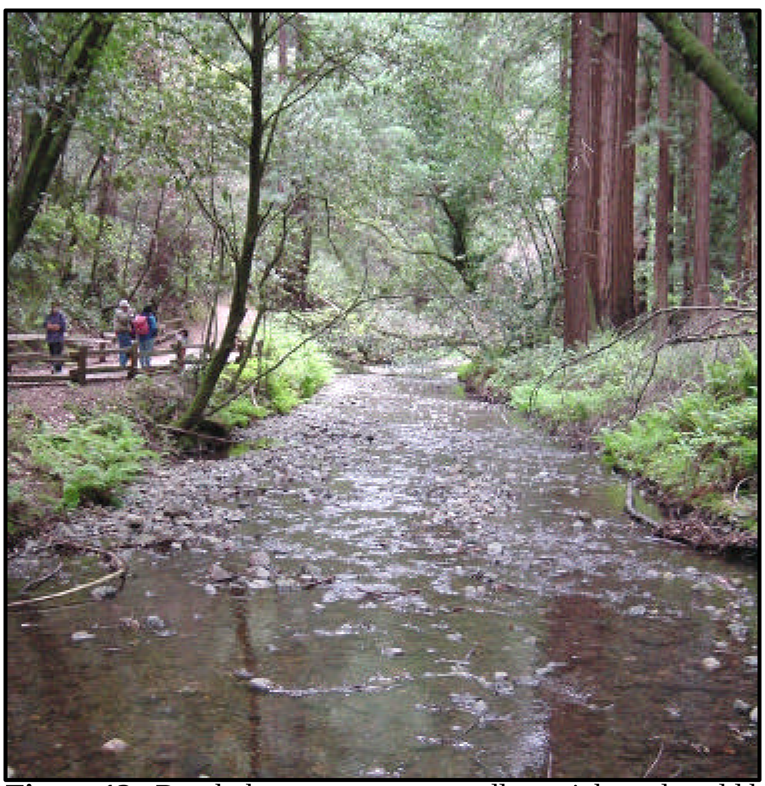

Figure 12. Reach that appears unnaturally straight and could have been straightened during CCC construction.

A recent NPS document examined the stream bank revetment types in Muir Woods and contained sketches of revetment types used. A cross section diagram of the type of revetment constructed by the CCC (Figure 13) shows rock protecting the bank from just below the top of the bank to the toe and extending about ¼ of the way across the bed. Figure 14 shows such bank toe armor. A group from the NPS recently probed the bed adjacent to some of the riprap sections and found no sign of bed armoring as shown in the diagram (Carolyn Shoulders, pers. comm. 2001). However, some riprap sections appear to extend below the bed such as section R-11 and bed aggradation may have covered the rocks at bank toes.

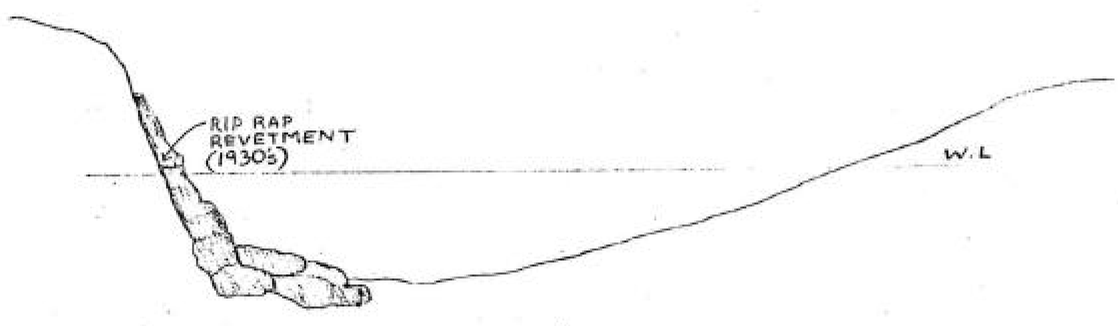

Figure 13. Cross section diagram of CCC rock revetment construction showing the bank protected along the toe and into the channel bed (From Howell and Milestone, 1981).

Figure 14. Rock riprap armoring the stream bank and extending into the channel as depicted in Figure 13 (from NPS Archives).

Existing Channel Conditions

Geomorphic Conditions

Riprap now armors the outside banks at 19 out of 29 bends, and along seven straight reaches, resulting in a flatter channel cross section than would be expected because flow circulation cannot create scour pools and undercut banks on the outside of the meander bends as it can where banks are not armored (Figure 15). Cross-sections of areas with riprap (Appendix 2) show flatter streambeds or, as in section L-11, a narrow channel adjacent to the riprap with a high gravel bar opposite the riprap. Without the ability to erode the outside bend and move in that direction, the channel also cannot create a point bar that grows and evolves as the channel moves.

Figure 15. Undercut bank with pool on a non-riprapped meander bend in Muir Woods. Tree roots and ferns and a bedrock outcrop stabilize the bank.

Pebble count data (Appendix 3) shows the range of particle sizes for exposed grave beds on Redwood Creek within the monument boundary. Overall, average particle size decreases downstream, with a few anomalies. Bar 7 was among the bars with larger average particle size, although it is at the downstream end of the study reach. It lies just downstream from Bridge 1, which is reinforced with riprap along the banks. Some of this riprap falling into the channel could account for the larger average particle size here. Bar 41, the uppermost bar sampled, is among the bars with smaller average particle size, contrary to the trend expected overall. Bar 41 is opposite Riprap R-11, but we attributed the small particle size to low velocities from the sharp bend and a possible backwater effect from the next downstream bend which is also sharp relative to other bends in the creek and the channel is constricted. Larger particle size resulting from riprap pieces falling into the bed (such as at Bar 7) can alter bed mobility and spawning ability.

The upper reaches of Redwood Creek are not freely meandering, that is the channel does not create large meander bends and then abandon them as it switches to a new course as seen in lowland rivers. However, some reaches in Muir Woods appear to be unnaturally straight. Based on the historical information, it is unclear whether the channel may have been straightened with bulldozers during the riprap installation project. Further research such as bank coring to look for fill, or location of more specific historical park documents could answer this question.

Hydrologic Conditions

Barth and Kimball (2001) used a variety of methods to estimate the 2 and 100-year recurrence interval peak flows and modeled the associated velocities and water surface elevations using a range of standard methods and compared the results.

Based on the cachment size of 3.65 mi^2 (delineated from a USGS 7.5-minute topographic map), Barth and Kimball (2001) estimated 2-year peak flow ranges from 180 to 260 cfs. We found a greater range of estimates for the 100-year peak flow, from 880-1500 cfs. Using an average of the calculated 2-year flows and a Manning's n estimate of 0.033 (PWA, 1994), modeled channel velocities ranged from 6.3-7.6 fps. This shows that flow estimates can vary widely depending on the method used and depending on the Manning's n estimate. However, the gaging transfer method should be more accurate because it uses data from this system, rather than the other methods, which average data from the region including drier areas. Gaging transferal results were: Q2=560 cfs with 7.6 fps velocity and Q100=2610 cfs.

Estimates showed that the Q2 velocities in Muir Woods are higher than suggested by FEMA (5 fps) for a channel with similar characteristics to avoid flood damage. However, since there is little infrastructure in danger of being eroded and some bank erosion is the goal of the project to achieve undercut banks and improve salmonid habitat, higher velocities than acceptable by FEMA may be desirable. Also, textbook estimates are not accurate since they are averages of velocity ranges.

Ecologic Conditions

The vegetation in the narrow valley of Muir Woods has suffered trampling by automobiles, hikers, and picnickers, and plant removal by visitors for their home gardens. As a result, the banks of Redwood Creek and the floodplain terrace have much less vegetation than historically existed. Lack of bank and floodplain and terrace vegetation leads to instability of the banks and increased erosion. Also, runoff from the hill slopes and terrace is not filtered by vegetation before entering the creek, which could lower water quality in this case by increased sedimentation.

LWD was routinely removed from Redwood Creek in Muir Woods until 1981 (Mia Monroe, pers. comm. 2002). LWD removal can result in channel instability through channel incision (Bilby, 1984), widening (Maser et al., 1988), increased sediment transport, and shifting of thalwegs and gravel bars (Smith et al., 1993). Such instability can decrease pool frequency and area (Bilby, 1984), and channel complexity (Swanson et al., 1984) and increase riffle area (from Hilderbrand et al. 1997).

Summary

The stream bank stabilization works constructed by the CCC were not new to Redwood Creek, rather a continuation of efforts to control bank erosion and associated channel movement in order to protect the Redwood forest and park infrastructure. Whereas brush revetments had been used before, the CCC used large rock to armor both the channel banks and the bed. The stated reason for installing the riprap in the 1930s was for erosion control, which had been a concern since the 1925 flood. However, the 1925 storm was the largest on record to date, so such high flows in Redwood Creek and the response of the channel were unlikely to have been seen previously. So the view of the erosion as "catastrophic" could have resulted in part from a lack of context of the extent of the storm and how the channel would respond. Installing the riprap after such bank erosion and incision acted to halt the natural channel recovery process that may have happened over time. If the riprap were not installed and LWD not removed from the channel, it is likely that the channel would have aggraded from sediment trapped by LWD, and formed point bars and more gently sloping banks. Now, after LWD has been left in the channel for 20 years, as much as 3 feet of aggradation has occurred in some places (Mia Monroe, pers. comm., 2002).

Flows entering the reach of Redwood Creek through Muir woods were unlikely to have been severely altered by human activity. The last major fire had been almost 70 years earlier, and grazing and logging had probably not affected the upper watershed. Thus, the vegetation in the upper watershed was probably intact except where firebreaks and trails were cleared. Runoff from inside Muir Woods itself may have been affected by the lack of vegetation and soil compaction resulting from human activities within the monument. Lack of bank vegetation could have led to slightly increased runoff and localized bank instability.

Because historical land uses do not appear to have significantly affected the upper Redwood Creek watershed, the natural flow regimes of Redwood Creek are likely mostly intact. Revegetation programs are in place to restore the bank and forest vegetation in Muir Woods National Monument and LWD is allowed to accumulate in the channel. However, the persistence of the riprap limits the channel's ability to create and maintain aquatic habitat. The presence of riprap and the removal of LWD are likely the main factors that led to reduced channel complexity and juvenile rearing habitat. Removal of sections of riprap could provide added channel complexity and increase habitat value through allowing the natural creek processes to restore channel dynamics. However, monitoring and adaptive management would be necessary to mitigate for any adverse impacts of riprap removal such as excess erosion or channel incision. The geomorphic processes that create undercut banks still exist in Redwood Creek, as can be seen where riprap is failing at some riprap sections (Figure 16). Therefore removal of riprap can be expected to result in creation of these important salmonid habitat features.

Figure 16. Downstream end of riprap section R9. Note the rock slumping into the channel and the bank scour on the left.

V. RESULTS: RIPRAP EFFECTS ON CHANNEL FORM AND HABITAT

Rock riprap covers 3360 of the total 11090 feet of streambank on Redwood Creek, about 30% of the length of streambank (60% of the channel length). However, the extent of riprap effects is greater than the linear percentage of riprap cover. The riprap was installed at points of erosion, mostly the outsides of meander bends. So the reduction in bank erosion and system dynamics was greater than implied by the percentage of bank riprapped.

Furthermore, the riprap affects channel geometry both upstream and downstream. For example, without bank erosion on outside meander bends, the inside point bars do not migrate and evolve to floodplain areas (Figure 17). The result of these extended effects is that it is difficult to conclude from the data available what effects the riprap is having on the nearby reaches.

The most effective gauge (a pure test case) would be to study differences between Redwood Creek and a reference stream with the same characteristics as Redwood Creek, but without riprap or anthropogenic effects. Studying the distribution, diversity, and abundance of aquatic insects in Redwood Creek may provide useful insights because aquatic insects are not very mobile and will tend to stay in reaches of suitable habitat. Fish are more mobile and will move between small areas of good and bad habitat. Therefore the distribution of aquatic insects within the monument could indicate local effects of riprap, while using fish data would require comparing the entire monument reach with another, non-riprapped reach.

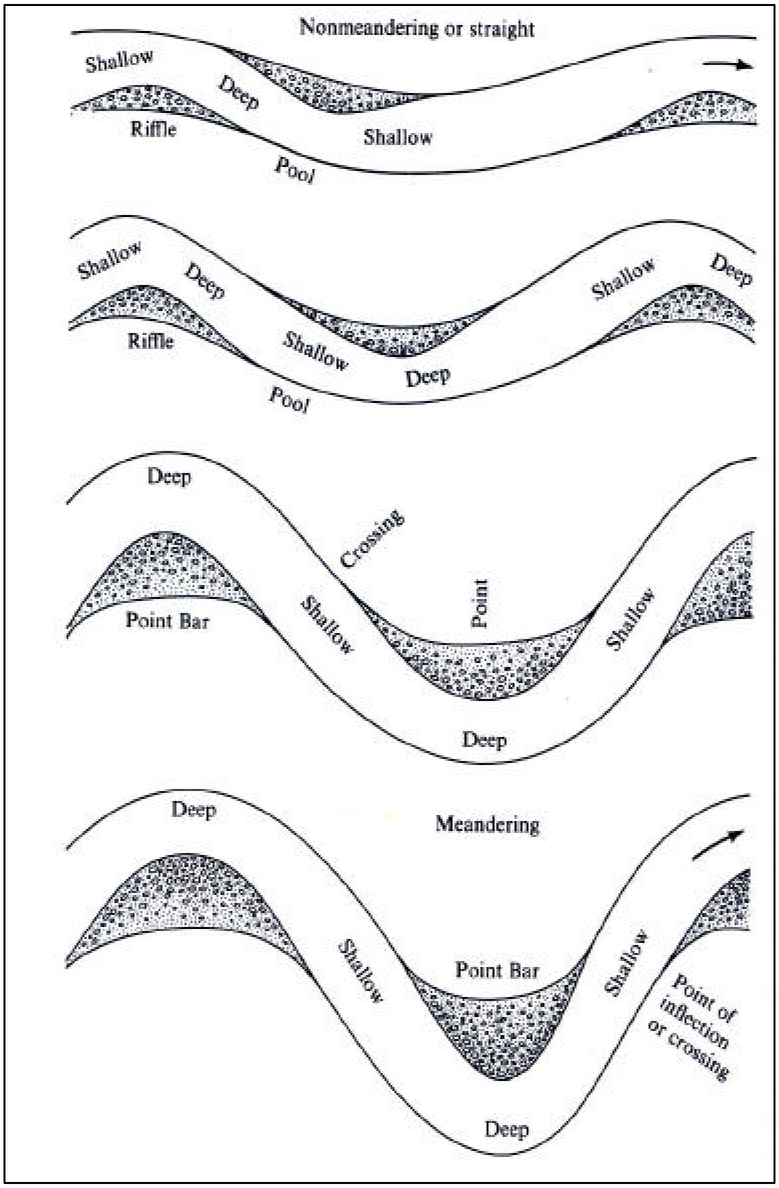

Figure 17. Diagram illustrating channel meandering and point bar evolution (from Dunne and Leopold, 1978)

Effects on Channel Form

Long Profile Analysis

Long profiles of creek reaches in both riprapped (in Muir Woods) and non-riprapped (in the state park) areas are shown in Appendix 4. Both upstream and downstream of the monument, surveyed reaches had higher pool frequencies than did the reach inside Muir Woods, which has been confined with riprap. In the surveyed non-riprapped reach, downstream from the monument boundary to the concrete bridge, pool to stream length ratios were one pool per 92 ft (28 m) of stream channel. In the other surveyed non-riprapped reach, from the upstream monument boundary into the State Park, average pool frequency was one pool per 130 ft (40 m). In the riprapped reach, inside Muir Woods, average pool frequency was one pool per 169 ft (51 m). Cross sections (Appendix 2) show a flat channel bottom. Pools would be expected at meander bends such as at L11, but the presence of riprap appears to have altered the channel profile.

Habitat Typing Analysis

Table 2 shows composition of habitat types in Redwood Creek taken from July 1998 data supplied by NPS. An abrupt change in composition is seen between Muir Woods and the reach downstream. The downstream reach without riprap is dominated by pools[4], with percentage of pool cover 59% and riffle coverage 28%. In the riprapped Muir Woods reach, pool coverage changes to 39% while riffle coverage grows to 48%.

Table 2. Breakdown of habitat types in the three study areas of Redwood Creek: the Muir Woods riprapped reach, the unriprapped downstream reach, and the unriprapped upstream reach. Data is from habitat typing surveys by NPS.

Muir Woods Riprap Reach Slope=1.2%					Downstream Reach Slope=1.1%			
Tags	Habitat Type	Length (m)	% of Total		Tags	Habitat Type	Length	% of Total
51-68	Backwater	15.5	0.8		35-50	Backwater	54.1	3.3
51-68	Flatwater	202.4	11		35-50	Flatwater	150.6	9.3
51-68	Pool	723.9	39.2		35-50	Pool	951.4	58.6
51-68	Riffle	878.5	47.6		35-50	Riffle	455.5	28.1
51-68	Other	26.6	1.4		35-50	Other	11.3	0.7
51-68	Total	1846.9	100		35-50	Total	1622.9	100
Upstream Reach Slope=1.5%[1]								
Tags	Habitat Type	Length	% of Total					
69-74	Backwater	4.5	0.8					
69-74	Flatwater	31.2	5.6					
69-74	Pool	225.2	40.5					
69-74	Riffle	275.9	49.6					
69-74	Other	19.2	3.5					
69-74	Total	556	100					

Separating the Muir Woods reach into sections (Table 3) shows that the percentage length of riffles increases moving upstream. However the percentage length of pools is about the same for the two lower sections in Muir Woods (41-42%) and the upstream reach outside of Muir Woods (40%). But the upstream section in Muir Woods has a much lower percentage length of pools (33%). The upstream section of Muir Woods also has a higher percentage of riffles (57%) than the upstream reach outside of Muir Woods (49%).

So while the Muir Woods reach would be expected to have a higher percentage cover of riffles than the downstream reach because it is progressively steeper, it would also be expected to have a lower percentage cover of riffle than the upstream reach, which it does not. The Muir Woods reach would be expected to be more similar in character to the downstream reach because the two reaches have similar slopes and drainage areas, while the upstream reach has a slightly higher slope and a much smaller drainage basin (Figure 1). The

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[4] Pools were classified as having a greater maximum depth than dept at the tail of the pool. Flatwater areas had maximum depths equal to tail depths (Darren Fong, pers. comm. 2002).

presence of riprap coincides with an increase in riffle area and a reduction in pool area in the Muir Woods reach. Reduction in pool area has led to a reduction in fish biomass (Hortle and Lake, 1983; Schmetterling et al., 2001).

Table 3. Muir Woods reach divided into sections showing percentage length of habitat types. Data is from habitat typing surveys by NPS.			
Lower Section Slope=1.37%			
Tags	Habitat Type	Length (m)	% of Total
52-56	Backwater	15.5	2.25
52-56	Flatwater	82.6	12.02
52-56	Pool	285.6	41.57
52-56	Riffle	276.7	40.27
52-56	Other	26.6	3.87
52-56	Total	687	100
Middle Section Slope=1.0%			
Tags	Habitat Type	Length (m)	% of Total
57-62	Backwater	0	0
57-62	Flatwater	60.3	10.88
57-62	Pool	237.7	42.89
57-62	Other	0	0
57-62	Riffle	256.1	46.21
57-62	Total	554.1	100
Upper Section Slope=1.37%			
Tags	Habitat Type	Length (m)	% of Total
63-68	Backwater	0	0
63-68	Flatwater	59.5	9.82
63-68	Pool	200.6	33.11
63-68	Riffle	345.7	57.06
63-68	Other	0	0
63-68	Total	605.8	100

Effects on Salmonid Habitat

Effects of the riprap in Redwood Creek on salmonid habitat were analyzed to assess potential benefits of various project alternatives. Data on live fish sightings and salmonid spawning sites were used to determine the distribution of fish and spawning activity with respect to riprap and therefore the effect of riprap on salmonid habitat.

The main limiting factor to salmonid abundance identified by the NPS is juvenile rearing habitat (Darren Fong, pers. comm. 2002). In Redwood Creek, spawning habitat is sufficient, however the existing habitat conditions do not support the number of fry being produced (Darren Fong, pers. comm. 2002). Smolt survival has a greater effect on population numbers than spawning rate. If a stream has reached its maximum carrying capacity for juveniles, increased spawning will not increase the number of juveniles (Quinn and Peterson, 1996). In such a case, as in Redwood Creek, to improve salmonid populations, the stream's juvenile carrying capacity must be increased. Improving the survival rate of smolts can be achieved through improving winter habitat (refugia, low velocity areas such as in LWD and gravel bars) and feeding areas (flooded point bars, secondary channels, and backwater areas), and summer rearing habitat (pools).

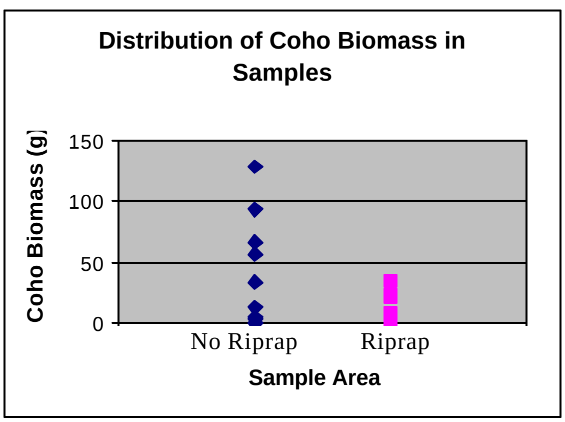
Juvenile Salmonid Distribution

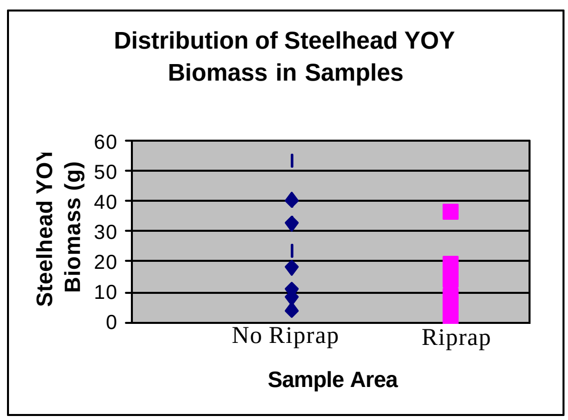
Juvenile salmonid sampling data from 2001 indicates reduced juvenile habitat in the Muir Woods reach with riprap. Data from combined samples in riprapped and non-riprapped reaches are outlined in Table 4. Biomasses of all salmonid groups are higher in the non-riprapped reach than in the reach with riprap.

Table 4. Biomasses of juvenile coho, and steelhead YOY, 1+ and 2+ in a riprapped and a non-riprapped area.

Site	Coho Biomass (g)	Steelhead YOY Biomass (g)	Steelhead 1+ Biomass (g)	Steelhead 2+ Biomass (g)
Non Riprap	400	264	632	82
Riprap	98	157	116	0

Figure 18 shows the distributions of juvenile salmonid biomass in samples from a riprapped reach in Muir Woods and from a reach without riprap at the downstream Muir Woods Boundary where LWD had been placed to induce pool scour.





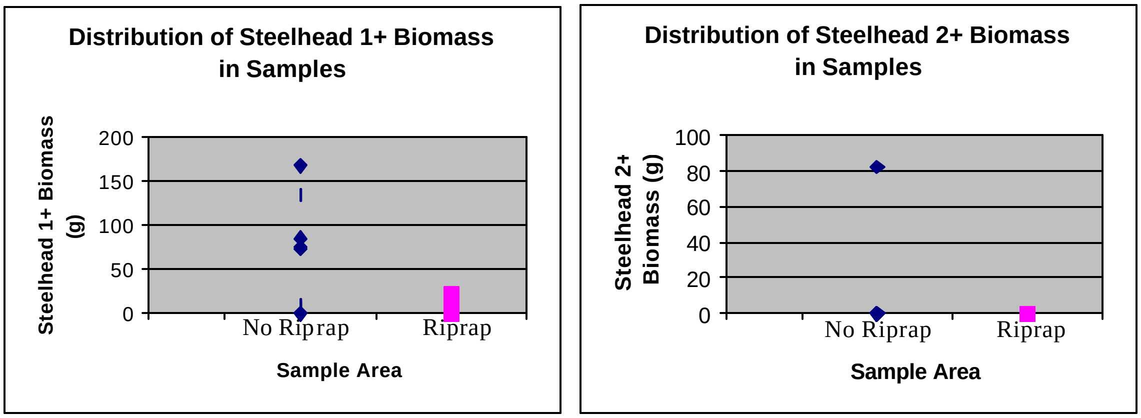


Figure 18. Distributions of salmonid biomass (coho and steelhead) in a non-riprapped reach and a riprapped reach on Redwood Creek in Muir Woods.

Results indicate that the downstream reach without riprap and where LWD was placed has higher quality rearing habitat based on higher juvenile salmonid biomasses found in this area than the reach with riprap. This reach is located just at the downstream end of the riprap in Muir Woods, and may or may not have residual effects from the riprap upstream. The presence of LWD and the associated pool could greatly influence the salmonid biomass in this reach.

Redd Distribution

Table 5 shows the numbers of definite redds (those with positive identification) sighted by NPS staff in surveys from 1997-2001 and ratios of redds per length of creek for the reach through Muir Woods and the upstream and downstream reaches.

Table 5. Number of Redds and Redd-to-Creek Length Ratios for the three study areas of Redwood Creek.

Creek Section (station m)	# of Definite Redds	Ratio: Redds/Length of Creek	Slope
Downstream (46+5 – 51+10)	16	1:37.8 m	1.1%
In Muir Woods (52+10 – 68)	74	1:22.8 m	1.2%
Upstream (69 – 74+10)	8	1:63.8 m	1.5%

In the 5545 ft-long (1690 m) riprapped reach through the monument, 16 definite redds were counted by NPS staff. In the non-riprapped upstream 1673 ft (510 m) and downstream 1985 ft (605 m) sections, eight and 16 redds were counted respectively. Both the upstream and downstream sections surveyed were short relative to the length of the monument reach, so may have missed areas of high spawning activity such as was seen in the area downstream of Bridge 2 inside the monument. The upstream reach lies above the confluence with Fern Creek and therefore has less flow than the lower reach through the monument. This area likely has smaller pool tailout and riffle areas, which may account for limited spawning. Historically, the reach through Muir Woods could have been the main spawning reach with optimal gravel size and slope and the numbers of redds could be reduced from historical levels. Also, as the habitat studies show, the reach through Muir Woods has more riffle area than the upstream and downstream reaches, which is likely caused by the riprap. So the riprap may have converted historical pool areas to riffle, creating spawning habitat at the expense of oversummer habitat and winter high-flow refugia.

Due to the close proximity of the riprap sections and the roughness of redd location data, we could not draw any conclusions from comparing habitats preferred and most used by salmonids with their proximity to riprap or the effects of riprap on salmonid use of the adjacent area.

Adult Salmonid Distribution

Table 6 shows the numbers of live adult salmonids (coho and steelhead) sighted by NPS staff and ratios of fish per length of creek for the reach through Muir Woods and the upstream and downstream reaches.

Table 6. Number of Salmonids and Salmonid-to-Creek Length Ratios for the three study areas of Redwood Creek.

Creek Section (station m)	# of Live Adult Fish	Ratio: Fish/Length of Creek	Slope
Downstream (46+5 – 52+10)	39	1:15.5	1.1%
In Muir Woods (52+10 – 69)	109	1:15.5	1.2%
Upstream (69 – 74+10)	17	1:30	1.5%

Fish are mobile and so analyzing their presence or absence to determine effects of riprap is difficult. Also, some fish may not have been sighted and counted in the survey or may have been counted more than one time. However, this data does indicate limited numbers of salmonids in the upstream reach, which corresponds to the lower flows in this reach and the fewer redds counted.

Effects on Aquatic Insect Habitat

As aquatic insects are the major food source for juvenile salmonids and provide the link between primary nutrient production and higher predators (Merritt and Cummins, 1996), such as salmonids, they are extremely important to the Redwood Creek ecosystem. The goal of sampling aquatic insects was to determine the relative diversity in aquatic insects supported by the two types of banks, and thus to help assess potential habitat gains and losses from removing riprap. On the River Frome in southern England, Armitage et al. (2001) sampled aquatic insects on four bank types ranging from shallow sloping and vegetated to almost vertical with iron revetments. Over one year, they found a total of 115 taxa in the shallow vegetated bank, and only 32 taxa in the revetted bank. Insects were 5-6 times more abundant in the shallow vegetated bank than in the revetted bank.

The riprap on Redwood Creek protects the banks along meander bends and where the highest erosion rates were expected, as is typical of riprap projects. The rock sizes ranged from about 1-3 feet (0.3-1 m) in diameter. Water was typically fast-moving in the riprap areas, except in sample Area Five, which was a large pool. Banks left un-riprapped were therefore in areas of lower erosion rates, slow moving water with fine sediments. Some banks were undercut with roots exposed.

Appendix 5 shows data from the fifteen samples collected. 1558 insect individuals were found and identified to family level. Figure 19 summarizes aquatic insect family diversity and Figure 20 summarizes numbers of individuals found in the three strata: natural banks, riprap, and the bed. Thirty-eight different families were identified among all samples combined. Of those, 32 different families were found in samples from natural bank areas and only 18 different families were found in riprap samples. Natural banks had a 178% higher family richness than areas with riprap.

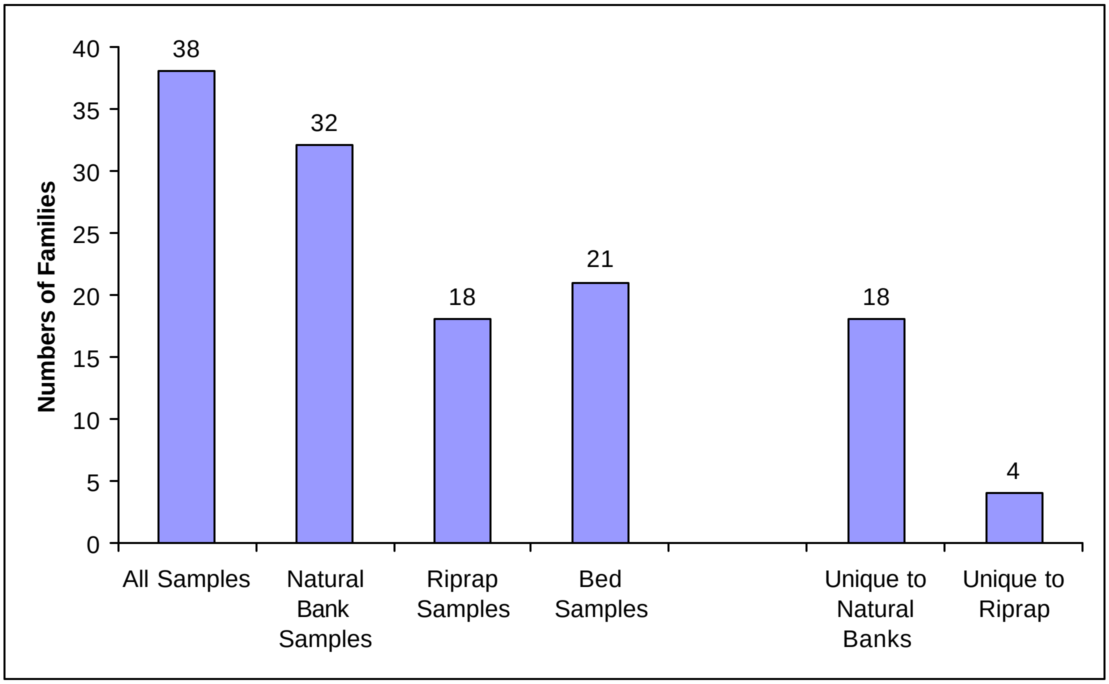


Figure 19. Numbers of aquatic insect families found in the three strata and numbers of families found only in natural banks versus those found only in riprap.

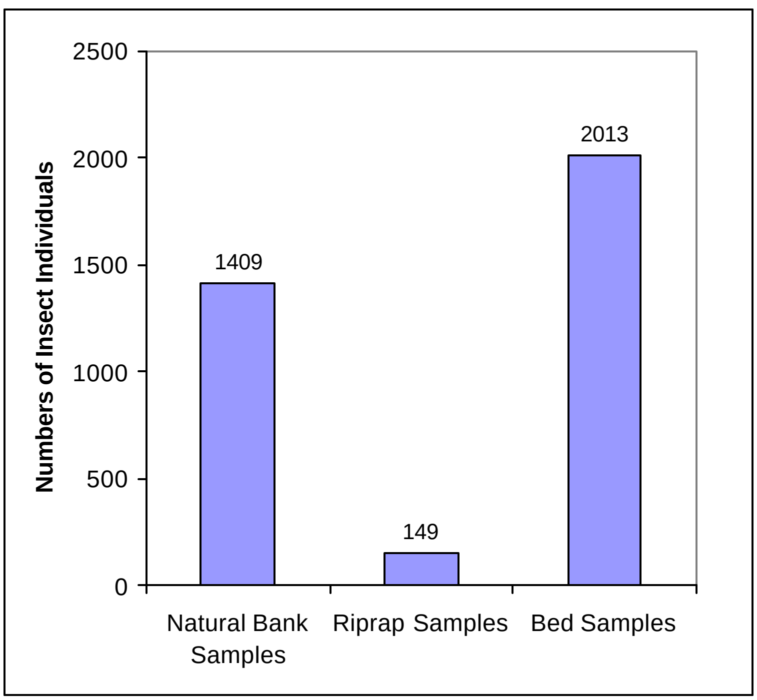


Figure 20. Total numbers of insect individuals found in the three strata.

Figures 21 and 22 show the distribution of the samples from riprap areas and natural bank areas. The lower range of samples from the natural banks does overlap with the upper range of riprap samples. The riprap sample from Area Four had 11 families, which is equally as abundant as one of the natural bank samples (at Area Two), but the natural bank sample from Area Four had 16 families. The downstream most riprap sample had 57 individuals, while the upstream most natural bank sample (with the smaller drainage area) had 51 individuals. Area Five lies upstream of the Fern Creek confluence and has a much smaller drainage area than the lower samples. Means and standard deviations for the samples are shown in Figure 23.

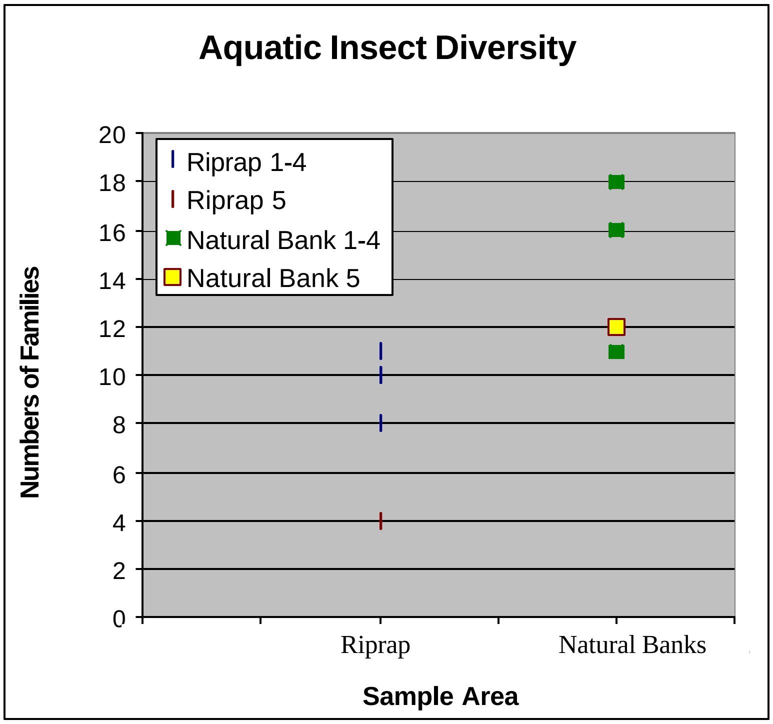


Figure 21. Distribution of numbers of aquatic insect families found in each sample for riprap and natural bank areas. Note that in the riprap areas, two samples had 10 families, and in the natural bank areas, two samples had 16 families. Area Five samples, with lower flow, are highlighted.

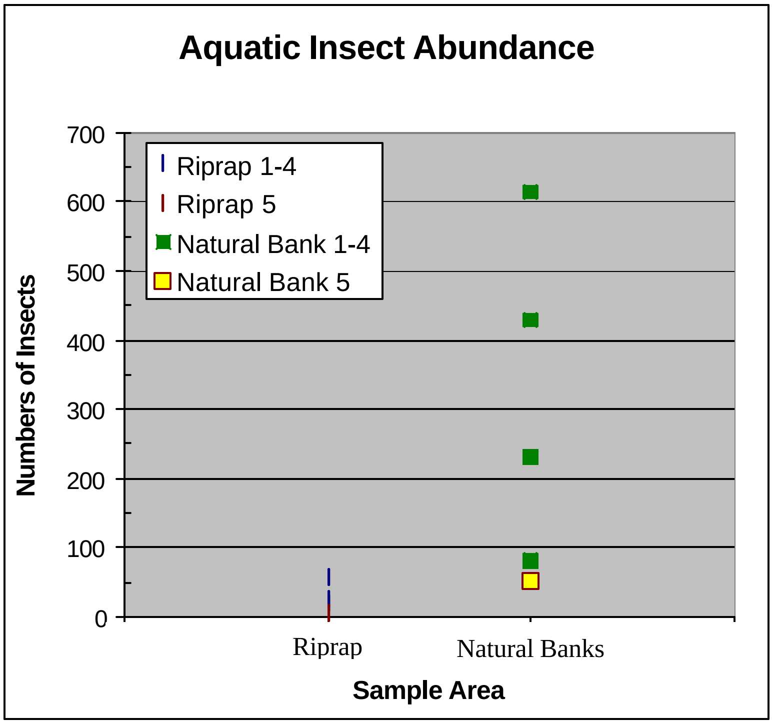
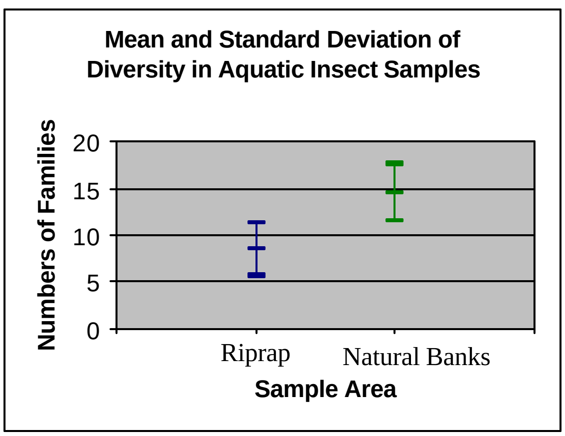


Figure 22. Distribution of numbers of aquatic insects found in each sample for riprap and natural bank areas. Area Five samples, with lower flow, are highlighted.



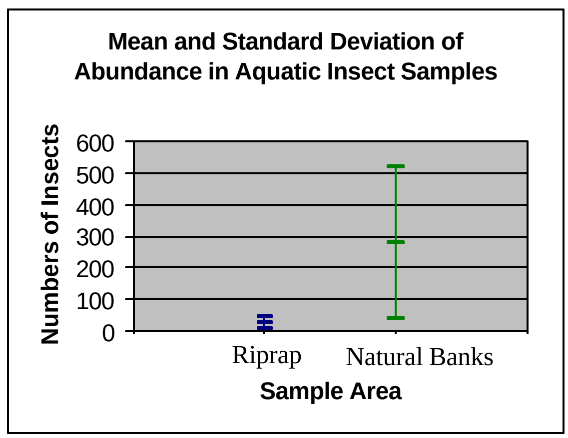


Figure 23. Plots of means and standard deviations for aquatic insect diversity and abundance in samples from riprap and natural bank areas. Note that means of non-riprap samples are higher than riprap samples, however there is some overlap with the standard deviations.

Table 7 shows insect families that were present in riprap samples but were not found in natural bank samples. Four families were found to be unique to riprap areas with five total individuals.

Table 7. Families found unique to riprap samples (Feeding Group and Stream Habitat from Merritt and Cummins 1996).			
Family	Number of Individuals	Feeding Group	Stream Habitat
Collembola Sminthuridae	1	Collector/Gatherer	Margins
Ephemeroptera Heptageniidae	2	Scraper	Erosional
Ephemeroptera Siphlonuridae	1	Collector/Gatherer	Erosional
Plecoptera Perlidae	1	Predator	Erosional
4 Total Families	5 Total Individuals		

Ephemeroptera: Heptageniidae are classified as scrapers, clinging to rocks in fast water (Merritt and Cummins, 1996), and would not likely be found along banks without rocks or fast water, as in the natural banks sampled in this study. However, Ephemeroptera: Heptageniidae were found in greater abundance in bed samples (Appendix 2) than in riprap samples, implying the bed is more suitable habitat for this family. Removal of riprap is therefore not likely to affect this family.

Plecoptera: Perlidae are also clingers, requiring moving water and are not likely to be found in the sediments of natural banks. Ephemeroptera: Siphlonuridae are classified as swimmers and climbers in mostly lentic habitats, although some genera like erosional habitats (Merritt and Cummins, 1996). This individual would need to be identified to genera level to determine its most desired habitat. Then analysis could be made of why it was only found in the riprap. Collembola: Sminthuridae are classified as semi aquatic and lives along water margins (Merritt and Cummins, 1996), and so might be expected along all margins, including the natural banks. In sampling, we tried to sample only areas in water and not the margins, so we cannot assume that Collembola: Sminthuridae are unique to riprap areas based on one individual found. This individual could have fallen into the water or the sample from the margin. Samples from the margins of natural banks are needed to determine if this family is in fact unique to riprap areas.

Table 8 shows insect families found in natural bank areas but not in riprap areas. Eighteen families were unique to natural banks with 428 total individuals. The high numbers of Odonata: Cordulegastridae could be attributed to eggs recently hatching in the area of Natural Bank 1 which had 332 Cordulegastrids, especially since they were small and therefore probably early instars. However, even without the Cordulegastrids, 47 individuals in 17 families were unique to natural banks. This is significantly higher than the numbers of families and individuals unique to riprap.

We calculated our sampling precision to determine the range in my samples and if more samples would be needed to represent the whole aquatic insect community for each stratum. The precision for the five riprap samples was 57%. For the five natural bank samples, the precision was 76%. Accepted precision for sampling aquatic insects is around 40% or lower (Vince Resh, pers. comm., 2001). A lower level of precision (a higher percentage) signals that more samples may be needed to achieve more representative sample populations. To achieve a precision of 40%, five additional samples would need to be taken from riprap areas and thirteen from natural bank areas.

Both riprap and natural bank samples from Area Five had significantly fewer individuals than the other four areas. Recalculating the precision for only Areas One through Four gave better rates of precision. The four riprap samples had a precision of 46% and the natural bank samples had a precision of 68%. Sample Area Five was upstream of the confluence with Fern Creek, and so had less water than the other four sampling areas. This could account for the reduced numbers of individuals collected.

Table 8. Families found unique to natural bank samples. Feeding Group and Stream Habitat from Merritt and Cummins (1996).

Family	Number of Individuals	Feeding Group	Stream Habitat
Coleoptera Dytiscidae	1	Predator	Depositional
Coleoptera Elmidae	21	Collector/Gatherer	Erosional
Diptera Athericidae	2	Predator	Erosional/depositional
Diptera Dolichopodidae	1	Predator	Margins
Diptera Empididae	1	Predator	Erosional/depositional
Diptera Pelecorhynchidae	2	Predator	Depositional
Diptera Stratiomyidae	1	Collector/Gatherer	Margins
Diptera Tanyderidae (?)[5]	1	Unknown	Erosional
Hemiptera Gerridae	2	Predator	Surface
Hemiptera Saldidae	1	Predator	Lentic
Megaloptera Sialidae	1	Predator	Erosional/depositional
Odonata Aeshnidae	1	Predator	Lentic littoral
Odonata Gomphidae	2	Predator	Depositional
Odonata Cordulegastridae	381	Predator	Depositional
Trichoptera Calamoceratidae	5	Shredder	Erosional
Trichoptera Hydropsychidae	1	Collector/Filterer	Erosional
Trichoptera Odontoceridae	2	Shredder	Erosional/depositional
Trichoptera Sericostomatidae	2	Shredder	Erosional/depositional
18 Total Families	428 Total Individuals		

Conclusions

Results indicate that riprap is confining the channel and reducing the channel's ability to create and maintain valuable aquatic habitat. From counting pool abundance on long profile surveys of Redwood Creek through Muir Woods and in the state park, we found that the riprapped reach through the monument had a lower extent of pools per length of stream

[5] The insect identified as Diptera Tanyderidae did not exactly fit the key for that family, however was closer to Tanyderidae than any other family. It is therefore identified as Tanyderidae and noted with a question mark.

than in the non-riprapped upstream and downstream reaches surveyed. However, riffle habitat and thus salmonid spawning sites were more abundant. Cross sections also showed a flat channel bottom through riprapped areas. Results indicate that riprap has increased the ratio of riffle to stream length at the expense of pool habitat. Reduction in pool area can lead to lower fish biomass (Hortle and Lake, 1983; Schmetterling et al., 2001). Salmonid rearing habitat is more likely to be limiting populations than spawning habitat, so the net effect of the riprap induced changes is probably negative for salmonid populations.

Higher juvenile salmonid biomass was found in a non-riprapped reach with placed LWD than in a reach with riprap. This indicates a negative effect of riprap on juvenile salmonid biomass, however the data is only from two areas in one year.

Significantly higher numbers of aquatic insect individuals and families were found in natural bank areas than in riprapped areas. Only four families were found uniquely in riprap, whereas 18 families were found solely in natural banks. The high family diversity and numbers of individuals found in natural banks indicate that natural banks are more valuable habitat for aquatic insects, and that riprap has probably reduced aquatic insect diversity along Redwood Creek.

VI. EVALUATION OF PROJECT ALTERNATIVES

Because the presence of riprap in Redwood Creek has altered channel processes and reduced pool habitat for juvenile rearing, the NPS is considering removing sections of riprap on a pilot basis to evaluate the effectiveness of this approach in improving juvenile rearing habitat and restoring channel processes. In considering pilot riprap removal, the NPS wanted to examine various alternatives to riprap removal. Four project alternatives were analyzed, including: no action, installation of LWD, riprap removal only, and riprap removal plus LWD installation. For each alternative, we analyzed the extent NPS project goals would be achieved. We combined a review of current scientific literature and field observations to determine whether natural fluvial processes would be restored and provide sustainable habitat improvements. Table 9 summarizes the project goals achieved by each alternative.

Table 9. Summary of project goals achieved by each alternative. The extents to which each goal is met and potential negative impacts are discussed under each alternative.

	Create Pools	Provide Cover	Provide Refugia	Create Undercut Banks	Create Meander Bends	Restore Natural Processes	Possible Negative Impacts
Riprap Removal	X			X	X	X	X
LWD Installation	X	X	X				X
Riprap Removal Plus LWD	X	X	X	X	X	X	X
No Action							X

Riprap Removal

Potential Benefits of Riprap Removal

The riprap in Redwood Creek is creating unnatural flow patterns and confining the channel to a set course. It is interfering with the creek's natural processes and ability to create and maintain adequate salmonid habitat. Removing the riprap would allow the banks to be scoured and undercut and the channel to meander. Pool-riffle sequences would also be enhanced by increased sinuosity of the channel, which achieves the goal of increasing salmonid habitat. Overall, the pools in the monument are less frequent, smaller and more shallow than those in non-riprapped reaches. Because the riprap is protecting the banks where pools would form naturally, most pools are in the center of the channel and lack the overhanging banks favored by Coho salmon. Removing the riprap and allowing the channel to scour its banks and create meander bends may foster creation of overhanging banks with associated pools.

Potential Impacts of Riprap Removal

If sections of riprap are removed, mitigation measures at the point scale may need to be implemented in the case of undesirable effects. Based on data and observations of Redwood Creek, the following are some impacts that could result from removing riprap. They should be considered in conjunction with the benefits of removal when proceeding with pilot project planning.

1. Bank and channel bed impacts from the removal process itself, such as from machinery, rock extraction, and worker access.
2. Sediment resulting from bank scour. Depending on the stability of the banks after rock removal, more or less sediment would be expected from the banks. If the banks were backfilled after the riprap was installed, more sediment would be expected to enter the channel shortly after removal because these fill sediments would be less stable. However, if the banks were not backfilled and are held with roots, less scour, and therefore sediment, would be expected.
3. Potentially higher rates of erosion due to remaining watershed alteration or because of the continued presence of riprap upstream of the two sites. With riprap present upstream, velocities may be higher and result in higher erosion rates. Installation of LWD can act to mitigate high velocities.
4. Reduction of riffle habitat and therefore of spawning habitat. As pools form, some riffle area is likely to be replaced by pool area. This may reduce spawning habitat, but create much-needed rearing habitat.
5. In the long term, meandering may lead to undercutting of heritage Redwood trees in the park, which would be natural recruitment of LWD to the system but might be viewed negatively by those interested in protection of the large Redwoods.

Simply removing the riprap may not be enough to induce meandering and pool and bank scour in the short term. Inducing such processes by installing LWD is likely to lead to faster results and creation of salmonid habitat.

Installation of Large Woody Debris

Under this alternative, LWD would be placed in the channel at sites with riprap and little channel complexity. Studies involving channel response to LWD placements and configurations are summarized in Appendix 6. Several issued should be considered in designing LWD structures based on the desired performance of the LWD.

1. Mobile or Fixed

   LWD that is fixed and cannot move will have more longevity and be more predictable than LWD that is free to migrate downstream. Migration downstream can cause pieces to break, and once smaller, they would have less effect on channel morphology, hydrology and habitat. Also, migrating pieces could endanger bridges. However, LWD migration is a natural process. Installing larger pieces of LWD that can be wedged in the channel more closely mimics natural processes than using cables to secure logs.

2. Size and Species

Smaller trunks such as from bays and alders will provide less cover, have a smaller effect on the hydrology needed to scour pools, and have less of a trapping potential for sediments. These species will also decay more rapidly than redwood, which is known for its resistance to decay. Redwood tops or multi-trunk bay trees, with their branches in the channel would have a higher sediment trapping potential than one large straight trunk. Also, branches act to break up pools into smaller sections, giving more cover to fish.

3. Composition

Interlocking log jams provide more complex cover and may have higher trapping potential than single logs. Orientation of LWD is another factor. Figure 24 shows various log orientations studied by Hildebrand et al. (1997), Cherry and Beschta (1989), and Hildebrand et al. (1998). Downstream oriented logs have been found to provide some bank protection whereas upstream oriented logs can cause more bank scour (Hildebrand et al., 1997; Cherry and Beschta, 1989).

4. Availability and Access for Placement

I have located potential sources of LWD near the two proposed pilot sites. 150 ft (45 m) upstream of the Lower Boardwalk site and at the Upper Boardwalk site. Consideration should be given to what sizes and species of wood could be located elsewhere in the region. Large, heavy Redwood logs may be more difficult than smaller Bays or Alders to place in the channel without damage to banks.

Potential Benefits of Installing LWD

Given the above, the 'LWD-only' option may provide increased pools, increased cover for salmonids, and some bed aggradation from sediment trapping. Use of LWD is a 'natural' technique, which the NPS favors. LWD in streams increases roughness reducing flow velocities, creates scour pools, provides cover, stabilizes banks, traps sediment and organic matter, controls gradient, provides refuge areas from high flows, provides nutrients, and directs flow (Castro and Sampson, 2000; Cederholm et. Al, 1997; Cherry and Beschta, 1989; Crook and Robertson, 1999; Robison and Beschta, 1990; Schmetterling and Pierce, 1999). By installing LWD, some habitat benefits can be achieved without the potential risks associated with removing riprap.

Higher water surface elevations will result from the decreased conveyance area and increased resistance of LWD installation. LWD in the channel will increase channel roughness, which lowers velocities and therefore increase water depth. This could provide floodplain reconnection in certain areas of the Monument, which would improve overall forest health.

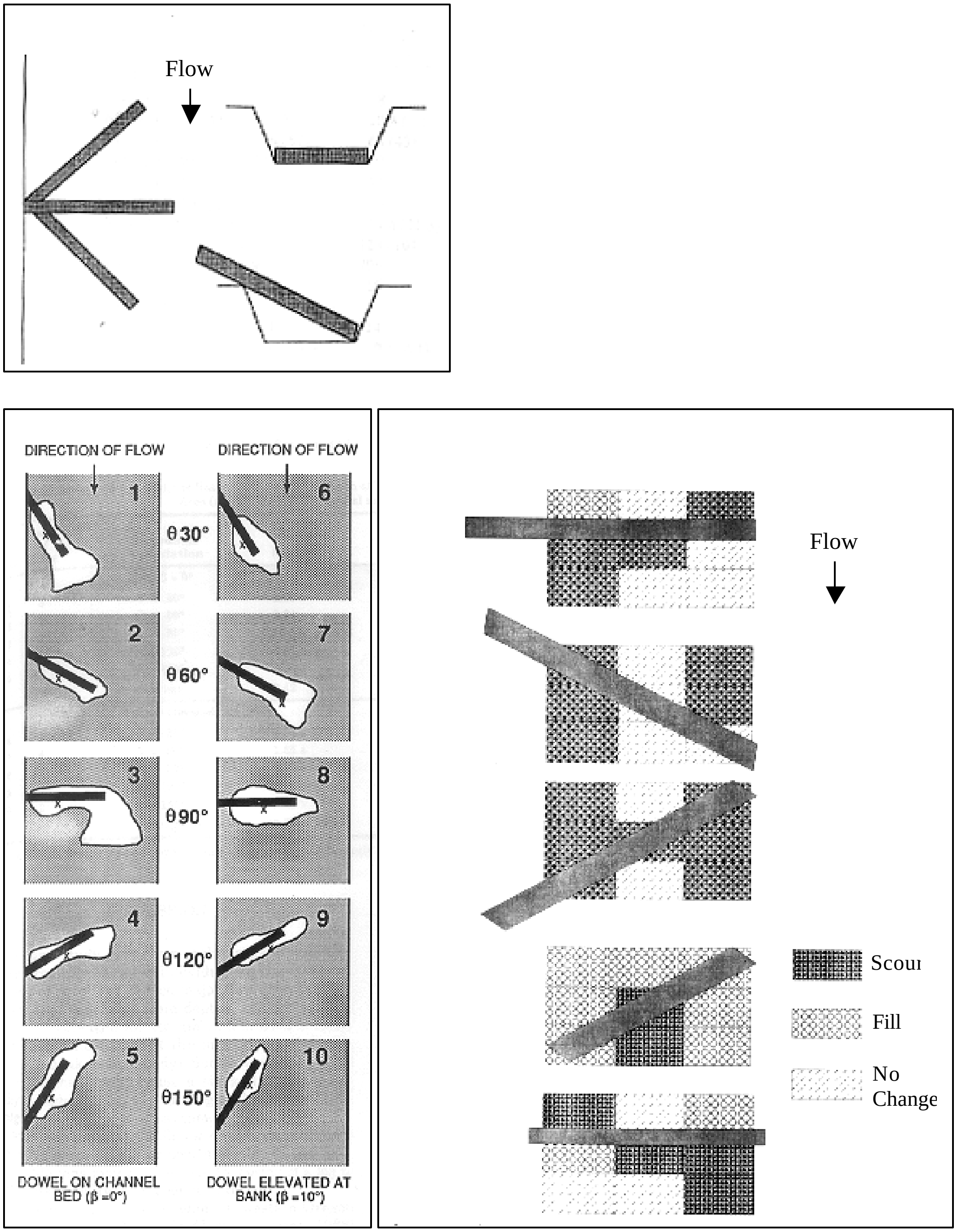


Figure 24. Diagrams showing possible orientations of LWD with associated scour patterns (from Hildebrand et al., 1997; Cherry and Beschta, 1989, and Hilderbrand et al., 1998 respectively).

Potential Impacts of Installing LWD

Flooding of parts of the Monument valley may result because of the higher water surface elevations from installing LWD. This could be a benefit as it provides floodplain connectivity, or it could be considered an impact to park infrastructure or visitor use. Periodic maintenance will be required to keep large debris jams from forming and damaging bridges or bridges may need to be raised to allow for LWD passage.

LWD in the channel has a limited lifetime, depending on the size and species of the wood. Some large Redwood logs or logs fixed to the channel banks may persist for decades, however, movement of LWD downstream is part of the system's natural processes, so fixing LWD to the banks may not be desirable. If smaller, unfixed logs are used, their benefits may only last a decade or less in any given location due to log movement.

Only adding LWD to the channel would not fulfill the stated NPS goals for Redwood Creek. Restoration of natural fluvial processes leading to sustainable habitat creation, which are the stated NPS goals driving any action in the creek at this time, would not occur under this method. The LWD only option would not allow for the formation of overhanging banks and pools on the outside of meander bends. With the banks confined by riprap and unable to meander, LWD would not be recruited so continued LWD additions would be necessary, which is not sustainable. The LWD Only option also does not address the aquatic insect habitat, and by extension salmonid food supply, lost to the riprap. Adding LWD would not mitigate for the lost aquatic insect habitat found in natural banks and so would not lead to the increased aquatic insect abundance and diversity expected with riprap removal.

Riprap Removal Plus Addition of Large Woody Debris

Potential Benefits of Riprap Removal Plus LWD Installation

LWD stabilizes banks in a 'natural' way while improving habitat value and cover for salmonids. While riprap removal best achieves park goals by allowing natural processes to create channel form and habitat, addition of LWD can further improve salmonid habitat by providing refugia and cover and induce pool scour. Also, LWD would provide immediate habitat benefits by providing cover and low velocity areas. By varying placement of LWD, rates and locations of scour can be somewhat managed. If riprap is removed as a pilot project, addition of LWD could slow bank erosion rates, which will vary depending on the presence of bank vegetation and roots and whether the CCC project included backfilling of the riprap sections. Two potential riprap removal sites are described in the following chapter.

Potential Impacts of Riprap Removal Plus LWD Installation

Impacts of riprap removal and of adding LWD are discussed in above sections. To summarize, riprap removal could lead to temporary increased sediment input, excess bank erosion, channel incision, and loss of riffle habitat. LWD installation could lead to temporary disruption of bed and banks from installation, or a loss of riffle habitat.

No Action

Potential Benefits of No Action

Any activity in the stream channel or on the banks has the potential to adversely affect the system or ecology. As discussed above, removing the riprap could lead to increased sediment input, temporarily unstable banks, increased bank erosion or incision, or temporary disruption of the ecosystem. Installation of LWD could temporarily disturb the banks and bed, increase water surface elevations, or endanger bridges.

Potential Impacts of No Action

Following 70 years with little maintenance, the riprap on Redwood Creek remains mostly functional. The riprap is large relative to the scale of Redwood Creek. Some areas are failing, such as the downstream end of section R9 and parts of L11 where the rock has slumped into the channel; however, creek flows have not moved the rock very far. Based on these observations, it is not likely that the rock will be moved by the creek and integrated into the bedload in the short term. In fact, since almost 70 years have elapsed with little movement of these oversized rocks, the timescale of stream recovery without intervention could be centuries. Even then, large rock not characteristic of the natural channel system would remain, potentially affecting channel hydrology.

The riprap currently prevents the stream banks from being undercut and prevents pools from being scoured on the outside of meander bends, both of which create valuable habitat for salmonids. These undercut bank and pool habitats are rare in the reach of Redwood Creek inside Muir Woods National Monument. These habitats are considered limiting factors to increasing the populations of threatened coho salmon and steelhead trout. If riprap is left in the channel, it will continue to prevent meander bends, undercut banks, and pools from forming. Without action, these habitats will remain limiting factors for salmonid populations, potentially for centuries.

Summary

Riprap removal could provide valuable salmonid habitat benefits. Potential benefits include habitat in the form of overhanging banks, increased pool frequency, and refugia during high recurrence interval storms. Options that do not include riprap removal do not meet the stated NPS goals for Muir Woods because they do not lead to restored fluvial processes and self-perpetuating habitat creation. Simply adding LWD to the channel may recreate some of the natural channel form (without overhanging banks), but the processes would be missing.

Riprap removal plus addition of LWD will best achieve the stated NPS goals by restoring natural channel processes, which lead to sustainable habitat creation and recruitment of LWD. Riprap removal should happen on a pilot basis first to gage the reaction of Redwood Creek and any adverse impacts to advise removal on a larger scale.

VII. PROPOSED PILOT RIPRAP REMOVAL PROJECT

As part of this project, the NPS selected two sites in Muir Woods to analyze potential pilot riprap removal projects based on their geomorphic characteristics and potential for habitat improvement post riprap removal. The Lower Boardwalk site has two riprap sections and the Upper Boardwalk site lies directly upstream with three riprap sections (Appendix 1).

Pilot Site Selection

We selected potential pilot sites using the following criteria set forth by NPS:

1. Potential to improve juvenile salmonid habitat.
2. Reduced risks to park infrastructure such as bridges and trails.
3. Probable historical channel conditions.
4. Relative accessibility for removal of the large rock.
5. Potential value of the riprap as a cultural resource (having been installed by the CCC in the 1930s).
6. Visibility to visitors creating opportunities for interpretation and education about stream dynamics and habitat.

Sites were selected by the project managers at the NPS and GGNRA based on the agency's goals and on initial findings of this study. An initial site selection table (Table 10) was prepared identifying and comparing six potential pilot sites. Existing conditions, salmonid habitat value, inferred effects of the riprap on the reach and habitat, proposed project actions, and potential post-project changes were outlined. Selection of those six sites from the 28 total riprap sections was done using the criteria established by the NPS. Most of the selected sites contained more than one section of riprap as processes are linked and removal of only one section may lead to little channel change or, most likely, increased scour caused by another section. Members of the NPS staff, including the project manager, Muir Woods supervisor, park hydrologist, and fish biologists, then met to discuss the six sites and select two for further examination. Site selection for a pilot removal project will be made by the NPS, based on input from this study.

Table 10. Six potential pilot sites identified and characterized for potential riprap removal based on criteria set forth by the NPS.			
Pot. Pilot Site	Project Actions	Characteristics	Constraints
R5	Remove riprap	Already a meander bend but lacking scour. Likely to continue cutting the right bank after removal. No existing lateral scour pool to destruct in removal. Highly visible and easily accessed. Downstream is an area with high spawning rates.	Bridge 2 directly downstream, which could require replacement in the long-term.
L7	Remove riprap, add LWD to deflect incoming flow from tributary? and induce meandering	Straight reach upstream of Bridge 3 with little to no habitat value. Bedrock upstream to induce meandering. Low terrace in this area makes floodplain connectivity a possibility, especially with some LWD or a redwood falling in to increase the water surface elevation. Potential to improve not only stream health, but also overall forest health with flooding to aid redwood seedling recruitment.	Trail about 3m away on left bank.
R7, L10	Remove both sections of riprap, add LWD deflectors to induce bank scour.	Straight reach with meandering likely only in the long-term, little to no current habitat value. Potential to experiment with additions of LWD to induce meandering and improve habitat.	
R8, L11, R9 trio	Remove three consecutive riprap sections, plant woody riparian vegetation along the left bank	Some sinuosity but further meandering constrained by the riprap. After removal, meandering likely to occur on its own. Fallen tree on right bank could be moved to channel.	Little vegetation on left bank for LWD recruitment. A redwood cluster on left bank about 3m from edge.
L14, R11	Remove both sections of riprap or just R11	Meander process existing but constrained by riprap. Scour likely in the short-term with LWD recruitment following.	Trail close to L14.
L15	Remove riprap	Sharp meander bend, at upstream end of Monument so less disruption of fish by visitors, existing LWD.	Could interfere with Bridge 4.

Estimating Potential Future Channel Change

An important element for the NPS is estimating channel movement after riprap is removed to assess benefits from the project. Sites for potential pilot removal were identified as having low risk of impact to infrastructure, and having leeway for channel movement without undercutting trails, bridges, or old growth redwoods. Potential future channel change was estimated by projecting the current direction of flow at a location, extending the trajectory in the same direction, and assuming it would erode the bank. The characteristics of meanders in this channel (i.e. the approximate extent of lateral channel movement in one direction before turning back to cut the opposite bank) could be estimated by looking at existing meander bend wavelengths upstream and downstream, and then superimposing those at the pilot site, using the above trajectory. However, the amount of scour depends on bank composition. If the CCC project involved backfilling of the riprap sections, more scour could be expected, as the fill would not be as stable as existing bank. If the riprap was not backfilled and roots hold the banks, less scour would be expected. Soil cores taken from behind riprap sections could indicate the cohesiveness of the banks and the potential for scour.

Where flow is currently straight with little tendency to meander, we recommended installation of LWD. Channel movement caused by this LWD will be determined by the size and orientation of the LWD.

Assessment of Site R7-L10: Lower Boardwalk

Description

R7 is a 105 ft (32 m) section of riprap on the right bank; L10, a 125 ft (38 m) section of riprap on the left bank, located just upstream (Appendix 1). The channel has a slight curve at L10, then straightens and flows past R7, continuing straight for a total of 260 ft (80 m). Stream flow is deflected by the R8 riprap on the right bank upstream of L10, then crosses over to the left bank where it flows into L10. At the downstream end of L10, the flow leaves the left bank and crosses the channel to the right bank along R7. R7 then directs the flow straight downstream. This channel crossing flow represents an incipient meander. Cross sections (Appendix 2) show the flat bottom channel form in this reach.

The 200 ft (62 m) reach containing R7 and L10 consists mostly of riffle with 65 ft (20 m) of shallow glides and one small pool in the center of the channel. The reach currently has poor habitat value so disruption due to the removal project would be minimal. Such impacted habitat also means a higher potential for significant habitat improvements resulting from riprap removal.

Site Attributes

The Lower Boardwalk site has poor juvenile salmonid habitat value, making it a good candidate for pilot riprap removal. No existing high-quality habitat would be disturbed, and there is high potential for significant habitat improvements.

The NPS staff also identified this site as a good location to experiment with reintroducing meanders to the channel through riprap removal and LWD placement to increase channel dynamics and salmonid habitat. A fallen tree 150 ft (45 m) upstream is a potential source of LWD for placement at this site.

According to the NPS, a creek side trail was removed in the past to make room for possible future channel movements. Thus, NPS does not see trail constraints at this site. This site is not particularly visible from the remaining trail, but was selected anyway due to its potential for significant habitat improvements.

The R7 riprap is failing with most pieces at the downstream end in the channel or at the toe of the bank. Riprap section L10 is also beginning to fail at the downstream end, having a slump interrupting the section.

Inferred Effects of Existing Riprap

Two sections of riprap, R7 and L10, have kept the channel straight through this reach. Without riprap section L10, bank scour might have continued at the upstream end of L10 where flow hits the left bank after crossing the channel from R8, resulting in more of a bend than currently exists. Similarly, where flow crosses from the left bank at L10 toward the right bank, bank scour might have occurred without the presence of the riprap R7. With this bank scour, the banks would have been undercut, providing cover for salmonids, or with more intense scour, pools may have formed and LWD recruited providing excellent habitat for salmonids. Pieces of riprap in the channel have altered the substrate composition, resulting in unnaturally large sizes of some particles, which are immovable even in the highest flows.

Description of Proposed Riprap Removal Project

Removal of both sections of riprap, R7 and L10, is proposed. Due to the straightness of the reach, meander bend formation is only likely in the long-term. Therefore this site would benefit from the addition of LWD to direct flow at opposite banks and induce meandering.

Two placements of LWD are recommended. The first is recommended on the right bank just above the slight bend at L10 to direct flow toward the left bank where the slight bend has been started. This would induce scour of the left bank and enlarge the bend. A second placement of LWD is recommended on the left bank at the downstream end of the existing bend. This would direct the flow from the downstream side of the bend at L10 to the right bank at the former site of R7, continuing the meander process. Placement of LWD would also induce pool formation and provide cover for salmonids in the channel.

Future Conditions

With placement of LWD on the upstream, right bank of L10, flow could be directed over to the left bank to induce bank scour and start a meander bend. With the addition of LWD on the downstream, left bank of L10, flow could be directed over to the right bank at R7, inducing scour and continuing the meander process. Two pools are anticipated to form, one at each bend.

Future LWD recruitment is likely. Two bay trees are near the channel and likely to be undercut at L10 and fall into the channel as LWD. Three alder trees may potentially be recruited as LWD in the long term. Depending on the rate of bank scour, more or fewer trees will be undercut than mentioned.

Assessment of Site R8-L11-R9: Upper Boardwalk

Description

The Upper Boardwalk site (Appendix 1) is a reach containing a bend in the left bank with riprap armoring the right bank above and below the bend, and the left bank at the bend. There is also a slight bend in the right bank at R8. The downstream-most section, R8, is 100 ft (31 m) in length, L11 is 90 ft (27 m) in length, and the upstream-most section, R9, is 85 ft (26 m) in length.

The downstream end of riprap R9 is failing and most rocks are in the channel or at the toe of the bank. The bank in this area has been scoured, exposing roots of a redwood cluster. The downstream end of riprap L11 is beginning to fail with some rocks in the channel.

Flow impinges R9 about in the center of the section and scours the bank at the downstream end before crossing the channel to the left bank. The flow hits L11 at the upstream end and is channeled by the riprap around the bend and then crosses over to R8 where again it is straightened by the riprap. The boardwalk trail is 7.7-11 ft (2.3-3.4 m) away from the bend at L11.

Flow is toward the bank at the site of the lookout, downstream of the end of the boardwalk. Two pools are in this reach, one at the downstream end of L11 and the other at the downstream end of R8 where a log has fallen and one end is resting at the edge of the channel on the right bank. Thus there is some existing habitat, however the flow path shows the tendency of the channel to meander, which could lead to undercut banks, scour pools, and increased occurrence of LWD recruitment if riprap were removed.

Site Attributes

Geomorphic processes at this site appear mostly intact and creation of undercut banks is likely following riprap removal. Therefore short-term habitat benefits are likely. This site is highly visible from the trail, making it an excellent area for visitor education.

This site is located in the area adjacent to the boardwalk trail, which has been designated as the pilot area for overall ecosystem restoration. The NPS felt that pilot restoration projects should continue in this area for maximum benefit before moving to other areas.

Inferred Effects of Existing Riprap

Placement of riprap in this reach has confined two meander bends, eliminating the opportunity for further bank scour and expansion of the bends. Pools have formed despite the riprap, although the one near L11 is small and the one at R8 is associated with a log that has fallen in the channel.

By stopping the meander process, the riprap has also stopped LWD recruitment from trees being undercut and falling into the channel. Formation of undercut banks has also been stopped so there is very little cover for fish.

Description of Proposed Riprap Removal Project

Removal of all three sections of riprap is proposed. This would allow the reach to have both left and right banks scoured in order to achieve maximum habitat benefits. Placement of LWD is not necessary at this site because of the existing tendency of the channel to meander. However, addition of LWD on the left bank at R9 could induce further meandering on the left bank. Also, addition of LWD at L11 could act to provide some bank protection as this is near the boardwalk lookout. LWD can also trap sediment, create pools, and provide cover for more immediate habitat benefits. This site would be a good location for informational signs to educate visitors about the project.

Future Conditions

Meandering is likely to continue unassisted after riprap removal. Existing channel bends suggest this reach will continue to scour the left bank at L11 and return to scour the right bank at R8. Existing scour at the downstream end of R9 suggests this area will continue to scour after riprap removal. Placement of LWD on the left bank of R9 would induce more scour at the downstream right bank, but is not necessary as the meander process is already started at L11 and R8.

The redwood cluster and alder at the downstream end of R9 may be recruited as LWD by future bank scour. However, they have been undercut for many years with little to no change (Mia Monroe, pers. comm. 2002) so their recruitment as LWD is not definite. L11 lacks significant bank vegetation, but two alders and one bay at the bank edge and in the riprap are likely to fall into the channel in the short-term. Depending on long-term bank scour at L11, two large redwoods may be recruited as LWD and the boardwalk lookout may have to be narrowed or relocated. LWD could be installed at L11 to reduce bank scour and protect the redwoods and boardwalk. One redwood and one alder are likely to fall into the channel at R8 in the short-term. Banks at all three sites are likely to be undercut after riprap removal with pools forming at the bends, potentially augmented by installed or recruited LWD. If reduced scour is desired at L11 to protect the boardwalk, LWD could be installed as outlined above in a manner to protect the bank or divert flow to the right bank.

VIII. MONITORING

Monitoring of restoration projects is important to identify the effects and success of the specific project, to comply with any permit conditions, and to add to the scientific knowledge of river restoration. For Muir Woods, monitoring of any riprap removal or LWD installation combined with an adaptive management strategy, where any undesired effects of the project are mitigated for, is recommended. Methods for monitoring the creek after riprap removal or LWD installation are outlined. Methods, frequency and baseline data from this study will be provided to NPS to provide a basis for future monitoring.

Given the uncertainty inherent in predicting the response of the channel to riprap removal, it make sense to approach the removal within an adaptive management framework, through which the channel response is monitored and the results of monitoring used to inform future management decisions. For example, if the pilot riprap removal projects do not result in formation of new pools and increased cover within a given period of time, the reasons for this can be investigated (e.g., lack of flows sufficiently high to scour the bed and sculpt a more complex channel), and if indicated, more proactive management actions could be added, such as direct addition of LWD to promote pool development. Also, if undesired bank scour is seen, LWD could be installed to protect the bank. Channel bed elevation should be monitored and any incision mitigated for with bed controls to prevent channel deepening and associated effects. Other concerns include undercutting of heritage redwoods and increased sediment loading downstream.

Suggested Methods

Geomorphic and habitat data collected by this study will be compiled and given to NPS for use as baseline data. These include cross sections, long profile, pebble count, and aquatic insects data. Additional cross sections may need to be surveyed to provide adequate upstream and downstream boundary conditions, with the project and associated cross sections in between. The upstream and downstream cross sections can then provide a standard for comparison with cross sections in the project area.

Cross section and thalweg profile surveys should be completed on a yearly basis for the first three years after project implementation so that channel movement can be associated with the flows from that year. After this, surveys can be less frequent and should at least be completed after years of high flows (e.g. a 5-year recurrence interval flow) to mark changes in stream profile and gauge project effects. NPS interns can accomplish this work at relatively little cost. Cross sections should be surveyed in areas without riprap so that comparison can be made between the channel profiles of riprapped and non-riprapped areas.

Salmonid spawning surveys should continue on a yearly basis to gauge effects of the project over time in relation to the entire Muir Woods reach. Flow data and relative abundance of spawners should be included to give context to spawner numbers in the project reach.

The aquatic insect study could be repeated in the spring or early summer to determine the effect of seasons on preferred aquatic insect habitat in Redwood Creek. Further analysis of the desired precision of the samples is necessary before relying on this data to gauge effects of removing riprap. If greater precision is desired, more samples should be collected and compiled to achieve better representation of the aquatic insect communities in each stratum. After riprap removal, further aquatic insect sampling could gauge the effects of riprap removal on insect abundance and diversity in project areas.

Suspended sediment should be sampled during a storm or a series of storms early in the water year before removal to inform an overall sediment budget for the watershed. When a pilot site is selected to proceed with removal, the amount of sediment in the area of bank desired to scour could be calculated. However, with addition of LWD, some sediment would be expected to accumulate, so could mitigate for some of the sediment input from bank scour. Suspended sediment sampling should be repeated after pilot riprap removal to gauge effects of larger scale removal.

Project Evaluation

Specific measures of success for the project should be established by the NPS before implementation. These include descriptors of what constitutes adequate pool size and depth, undercut banks, meander bends, and LWD recruitment. After riprap removal, the project should be evaluated to determine whether it is achieving the goals. Criteria for evaluating project success should be based on the restoration goals and objectives (USDA, 1998). The NPS goals were outlined earlier in this report and should be used to set evaluation criteria before the pilot riprap removal project is implemented.

Removal of riprap has rarely been done and so any riprap removal on Redwood Creek should be studied and documented to provide the environmental planning profession with more references on a little utilized stream reclamation method.

IX. SUMMARY

The NPS is investigating removing sections of riprap in Redwood Creek on a pilot basis as part of an ongoing program to restore the creek ecosystem and the overall Muir Woods ecosystem. Historical channel conditions and change were researched to identify the extent of human-induced channel and watershed change. The upper watershed is mostly intact with some human impacts such as fire roads and trails, however stream processes through Muir Woods National Monument are obstructed by the presence of riprap along stream banks.

A review of current literature revealed that riprap results in reduced channel complexity and associated habitat value. A study of the current channel geomorphic, hydraulic, and ecologic conditions showed that the reach of Redwood Creek with riprap had a lower pool frequency that non-riprapped reaches. Without riprap armoring the banks and confining the channel, the current channel processes are likely to be sufficient to create complex channel form such as scour pools and undercut banks. However, at some sites, additions of LWD would spur such activity.

Analysis of fish data indicated Redwood Creek in Muir Woods provides suitable salmonid spawning habitat but that juvenile rearing habitat is lacking. The presence of riprap has led to more riffle habitat but less pool habitat, which would be good for spawning but detrimental to juvenile rearing.

A study of aquatic insect distribution on Redwood Creek found more diversity and abundance of aquatic insects in natural bank sites than in riprapped sites. Removing riprap would likely lead to an increase in aquatic insects, which is an increase in the food source for salmonids.

Because of the large rock size used for the riprap, and the lack of rock movement over the last 70 years, the channel is unlikely to restore itself by incorporating the rock into the bedload and moving it downstream. With the continued presence of riprap, pool formation, LWD recruitment, channel meandering, point bar evolution, and overhanging bank formation are obstructed. Removing the rock from the channel on a pilot basis would allow the channel to migrate and create complex habitat. Two pilot removal areas were selected and characterized. They were found to best fit the NPS criteria for pilot removal. Removal of the riprap combined with placement of LWD would meet the NPS goals for restoring natural processes and sustaining aquatic habitat and forest ecology. Merely placing LWD in the channel would likely lead to increased juvenile rearing habitat, however the life of the LWD would be limited and so not sustainable. Because LWD can act to reduce flow velocities, protect banks, direct flow, trap sediment, and provide habitat value, we recommend that any riprap removal be combined with LWD placement.

The NPS can use information in this report in deciding whether the long-term benefits of riprap removal outweigh the costs such as of removal itself, bank damage from removal, maintaining the monument with an unconfined channel, and sediment from bank scour. These concerns must be addressed when deciding if riprap removal is best for Muir Woods at this time.

This report provides information on which the NPS can evaluate the need for riprap removal and apply for the necessary permits. If the NPS decides to remove pilot sections of riprap, a detailed monitoring plan should be outlined to include evaluation criteria, feasible data collection methods and timeframe, and plans for adaptive management.

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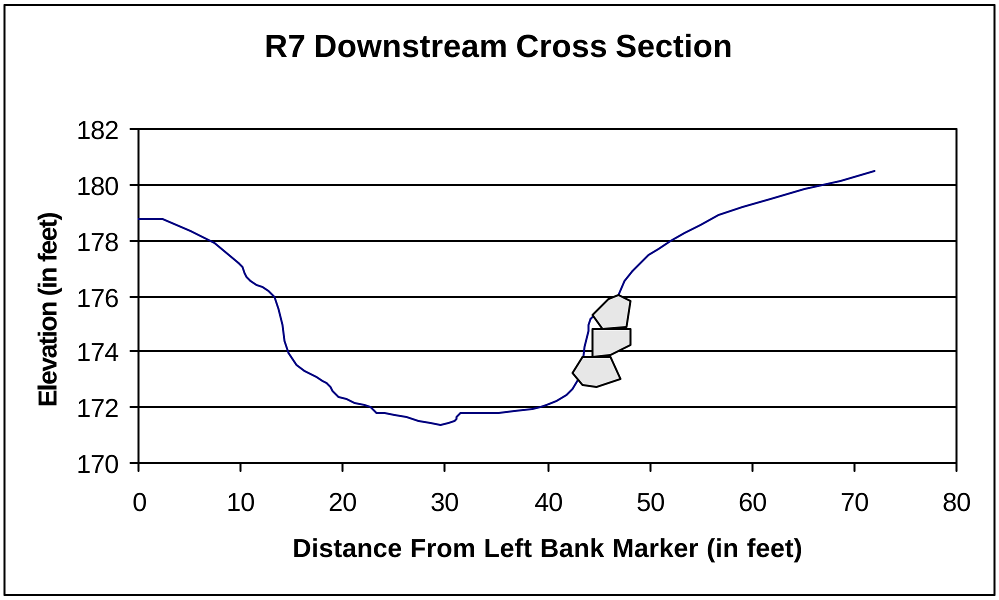
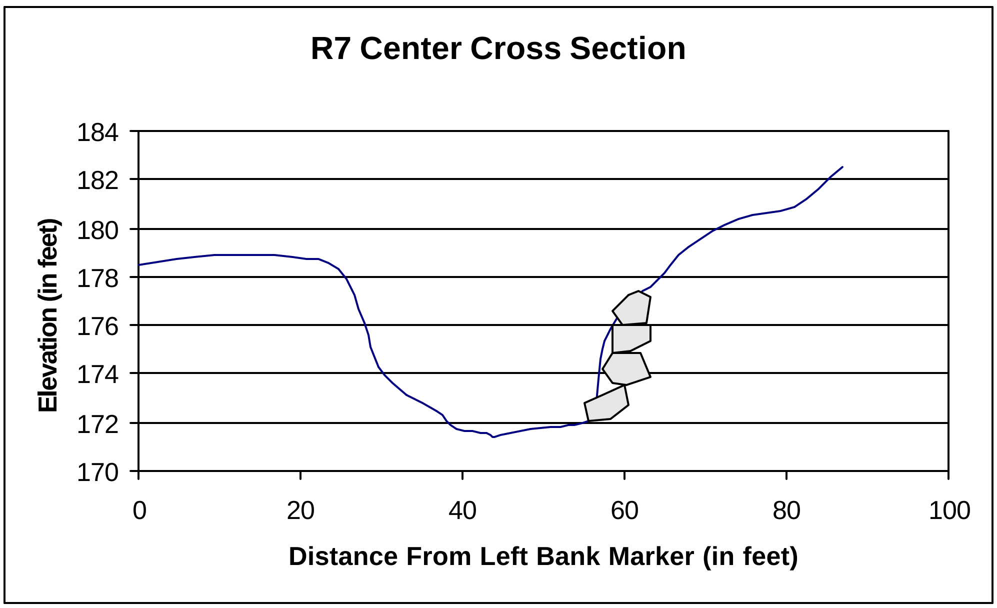
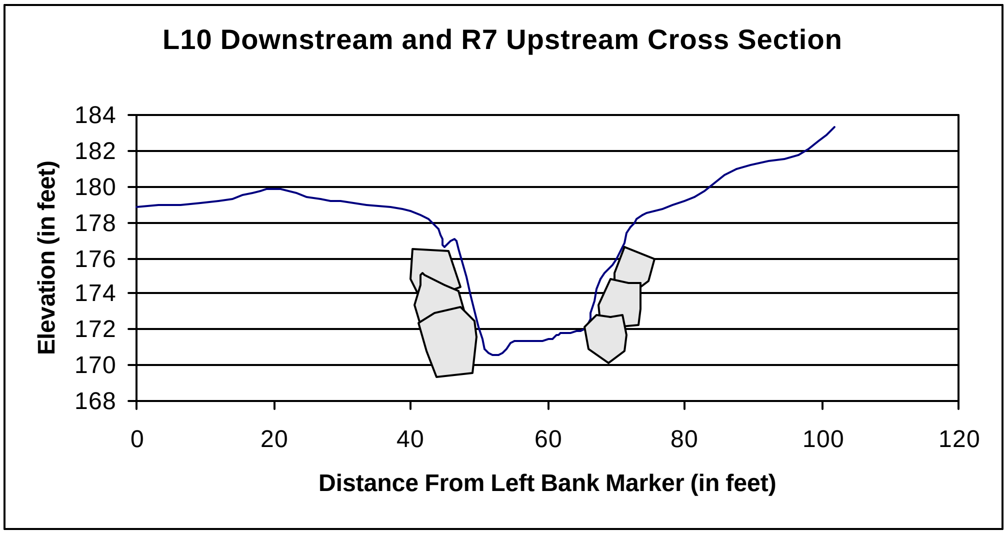
XI. APPENDICES

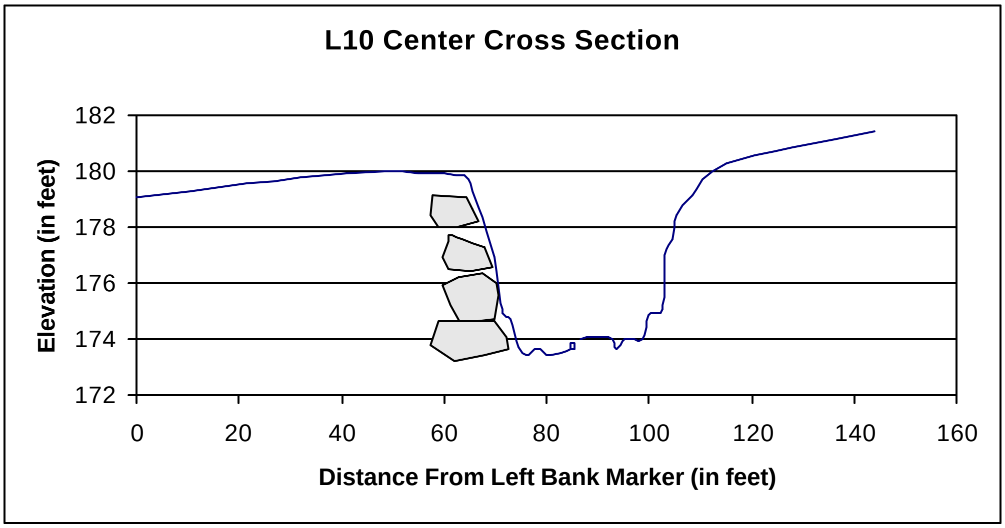
Base Map

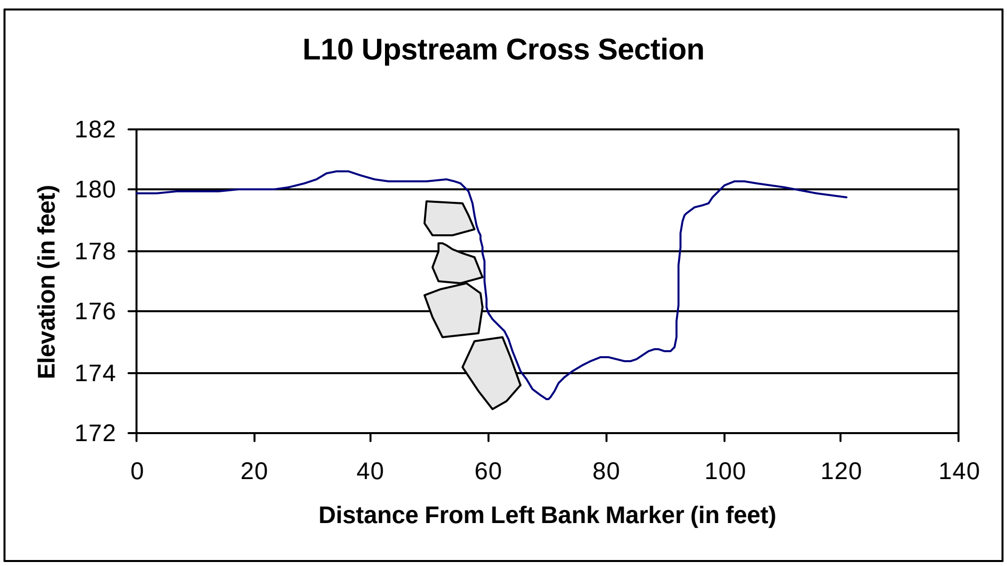
Appendix 2. Cross Section Plots

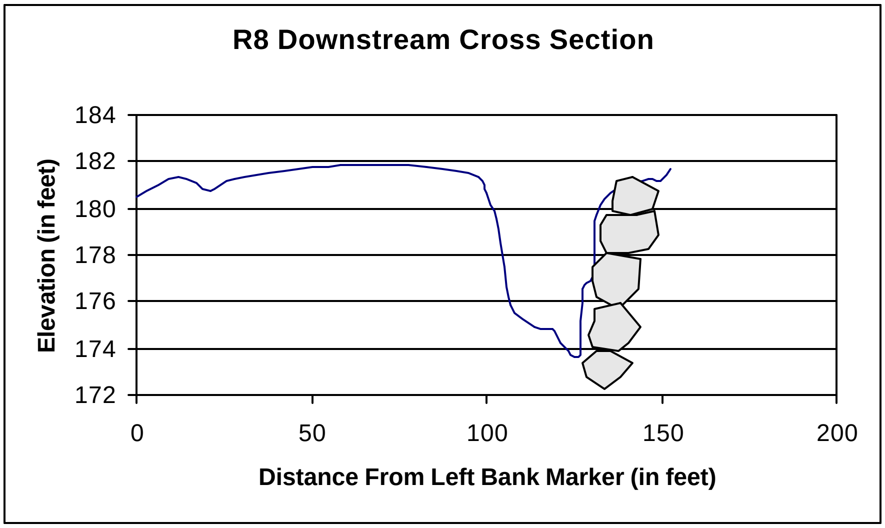


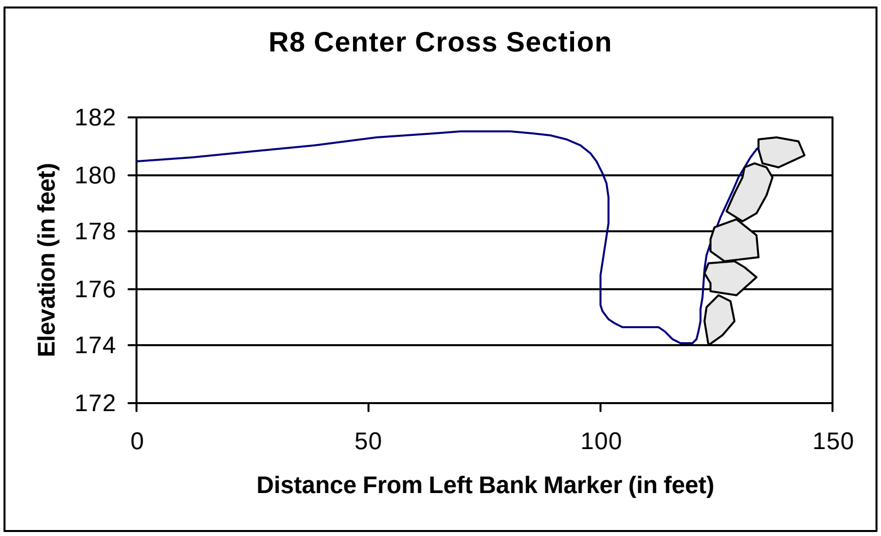


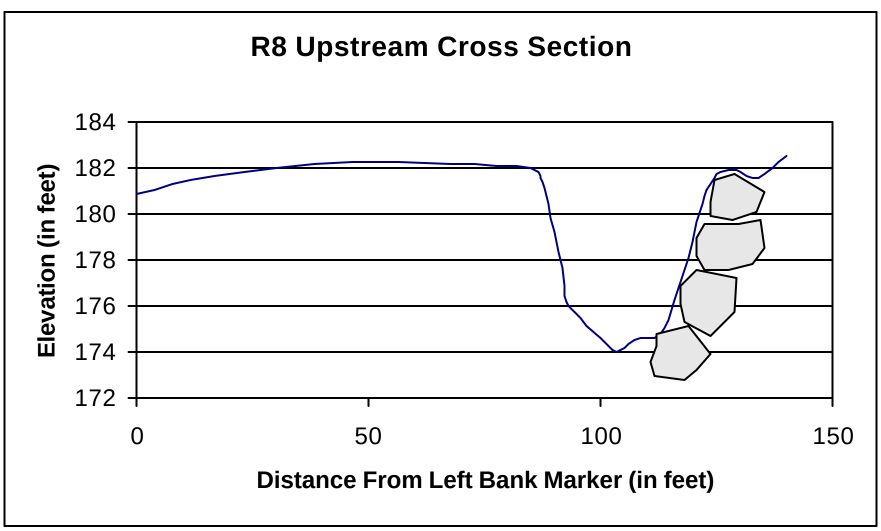

L10 Downstream and R7 Upstream Cross Section
Elevation (in feet)
184
182
180
178
176
174
172
170
168
0
20
40
60
80
100
120
Distance From Left Bank Marker (in feet)

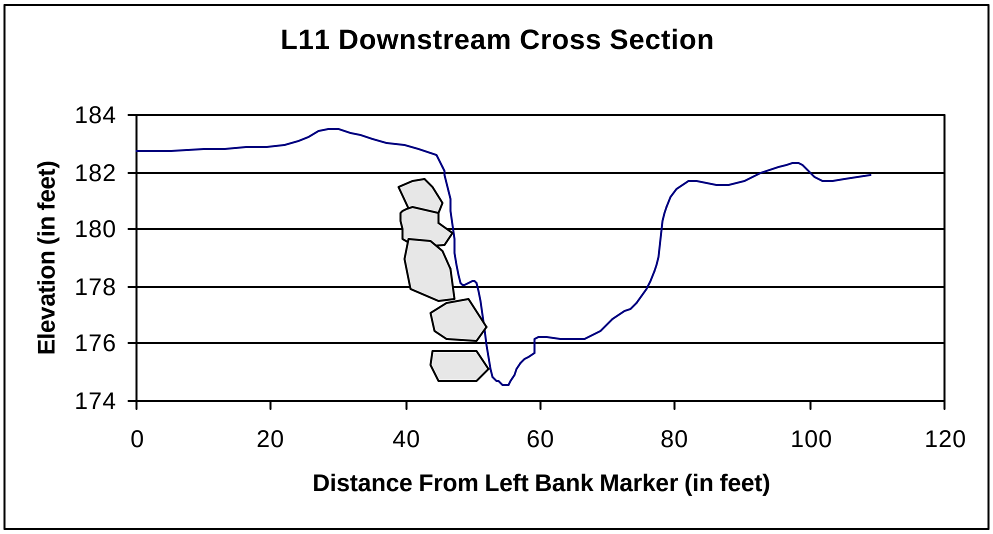

L10 Center Cross Section
Elevation (in feet)
182
180
178
176
174
172
0
20
40
60
80
100
120
140
160
Distance From Left Bank Marker (in feet)

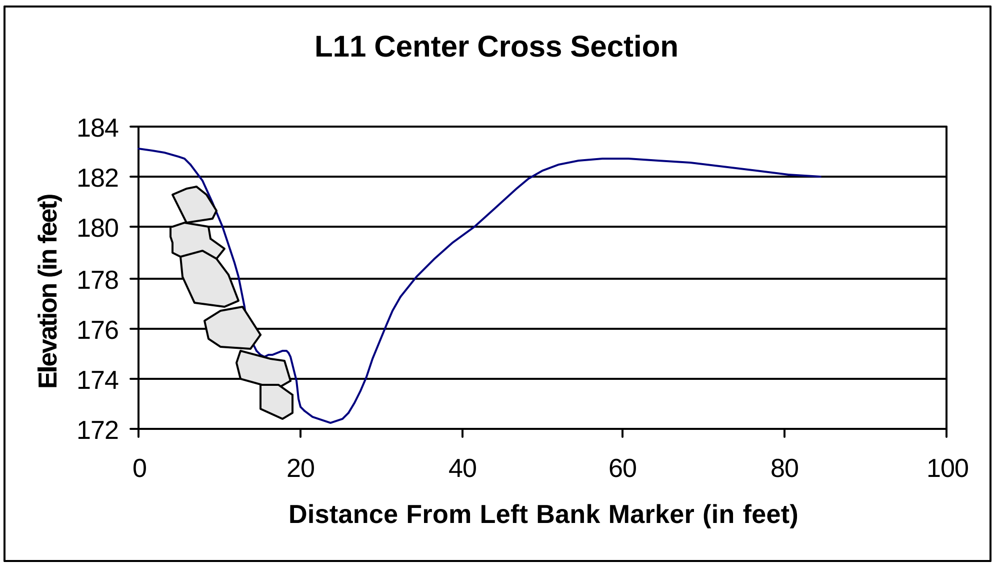

L10 Upstream Cross Section
Elevation (in feet)
182
180
178
176
174
172
0
20
40
60
80
100
120
140
Distance From Left Bank Marker (in feet)

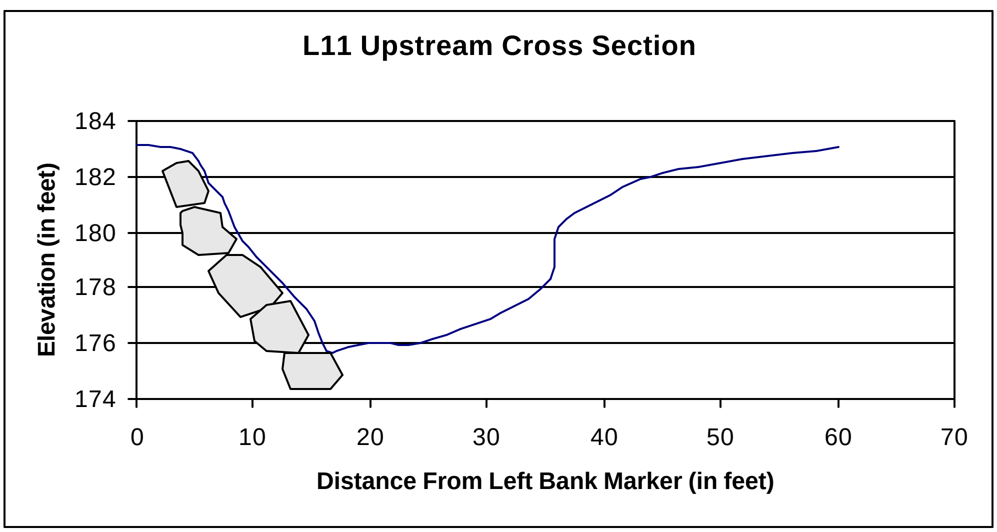

R8 Downstream Cross Section
Elevation (in feet)
184
182
180
178
176
174
172
0
50
100
150
200
Distance From Left Bank Marker (in feet)

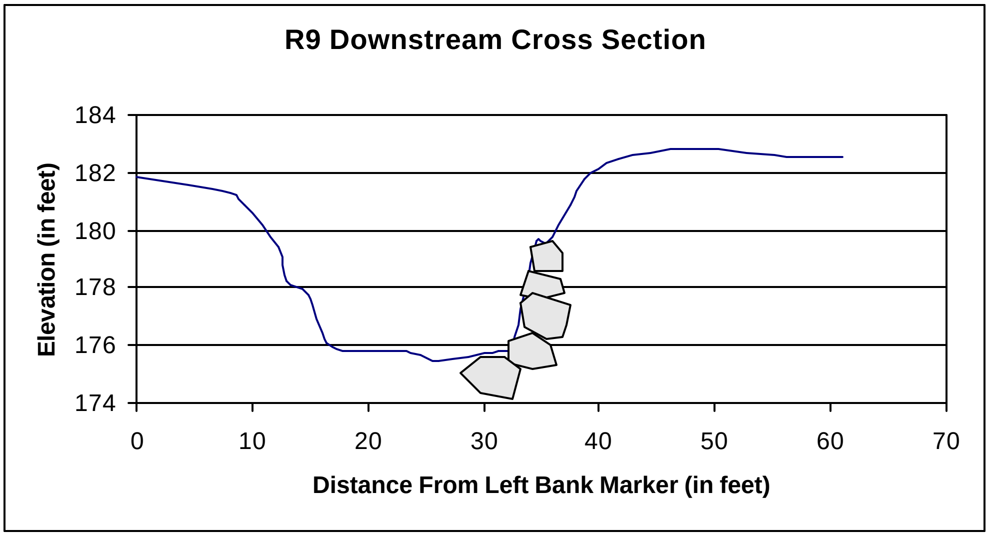

R8 Center Cross Section
Elevation (in feet)
182
180
178
176
174
172
0
50
100
150
Distance From Left Bank Marker (in feet)

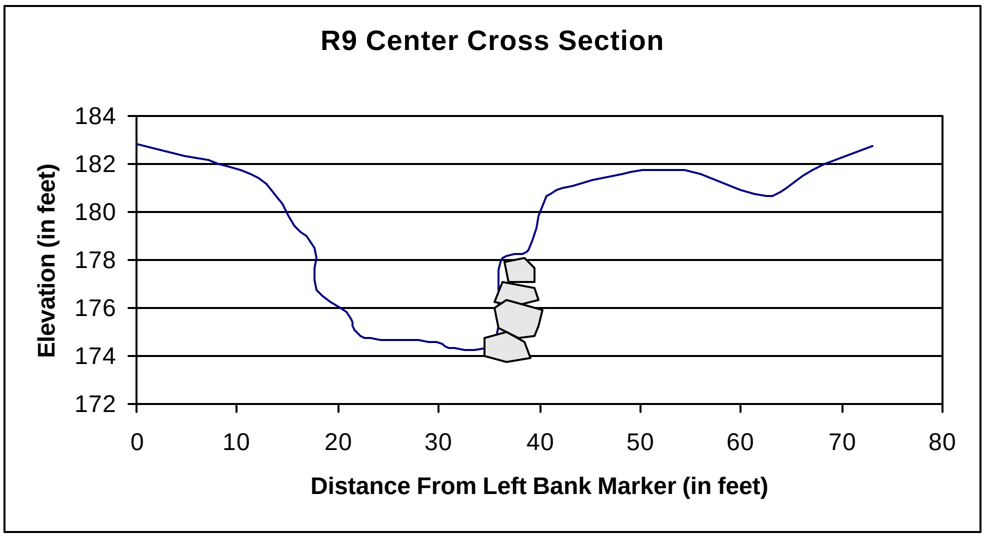

R8 Upstream Cross Section
Elevation (in feet)
184
182
180
178
176
174
172
0
50
100
150
Distance From Left Bank Marker (in feet)

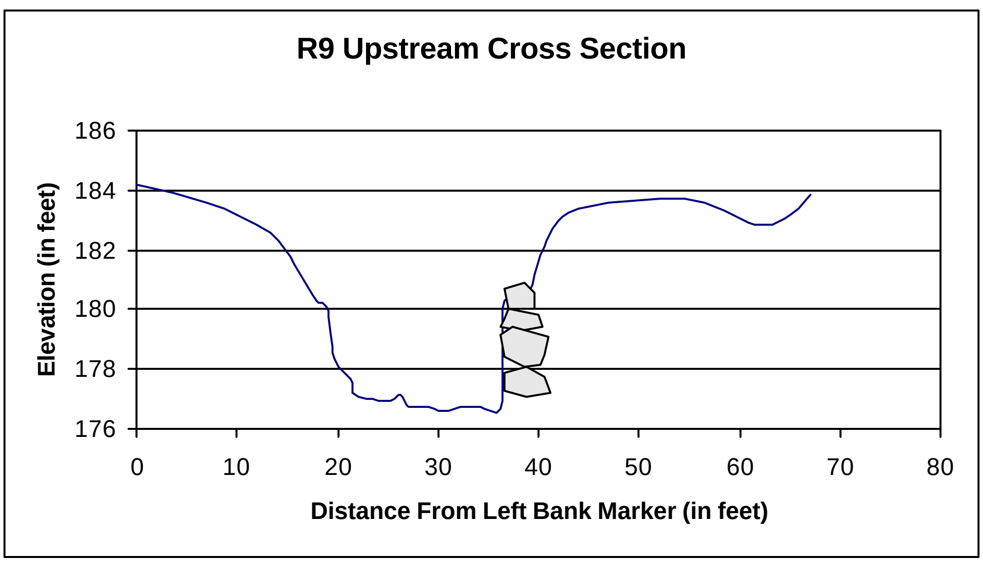

L11 Downstream Cross Section
Elevation (in feet)
184
182
180
178
176
174
0
20
40
60
80
100
120
Distance From Left Bank Marker (in feet)


L11 Center Cross Section
Elevation (in feet)
184
182
180
178
176
174
172
0
20
40
60
80
100
Distance From Left Bank Marker (in feet)


L11 Upstream Cross Section
Elevation (in feet)
184
182
180
178
176
174
0
10
20
30
40
50
60
70
Distance From Left Bank Marker (in feet)

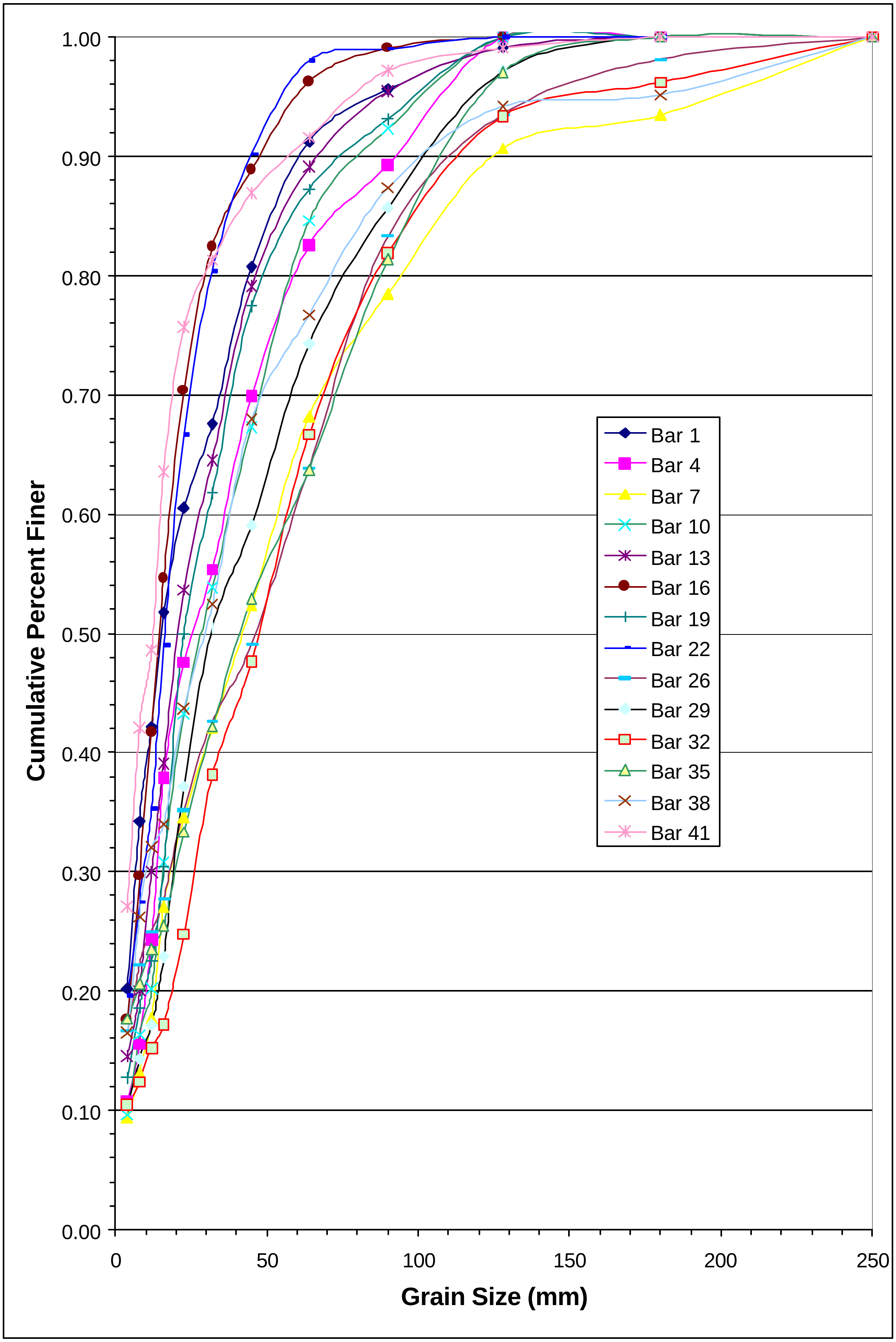

R9 Downstream Cross Section
Elevation (in feet)
184
182
180
178
176
174
0
10
20
30
40
50
60
70
Distance From Left Bank Marker (in feet)


R9 Center Cross Section
Elevation (in feet)
184
182
180
178
176
174
172
0
10
20
30
40
50
60
70
80
Distance From Left Bank Marker (in feet)


R9 Upstream Cross Section
Elevation (in feet)
186
184
182
180
178
176
0
10
20
30
40
50
60
70
80
Distance From Left Bank Marker (in feet)

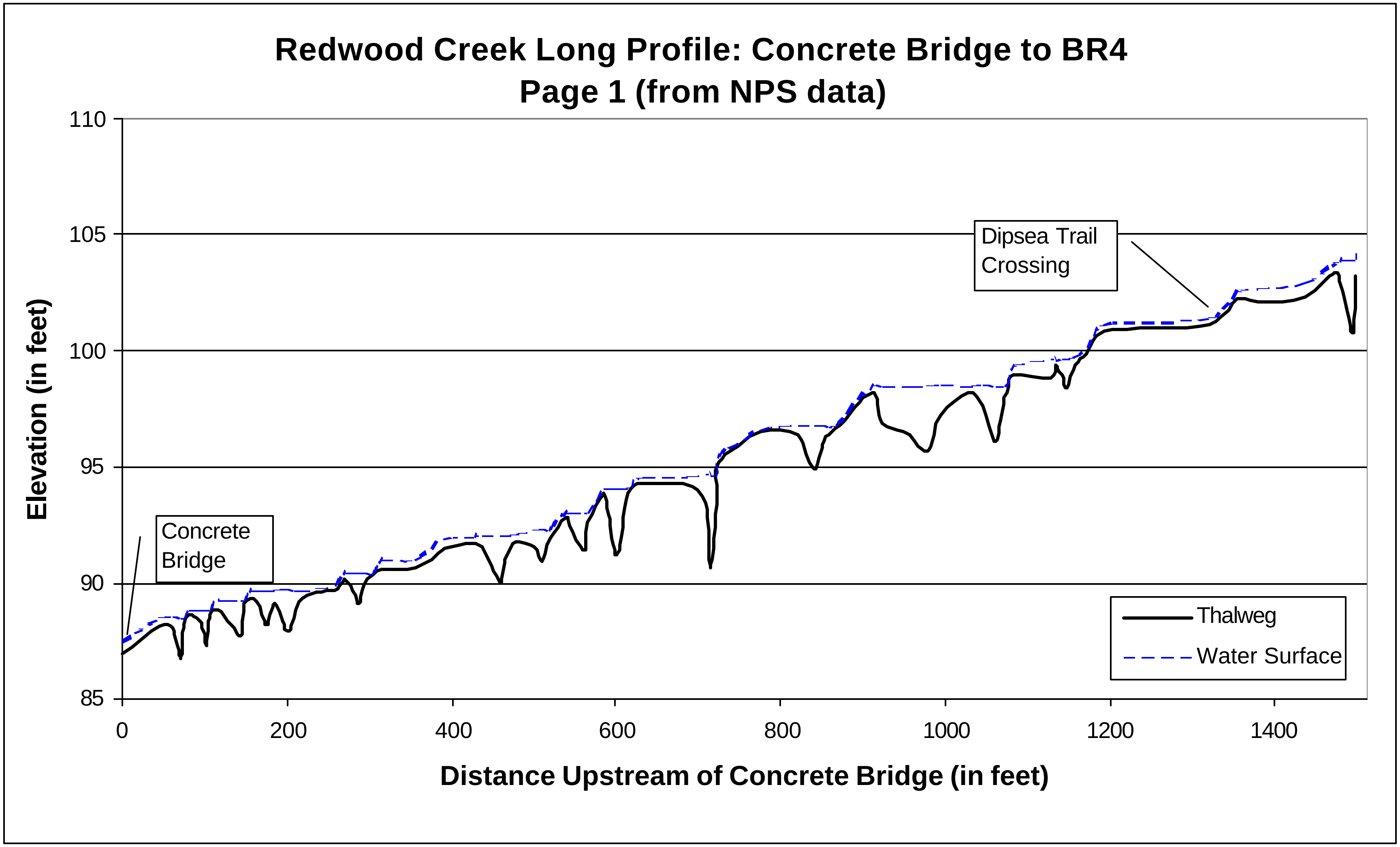
Appendix 3. Pebble Count Data

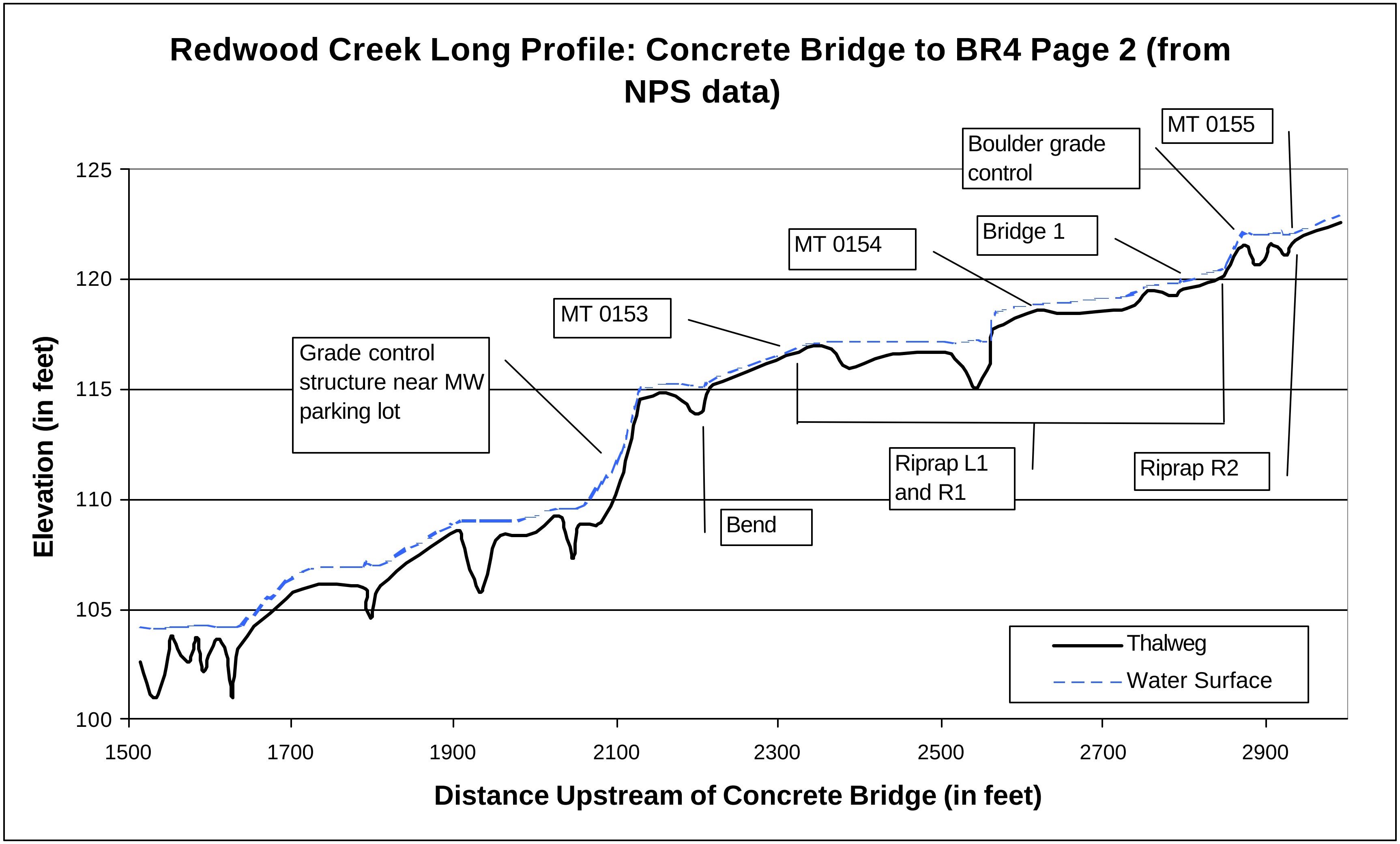
Starting from downstream park boundary moving upstream. Counting every third exposed bar. Bar numbers are noted on base map. Approximately 100 Pebbles counted per bar. Bar 25 was skipped due to high vegetation coverage.												
Bar #	<8mm	8mm	12mm	16mm	22.6mm	32mm	45mm	64mm	90mm	128mm	180mm	250mm+
1	23	16	9	11	10	8	15	12	5	4	1	
4	11	5	9	14	10	8	15	13	7	11		
7	10	4	5	10	8	8	11	17	11	13	3	7
10	10	7	4	11	13	11	14	18	8	8		
13	16	6	11	10	16	12	16	11	7	4	1	
16	19	13	13	14	17	13	7	8	3	1		
19	13	6	4	8	20	12	16	10	6	7		
22	20	8	8	14	18	14	10	8	1	1		
26	18	6	3	3	8	8	7	16	21	11	5	2
29	11	4	3	6	15	14	9	16	12	12	3	
32	11	2	3	2	8	14	10	20	16	12	3	4
35	18	3	3	2	8	9	11	11	18	16	3	
38	17	10	6	2	10	9	16	9	11	7	1	5
41	29	16	7	16	13	6	6	5	6	2	1	



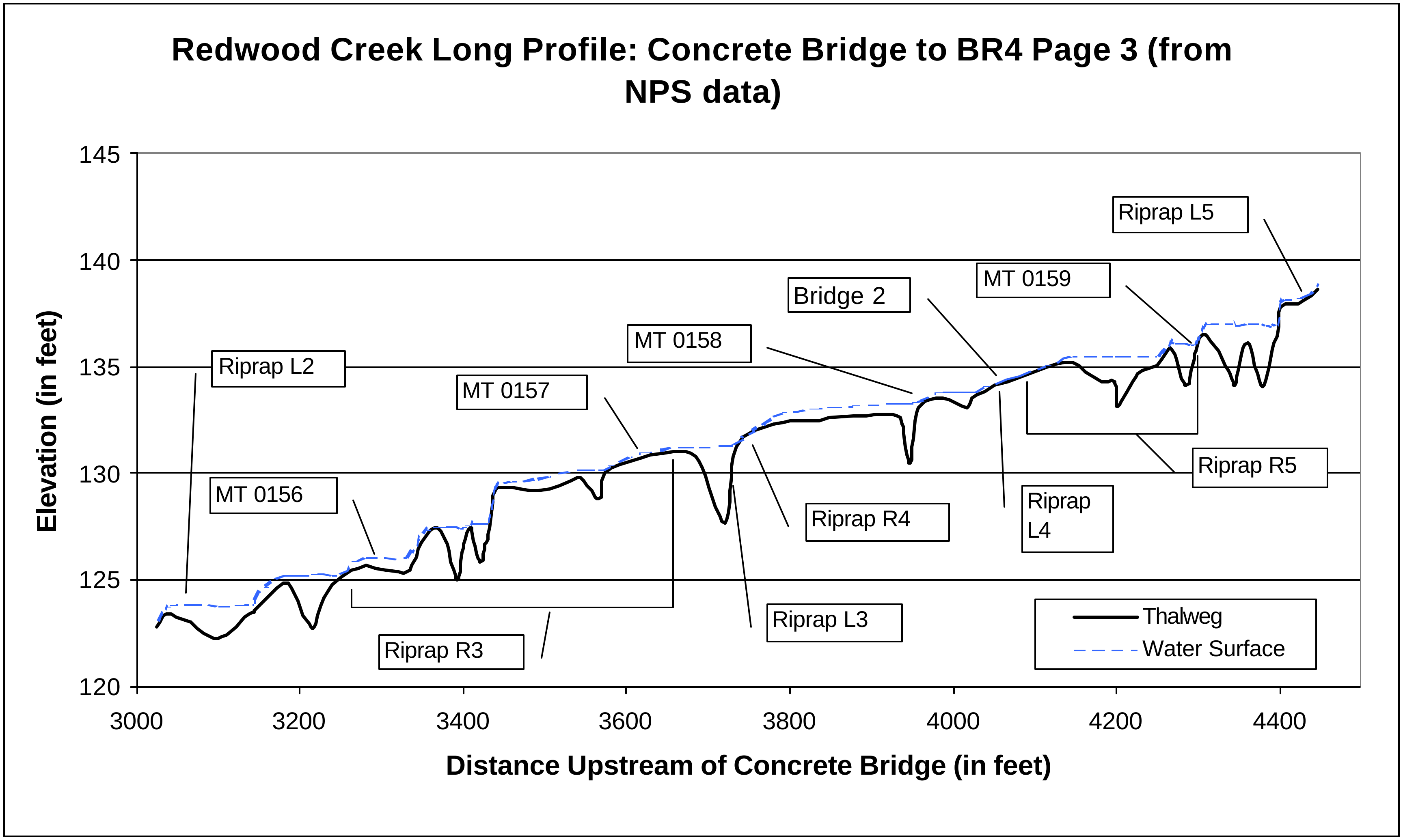
Cumulative Percent Finer
Grain Size (mm)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
50
100
150
200
250
Bar 1
Bar 4
Bar 7
Bar 10
Bar 13
Bar 16
Bar 19
Bar 22
Bar 26
Bar 29
Bar 32
Bar 35
Bar 38
Bar 41

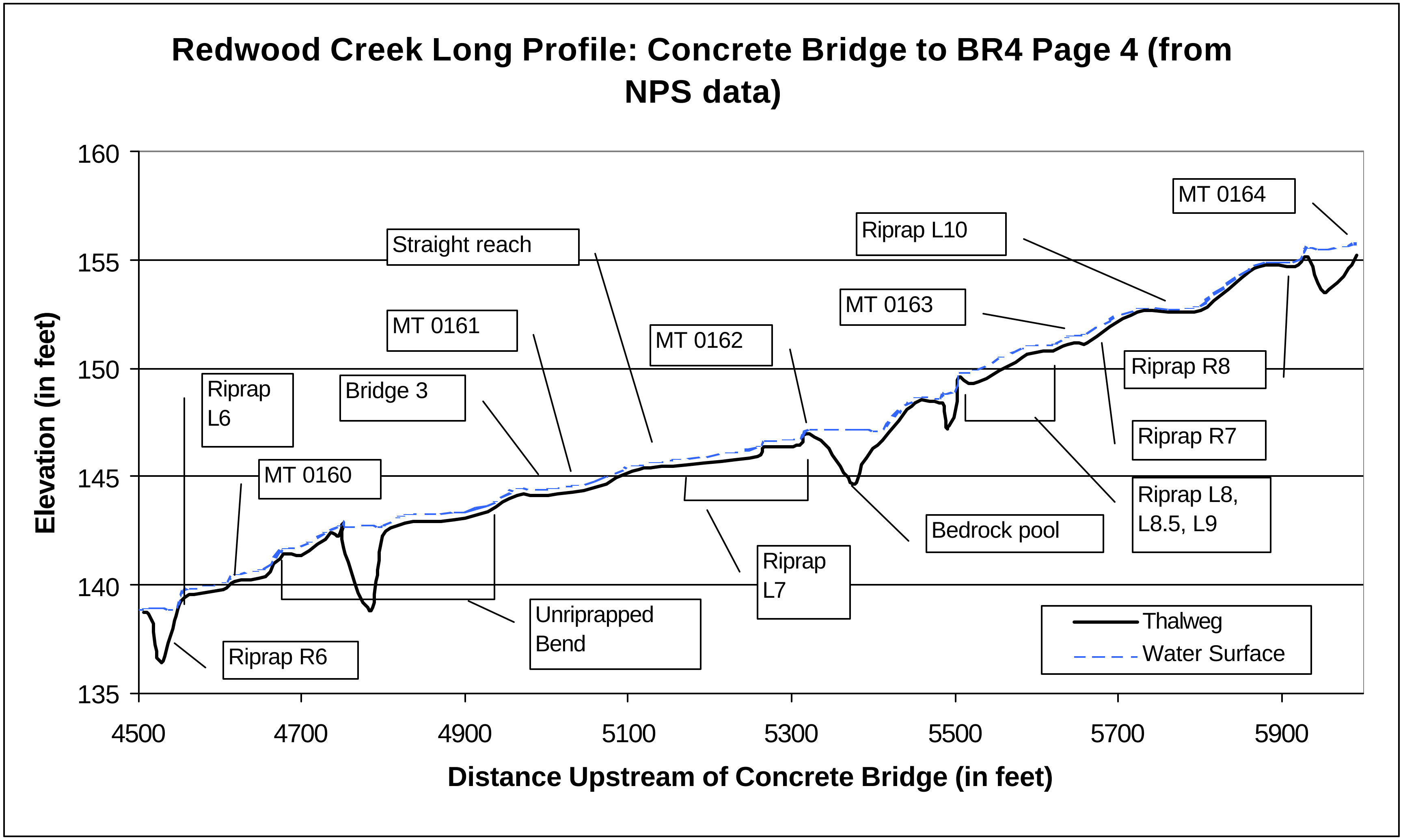
Appendix 4. Long Profile Plots



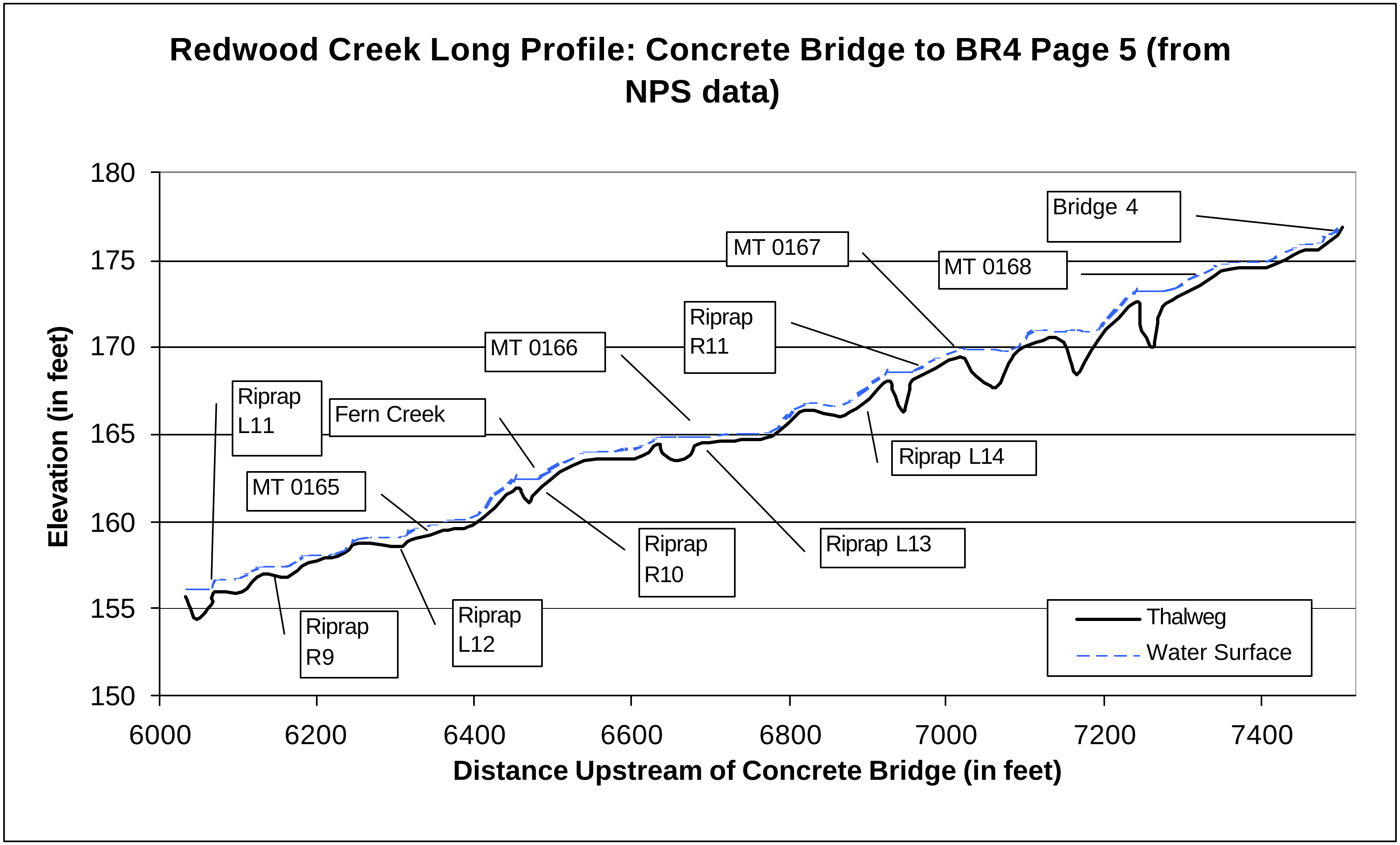


Redwood Creek Long Profile: Concrete Bridge to BR4 Page 2 (from NPS data)
Elevation (in feet)
Distance Upstream of Concrete Bridge (in feet)
125
120
115
110
105
100
1500
1700
1900
2100
2300
2500
2700
2900
Grade control structure near MW parking lot
MT 0153
MT 0154
Bridge 1
Boulder grade control
MT 0155
Bend
Riprap L1 and R1
Riprap R2
Thalweg
Water Surface

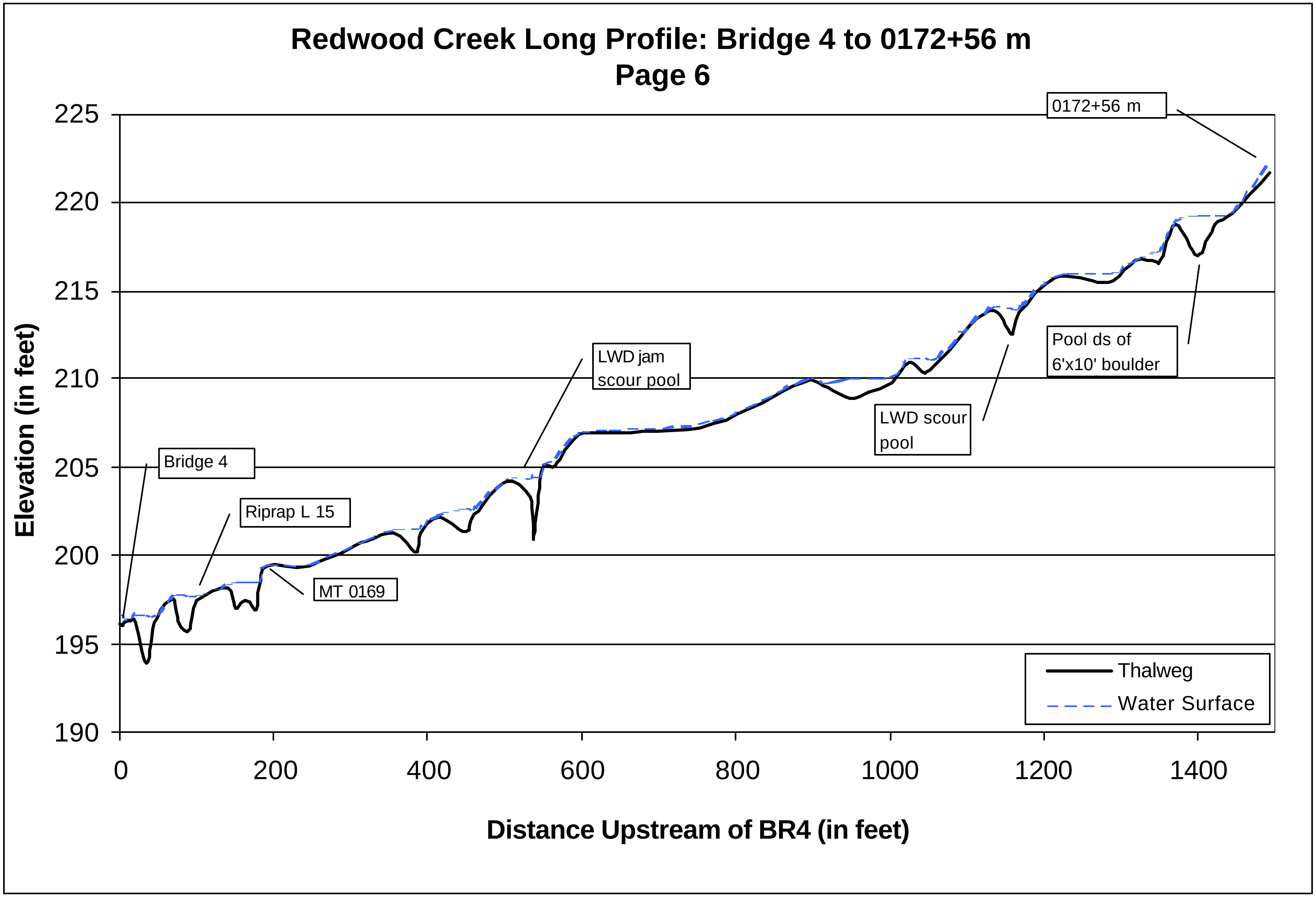

Redwood Creek Long Profile: Concrete Bridge to BR4 Page 3 (from NPS data)
Elevation (in feet)
145
140
135
130
125
120
3000
3200
3400
3600
3800
4000
4200
4400
Distance Upstream of Concrete Bridge (in feet)
Riprap L5
MT 0159
Bridge 2
MT 0158
Riprap L2
MT 0157
MT 0156
Riprap R5
Riprap R4
Riprap L4
Riprap L3
Riprap R3
Thalweg
Water Surface



Redwood Creek Long Profile: Concrete Bridge to BR4 Page 4 (from NPS data)
Elevation (in feet)
160
155
150
145
140
135
4500
4700
4900
5100
5300
5500
5700
5900
Distance Upstream of Concrete Bridge (in feet)
Straight reach
MT 0161
Bridge 3
Riprap L6
MT 0160
Riprap R6
Unriprapped Bend
MT 0162
Riprap L7
Bedrock pool
MT 0163
Riprap L10
MT 0164
Riprap R8
Riprap R7
Riprap L8, L8.5, L9
Thalweg
Water Surface



Redwood Creek Long Profile: Concrete Bridge to BR4 Page 5 (from NPS data)
180
175
170
165
160
155
150
Elevation (in feet)
6000
6200
6400
6600
6800
7000
7200
7400
Distance Upstream of Concrete Bridge (in feet)
Bridge 4
MT 0167
MT 0168
Riprap R11
MT 0166
Riprap L11
Fern Creek
MT 0165
Riprap L14
Riprap R10
Riprap L13
Riprap R9
Riprap L12
Thalweg
Water Surface



Redwood Creek Long Profile: Bridge 4 to 0172+56 m
Page 6
Elevation (in feet)
225
220
215
210
205
200
195
190
0
200
400
600
800
1000
1200
1400
Distance Upstream of BR4 (in feet)
0172+56 m
Pool ds of 6'x10' boulder
LWD scour pool
LWD jam scour pool
Bridge 4
Riprap L 15
MT 0169
Thalweg
Water Surface

Appendix 5. Aquatic Insects Sampling Data

Insect Family	RR 1	RR 2	RR 3	RR 4	RR 5	NB 1	NB 2	NB 3	NB 4	NB 5	Bed 2	Bed 3	Bed 4
Coleoptera Dytiscidae (P)						1							
Coleoptera Elmidae (C/G)						13	1	3	2	2		3	
Coleoptera Psephenidae (Sc)	2							1	2		2		
Collembola Poduridae (C/G)	5	6	2	4	1		1	7	5	1			
Collembola Sminthuridae (C/G)				1									
Diptera Athericidae (P)						2					1		1
Diptera Ceratopogonidae (P)	1	1	6	1		8	18	4	10	7		17	4
Diptera Chironomidae (C/G, few P)	20	6	7	18	4	192	39	144	337	28	487	529	76
Diptera Dixidae (C/G)	1		1	4	1	1	1	5	4	2			1
Diptera Dolichopodidae (P)										1			
Diptera Empididae (P)									1				
Diptera Pelecorhynchidae (P)								2					
Diptera Psychodidae (C/G)	12	3		2		1	1	2		1	1	1	1
Diptera Stratiomyidae (C/G)						1							
Diptera Simuliidae											2	7	1
Diptera Tanyderidae (?) (u)										1			1
Diptera Tipulidae (Sh)	1			1			1	1	2	1			3
Ephemeroptera Baetidae (C/G)		1	1	4	1			1	2		451	121	8
Ephemeroptera Ephemerellidae (C/G)	7		2			14					4	14	6
Ephemeroptera Heptageniidae (Sc)		1	1								5	19	2
Ephemeroptera Leptophlebiidae (C/G)			3			33	5	13	42	2	13	6	1
Ephemeroptera Siphlonuridae (C/G)			1										
Hemiptera Gerridae (P)						2							
Hemiptera Saldidae (P)							A						
Hemiptera Veliidae (P)	1	1						1			4		
Insect Family	RR 1	RR 2	RR 3	RR 4	RR 5	NB 1	NB 2	NB 3	NB 4	NB 5	Bed 2	Bed 3	Bed 4
Megaloptera Sialidae (P)									1				
Odonata Aeshnidae (P)						1							
Odonata Gomphidae (P)									1	1		1	

Odonata Cordulegastridae (P)						332	5	34	10				
Plecoptera Capniidae											5	15	21
Plecoptera Nemouridae (Sh)		2		2		6	9	6	9	4	141	27	6
Plecoptera Perlidae (P)				1									
Trichoptera Calamoceratidae (Sh)						4			1				
Trichoptera Hydropsychidae (C/F)						1							
Trichoptera Lepidostomatidae (Sh)	7					1						4	
Trichoptera Odontoceridae (Sh)								2					1
Trichoptera Polycentropodidae (C/F)			1	1				5			1	3	
Trichoptera Sericostomatidae (Sh)						2							
Total # Insect Individuals	57	21	25	39	7	615	82	231	430	51	1117	767	133
Total # Insect Families	10	8	10	11	4	18	11	16	16	12	13	14	15

Primary feeding groups according to Merritt and Cummins (1996) P=Predator C/G=Collector-Gatherer Sc=Scraper Sh=Shredder C/F=Collector-Filterer (u)=unknown

RR=Riprap Samples NB=Natural Bank Samples Bed=Bed Samples

Large Woody Debris Literature Review Table	
AUTHORS / METHODS	**RESULTS**
CHERRY, J. AND R. L. BESCHTA, 1989 Flume experiment using wooden dowels to model scour from placement of LWD. Flume dimensions were 6.1 m long, 0.4 m bottom width, 2:1 side slopes, and 0.008 slope. Sand was used as substrate with flow ranges of 1.1-2.8 l/s for runs of 7.5 hours. Dowels were 1/10-1/100 actual LWD sizes and modeled in different orientations for 28 runs.	Dowels placed flat on bed - Pool along entire length and pool thalweg near its middle regardless of orientation, more scour downstream. Greatest scour for these was with dowels perpendicular to flow (è = 90°), next greatest when oriented upstream (è = 150°). When oriented upstream, most scour was at base close to channel bank and bank erosion increased when dowel was submerged. Dowels with one end resting on the bank – Tended to have more localized scour than flat dowels. Scour usually farther from the bank, with pool thalwegs from the middle to the end of the dowel. Greatest pool area was with the dowel perpendicular to flow. In general, dowels oriented upstream had deep scour and increased potential for bank erosion. Dowels perpendicular or oriented downstream were thought to be more stable with less bank scour and less potential to move. Downstream dowels deflected scour form the bank. Perpendicular dowels had the most scour.
BESCHTA, R. L., 1983 Flume experiment using 6-20 cm cylinders to analyze changes in bed morphology from LWD installation. Looked at the effect of water discharge, LWD diameter and elevation above the bed on the size of pools created.	Depth of scour increased with increased discharge. Maximum scour depth occurred when flow overtopped the cylinders but typically did not increase with further increased flows. Pool thalweg tended to move downstream with increased flows. Pools were larger and deeper with large pieces or multiple pieces of LWD elevated above the bed than single pieces.
Hilderbrand, R. H., A. D. Lemly, C. A. Dolloff, and K. L. Harpster, 1998 and Hilderbrand, R. H., A. D. Lemly, C. A. Dolloff, and K. L. Harpster, 1997 Installed LWD both systematically and randomly in two 250 m test sections on the North Fork Stony Creek in southwestern VA to test the effects on pool formation, fish habitat, and macroinvertebrate habitat and to test LWD orientation and stability. Stony Creek has a slope	Barbours Creek – little change from pre-treatment conditions. 2 pools formed underneath logs perpendicular to the channel in the randomly placed section, but 2 other pools were converted to riffles, leaving no net change. No change in the systematic test section. Stony Creek - Rates of log stability were the same in both test sections with no variables influencing movement however, for both sections, logs longer then 1.5-2 times the

of 1%, 5 m width and a sandstone bed with cobles, gravels, and sand. The systematic test section had LWD placed to deliberately alter stream habitat, the random section was aimed at imitating natural log drop. Quantified changes in bed through cross sections. Authors note that sample sizes were small and results only trends. Also installed LWD in high-gradient Barbours Creek with 3-6% slope and 5 m average width.	channel width (7.5 m long) were less likely to move than logs shorter than 5.5 m. Single logs and log jams moved with the same frequency and jams tended to stay together. Longer logs tended to move either shorter distances (2 m) or longer distances (20 m), implying that they are more stable, but once moving have greater momentum. Logs with one end resting on the bank-upstream and downstream oriented logs had scour in the middle cross section and aggradation in the upstream and downstream cross sections. Most scour was downstream of the logs and along the banks. Upstream facing logs had scour on both sides of the channel. Logs flat on the bed – The 7 pools formed in the study were with logs flat on the bed. Logs placed at an angle to the flow had aggradation on both sides of the channel and upstream of the log with scour downstream of the log. Perpendicular logs had scour in a diagonal pattern with some aggradation. Found average elevation change to be the same, implying redistribution of substrate; that aggradation at one area of the cross section was balanced by degradation at another. They also noted possible longitudinal redistribution by the logs trapping sediment coming from upstream while losing some sediment to scour. This could mean no net increase in sediment transported downstream. Overall found pools were created by LWD laying flat on the bed and single logs were more influential than log jams. Recommend using logs with branches or root wads because they are less mobile and using decay-resistant tree species from outside the riparian area to conserve future LWD supply.

SCHMETTERLING, D. A. AND R. W. PIERCE, 1999

Installed 66 LWD and boulder structures in the lower 4.8 km of Gold Creek in western Montana to increase pool frequency and channel complexity. Gold Creek is a third order stream with a drainage area of 98.6 km^2. The test section had 2 channel types, which were characterized using the Rosgen classification system (B and C-type channels). The B channel was laterally confined with cobble and gravel substrate and the C channel was laterally extended, slightly incised and sinuous. In the B-type channel, installed configurations were 5 debris collectors, 23 log dams, 6 lateral scour, and 13 rock-formed pools. In the C-type channel, configurations were 6 log dams, 8 lateral scour, and 5 rock-formed pools. Structures were installed and pools were excavated using a track-mounted excavator. Pools and structures were surveyed before and after a 50-year flow and success of the structure to withstand the flow was determined by whether the structure was intact and the pool twice as deep as the adjacent riffle.

55 of the structures were determined to be intact after the 50-year flow. Structures and pools in the B-type channel were more successful than those in the C channel attributed to the sinuosity of the C channel. Logs set at least 2 m into the bank were more successful than logs not set as deeply. Logs installed for cover were also attributed with areas of lower velocities, which can be refugia for fish.

Debris collection structures resulted in downstream scour and shallow backwater areas. They had less impact on the channel during placement because pools were not excavated.

The authors noted that installation of LWD structures and pools is not sustainable in the long-term unless there is LWD recruitment through natural processes.