WATERSHED REHABILITATION IN REDWOOD NATIONAL PARK AND OTHER PACIFIC COASTAL AREAS

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Edited by R.N. Coats

CENTER FOR NATURAL RESOURCE STUDIES OF JMI, Inc.
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PREFACE

With the expansion of Redwood National Park in 1978, the National Park Service embarked on an ambitious program to rehabilitate disturbed and cut-over forest lands on steep and highly erodible terrain in the basin of Redwood Creek, Humboldt County, California. Fortuitously, this program has coincided with a period of rapidly growing interest among watershed scientists, land managers and practitioners in the problems, processes and limitations of steep forested lands. In keeping with the National Park Service's long tradition of respect for basic research, the watershed rehabilitation program at Redwood National Park has played an important role in the growth of the professional "watershed community", and has contributed valuable information on both specific rehabilitation techniques and basic watershed processes. The purpose of this volume is to bring into focus both the recent work of the Park's rehabilitation program and other work relevant to the problem of maintaining and restoring watershed values in Pacific coastal areas. It complements the collection of "Readings in Watershed Management and Rehabilitation" which was distributed at the August 1981 Symposium.

The papers in this volume are organized into five sections. These are: 1) Processes and issues relating to watershed rehabilitation; 2) Restoring vegetation for erosion control and natural succession; 3) Hillslope processes and rehabilitation techniques; 4) Stream channel processes and fisheries restoration; and 5) Management alternatives, case studies and cost effectiveness. The flow of papers is meant to follow the flow of both watershed and thought processes that managers go through when grappling with the problem of watershed rehabilitation in steep forested lands.

ACKNOWLEDGEMENTS

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Taylor Miller, Laurel Collins, Joan Florsheim and Patti Kolb of the Center for Natural Resource Studies all contributed to organization and administration of the Symposium and publication of the Proceedings. David Nagler and Sue Breitenbach of J. Lewis Associates and William Israel and the staff of the Jolly Giant Conference Center provided invaluable assistance with Symposium arrangements and facilities.

We extend our sincere appreciation to the National Park Service Western Region and the technical and clerical staff of Redwood National Park for their enthusiastic support of the Symposium and tireless efforts to make it a success. We particularly thank Howard Chapman, Director, John Davis and Gerard Witucki of the National Park Service Western Regional Office and Robert Barbee, Redwood National Park Supervisor for their support and interest, and Lee Purkerson, Bill Weaver, Lisa Babcock, Danny Hagans, and Ron Sonnevil for technical assistance in conducting the Symposium and field trip.

Of course, we must especially thank the participants in poster session and panel discussions at the Symposium and authors of the papers which follow for making the effort to share their experience in the emerging field of watershed rehabilitation.

Robert N. Coats, Editor

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WATERSHED REHABILITATION: A PROCESS VIEW

Robert R. Ziemer [1]

ABSTRACT

The most effective control of erosion, in both physical and economic terms, is through prevention because once natural erosion is accelerated, corrective action is not only expensive but seldom entirely successful. To control erosion it is important to understand the forces that cause material to move or resist movement. Once the forces and processes of erosion are understood, proposed erosion control measures can be evaluated for anticipated effectiveness. The successful control of erosion is as much a philosphical and political problem as a technical one.

INTRODUCTION

Earth scientists often look only at the physical processes of watershed rehabilitation. And yet, land management decisions are as much based on economic, social, and political processes as on physical processes. This paper provides a glimpse into how these diverse processes interact to influence erosion and subsequent rehabilitation efforts.

Rehabilitation is the restoration to a former state or capacity. Implicit in the term is the assumption of a degraded condition. In wildlands, the greater the degradation, the greater the public visibility and, therefore, the greater the pressure for restoration or rehabilitation. Unfortunately, the greater the perceived "need" for rehabilitation, the lower the probability that rehabilitation efforts will be successful. Thus, this dilemma: The greater the public outcry that "something be done," the smaller the opportunity to actually succeed.

The public perceived that portions of Redwood National Park and surrounding areas had reached an advanced state of degradation. Accordingly, Congress, through P.L. 95-250, directed the Secretary of the Interior to undertake "the rehabilitation of areas within and upstream from the park contributing significant sedimentation because of past logging disturbances and road conditions ... [and to] undertake and publish studies on erosion and sedimentation originating within the hydrographic basin of Redwood Creek with particular effort to identify sources and causes, including differentiation between natural and man-aggravated conditions, and shall adapt his general management plan to benefit from the results of such studies" (Public Law 95-250, Sec. 101[a][6]).

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Generalizations about the control of erosion are both difficult and risky to make. It is usually possible to find as many examples in which a generalized erosion control measure is ineffective as in which it is effective. To control erosion it is important to understand the forces that cause material to move or resist movement. Once the forces and processes of erosion are understood, proposed erosion control measures can be evaluated for anticipated effectiveness.

The most effective control of erosion is through prevention because once natural erosion is accelerated, corrective action is not only expensive but seldom entirely successful. In Redwood National Park, the opportunities for prevention of erosion may be limited, but not entirely lacking. In most of the Pacific coastal region, however, active prevention rather than rehabilitation is the most effective means to control accelerated erosion.

Much of the concern over erosion from forested coastal areas is directed more to the degradation of stream resources by the eroded material than to the loss of soil and nutrients from hillslopes. Consequently, erosion management is often deemed successful if eroded material does not enter a stream. Furthermore, it is often commonly assumed that ground disturbance and erosion are closely correlated, and that soil detachment and movement increase the likelihood that sediment will be transported to and by a stream. Such assumptions are usually weak links in understanding and controlling erosion.

Rehabilitation of areas eroded by simple processes is likely to succeed, but a similar effort aimed at complex erosional processes is likely to fail. Consequently, managers tend to concentrate rehabilitation efforts on the simple processes and ignore the complex processes that require detailed on-site geophysical study. Unfortunately, successful control of the simple process may represent only a minor and insignificant portion of the total erosion within a steepland watershed.

This paper discusses how some interactions of climate, soil, geology, topography, and vegetation can affect erosion processes, and describes three types of erosion: surface, channel, and mass erosion. Each type can occur singly, but more commonly erosion of Pacific coastal areas is a composite of the three.

TYPES OF EROSION

Surface Erosion

Surface erosion is characterized by the lack of permanent channels. Sheet and rill erosion are forms of surface erosion in which individual soil particles are moved by raindrops, thin film flow, and concentrated surface runoff. In undisturbed coastal forests, surface erosion is generally insignificant because infiltration rates usually exceed rainfall intensities and the soil surface is protected by forest litter. Disturbance by logging, road construction, wildfires, or mass erosion, however, exposes mineral soil where the naturally high porosity of forest soils may be severely reduced by raindrop impact and compaction by heavy equipment. Fire can also produce water repellency in soils (DeBano 1981). If the flow of water over bare areas is not controlled, surface erosion may progress from sheet to rill and then to channel erosion as gullies are formed.

The best known method for predicting surface erosion is the Universal Soil Loss Equation developed for agricultural lands in the Midwest by the Soil Conservation Service, U.S. Department of Agriculture (Foster 1977). Attempts to apply it to steepland forest areas generally have been unsuccessful--mainly because of inappropriate basic assumptions (Wischmeier 1976). Most erosion from forests is not the result of sheet overland flow.

Many techniques have been developed to control surface erosion, including contour terracing, grass seeding, and mulching. These methods are intended to reduce both raindrop impact and the energy of surface sheet wash, and to create a root network to hold individual soil particles in place. Water bars on roads or skidtrails serve as a form of contour terracing used to reduce the concentration of surface runoff and to prevent surface erosion from becoming channel erosion. More effort has been devoted to reducing man-induced surface erosion in forested steeplands than to any other form of erosion because it is the most easily controlled. But surface erosion is the least important of the erosion types found in Pacific coastal forests (Kelsey, et al. 1981).

Channel Erosion

Channel erosion is the detachment and movement of material from a gully or stream channel. The material may be individual particles derived from the channel skin, or it may be material previously deposited in the channel by surface or mass erosion. The amount of erosion may be directly related to the amount and size of material being transported within the channel. This condition is evident particularly in channels where energy available to transport material and the supply of that material are at an equilibrium. If the supply is decreased below the transport capability, the channel bed tends to erode. If the supply of particles to a stream is increased, the transport capability may be exceeded, and net channel bed erosion ceases while the channel aggrades. As channel beds aggrade, bank erosion may be accelerated if the stream is directed against vulnerable banks by the aggraded bed. In forested steeplands, however, there is commonly an energy excess and a supply deficiency--at least for the smaller grain sizes (Rice, et al. 1979). Channel erosion in forested steeplands is related more to the resistance of the bed material to erosion than to the availability of energy to transport that material.

Some steepland channels become unstable only when an energy threshold is exceeded. Erosion resistance may be provided by a bed composed of relatively large particles, commonly called an armor layer, and by the incorporation of large organic debris into the channel. Organic debris reduces the local channel gradient and creates a stepped channel where energy is spent as turbulence when water cascades over successive logs into pools. Upstream of these logs is a flat reach containing readily transportable material. If the large particles or logs are moved, as by the process of high discharge or by decay of the organic debris, erosion can proceed rapidly until new bed resistance is encountered (Beschta 1979, Bryant 1980).

Finally, some steepland channels may be rapidly eroded at a rate dependent upon the energy supply. An example of such channels are newly forming and transient gullies in mass erosion terrain.

Land management activities influence channel erosion principally by the following: placing readily erodible material in existing channels; introducing large organic debris into small channels; increasing surface runoff from bare and compacted soils; modifying the surface microdrainage network by roads, tractor trails, and ditches; and converting subsurface drainage to surface runoff (i.e., by intersecting subsurface flow with road cuts). When the existing drainage network is modified, some channels may receive less water while others receive more. Erosion would be expected to decrease in the channel with reduced flow and increase in the channel receiving the additional water. If water is routed from an actively eroding channel to a resistant one, however, net channel erosion could be reduced.

A common control measure to reduce channel erosion is to increase the particle-size of the material in the bed and channel margins sufficiently so that the stream can no longer transport the material. To be successful, particles must be large enough to withstand the energy of large stormflows and be sufficiently extensive to prevent undercutting. If either condition is not met, this effort to control channel erosion will be unsuccessful.

Stepped erosion-resistant channels have successfully been created by using artificial check dams to control channel erosion. In steep channels, this practice is an expensive measure because the dams must be closely spaced to prevent accelerated erosion between dams and subsequent failure of the dam by undercutting.

Mass Erosion

Mass erosion is the downslope movement, *en masse*, of soil or rock, in response to gravitational stress. In steeplands, mass erosion includes a large variety of processes that range from slow and subtle deformation of the soil mantle (creep) to rapid, discrete failure of hillsides (debris avalanche) and stream channels (debris torrent). In undisturbed forested steeplands, mass erosion is the dominant mechanism by which soil is transported from hillslopes to stream channels. Land management activities can dramatically increase the probability of certain types of mass erosion, but influence other types only slightly (Swanston 1976).

Creep is the slow downslope movement of the soil mantle where the long-term gravitational shear stress is large enough to produce permanent deformation but too small to cause discrete failure. Creep is the most common and widespread mass erosion process in steeplands, but is the least understood and documented. It occurs at varying rates and depths in all sloping cohesive soils. Changes in the rate of creep of a given slope seem to be correlated with changes in the piezometric level in the slope. Measurements of borehole deformation in a variety of geologic materials in Pacific coastal forested areas suggest annual creep rates of less than 10 mm/yr. These rates vary widely with climatic stress even within the same geologic material (Swanson and Swanston 1977). Measurements in the Redwood Creek basin show a definite seasonality in the rate of creep. The deformation rate of some boreholes is highly correlated with the amount of winter precipitation, while the deformation of other boreholes seems independent of precipitation. Consequently, the effect of land management on creep rates is poorly documented.

Although management-induced changes in creep rate may be nearly impossible to measure, the quantity of material delivered by creep to the numerous stream channels in the area can be large. For example, if timber cutting increased the average creep rate in a catchment from 3 to 10 mm/yr, the change would probably not be noticed--even by detailed hillslope observation. But the quantity of soil added to stream channels would be trebled, and the change in sediment transport may be easily detected. In ephemeral streams, soil may be delivered continuously to channels throughout the year but is transported from the channels only during large storms as episodic pulses.

Earthflow can be considered accelerated creep where shear stress exceeds the strength of the soil mantle and results in discrete failures. These failures may range from less than a hectare in area and a meter in depth to several square kilometers in area and tens of meters in depth. The rate of movement of earthflows, as of creep, may be imperceptibly slow, but can exceed a meter per day (Kelsey 1980). Movement may be continuous, seasonal, or episodic. Like creep, deep-seated earthflows may be affected little by timber cutting or road building unless the distribution of mass or water within the slide is changed substantially. The distribution of mass can be changed by excavations that undercut the toe of the earthflow, removing downslope support. Road fill can add mass to the head of an earthflow, adding to the gravitational forces contributing to slope failure. Roads can also modify the water relations within the earthflow. Road cuts can intercept subsurface flow. If this water or surface road drainage is diverted away from the earthflow, the slide below the road may become more stable. If water is diverted onto the slide, dormant earthflows may be reactivated. Timber cutting can also modify the internal water relations of the earthflow.

Evapotranspiration by forests may deplete 50 to 75 cm of soil moisture per year (Ziemer 1981). In a Mediterranean-type climate having warm, dry summers, a substantial soil moisture deficit can reduce both piezometric head and the slide mass. Vegetated dormant landslides may be reactivated if the forest cover is removed. This step effectively adds water normally removed from the slope by evapotranspiration. The more active earthflows are often moving too rapidly for trees or other deep-rooted perennial vegetation to become established.

The potential effect of land use manipulation on earthflows is correlated with the scale of both the earthflow feature and the activity. A small tractor trail crossing a massive earthflow would have less effect than a large road undercutting a small, shallow potential failure surface.

There are interactions and feedback mechanisms between erosion types. In some cases, channel incision undercuts the toes of earthflows, upsetting the balance of forces on the hillslope. In other cases, aggradation with accompanied increases in bank erosion undercuts the toes of earthflows. In small, steep streams, incision is more common than aggradation, while in large, low-gradient streams, the reverse is true. Accelerated earthflow erosion, in turn, can modify other types of erosion.

Debris avalanches are rapid, shallow hillslope failures generally found in shallow noncohesive soils on steep slopes where subsurface water concentrates. Plant roots can reduce the frequency of these shallow failures. Roots can anchor through the soil mass into fractures in bedrock. They can also develop lateral support by crossing zones of weakness to more stable soil as well as providing long fibrous binders within a weak soil mass. In deeper soils, root-anchoring to bedrock becomes negligible, but the lateral support by roots remains. In marginally stable areas, debris avalanche frequency may increase after trees are cut, as their root systems progressively decay (Ziemer 1981). Depletion of soil water by evapotranspiration requires additional rainfall to saturate the slope. Debris avalanches occur primarily during periods of rapid snow melt or high rainfall when piezometric levels are high (Swanston 1970). Once soil moisture deficits are satisfied and the soil is saturated, the influence of winter evapotranspiration on soil water becomes negligible. In unaltered forest soils, subsurface water often quickly flows through interconnected root channels and other macropores. But if forest soils are disturbed, these subsurface conduits can collapse or become plugged, delaying drainage, increasing piezometric levels, and resulting in slope failure.

Although many studies have documented debris avalanche erosion after logging, road building appears to increase the frequency of debris avalanches much more than does timber cutting. In addition to profoundly affecting the soil water regime, road cuts can intersect and undercut the shallow failure surface. And road fills can add a substantial mass surcharge to the slope. These effects become relatively less important as the depth to the failure surface increases.

<u>Debris torrents</u> are the failure and rapid movement of water-saturated soil, rock, and organic debris in small, steep stream channels. Debris torrents might be considered a transitional link between mass erosion caused by a debris avalanche, and channel erosion. They typically occur during periods of high precipitation and streamflow. They may be started by a debris avalanche that enters the channel, or they may result from an initial failure of accumulated debris within the channel. Typically, as debris from the initial failure moves downslope, it entrains large quantities of additional material obtained from the channel banks and bed. The resulting channel may be scoured to bedrock for a great distance until the channel gradient lessens and deposition occurs (Costa and Jarrett 1981).

Debris torrents may start in channel reaches where fluvial channel erosion is typically small. In these reaches, water may flow through the interstices of accumulated organic material and coarse noncohesive rock and soil. As the volume of subsurface flow increases, the piezometric level within the accumulated debris rises, ultimately leading to failure at some critical piezometric head. Debris torrents appear to be episodic. They recur whenever there is enough noncohesive debris accumulated in the steep channel and water to mobilize that debris (Takahashi 1978).

Land management activities may increase the frequency of debris torrents by increasing the quantity of water delivered to a channel or by increasing the quantity of debris in a channel, or both. Channel flow can be dramatically changed by roads intercepting subsurface flow, rerouting of microdrainage networks, and the concentrating of surface runoff from compacted road or tractor trails. Material from accelerated hillslope erosion can increase the amount of debris accumulated in channels. Road fills at stream crossings place a large mass of rock and soil in channels. Road culverts in small steep stream channels are commonly plugged with soil and organic debris, resulting in saturation and failure of the road fill. Failure of road crossings is a principal cause of accelerated channel erosion and debris torrents in many forested steepland areas.

DISCUSSION

Where and how land is managed are primary considerations in efforts to reduce steepland erosion. The "how" is often thought to be completed with planning. Although sound planning is a major and necessary step in minimizing erosion, its implementation is all too often underplayed. The on-the-ground operator is the key to success or failure of a plan. Commonly, little effort is expended to include operators in the planning process. In general, their skills have been developed through personal experience of what seems to work. Unfortunately, what works best for dragging a log or constructing a stream crossing may not be best for reducing erosion. An important part of reducing steepland erosion is successful interactions between planners and operators. Success is often based as much on personalities as on their technical abilities.

The cumulative impact of management activities on erosion is a matter of concern. A common assumption is that if a small proportion of the area is logged, the rest will buffer the effect of the logging on downstream values. The proportion of a catchment that can be logged without undue degradation of the stream resource is, however, a matter of conjecture. This sort of assessment is appealing in its simplicity, but assumes erosion sources are uniformly distributed and that there is an equal probability of erosion occurring at any given location. Most steepland erosion occurs in a few areas, and most of the remaining area produces only a small amount of erosion. To effectively minimize erosion in steeplands, it is more important to specify <u>where</u> land is to be treated than to be concerned with <u>how much</u> land is to be treated. A small amount of activity conducted in the wrong place can result in a great deal more erosion than a large amount of activity conducted in locations which are erosion resistant.

The key to successful management of erosion is the ability to 1) identify potentially erodible sites, 2) correctly assess appropriate activities on those sites, and 3) have a political or regulatory system that fosters the appropriate action. In some cases, the only appropriate action is to do nothing. The cost required to correct management-induced erosion is often far beyond the benefits obtained from the land management activity or the costs required to follow a more sensitive alternative.

The time must be lengthened for which costs are evaluated relative to benefits. In general, the current period of concern of land management-related erosion is short--several years at most. This is perhaps acceptable for surface erosion, but channel erosion and mass erosion may follow land treatment by many years or even decades.

The effectiveness of erosion control, if evaluated, is often on the basis of the "typical" meteorological event. But channel erosion and mass erosion, which produce the erosional features that are generally considered to be "unacceptable," are usually associated with rare meteorological events.

Efforts to control erosion from the typical runoff event could lead to more erosion during the large storm. For example, small log check dams may effectively trap sediment and curtail erosion during average-size storms, but may provide a large source of material if these small dams fail during a major event. Such an erosion control effort may not reduce the amount of material transported during the long term, but simply change the time-related distribution of sediment yield. In some cases, the transport of a large quantity of material within a short period may be more destructive than the same quantity being transported over a long period. Large sediment pulses may produce pronounced deposition downstream. Channel aggradation may then lead to secondary erosion from deflected flow, which undercuts and oversteepens stream banks. Accumulation of material behind small check dams in a steep channel may also predispose the channel to mass failure as a debris torrent, which may be many times more destructive to downstream values than would continued transport of eroded materials.

A potentially useful system for managing erosion would be an Erosion Danger Rating--conceptually similar to the Fire Danger Rating used for forest fire planning. The Erosion Danger Rating would encompass a number of variables that predict the probability of erosion, including weather forecasts. Requirements for personnel and equipment would be based on predicted erosion damage. For example, if a large storm is forecast, certain measures might be taken to reduce erosion related to road plumbing: vulnerable culverts could be inspected and cleared in advance of the storm, critical road-side drainage ditches could be cleaned, and road berms could be repaired. During the storm, additional workers could be hired to patrol roads to prevent minor plumbing problems from developing into major failures. This sort of approach has been used successfully on the Siuslaw and Mendocino National Forests, where the frequency of road-related erosion has been dramatically reduced.

One method to minimize road-related debris torrents is to install "oversize" culverts or to bridge the water-course. This method is often rejected because of its high initial expense. Construction costs are frequently viewed in the short term and fail to include maintenance and replacement, let alone long term social costs. If the accounting system included the total costs required during the life of the project, many current construction practices would probably be changed.

Many innovative techniques have been successful in reducing the failure rate of stream crossings. By identifying channels which have a high debris torrent potential, road crossings have been designed so that water and debris will easily pass over the road and down a resistant concrete- or rock-faced fill. Another effective technique to reduce road failures has been to color-code road posts at culverts to indicate the potential of plugging, for example, red for high, yellow for moderate, and green for low. Employees are instructed that whenever they cross a red culvert during the rainy season, they must stop and assure that it is free of debris. Yellow culverts are to be routinely checked after storms. Green culverts are only checked on a normal maintenance schedule.

Management activities can modify the stability of debris within the channel. The local gradient of a steepland channel, as well as its stability, is often controlled by bedrock. However, large woody debris, a natural component of forested steepland channels, can also control channel gradient. The residence time of large decay-resistant logs, such as redwood, in a channel may approach a geologic time scale--up to 500 years. Large logs of Douglas-fir may remain in a channel up to 200 years. When this organic debris decays, accumulated material is subject to channel erosion and, further, is available for rapid mobilization into a debris torrent.

Land management activities can influence both short- and long-term stability of debris deposits within channels. Mechanical removal of naturally accumulated large organic debris can release stored sediment within a short time, whereas decay allows intermittent releases over a longer time while new deposits simultaneously form behind recently fallen trees. Logging residue can greatly add to the organic loading of a channel, thus providing additional opportunities for debris deposits. These additional deposits can increase the risk of debris torrents in steep channels or predispose channels to increased erosion many years after logging as organic components eventually decay and release accumulated deposits. If channel stability is controlled by the long-term supply of large organic debris, and large trees adjacent to channels are eliminated by continued forest management, active channel erosion may follow the decay of existing logs because new large logs are no longer available for replacement. In intermittent channels, live roots from surrounding trees provide substantial strength and reinforcement to the channel bed. If these trees are cut, the strength of the debris composing the bed will progressively weaken as the roots decay. This condition may result in accelerated channel erosion or increased risk of a debris torrent.

To manage steepland erosion successfully, it is important to define the erosional concern. If the principal concern is the loss of soil productivity, then on-site erosion control is perhaps appropriate. If the concern is reservoir aggradation, perhaps on-site soil loss is not important as long as eroded soil is deposited on the slope or in a stream before entering the reservoir.

Traditional land management decisions rely on cost-benefit ratios limited to short-term economic factors of monetary outlay and income. Social costs and benefits are often not considered. The costs of erosion are often considered only when road maintenance or other direct costs are affected. Indirect costs such as loss of fish habitat, soil productivity, and long-term slope instability are difficult to quantify, either physically or economically. Nonetheless, indirect costs must be assessed.

Considering these uncertainties, sensitive land stewardship should identify the values at risk and direct erosion control activities toward processes most likely to affect those values. Steepland erosion is controlled most effectively, in both physical and economic terms, by preventive land-use practices rather than corrective action. Management of steepland erosion is merely the appropriate application of varying levels of care and caution when dealing with terrain of varying erosional sensitivity.

We tend to fix our mistakes. The public often demands that we attend to actively eroding sites--whether management-induced or natural. However, unless more effort is devoted to prevention rather than to correction, we will continually be playing a game of catch-up.

The successful management of erosion is as much a philosophical and political problem as a technical one.

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MANAGEMENT OF WATERSHED REHABILITATION--

REFLECTIONS FROM MT. ST. HELENS AND REDWOOD CREEK

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Abstract

A critical examination of recent major watershed rehabilitation programs in the western United States reveals five basic guidelines for conducting such programs: 1) state long- and short-term objectives, 2) use an interdisciplinary approach at all stages, 3) consider erosion processes and fate of sediment in planning erosion control measures, 4) define costs of full, partial, and no treatment, and 5) provide independent evaluation of programs.

Many major watershed rehabilitation projects begin in an uneasy, high profile, get-something-on-the-ground-in-a-hurry, politically-charged environment. Despite differences in physical setting, ultimate objectives, and other considerations, these political factors result in a set of problems common to many watershed rehabilitation projects.

Watershed rehabilitation projects at Redwood Creek, California, and Mt. St. Helens, Washington, present some instructive contrasts and similarities. Legislation expanding Redwood National Park provided for rehabilitation of lands affected by road construction and timber harvest. This project is funded for an anticipated program of 10- to 15-year period, planned and conducted in part by scientists, and managed by a single Federal agency. The 1980 eruption of Mt. St. Helens, on the other hand, triggered a mix of responses by many agencies and organizations working with overlapping responsibilities in a crisis environment. Planning horizons for treating watershed problems at Mt. St. Helens have generally spanned only a matter of months to a few years, in part, because funding for rehabilitation and hazard control has come in short-term allocations for specific projects.

Examination of the successes and problems of these two quite different projects reveals five criteria for successful, efficient design and execution of a large watershed rehabilitation program:

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1. STATEMENT OF OBJECTIVES

Planning of any watershed treatment should begin with a statement of objectives. The range of alternatives is described schematically in Figure 1 modified after Magnuson et al (1980). The reference point or initial condition may be more elusive than generally accepted even in the Pacific Northwest where European man is a relatively recent arrival. In the Northwest poorly documented land use practices in the 1850-1900 period predate the memory of the oldest old-timers. Watershed treatment of the present degraded condition (Figure 1) can have the objective of restoration to the initial condition with tacit acceptance of both good and bad attributes of the more natural initial state. Enhancement, on the other hand, is designed to make improvements that make the system less natural, less like the initial condition. Rehabilitation could be viewed as a mix of enhancement and restoration objectives.

In transferring rehabilitation measures from one area to another it is important to confirm that the measures will meet project objectives at the second site. Rehabilitation work in Redwood Creek basin, for example, is becoming a benchmark for work elsewhere, but we must be alert to the special restoration-oriented objectives of the Park Service as practices demonstrated on Park lands are carried to sites where enhancement is a primary concern.

Short- and long-term aspects of objectives must also be reconciled. A well recognized example of this problem is the use of grasses, particularly exotics, for short-term erosion control purposes where native shrubs and trees are desired in the long run. Problems of advancing beyond the grass stage can arise from simple competition for resources or allelopathic interactions.

2. INTERDISCIPLINARY APPROACH

It is essential that an interdisciplinary approach be used at all stages of a project--planning, execution, and evaluation. If an interdisciplinary team is not embodied within project administration, an outside team should be established for periodic review.

This interdisciplinary approach will reduce the incidence of different groups working at cross purposes in an area and the inadvertent aggravation of one problem by another activity that may at first appear unrelated.

An interesting, hypothetical link between very different problems arose in rehabilitation efforts at Mt. St. Helens. Grass seed and fertilizer was applied in September 1980 to a few thousand hectares of the blast zone for purposes of erosion control. Additional seeding and fertilizer application was proposed for Spring 1980. At the same time a number of pneumonia-causing microorganisms, including species of *Legionella*, one species of which causes Legionnaires disease, were found in high abundance in several water bodies. These pathogens were part of rich, microbe-dominated, nitrogen-limited ecosystems. If nitrogen fertilizer applied to upland areas for

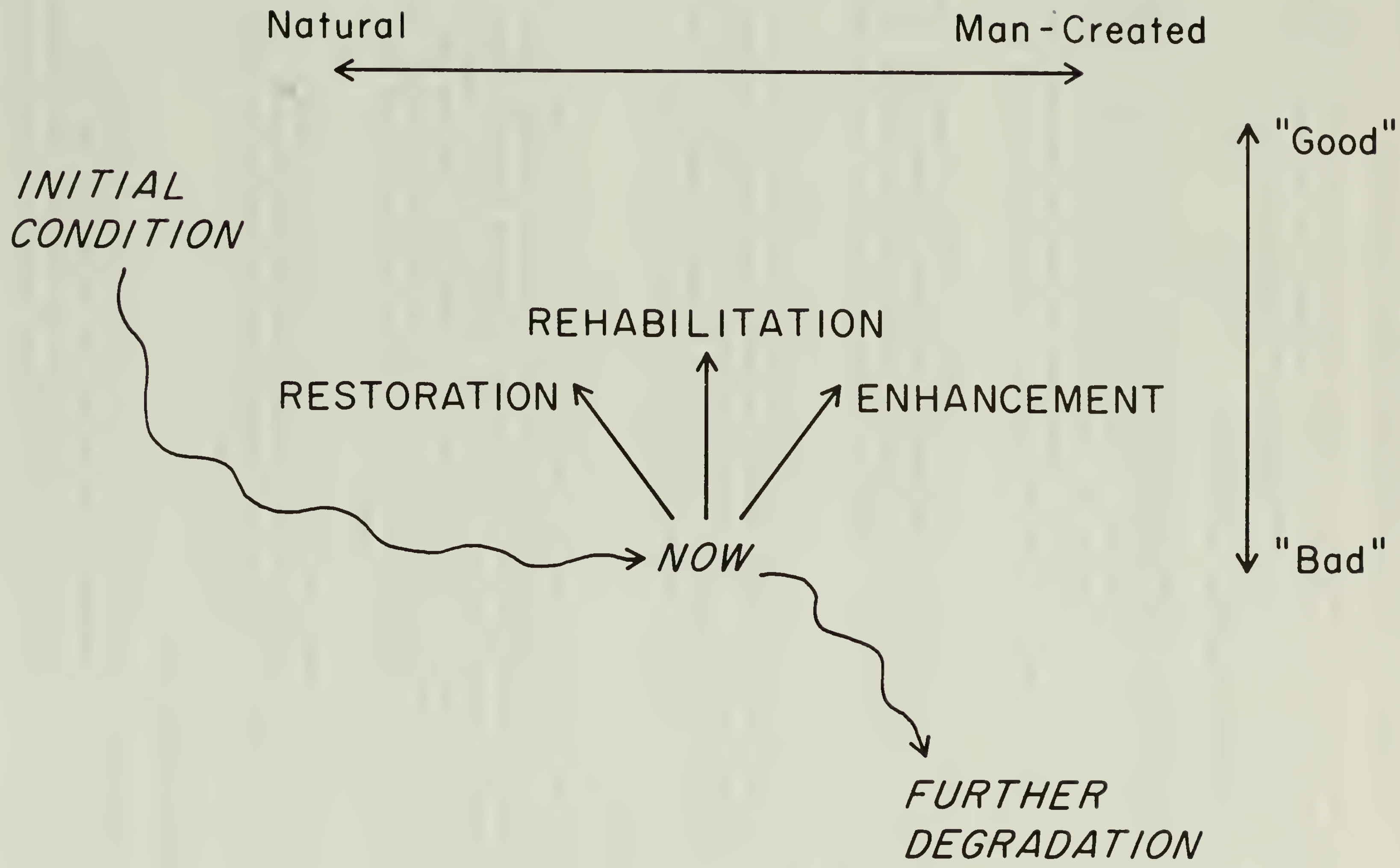

Figure 1. Schematic definition of restoration, rehabilitation, and enhancement (modified after Magnuson et al, 1980). See text for discussion.

erosion control purposes were to enter key waterbodies, overall microbial activity and abundance of pathogenic organisms could increase.

Unexpected linkages occur commonly in complex natural systems, hence the course of watershed rehabilitation should be tracked from an interdisciplinary viewpoint in order to detect undesirable secondary effects.

3. EROSION PROCESSES AND FATE OF SEDIMENT

Planning of erosion control measures should be based on knowledge of overall soil and sediment movement through drainage basins. Key points are identifying dominant processes, applying methods to treat those processes, where treatment is justified, and considering the fate of sediment derived from areas proposed for treatment. The relative importance of erosion processes and the success of control measures can be judged by calculating erosion budgets before and after treatment.

Certain "band-aid" approaches are sometimes applied indiscriminantly. Some grass seeding at Mt. St. Helens, for example, was done in areas where the dominant erosion processes are river channel cutting and mass failure of 30+m high banks, processes that completely disregard even the most vigorous grass cover.

Other seeding proposals at Mt. St. Helens included areas that contribute sediment to natural lakes. These natural sediment traps control sediment delivery to downstream areas. The purpose of protecting of downstream areas, the stated purpose of the program, would not be served by seeding in basins that feed natural, efficient sediment traps with high storage capacity.

4. DEFINE COSTS

Cost - benefit analysis is a part of most justifications for rehabilitation work, but it is open to manipulation to justify objectives decided upon on other grounds. Motivations for carrying out watershed rehabilitations, aside from economic considerations, are strong, running the full range of human emotions from "paying for past wrongs" to "doing all the good you can". We simply encourage more objective evaluation when millions of dollars are at stake and there should be less fear of doing nothing if that is justified on all but political grounds.

A certain "politics of name" may occur in crisis situations. When a "rehabilitation team" is appointed to evaluate alternatives there is a certain implicit charge to come up with rehabilitation programs and doing nothing may not seem like a viable alternative.

5. INDEPENDENT EVALUATION

Periodic, independent, objective evaluation is particularly critical to maximize efficiency of management of a project and to provide the best documentation of effectiveness of rehabilitation activities. This documentation would then be available for planning future projects. These activities could be funded by a 3 to 5% assessment of the total project budget. Just facing such an analysis would probably lead to sufficient increase in efficiency that the analysis would essentially pay for itself.

CONCLUSIONS

This set of guiding principles of watershed rehabilitation may seem obvious, yet they are commohly ignored for a variety of reasons--human nature, bureaucratic foibles, technical problems. The relatively long-term and well funded watershed rehabilitation programs at Redwood National Park are taking the lead in setting technical and administrative standards for future programs. There is need for better use of this base of experience when programs are needed in the future.

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SEDIMENT ROUTING IN STREAM CHANNELS:
ITS IMPLICATIONS FOR WATERSHED REHABILITATION

Mary Ann Madej and Harvey Kelsey[1]

Abstract. In the Redwood Creek watershed in northern California, the combination of naturally unstable terrain and intensive land use has created a need for erosion control programs to rehabilitate heavily disturbed slopes. Major sediment sources generally occupy small, inaccessible portions of the basin that are in the stream channel or on footslopes adjacent to steep stream reaches. Large volumes of sediment are stored within the Redwood Creek channel itself and form a sediment source for downstream reaches. The best available erosion control measures, exemplified by those currently in use in Redwood National Park, are effective in dealing with erosion problems on heavily disturbed hillslopes. Early treatment of problems can prevent possible downslope cumulative impacts. However, because of the inaccessibility of some major sediment source areas, there is a limit to effectiveness of erosion control. Total drainage basin rehabilitation is not technically feasible, and basin-wide erosion control becomes, in part, a problem of managing land within recognized geologic constraints.

INTRODUCTION

In the northern California Coast Ranges, where erosion occurs at the highest rate in the conterminous United States, the combination of naturally unstable terrain and intensive land use has created the need for erosion control programs to rehabilitate heavily disturbed watersheds. Erosion control treatments used on roads and gullies have been successful. However, in large drainage basins, 500-1000 km^2 in size, major sediment sources generally occupy small, inaccessible portions of the basin that are in stream channels or on steep footslopes adjacent to streams and are difficult or impossible to treat. A basin-wide management plan for erosion control in such watershed must consider all sources of sediment and their relative contribution to streams, and the transfer of sediment throughout the watershed.

A description of sediment routing in a watershed quantifies the amount of sediment derived from different source areas, hillslope erosion rates, timing of transport, and locations and volumes of channel-stored sediment. In a watershed, sediment is transferred from hillslopes to channels through several processes. Any disturbance to a watershed will affect both the processes and the rates at which they occur, and the result is generally an increase in sediment yield. A disturbance may come in many forms: intense storms, fires,

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conversion of forests to agricultural land, introduction of grazing livestock, road construction and timber harvest.

Some disturbances may be treated to reduce the excess sediment load, whereas other source areas are so widespread or inaccessible that prevention of sediment delivery to streams is impossible. Before any watershed rehabilitation program directed at correcting disturbance-related problems is initiated, all compoments of the sediment routing regime should be evaluated. If we can quantify the routing of sediment through a basin, then we can better evaluate the effectiveness of erosion control at different locations in a basin.

DESCRIPTION OF AREA

Redwood Creek drains 720 km^2 in northwestern California (Fig. 1). It is underlain by the pervasively sheared and folded Franciscan rocks. The combination of highly erodible rocks, recent uplift and a high annual rainfall (1250 - 2500 mm) causes a naturally high sediment yield from this terrain. Recent land use changes in the basin have accelerated erosion even more, and presently the sediment yield of Redwood Creek is about 3,200 $t/km^2/yr$. (U.S.G.S. Water Resources Data for California, 1976-1979).

The Redwood Creek basin has been disturbed by timber harvest, road construction, and intense storms in recent years. Logging was initiated by the 1940's, but widespread logging of old growth trees did not occur until the 1950's and 1960's. By 1964, most of the land in the upper third of the basin was logged and by 1974, few areas of old growth redwood existed outside of park boundaries.

Widespread road construction accompanied timber harvest. For example, in the expanded park over 600 km of major haul roads exist, plus thousands of kilometers of skid trails. The road network disrupts the natural drainage patterns, road cuts intercept subsurface flow, unmaintained culverts plug and wash out road fills, and road fills are locally unstable. The problems that are caused by roads, and the approaches taken in correcting them, are discussed more fully in other papers in this volume.

In addition, since large-scale timber harvest began in the 1950's, five large floods occurred, in 1953, 1955, 1964, 1972 and 1975. These floods, especially that of 1964, severely affected the basin. The most dramatic effects of the 1964 flood were associated with those areas in the upper basin recently disturbed by logging and road construction. Many landslides and severe bank erosion occurred, and 3 m of channel aggradation was common in many reaches of Redwood Creek. Severe sedimentation problems threatened the alluvial groves of old growth redwoods in Redwood National Park, and a study was initiated to evaluate sedimentation and erosion in the Redwood Creek basin.

METHODS

Our approach in studying the Redwood Creek watershed has been to quantify sediment source areas in the entire watershed, to evaluate the storage capacity of tributary and mainstem channels, to monitor the timing and magnitude of transport events, and to compare annual sediment yields from several terrain types and time periods. Using this data base, we can then evaluate the significant source areas in terms of total sediment contribution, estimate residence times of sediment problems, and rank sediment problems according to severity.

Volumes of 634 streamside landslides were measured along 30 km of Redwood Creek upstream of Highway 299. Additionally, landslide volumes in 17 major tributaries were measured. Dates of landslides were obtained from aerial photograph interpretation and dendrochronological determinations. All stored sediment in Redwood Creek above the present thalweg was mapped, measured and classified for 96% of the total length of the creek. Sediment was classified according to its mode of storage (point bar, flood terrace, channel bed, etc.) and to its potential mobility (stable, vegetated and difficult to mobilize; or within active channel and easily mobilized.) The amount of aggradation in the channel was estimated from old bridge surveys, discussions with local residents, and biological evidence. Stored sediment measurements were also made in 24 of 74 second-order or higher tributaries. A detailed procedure of the above investigations and the preliminary results are both discussed in Redwood National Park Technical Report 3 (Kelsey et al, 1981).

We are in the process of evaluating sediment contribution from fluvial erosion on hillslopes to complete the sediment source study. Gullies are mapped on 10-20 ha plots, which represent a range of geologic and land use conditions. We measure the volume of material eroded from the gullies, hillslope gradient and aspect. We also record the type of soil, bedrock geology, ground disturbance, predominant vegetation, the cause of gullying (where possible), the availability of water on a site, and the location. Preliminary results indicate that gullies developing on locally sensitive sites such as prairie lands contribute significant amounts of sediment to stream channels.

In order to assess sediment yield from the total basin, we have established several gaging stations on the mainstem of Redwood Creek and on major tributaries. This cooperative program between the National Park Service and the U.S. Geological Survey measures water and sediment discharge throughout the year. Thus sediment yields past several stations within and outside the park can be compared.

CONTRIBUTION OF SEDIMENT SOURCE AREAS

In the Redwood Creek basin, the major sediment source areas are streamside landsliding, debris slides and avalanches, gullying, earthflows, and stream bank erosion. In addition, sediment stored in the main channel of Redwood Creek was derived from other source areas, but now acts as a sediment source to downstream reaches. These sediment source areas make up only 17% of the total basin area (Table 1).

Landslides are most prevalent in the upper fourth of the basin. From the headwaters to Highway 299 (see Fig. 1) about 1,920,000 t of sediment was delivered to the mainstem by landslides since 1947. About 50% of the slides were associated with one or more roads. Most of the landsliding occurred during the 1964 flood. These landslides are generally on steep (60%) slopes adjacent to third-order or higher streams.

Sediment from landslides in tributary basins reached the mainstem of Redwood Creek relatively quickly. At present, tributaries store only a small percentage of the volume of sediment supplied to them by landslides (Pitlick, this volume). Major floods transport most of the tributary-stored sediment to the mainstem. The remaining sediment is usually trapped upstream of organic debris in channels. Thus, in the Redwood Creek basin, the relatively steep tributaries function more as sediment transporters rather than sites of long-term sediment storage.

TABLE 1

SEDIMENT SOURCE AREAS IN THE REDWOOD CREEK BASIN UPSTREAM OF PRAIRIE CREEK

Feature	Percent of Basin Area
Debris slides*	1
Debris avalanches*	0.2
Earthflows*	10
Very active earthflows*	2
Unstable streambanks*	3
Main channel stored sediment	0.5
TOTAL	16.7

* from Harden et al, 1978

Fluvial erosion on hillslopes is another major source of sediment. Gullying is common on logged areas where skid trails divert water and where road crossings on streams are abandoned. Gullies usually form within the first few years after a site is logged. Prairies are especially sensitive to water diversion by roads. Where logging occurred in the early 1970's, preliminary results indicate that the sediment yield from gullying ranges from 2500 t/km^2 on gentle, schist slopes with cohesive soil to 95,000 t/km^2 on steep sandstone slopes with noncohesive soils.

Rainsplash and sheetwash erosion occur on disturbed ground and compacted road surfaces, and they transport fine sediment to stream channels. Preliminary results suggest that in terms of total sediment input to Redwood Creek, sheetwash is not a major sediment contributor. Locally, however, the effects of rainsplash and sheetwash are severe and these processes are detrimental to restoring vegetation on disturbed sites.

Fill failures on roads and road washouts are also common on abandoned roads. Stream crossings vary greatly in size and distribution. Nevertheless, an average volume of road fill on a skid trail stream crossing is 60 - 70 m^3; of haul road crossings, 200 - 250 m^3. Road fills and crossings generally persist for several years, and it may take 10 - 50 years before a road crossing fails into a stream channel.

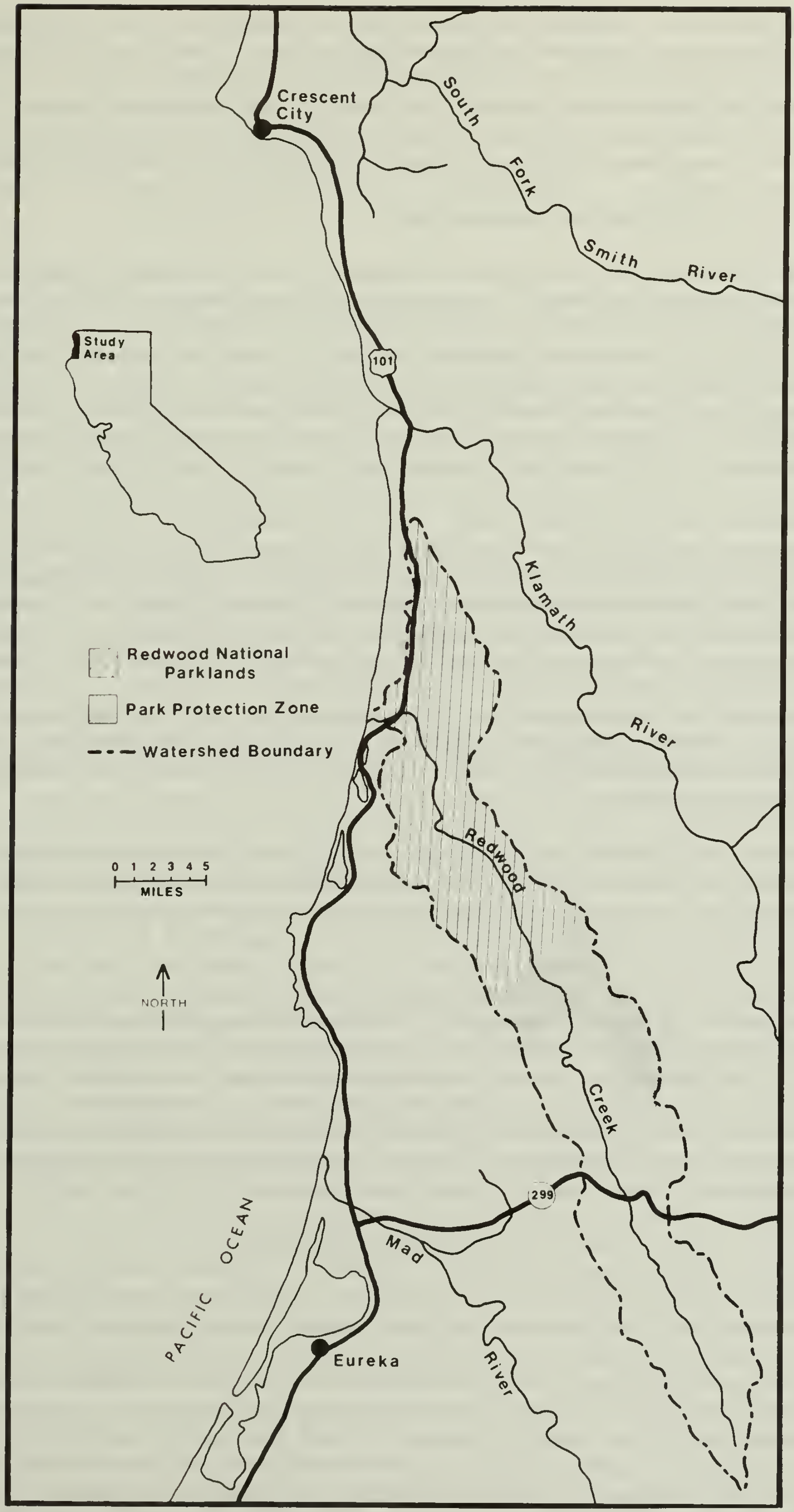

Figure 1: Location map for Redwood Creek watershed, northern California

Another major source of sediment to the reach of Redwood Creek in Redwood National Park is channel-stored sediment upstream of the park. This is well illustrated by evidence seen in the upper basin of Redwood Creek. The 1964 flood resulted in 1 to 3 m of channel aggradation in upstream reaches. From 1962 to 1966 the amount of sediment stored in the uppermost 21 km of Redwood Creek increased from about 40,000 t to over 2,000,000 t. Presently only 50% of that sediment remains in the channel, the other 1,000,000 t has been transported to reaches farther downstream.

Considering the entire length of Redwood Creek, we found that 17,000,000 t of sediment are stored in gravel bars and the channel bed of the mainstem. The annual bedload plus coarse suspended sediment is 150,000 - 450,000 tons/year (Knott, U.S.G.S., personnal communication). Thus the equivalent of 11 - 38 years of bedload and suspended sand discharge is stored in the mainstem of Redwood Creek. About 5,400,000 t of this sediment lies upstream of park boundaries, of which approximately 3,900,000 t is located within unvegetated reaches in the active channel and could be mobilized during high flows.

Spatial concentrations of stored sediment vary from 300 - 12,000 m^3 of sediment per 100 m of channel length. Thus, some reaches are obviously sediment storers whereas others are very efficient transporters. Identification of such reaches is essential in determining rates of sediment transfer in a watershed, and in recognizing reaches with potential sedimentation problems. Annual transport of bedload material out of the watershed is 150,000 - 450,000 t/yr. Because annual bedload transport out of the basin is only a fraction of the potential active channel sediment in the basin, transfer of material within the Redwood Creek basin itself is important in the definition of sediment routing for the watershed.

Land use disturbances initiated erosion from mass movement and fluvial processes in many localities. The resulting increase in sediment load in Redwood Creek caused several problems. Streambed elevation was raised as the channel bed aggraded. Channel aggradation was accompanied by channel widening and bank erosion. Bank erosion, in turn, undercut the toes of unstable hillslopes and in some cases caused the initiation of new landslides and the reactivation of old landslides. Streamside vegetation, such as old-growth redwood groves, were threatened by overbank flooding and an elevated water table. Pool/riffle sequences were disrupted, and streambed particle size decreased. Fish habitat and spawning grounds were disrupted. Aggradation in upstream portions of the stream became a source of sediment to downstream reaches. The transport of this channel-stored sediment can cause a similar sequence of problems in downstream reaches in future years.

TIMING OF SEDIMENT TRANSPORT

Timing of sediment transport is critical to aquatic life, especially to spawning anadromous fish because their eggs depend on streambed stability for survival. Sediment transport is a function of stream discharge, and thus rainfall. Most precipitation occurs predominately between October and April. The majority of sediment transport occurs during the two to six most intense storms of the winter. For example, about 85% of the total suspended sediment transported by Redwood Creek at Orick between 1971 and 1973 occurred in less than 5% of the time (Janda and others, 1975). On the average, more than 50% of annual sediment transport occurs only four days each year (Brown and Ritter, 1971; Kelsey, 1977). Infrequent, high-magnitude floods are major transporting events. For instance, in the 8,060 km^2 Eel River basin in northern California, 50% of the suspended sediment discharge for 1958 - 1967 occurred during the 30-day period December 23, 1964 to January 23, 1965 (Brown and Ritter, 1971). Because of these characteristics of sediment transport, erosion control and stream monitoring programs must be designed to work effectively during infrequent, high magnitude events.

IMPLICATIONS FOR WATERSHED REHABILITATION

A large watershed rehabilitation program is currently underway on logged lands recently added to Redwood National Park. These lands are in the lower third (240 km^2) of the Redwood Creek basin. The intent of the program, which was mandated by the U.S. Congress upon expansion of the Park (Public Law 95-250, March 27, 1978) is "to rehabilitate areas within and upstream of the park contributing significant sedimentation because of past logging disturbances and road conditions and to reduce the risk of damage to streamside areas of Redwood Creek" (U.S. House of Representatives, 1978). The current rehabilitation program in Redwood National Park deals with erosion problems that are accessible to equipment and work crews, and that are treatable with present technology. These constraints limit most rehabilitation work to recently logged hillslopes. The most significant rehabilitation treatments are the removal of road fill from stream crossings, the elimination of roads as barriers and diversions to runoff, the prevention of downcutting in gullies and newly excavated channels, and the revegetation of disturbed sites.

We feel the erosion control techniques used in Redwood National Park represent the current state-of-the-art in terms of types of problems that can be effectively treated (Kelsey et al, 1981). These techniques are used on recent (post-1970) tractor logged hillslopes and along the network of logging haul roads within the 20,000 ha park addition. Private lands within the basin upstream of Redwood National Park are presently not included in the program because untreated, logged areas still remain on park lands. Cooperative rehabilitation efforts with private landowners is a possibility at a future date.

The techniques used by Redwood National Park are most effective in controlling fluvial erosion from hillslopes, and they help ameliorate detrimental impacts on small tributary basins. Early treatment of problems may prevent downslope and downstream cumulative impacts. However, the effectiveness of current rehabilitation techniques is limited in terms of improving main channel conditions. Once sediment enters a channel it is difficult to prevent further sediment transport. Mass-wasting and channel-stored sediment are two major source areas that are not addressed to a great extent in the present program because they are technologically impractical to treat. Consequently, when considering the huge volumes of material involved in landslides and channel-stored sediment, total watershed rehabilitation is impractical. Erosion control techniques can ameliorate conditions in tributary basins, however, where less sediment is stored, and sediment flushing occurs more readily.

Some techniques that are based on a knowledge of stream processes may be useful on a small scale. Stored sediment in channels can be a sediment supplier to downstream reaches for years to come. Thus an extensive revegetation program directed at stabilizing eroding terraces and flood berms may be as or more effective in sediment control than the revegetation of slopes and may improve the aquatic habitat as well. Gravel excavation in critical areas may be necessary, although excavation is very expensive and may trigger troublesome side effects. In-channel devices may be installed to encourage pool formation in aggraded channels. Bank protection treatments may hinder bank erosion in critical reaches, where accelerated hillslope destabilization would cause further sediment problems.

CONCLUSION

Erosion control and rehabilitation measures can successfully treat problems on logged hillslopes. Early treatment of problems can prevent possible downslope and downstream cumulative impacts. An evaluation of sediment source areas shows, however, that major sediment source and storage areas are inaccessible and cannot be treated by present erosion control technology. Thus, the effectiveness of a total watershed rehabilitation program is limited by the physical processes which control erosion and sediment transport.

The above situation argues strongly for preventive erosion control through intelligent land management, minimal new road construction, and proper road maintenance. Preventive erosion control is feasible because erosionally sensitive areas can be identified, and many serious problems can be avoided with good land management practices. The challenge for watershed sediment control is in large part an economic, administrative, and political one of properly managing land within recognized physical constraints.

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FLOODS, SEDIMENTATION, AND ALLUVIAL SOIL FORMATION AS DYNAMIC PROCESSES MAINTAINING SUPERLATIVE REDWOOD GROVES

Paul J. Zinke[1]

There is an answer to the question as to why the redwood trees have shown such pertinacity of life in that particular environment, where their existence has been so successfully maintained, where other trees in other environments have shown no such life persistence. It is because that particular environment has proved to be peculiarly adapted to the well being of the sequoia, and conversely, the sequoia especially fits this particular environment. The reason for the great longevity of this forest species is that in that region there has been a perfect balance between the redwood tree and all or nearly all surrounding conditions. (Thomas Edison, 1926)

ABSTRACT

New sediment accretion to soil profiles was found to be related to tree ring growth acceleration in old redwood trees growing on alluvial soils subject to flooding. It is inferred that the vigor of growth of these trees is rejuvenated periodically by sedimentation of new soil material that is consistent in texture with past deposits. However, it was observed that drastic changes in quality of sediment, either due to change in texture, or in organic matter content, resulted in death to trees on these alluvial flats.

INTRODUCTION

The preservation of superlative redwood groves should be based upon an understanding of their relation to the dynamic processes of flooding and sediment deposition which has created and sustained them. Changes in these processes and the resulting change in conditions in these forests may be counter to preservation efforts.

The superlative groves of redwood (*Sequoia sempervirens* D. Don Endl.) on alluvial flats in north coastal California are both initiated and rejuvenated by relatively infrequent flood events. Management and preservation of these groves must involve a watershed management program that maintains a favorable magnitude and frequency of flooding and sediment transport. Long-term changes

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in the frequency of overbank flooding or in the quality of sediment may have unfavorable consequences for the vigor and longevity of the trees. This paper is concerned with the interrelationships between superlative redwood groves on alluvial soils and long-term watershed processes.

What are the conditions in which these tall trees have originated and survived? Can we use historical evidence as a basis for describing them, and what historical evidence is there? Have present conditions changed and in what manner? To what extent is restoration needed and feasible if deleterious change has occurred? How do we know what conditions at present may be deleterious, and how do we know if our actions are bringing them about? How do we achieve the proper balance between the requirements of these trees and environmental processes which affect the areas we presume to manage?

Finding answers to these questions requires a perspective in time that goes beyond the scope of daily decision-making based on economic and political criteria. It means assuming a perspective with a breadth in time comparable to the age of the trees. Frequently when we live and work in close association with the redwoods, it is difficult to maintain this perspective.

REVIEW OF PAST WORK

An awareness of the need for active management of the superlative groves is not new. In the early 1960's, Howard Libby of the Arcata Redwood Company established the "Tall Tree Committee" to advise the company on problems of sustaining the Libby Tree and the grove surrounding it (now known as the Tall Tree Grove of Redwood National Park). At that time, the top of the tree was dying back, and the bank of Redwood Creek was eroding. A series of steps was taken upon advice of the committee to solve the problems, including a revetment of a large redwood log against the bank, and moving the creek to the opposite side of the channel. This was done by excavating stream bed materials from one side of the channel and piling them alongside the eroding bank. During a period prior to this, Hammond Lumber Company had maintained the stream on the opposite side of the channel from the grove. This was done by the excavation of gravel and rock from the stream bed for surfacing roads. Since this operation stopped bed load had accumulated again and the stream shifted against the Tall Trees Grove bank. Thus the need for active management based on an understanding of natural processes continues.

The dynamic relationship between trees and soil of the superlative groves can be understood only in a whole watershed context. The soil of an alluvial flat was built up over centuries by flooding, which deposits the silt loam upon which the tall redwood trees grow. E. Fritz (1934) documented the history of deposition at Richardson Grove by examining the root system of a fallen redwood. He found that seven floods at varying intervals had deposited 11 feet of sediment. The root system of the tree responded to these continuous new layers of soil by developing successive layers of roots, each developing in what was the surface of the new sediment. Stone and Vasey (1968) found that redwood roots could rapidly grow upwards to occupy this new sediment. However, recreational use may impede this. Meinecke (1929) found that heavy foot or vehicle traffic results in soil compaction, which hinders the ability of roots to invade a new soil profile. Gravel introduced for road construction has the same effect.

The deleterious effect of flood-deposited gravels was verified later by Stone and Vasey in their studies. Helley and La Marche (1968) noted the relation between a change in sediment quality and the death of redwood trees along Blue Creek, a tributary of the Klamath River. In Rockefeller Grove at Bull Creek, the dynamic processes include not only flood, sedimentation, and bank cutting, but also fire (Zinke, 1977). These processes have led to the development of the largest biomass accumulation ever measured: 3461 metric tons per hectare, with a volume of 10,817 m^3 per hectare (Fujimori, 1977). In summary, there are dynamic events occurring in relation to redwood trees, some beneficial such as floods and related sediment, some detrimental such as floods with gravel and bedload deposition or excess compaction of soil.

I began soils studies relating to these problems shortly after the 1955 flood along the Eel River and its tributaties such as Bull Creek in order to understand some of these processes. This period of time has encompassed several flood depositions, as 1955, 1964, and 1974 in these groves, and has enabled the development of a chronology of the sedimentation for slightly more than a thousand years.

ALLUVIAL SOILS OF THE REDWOOD GROVES

The soil under a superlative redwood forest such as that at Bull Creek Flat is evidence of a dynamic process of periodic flooding and sediment deposition. The response of the trees varies. Sometimes growth accelerates and sometimes death occurs, either by felling the tree due to bank cutting, or swamping the base of the tree with sediment having undesirable characteristics.

The flood of 1955 cut a steep bank into the soils of Rockefeller Grove in lower Bull Creek Flat. I had a large pit excavated into this bank to expose the various sediment layers, as shown in Figures One and Two. A sketch of this pitface is shown in Figure Three. Soils were sampled at uniform intervals from this face. Samples were taken to allow measures of the soil bulk density (over dry weight per unit field volume), and various physical and chemical properties.

The most obvious feature of the soil was its layering in distinct beds of sediment deposition as seen in the figures. During excavation in the summer of 1958, the recent deposit of the flood of 1955 was apparent on top of the pit. This bed of recent flood sediment overlay at least fourteen other

Figure one: Upstream edge of Rockefeller grove on Bull creek showing cut bank from which soil samples were obtained.

Figure two: Detailed view of soil profile which supports the forest at Rockefeller grove showing successive layers of sediment with the deposit of the 1955 flood at the top, and the approximately 955 A.D. flood deposit in the hole at the base.

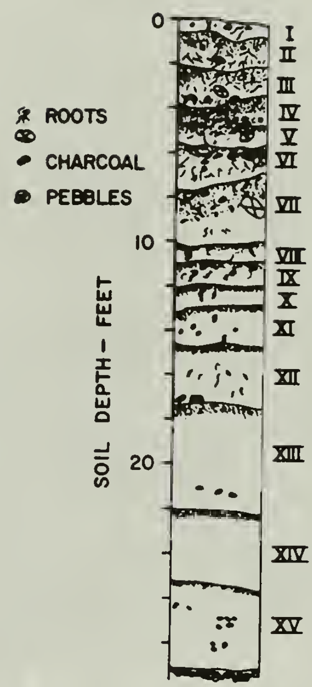

Figure 3: The deep alluvial soil with numerous flood deposit layers identified from youngest deposit as I, and oldest as XV.

identifiable sediment deposits. The soil was built of a column of sediment deposits 8.23 m deep, resting upon a stony layer that was obviously a stream deposit. The dynamic nature of the area was demonstrated by the flood of 1964 which tore another three meters out of this bank, felling a large tree. I subsequently measured this tree for foliage, bark, wood and root biomass and sampled it for chemical analyses (Zinke, Strangenberger, and Colwell, 1979). The flood of 1964 left a sediment deposit over the floor of the grove, and another flood and sediment deposit occurred in 1974. These have been monitored, and their properties determined. Thus, when one deals with an alluvial flat even with trees more than a thousand years old, the area is subject to continuous events of new flood and sediment accretion, bank cutting, and tree falling. Each site will have its own history, as well as extreme events shared in common with other sites, and this should be determined where such knowledge is critical to management perspective.

CHRONOLOGY OF SEDIMENT DEPOSITION

The chronology of the deposition layers is of immediate interest, since if this can be determined, it is possible to characterize the rate of the various dynamic processes occurring on the site, and the probability of occurrence of flood events that bring about sediment deposition.

Carbon 14 dating on deposited charcoal was carried out on the lowest of the sediment layers in order to obtain an age for the entire sediment profile (Dr. Hans Suess, School of Sciences and Engineering, U.C. San Diego, La Jolla). Charcoal samples from the bottom of the soil profile indicated an age of 1000 years $\pm$ 100 years.

Ages of nearby trees were of a similar order of magnitude; about one thousand years, with variation due to discontinuous rings, established by ring counts on a tree fallen in the 1955 flood. This indicated an age of 960 years at the cross section at 10 feet up the tree bole. The age of the lowest layer of this Bull Creek alluvium was judged to be 1000 years, substantiated by both the radio-carbon dating, and the tree ring analyses. The first soil layer was therefore initiated by a flood deposited sediment in 955 A.D.

I found that tree ring growth on the trees had a periodic variation in width that coincided with sediment deposition. An example is seen in Figure 4, showing periodic annual radial growth based upon tree ring width measurements. These data indicate a series of intermittent accelerations in growth rate. Known dated floods of 1934, 1916, and 1861 correlate with the three most recent growth accelerations as indicated by wider tree ring widths after these dates. Not all floods, however, result in sediment deposition, as some floods remove surface materials (Fritz 1956). Flood frequency may actually be higher than the frequency of growth accelerating sedimentation.

In order to determine the frequency of growth accelerating sediment deposition, I plotted the cumulative radial growth against time for two trees (Figure 5). One tree was located at 159 feet elevation above sea level in

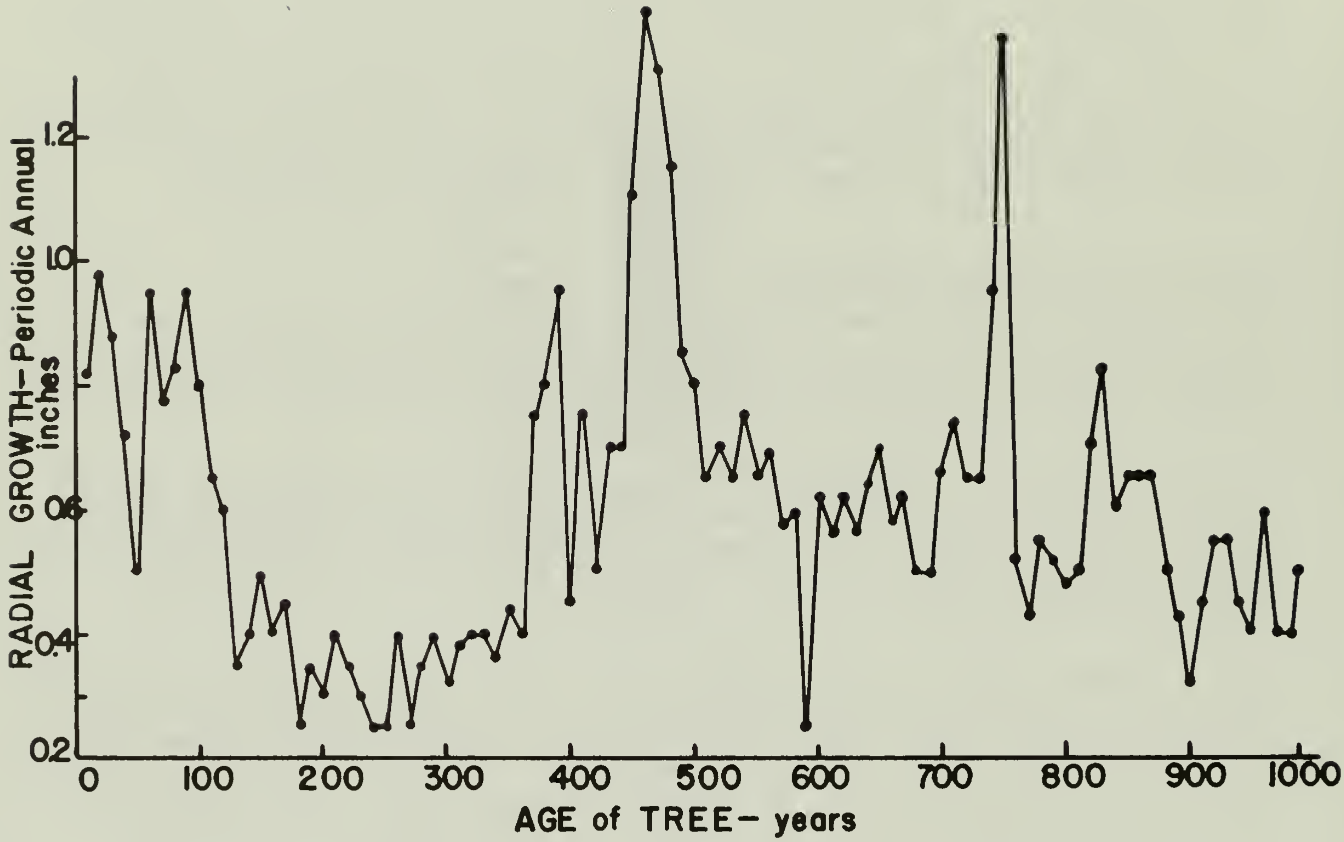

Figure 4: Radial width of tree rings measured on cross section of tree which fell near the deep soil excavation.

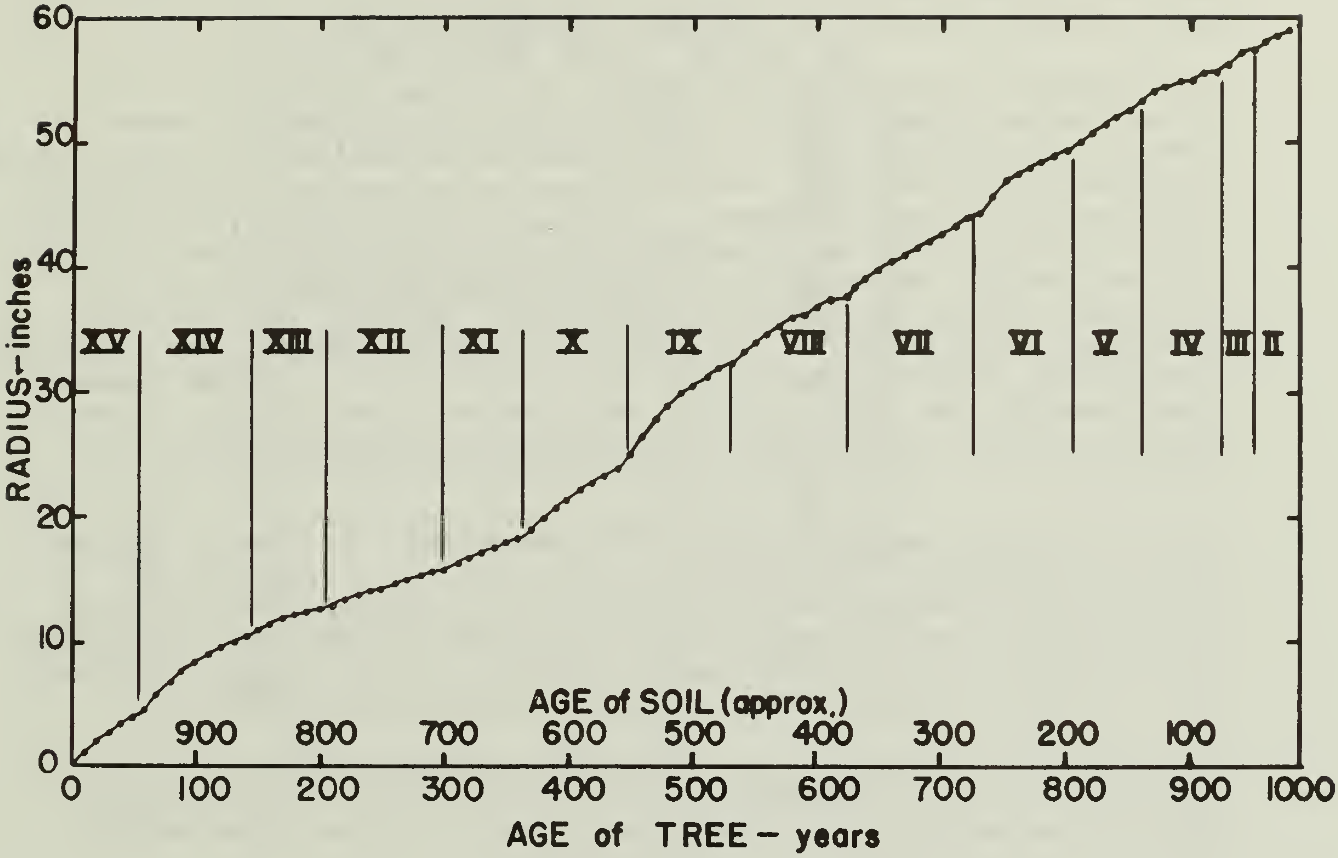

Figure 5: Cumulative radial growth and tree age from the tree which fell near the deep soil excavation in the flood of 1955.

the Rockefeller Forest at Bull Creek; the other was located at 170 feet elevation, but downstream in the Haas Grove on the main stem of the Eel River. Fourteen growth accelerations are shown, occurring at time intervals varying from 25 to 150 years. Table 1 shows the probability distributions for the intervals between periods of growth acceleration. As expected, the higher elevation tree at Haas Grove had a longer mean period between depositional events. Maximum stage of the 1955 flood was 178 feet above sea level at the confluence of the South Fork Eel and the Main Fork Eel; both sites are near the confluence and were inundated by that flood.

It is apparent that flooding and sediment deposition are periodic events, the only unique aspect being the length of the expected period between events on each alluvial flat. This will depend partly upon the natural regime of the particular watershed, and partly upon the elevation of the alluvial flat above the present streambed. In the case of the Rockefeller Grove flat on Bull Creek, the interval apparently did not change as the level of the flat rose through sedimentation because flooding heights are controlled by backwater due to the much larger flow of the main Eel level one mile downstream. This backwater type damming has been described on the Rio Grande by Kochel and Baker (1982). In the case of the Tall Tree flat on Redwood Creek, however, the main control is the elevation in the adjacent stream channel of Redwood Creek itself, as determined by bedload depositions in the creek.

There is a certain amount of error in the measurement of redwood tree age due to discontinuous rings (Fritz and Averell, 1924). This error may be 10% in a one thousand year old tree (E. Fritz, personal communication, 1961). This is about the magnitude of the error in radiocarbon dating for the same period. The error, although important in exact dating of a flood year, is not so critical in evaluating return intervals of events.

In addition to the frequency of occurrence of sedimentation events, it is important to evaluate the properties of the sediment, particularly with regard to the health of the trees. This vigor is already a problem with the Tall Tree as indicated by its top dieback.

PHYSICAL PROPERTIES OF SEDIMENTS AND DERIVED SOILS

I have measured various physical properties of the sediments and resulting soils in the alluvial groves along the Eel, and the Van Duzen Rivers. These properties were bulk density, or dry weight per unit field volume, the texture as percent sand, silt, clay, and the total depths of deposition. Sediment deposited in the 1974 flood along the Eel River was measured for volume weight and averaged 1.27 in Founder's Grove, and 1.21 in Rockefeller Grove. The sites were not significantly different, based upon 8 samples in each location. Apparently the value of 1.2-1.3 has been fairly consistent for the last thousand years as seems to be indicated for the bulk densities for the deep Bull Creek Flat profile plotted in Figure 6. For this profile, the bulk densities tend to be higher than for most forest soils, ranging

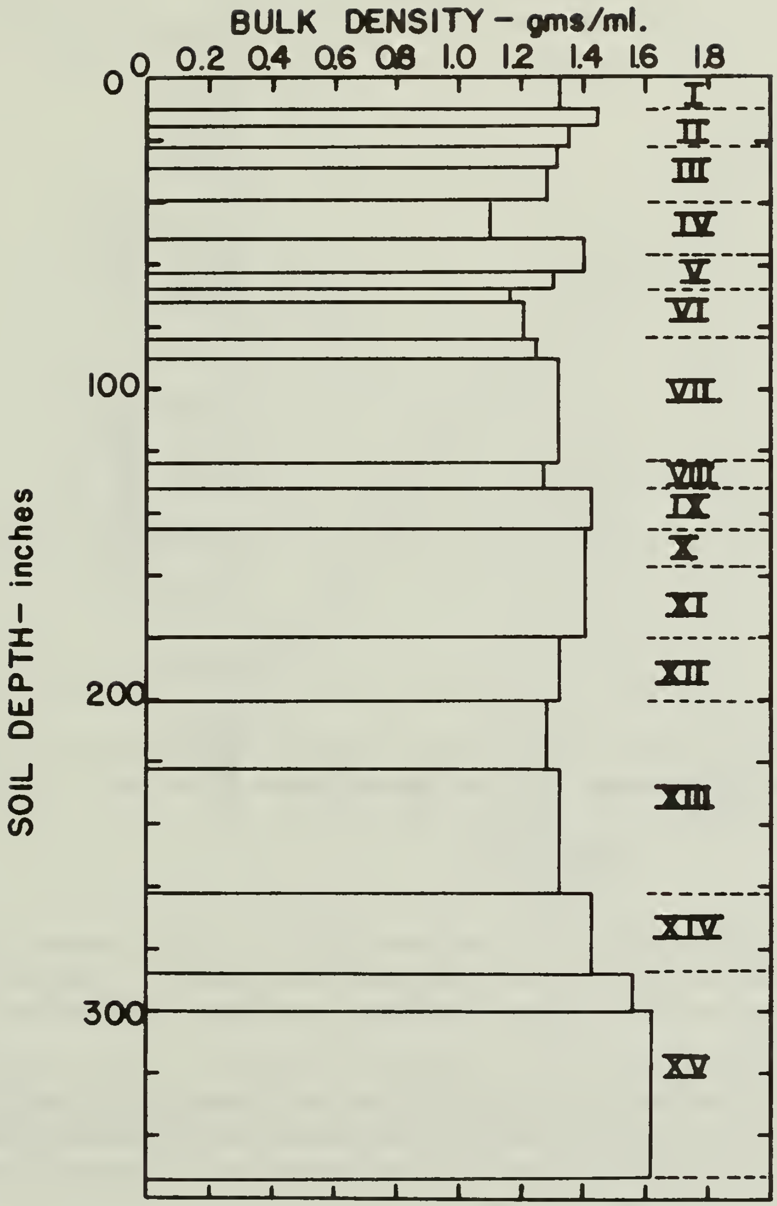

Figure 6: The bulk density (oven dry weight per unit volume) of the soil samples obtained from the deep soil excavation in Rockefeller grove. Original sediment initial density after first season settling ranged from 1.2-1.3.

Table 1: Cumulative probability of size of interval in years between tree ring growth accelerations assumed due to flood deposited sediment at two locations along the Eel River: Rockefeller Grove at 155' above sea level, and Haas Grove at 170' above sea level.[1/]

Cumulative Prob. % of Intervals	Rockefeller Grove years	Haas Grove years
≥10	27.3	48
20	31.3	57.3
30	36.5	66.4
40	43.3	76
50	51.9	86.4
60	63.4	98.2
70	79.3	112.5
80	103.3	131.2
90	148.0	160.8
n	14	27
mode	24.8	59.1
arith. mean	73.9	97.1

[1/] determined using Weibull function for cumulative probability. Using Chi-square, significance was .02 for Rockefeller Grove and .07 for Haas Grove.

from the 1.2 of the freshly deposited sediment to 1.6 in the lowest layers under compaction of the weight of the total sediment column. However, on surfaces which were exposed for longer periods, a surface soil below 1.2 in bulk density develops.

The coarse or gravel fractions were measured in all the samples, and for the sediment additions representing overbank flood stages and sedimentation there were few materials greater than 2 mm. in diameter. This was true for the entire depth of the sediment column.

A total of 1212 grams of sediment per square cm. of area was deposited during 1000 years on the Rockefeller Grove soil profile. Figure 7 shows the cumulative sediment amount during the centuries involved. Despite widely varying deposition intervals, the slope of this relation is fairly

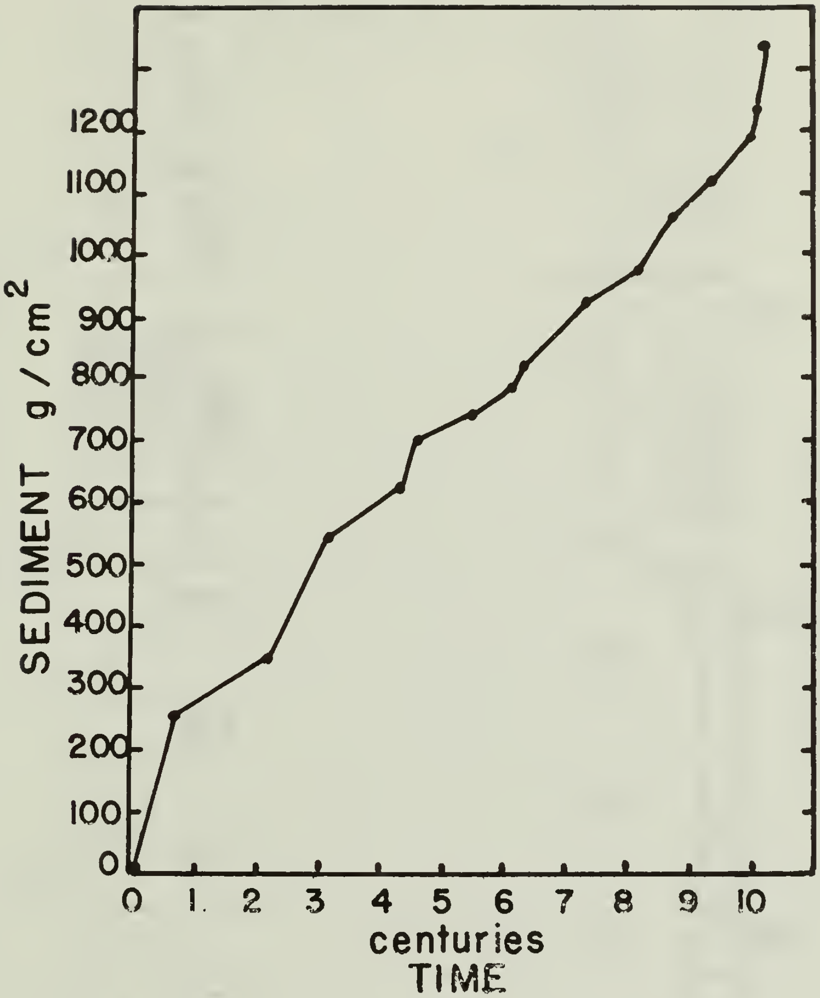

Figure 7: The cumulative sediment weight deposited during the past ten centuries at the Rockefeller Grove site. A value of 1212 grams per cm^2 measured up to 1955, with last plotted addition in 1964.

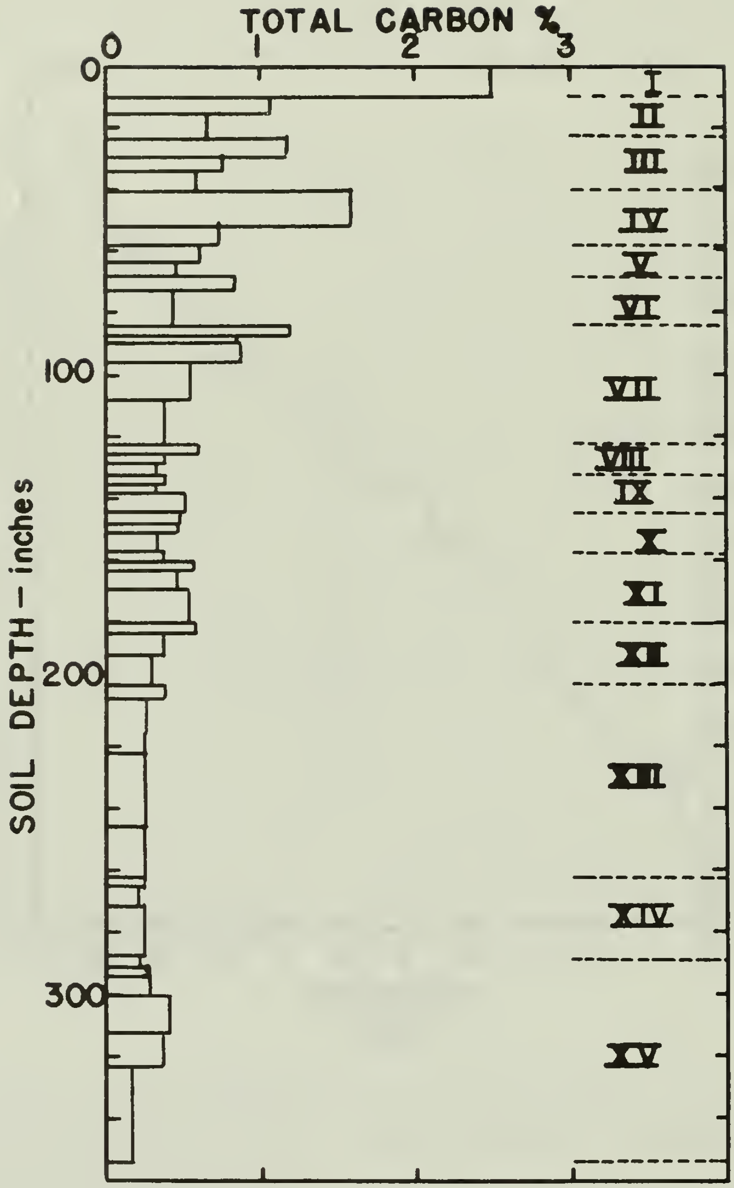

Figure 8: The carbon contents of the soil sample representing the various soil layers from the excavation in Rockefeller Grove (%C in the fine earth fraction less than 2mm on an oven dry basis.).

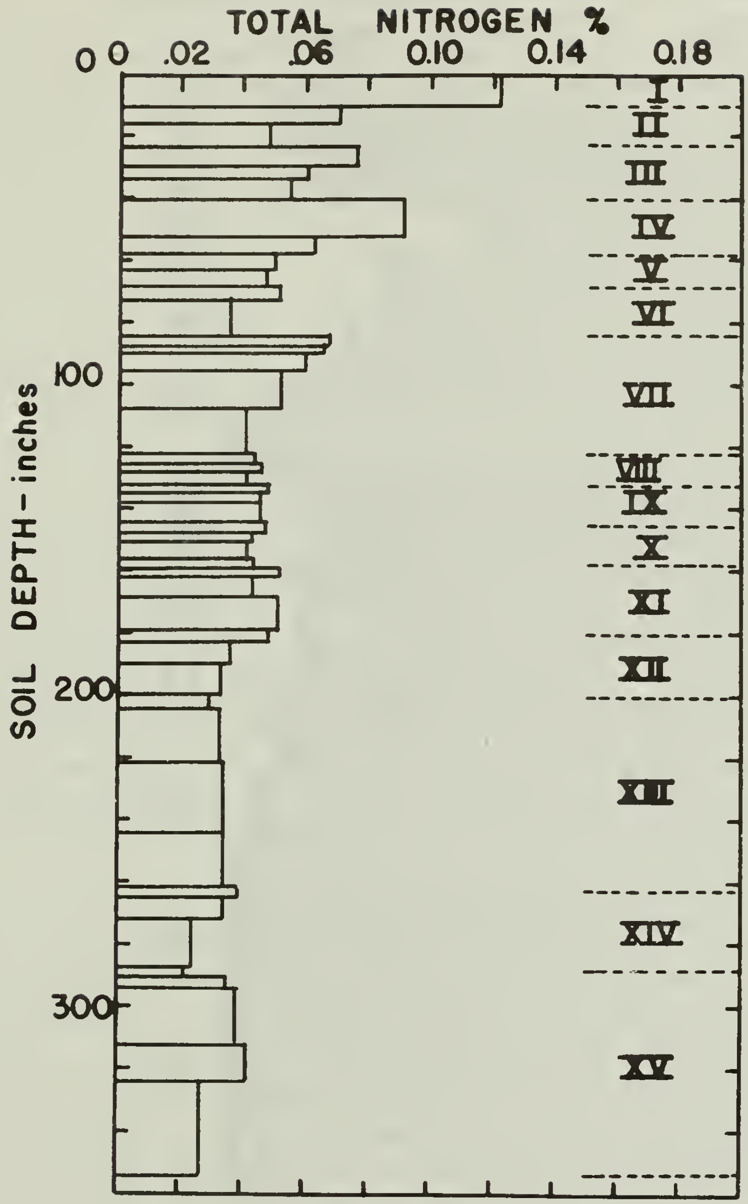

Figure 9: Total nitrogen contents of the soil samples representing the various soil layers from the excavation in Rockefeller Grove.

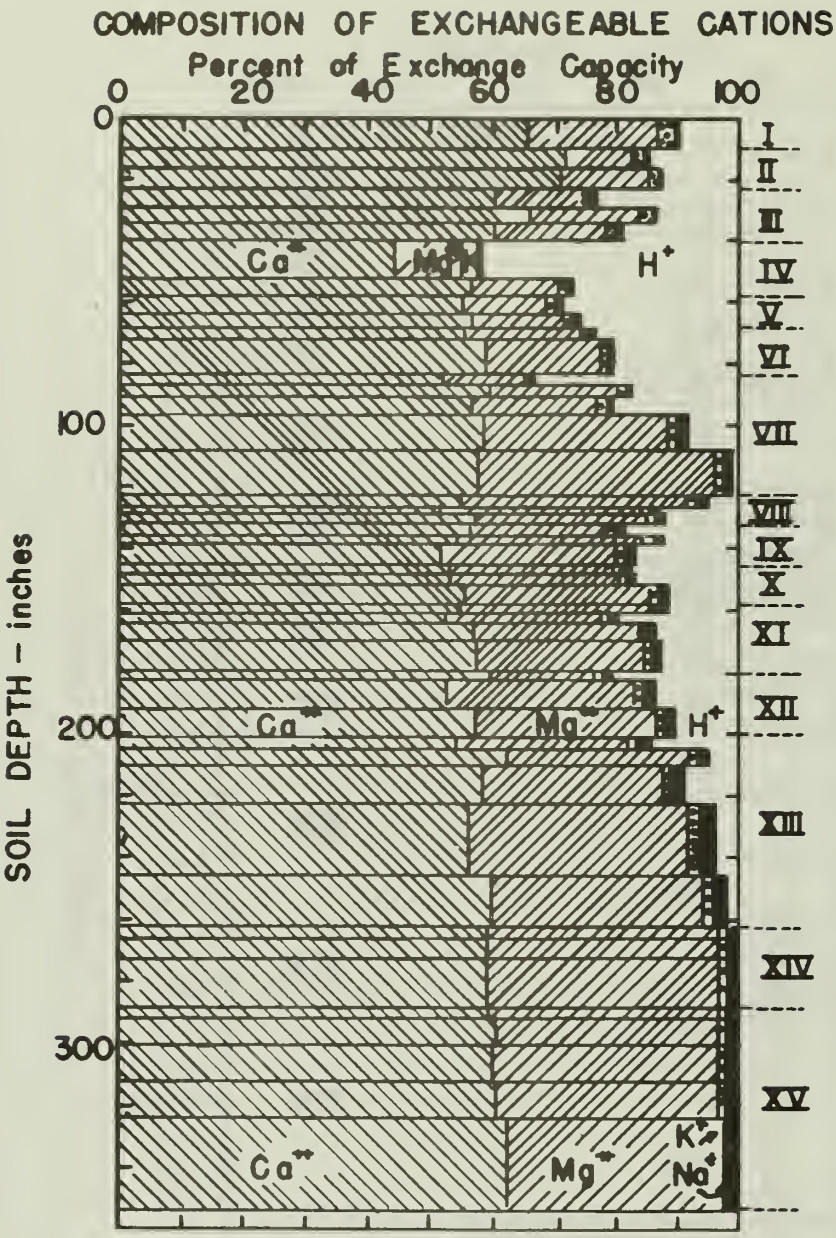

Figure 10: The exchangeable cation composition in the various soil layers in the Rockefeller Grove soil.

constant. Sixty percent of this deposition material was in the silt size fraction, or 728 grams. Fifteen percent of this material, 186 grams per cm^2 was clay less than 2 microns. The remaining 25 percent was sand (usually fine sand fractions). Sediment samples collected after the 1964 flood had slightly less clay content, averaging 13 percent for ten samples, and more silt with 71 percent, and less sand with 17 percent. However, there is a large variation within each deposition layer, with larger proportions of silt and clay in the topmost layers. This particle size distribution of the sediment resulted in no deleterious effects to the trees at the site, and was consistent for a long period of time. There is also textural variation across a redwood flat, with larger proportions of sand near the stream, and less inside the flat. Those concerned with preserving a grove for a long period of time on such a flat will need to anticipate a normal rate of sedimentation of a typical particle size distribution over the long period of time.

Each alluvial flat will have its own rate of accumulation based upon depth and duration of overflow flood waters. Of course, intervals between events will be variable. Certainly watershed disturbances such as fires, and natural landslides have occurred during the 1000 years of this record, and it is against this background that one needs to assess the possible effect of man-made disturbance of these hydrologic regimes. Figure 7 indicates that there may be periods of increased sedimentation, possibly due to local events augmenting sediment or to floods that are extreme in stage and duration. The trees are apparently unharmed as long as they are able to o-cupy the new sediment deposits with new roots, and are not physically felled by bank failure due to stream erosion, or sliding during the flood draw-down period.

CHEMICAL PROPERTIES OF SOILS DERIVED FROM SEDIMENT

Carbon, nitrogen, and various other chemical properties of the soil related to fertility were determined on the alluvial soils along the Eel River and Bull Creek. These elements generally show an increase in amount at the top of each new buried layer, decreasing to the top of the next layer. Successive surfaces of buried layers decrease in total content of these elements. This can be seen for carbon and nitrogen in Figures 8 and 9. It is apparent that both carbon and nitrogen are conserved in the buried layers, with an increase at each buried surface. These darker surfaces of the buried soils make it possible to identify the buried layers in the field excavation. Florence (1965) found that the new sediment, although low in fertility, had properties in terms of microbial processes that accelerated the availability of mineralized nitrogen and enhanced seedling survival. The various exchangeable cations follow a similar trend as seen in Figure 10, except that there is an obvious zone of depletion of these, and substitution by hydrogen in the most active current root zone above 2.54 meters depth. The consistent 60% calcium saturation below this depth is also of interest.

The return of redwood leaf litter to the soil surface with its content of the various elements most likely enriches the present sediment surface as long as it is exposed during the interflood interval. The extent to which this litter return enriches the particular soil depends upon the length of this interval, again a function of flooding probability, and height of the flat above the stream channel.

DEVELOPMENT OF THE FOREST ON SEDIMENT DEPOSITS

Redwood trees produce prodigious amounts of seed. During the redwood ecology studies in Humboldt Redwoods State Park, I collected seed along with leaf litter for several years. Seed counts were made of this material at locations along the South Fork of the Eel River, with seed amounts ranging from 2 to 27.9 million per acre per year. However, viability of the seed is less than 20%, and one rarely finds surviving seedlings from all this seed production each year in the groves. In contrast, following a flood year with sediment deposition, an invasion of young surviving seedlings, green as a lawn, develops on the new sediment deposit under the trees and as a margin to the grove. Figure 11 shows several age classes of such seedlings. In the foreground are the seedlings of the 1955 flood, in the middle the 1916 flood seedlings, and behind, the 1861 seedlings. Figure 12 is a photograph of Founders Grove. The seedling wave from the 1861 flood can be seen as a wall along the front of the grove itself composed of seedlings from floods of 100 years ago. Inside the grove are a few isolated giant trees, including the Giant Tree of Founders Grove, survivors of even earlier historic floods. Thus, the age class distribution within the superlative redwood grove gives us a clue to the periodicity of sediment-producing floods on that particular site, important information for the manager.

However, there may be detrimental effects of some flooding and deposition in redwood groves on alluvial flats. After the 1955 flood on upper Bull Creek Flat, we noticed that some of the large old trees of the grove had tops which were dying back. At the base of these trees we found deposits of sediment that were very coarse and gravelly, and choked with organic detritus. This material formed an abrupt interface with the previous silt loam deposits. Water perched at this interface during the wet season, and a blue anaerobic layer developed in the leaf litter which was buried there. The trees weakened by this abrupt change in quality of sediment were finally killed by redwood bark beetles (*Phleosinus sequoiae* Hopk.). Wherever the floods of 1955 and 1964 resulted in death to redwood trees along the Eel River, and Bull Creek, we found a deposit of coarse texture. E. Fritz (1956) reported that such a change in stream flow regime may be brought about by the sudden release of flood water and detritus due to the breaching of a log jam upstream.

A considerable loss of trees may also occur from actual failure of the stream banks where the stream cuts into such banks, and where quick drawdown following flooding causes saturated soil to slide along with trees into the stream. When these trees fall while the flow is still high, the tree bole is usually oriented downstream and parallel to the bank. Eventually such fallen trees protect the bank against further cutting by the stream. However, this natural tree groin formation formation is usually removed by the park manager, or if not, by poachers. This occurred at Cheatham grove on the Van Duzen River. This use of natural tree groins as a means of bank protection has been documented for large river systems by Framjl (1947).

Figure 11:Seedlings of various age classes identifying sediment deposits in Stephens Grove. Foreground seedlings from 1955, intermediate height from 1916, and taller saplings from 1861.

Figure 12:Seedlings from the 1861 flood sediment now forming a wall on the outside of the Founders grove at the confluence of the main Eel and the south Fork.

RELATION BETWEEN WATERSHED CONDITIONS AND THE SUPERLATIVE REDWOOD GROVES

The close relation between the vigor of the trees, the dynamic processes of flooding and sedimentation, and a thousand-year consistent quality of sediment free from coarse fragments, or excessive bank cutting by the flooding stream, is apparent. In the case of Redwood Creek as well as in the case of the superlative groves on alluvial flats along rivers to the south, the maintenance of these groves involves avoiding undue changes in these processes. The flood events will certainly continue to occur. But the quality of the sediments reaching the alluvial flats may change. If coarse bedload material is deposited on such a flat, then the result may be a serious decline in tree vigor.

The watershed management objectives needed to maintain the balance in sediment quality favorable to the trees involve two major areas of concern: the first, the control of the channel immediately adjacent to the grove; and second, the goal of maintaining watershed conditions that minimize adverse changes in the flood and sediment regime of the stream.

The immediate goal of channel management needed to protect the Tall Trees Grove requires an assessment of the problem of potential bedload deposition in the grove related to local aggradation. Designing the means of protecting the grove against such an event can be formulated, possibly using groins, revetments, or guiding of the stream to the opposite side of the channel. A similar problem occurred at Cheatham Grove along the Van Duzen River, where excessive bank cutting was gradually destroying the grove. The problem was treated by a series of gravel fill groins extending into the channel, which diverted the river to the far shore. Sale of the fallen trees from this Nature Conservancy Reserve paid for the necessary work. Along Bull Creek, the State Park Department utilized channel clearing, and gabbions and rock revetments along the channel bank.

Upstream watershed management objectives will require an assessment of sediment and bedload sources, and the development of cooperative ways of dealing with a wide variety of owners and land use conditions. I made an initial determination of sediment sources on Redwood Creek for a study of buffer zones to the Park (Stone, Grah, and Zinke, 1969). The entire watershed was surveyed with regard to soil types and their slopes in the course of the California Cooperative Soil Vegetation Survey, making it possible to determine where critical areas of high erosion potential are located. The sediment entering the stream channel is largely a result of bank cutting and land slides. Sediment sources can be related to soil types as mapped along the banks of the creek and its tributaries. The length of stream bank occupied by each soil type was determined for forty-two and one-half-miles of banks of Redwood Creek above the Emerald Mile.

These data (shown in Table 2) indicate that twenty-eight and three-quarter-miles of bank will be actively feeding material into the channel from compound slides. These are areas of the blue-grey colored Atwell and Yorkville soil series. It is these materials which give the waters of Redwood Creek their characteristic grey color. These soil materials contribute not only

Table 2. Soil types along 42.5 miles of Redwood Creek from the Redwood National Park boundary to the Snow Camp area of the Six Rivers National Forest.

SOIL TYPE	EROSION SOURCE POTENTIAL	MILES* OF BANK	PERCENT OF DISTANCE
Atwell (823) or Atwell complex with Masterson or Hugo	Very high potential with numerous compound landslides	28.0	33.0
Yorkville (752)	Very high with compound landslides	0.75	0.9
High Terrace (400)	Moderate with debris slides and bank cutting	12.0	14.1
Masterson (821)	Moderate to low, block slides if dip of schist is downslope toward creek	43.75	39.7
Hugo (812)	Low-moderate. Debris sliding if steep slope or vegetation removed	8.5	10.0
Recent alluvial soil low terrace (200)	Low, unless bank cutting occurs	2.0	2.3

*One mile of creek considered to have two miles of bank for this study.

to suspended sediment load but also to bedload, depending upon the proportion of coarse materials they contain. Stream cutting of the banks of the hgih terraces along the creek will be another source of bedload. These high terrace soils are historical beds of the creek and deltas of tributaries left stranded above the current grade of the creek as in Redwood Valley. There are 12 miles of such high terrace soils in the Redwood Valley area in the Beaver Creek and Minor Creek areas. Fifty-two and a quarter miles of moderately stable to stable banks occur along the areas where the Masterson and the Hugo soils line the creek. However, about half of these have slopes greater than 50% and thus are potential sources of increased sediment if surface erosion or mass movement is accelerated by land use activities. A minor distance of 2 miles of stream bank are occupied by recent alluvial deposits which have a low potential as sources of sediment and bedload. Given this array of sediment sources, the priorities of action needed to achieve stability of historic watershed processes can be attainted.

Most likely the Tall Trees Grove has a long history of flooding and sedimentation, as with other similar groves on alluvial flats, and it is necessary to see that this continues with minimum adverse change. This will be difficult, because the past half-century has been one of major changes on the watershed related to human use. As can be seen from the table, more than one third of the bank length is occupied by soils having a high erosion potential. These would be critical areas to monitor if it is thought that a problem requiring renovation exists. This evaluation does not involve tributary streams, for which a similar assessment should be made.

CONCLUSIONS

1. Each alluvial flat supporting superlative redwood groves is unique in its history of dynamic events of flooding, sedimentation, and response of the trees to these events.

2. The effects of sediment deposition may be detrimental or beneficial, depending upon the quality of the sediment deposited relative to the ability of the tree roots to invade this new material.

3. Fine sediment of a silt loam quality is generally beneficial, while coarse gravelly bedload deposits are detrimental.

4. Accelerated tree growth usually occurs following deposition of sizable amounts of beneficial sediment, and the increases in tree ring width can be used to date such flood-sediment deposition events.

5. An example of such a chronology is presented for Rockefeller Grove on Bull Creek Flat.

6. Redwood seedling survival is enhanced by new sediment deposition, resulting in age classes of trees in the groves dating such deposits.

7. The history of a particular grove such as the Tall Trees Grove can be interpreted by means of the sediment profile of the soil, by the tree ring history of periods of growth acceleration due to sediment, and by the age classes of trees present in the grove.

8. All of these indicate a history of dynamic flooding, sedimentation, and rejuvenation of tree growth on the alluvial soils of the superlative groves.

9. Management of these groves with the objective of their preservation must allow for such events and their maintenance.

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REHABILITATION AND LONG-TERM PARK MANAGEMENT OF CUTOVER REDWOOD FORESTS: PROBLEMS OF NATURAL SUCCESSION

Stephen D. Veirs, Jr. and William S. Lennox[1]

Abstract. There is no known natural equivalent of clearcut timber harvest in the redwood vegetation of Redwood National Park. Thus no prediction of future forest development on cutover parklands can be made without formulation of models based on data from young second growth forests and descriptions of the dynamics of uncut (old growth) forests. Preliminary observations suggest that Douglas-fir (*Pseudotsuga menziesii*) will be strongly over-represented with respect to coast redwood (*Sequoia sempervirens*) and that this condition may persist for centuries. Studies now underway may be used to predict long-term second growth stand dynamics and suggest rehabilitation methods for speeding the development of an old growth mimic.

INTRODUCTION

Old growth redwood forests occupy about 15,800 hectares (39,000 acres) in Redwood National Park. Redwood vegetation, especially in the northern half of its range in northern California has been categorized as a climax vegetation type (Weaver and Clements, 1939), but little data has been presented to support the view. Fritz (1929) described an all-aged redwood stand while Veirs (1980) found additional evidence to support the climax concept in coast redwood forests.

Within the present parklands approximately 20,650 hectares (51,000 acres) were clearcut during this century, producing even-aged second growth forests dominated by Douglas-fir (*Pseudotsuga menziesii*) instead of coast redwood (*Sequoia sempervirens*).

Park managers must evaluate the natural dynamics of old growth stands and the patterns of succession on the clearcut lands in order to establish long-term vegetation management policies. The objectives of these policies should be (1) to maintain the old growth forests free from substantive modern human influences and (2) to rehabilitate the second growth forests or speed their conversion to a mimic of the old growth forests in keeping with National Park Service policies (USDI, 1978).

BACKGROUND

Stable old growth redwood stands in and around Redwood National Park have been described as part of the long-term management research effort at

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Redwood. Typically these stands have low densities of overstory redwood and Douglas-fir (Table 1). The overstory redwood component of these stands is all aged with average ages of 200 to 800 years. Ages of a few individual redwood exceed 1,000 years, and the oldest redwood was more than 1,600 years old when cut. The Douglas-fir component of these stands is even-aged and occurs in various discrete age groups up to about 600 years. The age distributions are obviously in strong contrast with the ages of trees established following logging twenty, thirty, or sixty years ago.

No patterns of upland redwood succession have been described although some have been proposed (Stone and others, 1969, Cooper, 1965) in which redwood would be replaced by other species in the absence of fire.

Data exist for several normal old growth stands and several "young" stands of old growth redwood (Veirs, 1980). This type of information may be used to develop predictive models for "normal" redwood stand dynamics, while data from stands established following clearcut logging may be used to develop similar models for second growth stands. Based on predictions derived from these models, recommendations may be made for rehabilitation to restore or speed the restoration of second growth stands which mimic the natural old growth stands.

Stand density in relation to time has been described for both old growth and second growth forests including redwood (Harper, 1977). In the case of a climax forest type the number of standing trees decreases from young to old age classes. Most young trees present at any given time have little probability of surviving to older age classes or canopy tree status. In second growth stands this age pyramid is replaced by a pyramid of size classes. Of the many seedlings established about the same time following logging or burning in a forest, only a relatively small number will reach dominance. The balance die suppressed. In some special cases whole second growth stands may remain in an "autosuppressed" condition where there is little mortality and many very slow growing trees survive for long periods forming a stagnated stand (Diamond, 1978). This condition may exist in some stands within the park.

RESULTS

Stand density and tree age for redwood and Douglas-fir is presented in Table 1 for upland stands of old growth and second growth redwood forest and for stands reestablished following landslides. Alluvial forests are not discussed here, nor are the roles of associates and understory species including hemlock (Tsuga heterophylla), tanoak (Lithocarpus densiflora), grand fir (Abies grandis), big leaf maple (Acer macrophyllum) and others.

The ratio of redwood/Douglas-fir canopy trees (greater than 60 cm, dbh) in an old growth stand ranges from about 10:1 to 3:1 depending on individual stand history. In young second growth stands the situation is reversed, with Douglas-fir outnumbering redwood by a factor of 2 to 10, depending on aspect and slope position. These values are presented for discussion and should be interpreted with caution due to sampling limitations. Our sampling has not permitted us to establish mortality rates for either species in second growth stands, so we are not yet able to predict the composition of these stands in the post logging succession. It is clear that on most sites Douglas-fir is vastly over represented in comparison with normal old growth stands.

Table 1: Densities of *Sequoia sempervirens* and *Pseudotsuga menziesii* in upland redwood forest vegetation of various ages and conditions, Redwood National Park and vicinity.

STAND AGE AND DESCRIPTION	DENSITY OF STANDS (TREES/HECTARE)		RATIO
	COAST REDWOOD (Sequoia sempervirens)	DOUGLAS-FIR (Pseudotsuga menziesii)	REDWOOD / DOUGLAS-FIR
10 to 15 YEARS AFTER CLEARCUTTING	420	3,226	0.1
25 YEAR OLD THINNED CLEARCUT	522	325	1.6
60 YEAR OLD CLEARCUTS	112	343	0.3
REVEGETATED LANDSLIDE SURFACES 120 YEARS OLD			
1	245	163	1.5
2	808	17	47.5
3	209	38	5.5
STANDS LESS THAN 1,000 YEARS OLD (TREES >60 CM DBH) (3 STANDS)	97	11	8.8
STANDS MORE THAN 1,000 YEARS OLD (TREES >60 CM DBH) (9 STANDS)	37	14	2.6

The data for densities of redwood and Douglas-fir in stands reestablished following landslides which occured in 1861 are presented in Table 1. These landslides are not analogous to modern clearcut hillslopes. This is due to the relatively small size of the landslides and their low slope position. These factors would be expected to produce a more shaded, moist environment favorable to redwood reestablishment and is in strong contrast to the hotter, drier full sunlit conditions found on large clearcut and burned upland sites. For this reason data from only the largest (driest, hottest) of the three sites was used in the regression.

Selected data from Table 1 are plotted in a common logarithm form in Figure 1. Some liberties have been taken in selection and pooling of these data, presented here for conceptual purposes. Stand age for stands less than 1,000 years was taken as 500 years and stand age for stands termed "greater than 1,000 years" was taken as 1,000 years. Linear regressions were computed for redwood and Douglas-fir density in second growth and old growth stands, over time. From this data it may be observed that a redwood/Douglas-fir ratio of 1:1 occurs after stands reach 100 years of age. A ratio of 2:1 is obtained after 250 or 300 years.

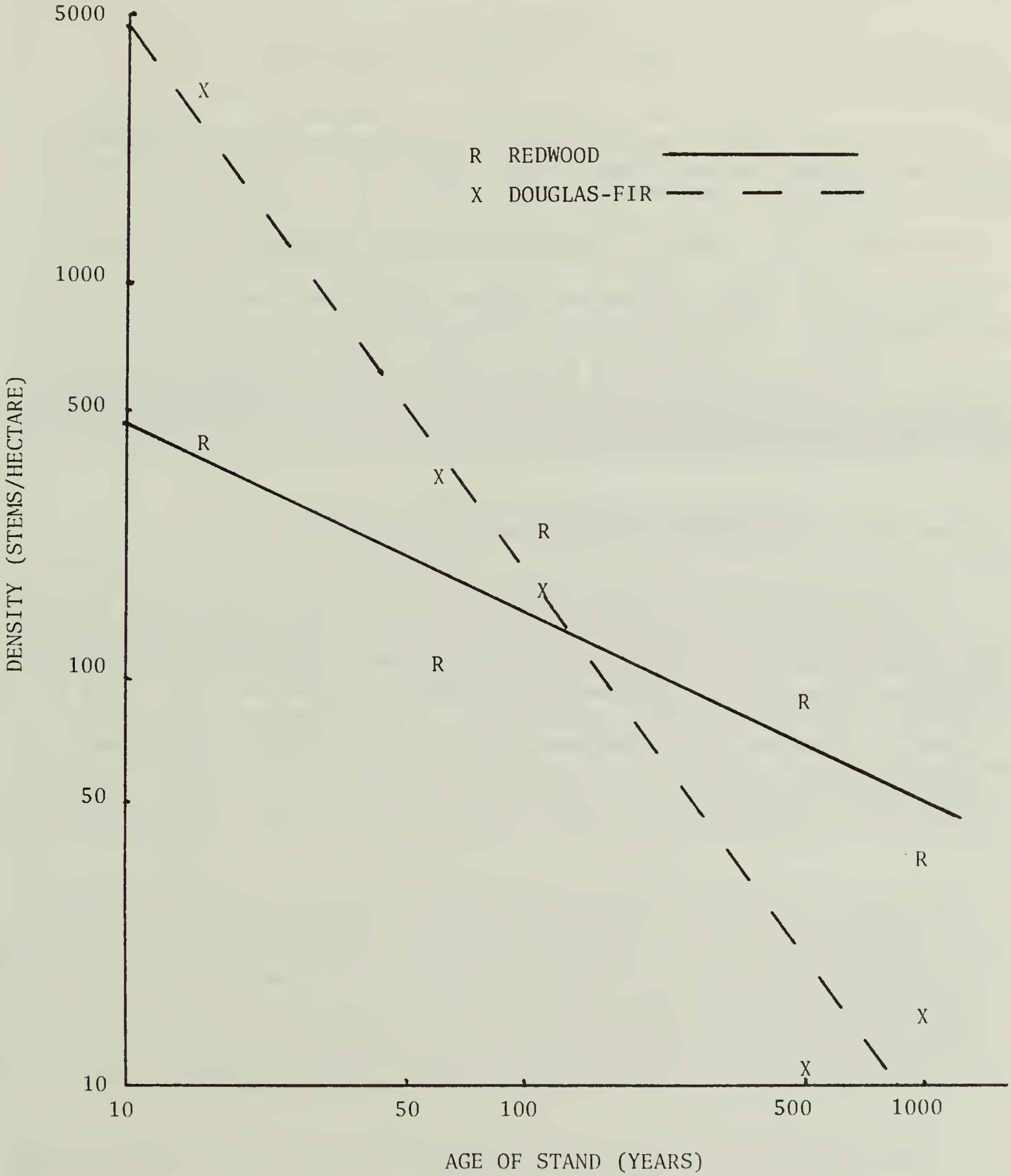
In 1978-9, shortly after park expansion, a large scale experimental thinning project was carried out in several second growth stands about 25 years after logging. Pooled data for these sites show that Douglas-fir numbers were reduced to about 60% of the redwood after operational thinning to several prescriptions. Results from similar sites can be used to demonstrate that thinning in a 25-year-old stand can produce a redwood/Douglas-fir ratio comparable with that found in an untreated 60-year-old stand. Thinning also substantially changes the visual and physical character of the treated second growth forests. Complete results of the thinning study will be presented elsewhere.

DISCUSSION AND CONCLUSIONS

Natural successional processes in second growth redwood vegetation may slowly restore a mimic of the former old growth forests on lands within Redwood National Park. The data presented here lend support to the idea that this process may take centuries. The question of the role of stump sprouting was not addressed, but clusters of redwood stems around stumps now occur in much greater numbers than similar natural clusters in uncut stands. Thinning young stands is a management tool which may be employed to adjust the redwood/Douglas fir ratio and to decrease densities. Our experience in thinning suggests that there are practical and political problems associated with thinning in stands older than 25 years. Increasing tree size is a barrier to mechanical thinning as the stand develops. Thinning may be useful in changing the visual and physical character of young stands. This might be desirable for certain park purposes beyond biological rehabilitation or stand naturalization. Early thinning to stand densities of 250-600 stems per hectare has produced stands similar to those observed in untreated stands 60 years old.

These stands, however, remain well above desired densities and Douglas-fir continues to be over-represented relative to redwood. Further artificial reduction of tree densities and alteration of species proportions by other procedures might be found to selectively accelerate individual tree mortality where desirable to continue speeding the return to a more nearly natural forest appearance.

Figure 1. Linear regressions of density changes over time in numbers of redwood and Douglas-fir in upland redwood. (Data from Table 1, untreated stands and landslide 1 only.)



Long-term management of old growth redwood forests and young second growth stands within Redwood National Park will depend on the acquisition of additional information concerning old growth and second growth ecological processes. Direct manipulation to speed stand naturalization is a tool which should be examined further on an experimental basis. Results of these studies may establish rationale and techniques which will speed the restoration of the natural grandeur of the virgin redwood forest in those stands leveled before establishment of Redwood National Park.

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A PRACTICAL APPLICATION OF DISCRIMINANT FUNCTIONS FOR CLASSIFYING SUCCESSIONAL VEGETATION COMMUNITIES IN THE FIRST TEN YEARS FOLLOWING LOGGING OF COAST REDWOOD FORESTS, IN REDWOOD NATIONAL PARK

William S. Lennox, Esteban H. Muldavin, James M. Lenihan, and Stephen D. Veirs, Jr.

Abstract. Successional patterns in one to ten-year old vegetation established following logging of upland redwood forest have been determined for the lower Redwood Creek basin in northwestern California. A classification of successional vegetation types was developed using cluster analysis and tabular comparison of releves. Two main groups were identified. The first included four remnant vegetation types re-established where disturbance due to logging was low. Where logging resulted in severe soil disturbance or removal, a more weedy flora became established which was divided into six types through a moisture gradient. Multiple discriminant analysis models were derived for the classification and can be used to predict potential vegetation on sites poorly revegetated or newly denuded in the watershed rehabilitation process in Redwood National Park.

INTRODUCTION

Redwood National Park was expanded in 1978 by 48,000 acres including approximately 36,000 acres of cutover forest lands which had previously been dominated by stands of coast redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menziesii*). With expansion, an extensive watershed rehabilitation program was authorized to control erosion and sedimentation and to reduce risk of damage to streamside areas on Redwood Creek. Part of this rehabilitation program (USDI, 1981) includes the use of plants for erosion control and to re-establish the natural vegetation of the parklands. This study was designed to investigate the patterns of vegetation succession on the recently logged forest lands as an aid in determining correct plant species for use on freshly denuded rehabilitation sites and inadequately revegetated areas of the park.

Previous research describes succession following logging in redwood as a rapid transition from a period of dominance by short-lived weeds followed by hardwood brush invasion and then conifer dominance. This is influenced by the proximity of seed source, slash treatment and soil surface conditions (Fritz, 1959). In the first five years after logging, herbaceous vegetation is most abundant. In the second five years, herb cover decreases and becomes quite scarce after ten years have passed. Shrubs are not abundant until six to ten years and remain dominant for an 11 to 20 year period. After 20 to 30

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years, conifers become the dominant cover (Dassman , 1968; Zinke, 1977). Waring and Major (1964) indicate that, in general, after disturbance by cutting or fire, light demanding species assume dominance, but the majority of original forest species are still present.

In this study, we describe in greater detail the pattern of early succession that occurs prior to re-establishment of conifer dominance and explore some of the underlying environmental conditions that may determine this pattern. This is done by constructing a classification (using cluster analysis and tabular comparison) of the vegetation communities that incorporates the successional processes as part of the community descriptions. Statistical models are then derived (using multiple discriminant analysis) to evaluate the factors which influence community development. These models may be used as a management tool for vegetation mapping, for direct site evaluation and for species selection for planting as part of the rehabilitation program for Redwood National Park.

STUDY AREA

The study area is in Redwood National Park within the Redwood Creek watershed of north coastal California. The Redwood Creek watershed trends in a north-northwest direction for 55 miles between adjacent drainages of the Mad and Klamath rivers; however, only the lower quarter of the watershed is included in the study area. This area consists of approximately 50,000 acres (20,250 ha) of which 36,000 acres (14,200 ha) are logged, 12,000 acres (4,850 ha) are virgin redwood forest, and 3,000 acres (1,200 ha) are coastal prairie.

The upland virgin forest vegetation of the study area can be described from preliminary results of vegetation classification studies by Lenihan (1981) in the undisturbed Little Lost Man watershed adjacent to the study area. These results suggest that the natural upland redwood vegetation of the lower Redwood Creek basin can be classified into three distinct types. The moist type is generally found at lower elevations, especially on lower, concave slopes. The mesic type is generally found at mid-elevations, especially on even topography. The dry type is generally found at higher elevations, especially on convex ridges.

Redwood Creek flows through the center of the study area, following the trace of the Grogan Fault. The basin's west side is underlain by the Kerr Ranch Schist, and dominated by the Masterson soil series. In contrast the east side in underlain by the Franciscan formation and dominated by the Hugo soil series.

The climate is maritime-mediterranean with rainfall occurring primarily from November through March. The summer months are characterized by coastal fog that may extend 15 miles or more up the basin.

The study area was subjected to intensive logging in the mid-1950's and continuing until park expansion in March, 1978. Early logging left scattered overstory seed trees. Clearcutting was the main logging method in the 1960's and 1970's using either tractor of high lead cable yarding. Tractor yarding was the most common, particularly on the older, higher elevation sites. Cable yarding did not become common until the lower slopes adjacent to the old boundaries of the park were reached. Only two units were cable yarded prior to 1973.

Slash burn following logging was a widespread practice but was not uniform. The majority of tractor yarded sites were burned whereas the majority of cable sites were not. Some sites were burned more than once with extensive hot fires, eliminating most logging debris and killing the residual vegetation. On other sites, burning was spotty and light, eliminating some litter and light slash, but leaving large areas of vegetation.

The variability in pre-logging vegetation, logging practice and environmental factors including aspect, elevation, and parent material has resulted in a complex mosaic of post-logging vegetation communities in the Redwood Creek drainage.

SAMPLING METHODS

A long-term study of successional change on a site was impractical because of the time limitations and immediate management needs. Instead, a sampling strategy of site-to-site comparisons was adopted. Many sites, in differing stages of development were compared and the successional processes inferred by grouping sites of similar floristic composition and environmental conditions into an age sequence. This then becomes a problem of analyzing vegetation patterns made complex by rapid successional processes. Our approach was to develop a classification of successional vegetation types to define the vegetation pattern. From the classification we analyzed the relationships of change in vegetation composition and structure within a particular vegetation type and relationships of vegetation types among each other, independent of time, as to their differing floristic and environmental characteristics.

Preliminary vegetation types were defined by a field reconnaissance in which the general species combinations that occur were identified. Each combination was then sampled by establishment of a "releve" or a plot within a floristically homogenous area (Mueller-Dumbois, 1974). Minimal plot size for the releve was established by developing species area curves from nested test plots. The minimal area was found to be 35 m^2 (400 ft.^{2}). Our releves ranged from 35 - 110 m^2, averaging 80 m^2.

Each releve included a complete inventory of vascular species stratified by height class: herbs (<1 m), shrubs 1 - 5 m), and trees (>5 m). Each species in each strata was assigned a cover-degree abundance value according to the Braun-Blanquet scale (Becking, 1957).

The following variables were also recorded: (1) Aspect with a hand compass; (2) Elevation from U.S. Geological Survey topographic map; (3) Slope in percent using a clinometer; (4) Terrain/Treatment factors: a. Tractor skid trails resulting from tractor yarding at harvest, b. Relatively undisturbed areas between tractor skid trails or "tractor islands," c. Evidence of cable yarding at harvest, d. Seepage areas or wet slumps, e. Sidecast or cutbanks of roads, f. Haul roads or landings, (5) Slope position calculated as the ratio (in percent) of the distance of a releve to the nearest drainage over total distance from ridgetop to drainage; (6) Percent slash cover by visual estimate; (7) Slash burning evidence present or absent; (8) Soil parent material; (9) Percent exposed mineral soil, or the percent of A Horizon soil removed, by visual estimate; (10) In addition, a soil profile on selected releves was taken with a hand auger with information recorded on soil horizons, color, depth, texture, structure, percent clay, rooting type and depth;

(11) The time since harvest of a site was determined from harvest records, historical aerial photographs or from annual ring counts on sprouting redwood. No complete harvest record was available at the onset of the project, thus sites were initially classified into broad age classes: young, medium, and old, until a definite timber harvest data could be assigned. This resulted in unequal size samples per year class in the final analysis.

A total of 361 releves were taken from June through September, 1979. Only sites logged between 1970 - 1978 were sampled (no logging occurred after March 1978). This represents an age span of one to ten years between logging and sampling.

DATA TRANSFORMATION AND ANALYSIS

The analysis was divided into three phrases: (1) The data transformation for analysis and computer processing; (2) The development of a hierarchial classification of successional vegetation types based on floristic composition using cluster analysis and tabular comparison techniques; (3) The development of multiple discriminant analysis statistical models (MDA) to quantitatively define the vegetation types floristically and environmentally. Finally optimal MDA models using a step-wise procedure for practical application in watershed rehabilitation and vegetation mapping were developed.

The releves were stratified into five age classes based on date of timber harvest: 1970 - 1972, 1973 - 1974, 1975, 1976, 1977 - 1978. The 1977 and 1978 sites were aggregated because the 1978 sites were harvested in early spring before the growing season and thus were more closely aligned with those of the previous season. Because changes in vegetation composition and structure appeared to occur at a slower rate with increasing age, the older sites were also aggregated to simplify the analysis.

The cover/abundance degree scale used in the field to record species cover was transformed to facilitate computer processing and numerical analysis after a scheme developed by Marrel (1979). The azimuth readings were transformed into a "solar exposure index" modified from Sawyer's Site Moisture Equivalency Index (1971). Azimuths are scaled from 1 to 16, with 1 being the warmest and 16 the coolest.

Since a species could be recorded in three different height strata, three independent records could result for the same species. We call each record a "species property." This study contains more than 250 such species properties based on observations of 180 different species in one or more height strata.

The classification phase of the analysis was an iterative process combining cluster analysis and classical phytosociological tabular comparison techniques to develop a hierarchial classification of successional vegetation types based on floristic composition.

Cluster analysis is essentially a tool for organizing data by associating similar entities (releves) into classes. The approach used was polythetic and agglomerative as described by Orloci (1967).

Due to both computer limitations and the need to reduce the dimensionality of the study, a maximum of 100 species properties were actually used in the numerical analysis at one time. The criterion for selection of a species

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Due to both computer limitations and the need to reduce the dimensionality of the study, a maximum of 100 species properties were actually used in the numerical analysis at one time. The criterion for selection of a species property was its presence in more than 5% of the total sample of releves, or 5% constancy, as defined by Becking (1957). Each age class was clustered separately using the same set of 100 species properties and their transformed cover values.

The cluster analysis was interpreted using tabular comparison. Synthesis tables (Becking, 1957) were constructed with releves in their clustered order in columns and species in rows. In this form, releve and species relationships can be directly analyzed by inspection. The determination of "significant" clusters is a matter of ecological interpretation based on acceptable levels of within group heterogeneity (based on cluster within group dispersion) and the location of differential species on the tables. Differential species are those species which serve to separate or define clusters on the basis of either their restriction to, or their high cover in, certain clusters. Significant clusters generally fell between 25% and 75% average within group dispersion. Above the 75% level, clusters tended to be highly heterogeneous. Either they could be separated at lower levels of the hierarchy into clusters clearly defined by differential species or they contained single anomalous releves that were clusters unto themselves because they were either unique or too heterogeneous in composition to classify at a lower level. These releves were labeled as transitional and not used in further group analysis.

Through an iterative process of rearranging releve and species orders on tables, blocks of differential species and associated releves were delineated, which defined types within each age class. We then grouped similar clusters, based on differential species blocks, from each age class and constructed the final classification of successional vegetation types. This classification describes the major vegetation communities and their successional progression from one to ten years after logging. This process is a modified version of the tabular comparison techniques outlined by Becking (1957) and Mueller-Dombois and Ellenberg (1974).

The next phase was to develop statistical models using multiple discriminant analysis to quantitatively define the floristic classification arrived at through cluster analysis and tabular analysis comparision, and to examine some of the possible extrinsic environmental factors which influence the successional patterns.

There are two objectives in the practical application of the vegetation type classification and associated MDA models. First, where vegetation is present, to classify and map it using MDA models based on floristic and environmental criteria together. Second, if vegetation is absent, as in the case after earth moving in rehabilitation of a site, to be able to predict potential vegetation using MDA models based solely on environmental criteria.

VEGETATION TYPE CLASSIFICATION & DESCRIPTION

The vegetation types are classified into two broad groups, Remnant and Invasion, based on the nature of species establishment. The Remnant Group is characterized by species common in the virgin forest understory which survived timber harvest and flourished. The typical dominant species are <u>Rhododendron macrophyllum</u>, <u>Lithocarpus densiflora</u>, <u>Vaccinium ovatum</u>, <u>Gaultheria shallon</u>, and <u>Polystichum munitum</u>. Other species such as <u>Oxalis oregona</u>, <u>Blechum</u>

spicanth, and Vaccinium parvifolium may be present but generally are not dominant. A sparse, scattered tree overstory may also remain, consisting of Tsuga hererophylla or Arbutus menziesii and occasionally Sequoia sempervirens and Pseudotsuga menziesii.

Within the Remnant Group, the vegetation types are described as follows:

1. Polystichum munitum/Oxalis oregana Type (P/O)
   This type is dominated by Polystichum in both the herb and shrub layers. Oxalis, Blechnum spicanth and Galium triflorum are characteristic components of the herb layer. Generally all remnant species begin with some cover and gradually increase until the site is covered. Gaultheria shallon, though it does not reach its optimum in this type, can be important in later years, co-dominating with Polystichum. Invading species such as Erectities prenanthoides can be strong early, but fade after the third or fourth year.

2a. Rhododendron macrophyllum/Vaccinium ovatum Type (R/V)
   This type is characterized by the dominance of Rhododendron, V. ovatum, and Lithocarpus in both the herb and shrub layers. In this type, total Rhododendron cover stabilizes by year three. Gaultheria, though present, develops little cover until year five after a decline of Rhododendron as it develops from a multi-branched sprouting form to a giant shrub. Loss of lower leaves effectively increases habitat available at ground level for Gaultheria.

b. Rhododendron macrophyllum/Gaultheria shallon Subtype (R/G)
   This subtype, like the R/V typic type, is dominated by Rhododendron, Vaccinium ovatum and Lithocarpus in the shrub layer, but by Gaultheria in the herb layer. Rhododendron fails to develop significant cover as a multi-branched sprouter allowing Gaultheria to dominate. Gaultheria is initially on the sites with fairly high cover (35%) and increases until year four with Rhododendron following a similar pattern in the shrub layer as a few branched giant shrub.

3. Lithocarpus densiflora/Whipplea modesta Type (L/W)
   This type is dominated by Lithocarpus in the tree and shrub layers, with Pseudotsuga menziesii occasionally co-dominating. Whipplea forms a low-lying mat under sprouting Lithocarpus. Lithocarpus definitely reaches its optimum in this type, but this vegetation type was found only in the older age classes (year five through nine), and the early phase remains undefined.

In contrast to the Remnant Group, the Invasion Group is characterized by species that are rare or absent in the virgin forest and invade the site after timber harvest. Examples are Alnus oregana, Ceanothus thyrisflorus, Baccharis pilularis, Carex dewyana, and Equisetum telmateia. The early years are often dominated by short-lived weedy species, including exotics such as Erechtities prenanthoides, E. arguta, Anaphalis margatacea, Ganaphalium chilense, G. purpureum, G. californicum and Epilobium paniculatum. Remnant type species may be present, but usually they have low cover values and are often merely maintaining themsleves on the site or declining. There are exceptions such as Iris douglasii, Arbutus menziesii, and Whipplea modesta which are capable of establishing themselves on new substrates and flourish with invading species.

The Invasion Group vegetation types are as follows:

1. Ceanothus thrysiflorus/Arbutus menziesii Type (C/A)
This type is almost exclusively dominated by Ceanothus with Arbutus, particularly in the shrub layer of older sites. Ceanothus attains an average cover of 70% by year eight and still has not peaked. At year three, when Ceanothus shrub cover peaks and it enters the tree layer, most other species are on the decline except for Arbutus which steadily increases in cover. Baccharis initially has a strong growth rate in competition with Ceanothus, but Ceanothus eventually prevails. Whipplea has a moderate cover in the younger years but also declines as the Ceanothus canopy increases. Smaller Ceanothus individuals decline in number as the dominant canopy closes. Ceanothus occurs primarily as a single age class.

2a. Baccharis pilularis/Whipplea modesta Type (B/W)
This is the most prevalent type within the study area. Both Baccharis and Whipplea attain their greatest cover in this type, dominating in the shrub and herb layers respectively. Both species increase in cover rapidly in the first three to four years and peak at five to six years. Unlike Ceanothus in the C/A type, Baccharis maintains reproduction, to some degree, after shrub layer establishment. Remnant type species can be present but generally do not flourish except for Iris and Whipplea.

b. Pseudotsuga menziesii/Whipplea modesta Subtype (P/W)
This subtype is also similar to the B/W typic type except that Pseudotsuga replaces Baccharis as the dominant in the shrub layer. This type is found only in older age classes and may reflect the silvicultural treatment (aerial seeding) during that time period.

c. Hypochoeris radicata/Aira caryophylla Subtype (H/A)
This subtype is also similar to the B/W type except that Baccharis, though present, is not robust and fails to reach shrub height (1 m), even after nine years. Overall vegetative cover is lower than cover for other types. Hypochoeris, Aira, and Lolium spp. replace Whipplea as the dominant ground cover.

3. Alnus oregona Type (A/A)
This type is dominated in all layers by Alnus. Whipplea can be an important component in the herb layer in early years; but after crown closure of Alnus, it declines. Baccharis pilularis shows a similar trend, increasing early and then declining when outpaced by Alnus.

4. Juncus effusus/Equisetum telmateia Type (J/E)
This is a broadly defined type which is characterized by dominance or co-dominance of several wet-site species including Juncus effusus, J. Bolanderi, J. Bufonius, Carex dewyana, Petasites palmatus, Typha latifolia, and E. telmateia, or E. arvense. Cover for any combination of species appears to reach a peak at year three and is maintained at a more or less constant level the remaining six years with little evidence of successional progression to a shrub community of either Baccharis or Alnus dominance.

STATISTICAL MODELS OF THE VEGETATION TYPE CLASSIFICATION

For each level of the classification hierarchy, separate floristic and environmental Multiple Discriminant Analysis (MDA) models are derived, beginning with the Remnant and Invasion groups. An MDA was used to separate the groups based on floristic disimilarities using 40 species that showed differential character in the constancy table. A total of 306 releves were used: 206 from the Invasion Group and 100 from the Remnant Group. A single discriminant function was generated which had a highly significant Chi-square (> .001).

THE REMNANT GROUP VEGETATION TYPE

An MDA was generated to quantitatively model the floristic difference among the Remnant Group vegetation types only. It was based on the 100 releves used to represent the Remnant Group in the previous MDA. Though the R/G Type is considered a subtype in the classification, for simplicity in analysis, it was entered in the MDA models at the same level as the other types. Twenty-three differential species were used as variables and the maximum of three significant discriminant functions were derived. The relative classification efficiency was 98% correct reclassifications indicating that the model, at least internally, is effective in differentiating vegetation types floristically.

To test for significant environmental characteristics that might be correlated with the floristic expression, another MDA was generated based on 11 environmental variables. Of the possible three functions, only the first two were significant and used in further analysis. These two functions together accounted for 97.5% of the total variation.

INVASION GROUP VEGETATION TYPES

A floristic MDA model of the Invasion Group vegetation types was generated on the basis of 30 species and 206 releves of the Invasion Group divided into their respective types. As with the Remnant model, the subtypes of the *Baccharis/Whipplea* (B/W) type have been considered at the same level as the types to simplify the analysis. The maximum of five significant functions were derived with a very high discriminatory power of 99.9% of the variation in the discriminant space attributed to group differences. The relative classification efficiency was 92% indicating that the Invasion Group vegetation types are also well differentiated floristically.

To determine if there are also significant environmental differences between the types, a MDA was generated based on the same releves and 15 environmental variables. Of five discriminant functions possible, the first four were significant (< .01), accounting for 98.9% of the total variation.

APPLICATION OF MODELS, THE OPTIMAL MODEL

For practical application in evaluation of existing or potential vegetation for sites being rehabilitated within Redwood National Park, "optimal" or easily applied MDA models were developed. These models were constructed by selecting variables that were easily measured in the field and then applying a stepwise MDA procedure to determine the best discriminators. This selection process resulted in reduced dimensionality (fewer variables) in the optimal models, but enough variables were retained to maintain the relative classification efficiency above 90% for the combined floristic/environmental models and 75% for the environmental models. The actual procedure for site evaluation and mapping using the optimal models is described in a separate paper (Lenihan, et al., 1981). It includes the field procedure, a vegetation type key derived from the optimal model and applications for park use. A simple computer program to compute vegetation type classifications of new sites using floristic/environmental data or environmental data only (for denuded sites) is also provided.

DISCUSSIONS AND CONCLUSIONS

From the classification and associated MDA models we can recognize two gradients of disturbance and moisture that effect succession after timber harvest in upland redwood forest vegetation. The influence of disturbance separates the Remnant Group of vegetation types from the Invasion Group. This is primarily a function of terrain (logging treatment) factors, which are correlated to precent mineral soil exposure, slash accumulation and slope. The sites may range from the slightly disturbed tractor island, with an intact surface soil, through the cable yarded condition with moderate disruption of the skid trail which may have little or none of the original soil mantle remaining. Logging also disrupts normal drainage patterns and soil moisture conditions. Examples include the re-direction of subsurface flows as surface water along skid trail patterns resulting in the dewatering of steep slopes and lowering of soil moisture levels. Conversely, the impoundment of water in areas of limited drainage and low slope may also result from logging caused changes in local topography. Overlain on this disturbance factor is an overall moisture gradient as measured here by separate individual vegetation types within the main groups. The hydric to moist conditions occur on cool northern aspects, at low elevation or low slope position and near the mouth of the basin. In contrast, the xeric conditions are found on the warmest southern exposures, high elevations or slope position and inland away from the influence of the ocean.

In the low disturbance conditions among the Remnant Group, the Polystichum/Oxalis (P/O) type occupies the moist end of the gradient; the Rhododendron/Gaultheria (R/G) type, the moist mesic; the Rhododendron/Vaccinium (R/V) type, the mesic; and the Lithocarpus/Whipplea (L/W) type, the dry mesic. A remnant type of the xeric condition is undefined. Additional field work may have resulted in definition of this type; however, the widespread impact of slash burning on these sites appears to have pushed the post logging vegetation into the Ceanothus/Arbutus disturbance type.

The Remnant Group successional vegetation types, as a whole, correspond closely to the herb and shrub unions described by Lenihan (1981) for upland virgin redwood forest types. Analogous remnant types are found following logging in the Pseudotsuga/Tsuga forest of the western Cascades of Oregon. Polystichum, Rhododendron, and Gaultheria are particularly important as shrubs in early succession (Steen, 1966; Morris, 1958; Issac, 1940). Dyrness (1973) has shown that on undisturbed soils Polystichum and Oxalis may dominate moist sites and Rhododendron, Vaccinium parvifolium, and Gaultheria on drier sites. Similarly, Yerkes (1960) mentions Oxalis showing preference for north-facing slopes and Whipplea south-facing. In the redwood region Zinke (1977) indicated that Polystichum can be common in the pioneer sere of his Redwood-Grand Fir forest type and that Whipplea is important in his Redwood-Douglas-fir hardwood type in conjunction with Lithocarpus and Arbutus.

As disturbance increases, the Invasion Group revegetation types become dominant. The Juncus/Equisetum and Alnus types occupy the hydric and moist mesic conditions respectively. Alnus is a common successional type in the Cascades supplanting Polystichum and associates with increased disturbance on moist sites (Franklin, 1979). In the redwood region, Becking (1966) mentions Alnus as a common successional species following natural disturbance in his Redwood/Oxalis alliance.

As conditions become more mesic the Alnus type gives way to the Hypochoeris/Aira type on highly disturbed sites and the Pseudotsuga/Whipplea and Baccharis/Whipplea types on less disturbed sites. The Baccharis/Whipplea type has elements of the North Coastal Shrub as described by Heady, et al., (1977) and Munz and Keck (1959) except instead of Gaultheria and Polystichum, Whipplea is the dominant herb (though the others can be present). The Pseudotsuga/Whipplea type results under similar conditions where aerial seeding was successful after harvest.

On the dry mesic to xeric sites that have been burned the Ceanothus/Arbutus type predominates. Zinke (1977) and Waring and Major (1964) indicate that normal succession in redwood can be shunted to Ceanothus chaparral similar to that described by Hanes (1977) except for the influence of Arbutus which is an element of the Mixed Evergreen Forest (Sawyer and Thornburg, 1977). Ceanothus thyrsiflorus chaparral is reported to extend into southwestern Oregon, primarily on burned sites (Hanes, 1977; Ingram, 1931).

In general the pattern of succession after timber harvest follows this trend: in the first three years short-lived annual and biannual herbs dominate followed by the development of shrub communities either from remnant plants that have survived timber harvest and flourished or from invading species capitalizing on the disturbed environment. The exceptions are the Hypochoeris/Aira and Juncus/Equisetum types, which occupy the most disturbed, driest and wettest types respectively. These show little trend towards shrub community development over 10 years time. It is probable that these sites will remain little changed as the second growth forests develop around them. Eventually reduced light levels eliminate all but the most shade tolerant species.

Successional patterns occurring on cutover redwood forest land beyond the period investigated in this paper remains to be examined in detail. Preliminary observations suggest that tree canopy closure can occur in ten to twenty years, depending on tree density. Harsh disturbed sites are slowest. Smaller areas of the Hypochoeris/Aira subtype remain unforested until tree canopies close over them from adjacent vegetation. Ceanothus/Arbutus stands may persist for twenty or thirty years, suppressing conifer growth until senescence breaks up the Ceanothus canopy. Repeated burning would be expected to perpetuate the Ceanothus/Arbutus type. In the absence of extensive burning, Pseudotsuga, Lithocarpus, and Arbutus dominated stands with Sequoia are expected to develop. In many cases, the trees which may eventually dominate these Ceanothus/Arbutus sites were established at the same time as the Ceanothus, but survive in a suppressed condition until the Ceanothus becomes senescent.

On most sites closure of a canopy dominated by Pseudotsuga and lesser numbers of Sequoia is expected followed by a rapid decline in cover for understory species. As these stands mature and competition related mortality opens the canopy slightly, shade tolerant native species are expected to recover their predisturbance dominance. On Alnus sites, Alnus outstrips other tree species in height growth, rapidly forming a canopy which may remain intact fifty or more years. As the Alnus reaches senescence, Sequoia Picea, Tsuga, and a few Pseudotsuga established at the same time as the Alnus will escape suppression and form the dominant long term forest canopy. Eventually Alnus is relegated to occasional openings resulting from natural disturbance factors.

With the exception of the Juncus/Equisetum type future tree dominants are usually present as seedlings in each of these early succession vegetation types. The duration of the successional pathway leading to reestablishment of forest conditions similar to the pre-logging pattern may be protracted. Pseudotsuga for example is strongly overrepresented in the post logging forests. Since this species may live well over 500 years in the study area (Veirs, 1981) the return to natural tree densities for the various types will take centuries.

Natural patterns of secondary succession in redwood forest revegetation are undescribed. Continuing studies in the forests of Redwood National Park and its surroundings are expected to bring about an understanding of the natural successional dynamcis of virgin redwood forest vegetation, the alterations resulting from modern human activity and the measures which may be necessary to perpetuate these forests as a naturally functioning vegetative system.

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A REVIEW OF THE REVEGETATION TREATMENTS USED IN REDWOOD NATIONAL PARK - 1977 TO PRESENT

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Abstract. The revegetation program in Redwood National Park treats freshly reshaped surfaces following physical erosion control work. Revegetation prescriptions are coordinated with physical site treatments to address surficial erosion control, slope stabilization and ecosystem restoration. The program has evolved from early use of wattles and unrooted stem cuttings to current use of nursery-grown cuttings, bare root and containerized seedlings. Grass seeding for immediate erosion control is being replaced by straw mulching. Experimentation continues for technique refinements and the wider use of native species. The most successful results are attributed to treatments which mimic natural vegetation patterns.

INTRODUCTION

Redwood National Park was established in 1968 to preserve significant examples of coastal redwood forests and the streams and seashores with which they are associated. Timber harvesting and related road construction in the Redwood Creek watershed outside the park combined with natural processes to pose iminent threats to downstream Park resources (Agee 1980). Naturally high erosion rates were greatly accelerated by intensive land use practices and unusually severe storms. Vegetation removal, alteration of hillslope drainages and development of an extensive logging road/skid trail network caused increased runoff, sediment yield, and accumulation of sediment deposits in major stream channels. Other problems included increased landsliding, filling, and widening of stream beds, erosion of stream banks, damage to streamside vegetation and overall degradation of natural aquatic ecosystems (Madej *et al*. 1980).

In 1978, Congress amended the Redwood National Park Establishment Act through Public Law 95-250 to enlarge the park by 48,000 acres of which 36,000 acres were recently logged. It directed that a watershed rehabilitation program be developed to minimize man-induced erosion and to encourage the return of a natural pattern of vegetation (see USDI 1981, Watershed Rehabilitation Plan).

In anticipation of congressional authorization to rehabilitate cutover timberlands, a pilot program was begun in 1977. The rehabilitation program

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has since moved from the developmental phase into full scale implementation in 1980, with continued monitoring for technique effectiveness and refinement.

Objectives of the Revegetation Program are: 1) accelerate the restoration of redwood forests and associated vegetation systems, 2) contribute to long-term slope stability through vegetation re-establishment, and 3) aid in reduction of surface erosion. This paper describes the revegetation portion of the Vegetation Management program and examines techniques of revegetation which were implemented in Redwood National Park from 1977 to present.

SEQUENCE OF REHABILITATION ACTIVITIES

The sites chosen for rehabilitation include former logging haul roads, skid trails and stream crossings, logging decks and landings, and prairie ranch roads. Park geologists and hydrologists assess the need for erosion control, selecting the most effective physical techniques to treat critical areas. In addition to erosion control, physical treatments are designed to promote the establishment of natural and planted vegetation by: 1) dis-aggregating rocked roads, 2) spreading excavated fill or soil over exposed bare rock, and 3) separating and returning buried topsoil to the surface.

Heavy equipment operations (stream crossing excavations, road outsloping and ripping, and water bars) result in freshly disturbed ground susceptible to surface erosion. In areas where stream crossings have the greatest potential for contributing material to creeks, grasses, shrubs, and mulches are used to reduce streamside sediment loss, with mulches providing immediate cover until vegetation can become established.

Vegetation is generally viewed as having a minor role in initial erosion control efforts, but over time becomes the primary defense against erosion on fully rehabilitated sites. Species with fibrous root systems secure surface soil and promote soil aggregation. Rhizomes bind larger blocks of surface soil. Large, deeply-penetrating roots give the subsoil greater shear strength. Low groundcover plants reduce raindrop impact, as do trees that produce abundant litter.

The vegetation staff develops site-specific vegetation prescriptions to promote long-term erosion control by rapid revegetation. Information for developing site-specific prescriptions is derived from an inventory of existing vegetation, site relief, and soil characteristics (soil color, texture, depth of groundwater or impermeable layers) of remnant and disturbed areas. Areas of high erosion and wildlife depredation potential are noted for special attention. Species and treatments are selected for each area to maximize survival and growth. Plant materials include seed and seedlings supplied by local nurseries and seed, transplants, and cuttings collected within the park. Mulches, seed, and fertilizer are applied after heavy equipment work. Wattles, cuttings, transplants, rooted cuttings, seedlings, and tree and shrub seeds are planted in winter. Documentation and monitoring programs are conducted throughout rehabilitation, and continue for several years. Results are used to evaluate the success of treatments and refine future prescriptions.

TREATMENTS AND EVALUATION

The development of the park revegetation program is reflected in both species and techniques employed. Prescription refinements have led to changes in quantities and types of treatments utilized (Table 1).

TABLE 1. Vegetation treatments, 1977-1980.

Year	Wattles	Unrooted Stem Cuttings	Transplants	Containerized Seedlings and Rooted Cuttings: Redwood	Douglas-fir	Sitka Spruce	Alder	Coyote Brush	Whipplea
1977	1,820 ft	1,800	9	230	450	496	0	0	0
1978	27,155 ft	301,120 sq ft (est. 129,300)	64	2,270	2,650	0	0	0	0
1979	2,823 ft	22,000	1,919	3,400 (+67,850)*	8,900 (+58,680)*	0	800	7,471	5,066
1980	0	40	835	30,700 (2,000)*	26,320	0	59,000	23,200	13,800

* Seedlings planted for reforestation of cut-over lands.

WATTLING. Early erosion control and revegetation techniques, such as wattling, were developed elsewhere and adapted for use in the Redwood National Park rehabilitation program. Wattles are bundles of woody branches partially buried in contour trenches and are intended to revegetate the site while providing physical barriers to ravelling and rill development. Willows (Salix, spp.) were the primary species used because they had been used elsewhere and were abundant. Willow readily sprouted, but did not survive the dry conditions found on most rehabilitation sites. Average initial survival on 1978 sites ranged from 48 to 93 percent with vigor declining in subsequent years on all but the wettest sites. Thimbleberry (Rubus parviflorus), salmonberry (Rubus spectabilis), blackberry (Rubus vitifolius), coyote brush (Baccharis pilularis var. consanguinea), and redwood (Sequoia sempervirens) were also tried with limited success. Alder (Alnus oregana), blueblossom (Ceanothus thrysiflorus), elderberry (Sambucus callicarpa), and rhododendron (Rhododendron macrophyllum) wattles did not sprout. In general, wattles grew well on wet northern exposures with fine-textured soils. However, even on dry rehabilitation units, wattles placed close to springs or streams exhibited high survival (Reed and Hektner 1981).

As a revegetation technique, results show that wattling can be effective when restricted to readily sprouting species and placed in areas of relatively high summer moisture. The potential for successful use of wattling in Redwood National Park is limited since most of the rehabilitation areas are very dry during summer. Wattles were used extensively in 1977 and 1978, more selectively in 1979 and deleted entirely from the program in 1980. Due to high cost and ineffectiveness, Weaver and Seltenrich (1981) recommended that the use of wattling as an erosion control technique also be discontinued. Other techniques have proven to be more effective and economical for both revegetation and erosion control.

UNROOTED STEM CUTTINGS. Unrooted stem cuttings were used in early efforts to promote revegetation and root growth for slope stability. Thimbleberry, willow, salmonberry, blackberry, alder, blueblossom, coyote brush, rhododendron, elderberry, salal, big-leaf maple (Acer macrophyllum), evergreen huckleberry (Vaccinium ovatum), whipplea (Whipplea modesta), and bay (Umbellularia californica), were used as unrooted stem cuttings. Willow and coyote brush had the highest survival after one year on 1978 sites with ranges of 41 to 89 percent and 25 to 47 percent, respectively. All other species averaged less than 5 percent survival in the first year. Despite initially high survival rates for willow and coyote brush, vigor and survival are declining on all but immediate streamside sites. Willow stem cuttings are now used only along streams. Unrooted stem cuttings have not been used extensively since 1979. Other means of establishing these species are being developed.

ROOTED STEM CUTTINGS AND SEEDLINGS. Large-scaled propagation allows dense planting which is expected to establish vegetative cover more rapidly. Coyote brush seedlings and whipplea rooted stem cuttings are now the most frequently used shrub materials. Willow, thimbleberry, Sierra gooseberry (Ribes roezlii var. cruentum), ocean spray (Holodiscus discolor), and hazel (Corylus cornuta var. californica) cuttings are being experimentally rooted to broaden the spectrum of species available for site-specific prescriptions.

Nursery-grown alder seedlings were successfully established on 1980 rehabilitation sites and will be planted on 1981 sites. Alder enhances soil development and restoration due to the associations it forms with nitrogen-fixing Actinomycetes. Establishment of nodules on nursery stock prior to out-planting improved survival and initial growth of seedlings (Sugihara and Cromack 1981). Other hardwoods that may be nursery-grown include madrone, tanoak, big-leaf maple, and Oregon white oak (Quercus garryana).

One-year old containerized redwood and Douglas-fir seedlings purchased from local nurseries have been used extensively in the revegetation program. Sitka spruce (Picea sitchensis) has been used in limited amounts. In general, initial survival has been less than 50 percent, however by the third year, those seedlings surviving have become well established. Predation by black-tailed deer and Roosevelt elk is high on conifers and shrubs, but does not always cause mortality. Fertilizer pellets, mycorrhizal inoculation, mulching, vexar tubes and Big Game repellant are being examined as methods for increasing survival and establishment. Preliminary investigations indicate that survival of two-year old bareroot Douglas-fir and redwood seedlings is much higher under the harsh conditions typical of the park rehabilitation sites.

FIELD TRANSPLANTS. Field transplanting permits the establishment of larger plants with well-developed root systems on sites where rapid vegetative cover and root expansion are desirable. Transplanting also allows greater use of species where seed collection, propagation or rooting techniques have not been successfully developed. Most transplants are obtained on-site and are already adapted to the local environment. Transplants have been successfully used since 1977 and include: alder, redwood, coyote brush, whipplea, salal, evergreen huckleberry, rush (Juncus, spp.), sedge (Carex, spp.), madrone (Arbutus menziesii), 'Alta' fescue (Festuca arundinacea), cattail (Typha latifolia), coltsfoot (Petasites palmatus), iris (Iris, spp.), deer fern (Blechnum spicant), bracken fern (Pterdium aquilinum var. pubescens), and sword fern (Polystichum munitum). Moderate sized transplants have done well and survival of whipplea and coyote brush increased with top-pruning. Cost and survival comparisons for transplants, rooted cuttings, and seedlings are planned for this year.

SEEDING. Establishment of early successional vegetation can be accelerated by artificially seeding native tree, shrub, and ruderal species. Localized dense stands of coyote brush, alder, sedge, and rush have been successfully established by direct seeding. Small quantities of maple, tanoak, blueblossom, cattail, dock (*Rumex crispus*) and chinquapin (*Castanopsis chrysolepis*) were seeded with little success. Continued technique development may allow these and other species to be utilized more extensively in the revegetation program.

Grass seeding is widely used for erosion control on disturbed areas. Annual ryegrass (*Lolium multiflorum*), 'Blando' brome (*Bromus mollis*), creeping red fescue (*Festuca rubra*), and vetch (*Vicia*, spp.) were used on 1977 sites. Ryegrass dominated, with cover over 70 percent the first year. Grass coverage has decreased each successive year, to presently less than 10 percent. Quail are thought to have eaten most of the vetch seed.

Annual and perennial ryegrass, 'Potomac' orchard grass (*Dactylis glomerata* 'Potomac'), velvet grass (*Holcus lanatus*), barley (*Hordeum vulgare*), fawn tall fescue (*Festuca arundinacea*), and crimson clover (*Trifolium incarnatum*), were used alone or in combination in 1978. Only ryegrass persisted past the first year in any amount. Initial coverage was spotty, varying from less than 1 up to 40 percent.

The 1979 seed mix included perennial ryegrass, orchard grass, creeping red fescue, and 'Highland' colonial bentgrass (*Agrostis tenuis* 'Highland'). Ryegrass dominated the first year but was replaced the following year by bentgrass with little change in overall cover. In general, cover was less than 10 percent on unfertilized areas and greater than 50 percent on fertilized areas. On one unit, spring cover averaged 50 to 75 percent with 250 lbs/acre and 75 to 90 percent with 500 lbs/acre ammonium phosphate / sulfate (16-20-1-13S) fertilizer. Fertilizer also stimulated ruderal species; cover averaged 35 to 50 percent with 250 lbs/acre fertilization compared to 2 to 4 percent on control plots (Popenoe 1981).

Bentgrass, creeping red fescue, fawn tall fescue, 'Blando' brome, 'Durar' hard fescue (*F. ovina* var. *duriscula*), Zorro fescue (*F. megalura*), 'Mt. Barker' subclover (*Trifolium subterraneum*), 'Lana' woolypad vetch (*Vicia dasycarpa*), and common vetch (*Vicia*, spp.), were used on 1980 sites. Grass cover increased with fertilization, with brome the most successful. In the first season, however, even without fertilization, the legumes dominated, averaging 50 to 75 percent cover, with only vetch doing well on poorly-drained blue clay sites.

It has been noted that timing of fertilization significantly affects relative species composition. Fall applications of fertilizer improve stand cover of seeded grasses while late winter applications favor woody invader species such as coyote brush.

Grass has been locally effective for controlling frost heaving, as well as rainsplash, sheet, and rill erosion but not until late in the season. Except in wet areas, dense grass cover has not been established prior to the first rains. In 1981, limited trials of fall hydroseeding of grasses with fertilizer and mulch produced a rapid ground cover of greater than 80 percent. Water availability and vehicle access limit the potential of this technique in the park. Hydroseeding is being done on roadcuts through prairies where conventional methods cannot be used. Grass is a vigorous competitor with native woody vegetation and greatly reduces natural invasion, an objective along prairie roads in Redwood National Park. This same competition with native woody species has led to more restricted use of grass seeding in forested units. Some of the effects of grasses on invading and planted species are being investigated on 1980 rehabilitation units.

MULCHES. Mulches, when spread immediately after heavy equipment work and prior to the first rains, are used to minimize surficial erosion. Mulches also reduce and disperse runoff (promoting infiltration) and reduce evaporation. On environmentally harsh sites, these factors favor re-establishment of vegetation. Straw mulches at 2,000 and 4,000 lbs/acre were found to reduce total herbaceous cover while increasing initial invading coyote brush seedling density. In addition to straw, redwood chips, hardwood bark, whole chipped Douglas-fir and Monterey Pine (Pinus radiata) mulches were used in 1979. Excessive handling costs and poor revegetation led to the elimination of all but straw mulch for 1980. Weedy contaminants from the straw have been found but have not persisted into the second year.

COSTS

In 1978, \$87,000 was spent for vegetation materials and installation. Of this, 74% (\$64,353) was for wattles, 19% (\$16,742) for unrooted stem cuttings and the remaining 7% (\$6,305) for all other revegetation.

By 1980, a changing emphasis in treatments and techniques enabled revegetation of larger areas for similar costs. Of approximately \$77,000 spent in 1980, less than 1% (\$40) was spent for unrooted stem cuttings, 2% for transplants (\$1,420), 26% (\$20,200) for seeding and fertilizing and 72% (\$55,500) for seedlings and rooted cuttings.

Table 2 shows the unit cost of major revegetation techniques used for 1978-1980, including materials and labor. Costs varied widely by site and by year

TABLE 2. Unit cost comparison of major revegetation techniques including materials and labor, 1978 - 1980.*

				Containerized Seedlings and Rooted Cuttings			
Year	Wattles	Unrooted Stem Cuttings	Transplants	Conifers	Alder	Coyote Brush	Whipplea
1978	avg. \$2.47/ft (\$1.00 - \$2.93)	avg. \$0.38 ea (\$0.10 - \$0.39)	\$0.60 ea	\$0.08 ea plus \$0.12 ea labor	-	-	-
1979	avg. \$1.16/ft (\$1.02 - \$1.79)	avg. \$0.26 ea (\$0.19 - \$0.85)	avg. \$1.48 ea (\$0.49 - \$2.21)	\$0.10 ea	\$0.10 ea	\$0.35 ea	\$0.35 ea
				(. . . . . plus undocumented labor costs . . . . .)			
1980	-	\$1.00 ea	\$1.70 ea (\$1.39 - \$3.00)	\$0.10 ea	\$0.125 ea	\$0.107 ea	\$0.125 ea
				(plus \$0.137 - \$0.216 ea for labor and overhead)			

* 1977 itemized treatment costs not available.

depending upon labor source and site conditions. Revegetation work was performed by request for bid contracts, cost reimbursable contracts, in-house labor and contract labor. Site accessibility, source of plant materials (obtained on-site vs. carried in) and difficulty of planting influenced total labor costs.

DISCUSSION

The revegetation program in Redwood National Park treats freshly recontoured surfaces following physical site treatment. In most cases the surfaces are nutrient deficient subsoils lacking native seed and micro-organisms. Environmental stresses due to summer drought and winter cold are intensified by the lack of canopy cover. Early rehabilitation projects relied upon species and techniques developed elsewhere for other conditions. Prescriptions such as willow wattling and grass seeding had been intended for immediate surficial erosion control and revegetation. These techniques often proved unsatisfactory in the environment of rehabilitation sites. Mulches have now been substituted for immediate surface protection while vegetative prescriptions address long-term erosion control through native vegetation re-establishment.

Current work concentrates on improving survival and establishment of planted vegetation and there is new emphasis on managing the seedbed environment to promote natural revegetation. Bulk native seed collection, processing, propagation, and planting techniques are being refined. Two-year old bare root conifer seedlings will be used more extensively, particularly on the harsher sites. Field trials examining the value of slow-release fertilizer pellets and treatments to minimize wildlife depredation are being conducted. Broadcast fertilization will be timed to favor establishment of native species. Experimental use of compost will begin next year and hydroseeding of native shrub species will be tested.

Vegetation treatments and techniques are most successful when they mimic the natural vegetation patterns adjacent to rehabilitation sites. Utilization of colonizing species improves prospects for successful plant establishment on harsh sites. Well-established native vegetation will assist in long-term slope stability and erosion control.

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THE ROLE OF SYMBIOTIC MICROORGANISMS IN REVEGETATION OF DISTURBED AREAS - REDWOOD NATIONAL PARK

Neil G. Sugihara and Kermit Cromack, Jr.[1]

Abstract. Symbiotic microorganisms play an important role in initial revegetation of disturbed areas. Nitrogen fixation and mycorrhizal associations improve the ability of plants to grow in and enrich nutrient poor soils. Establishment of these relationships on nursery stock prior to outplanting improves outplanting survival. Implementation of large scale inoculation resulted in increased survival and initial growth rates. In a forest nursery *Thelephora terrestris* survived sterilization processes for sytroblocks and provided inoculum for the following years crop of Douglas fir. Preliminary inoculations of redwoods with *Glomus fasiculatus* has achieved some mycorrhizal formation.

INTRODUCTION

The role of soil microorganisms in the ecosystem has long been poorly understood when compared with the knowledge of macroscopic organisms. However, with increased efforts to establish vegetation on disturbed sites, the vital nature of the roles of these groups is gaining greater recognition. Symbiotic soil microorganisms increase the availability, accumulation and cycling efficiency of many essential plant nutrients. These microorganisms improve the ability of plants to grow on nutrient deficient soils, and are essential to the success of many higher plant species in their natural habitats.

Soil erosion and nutrient loss caused by disturbances to mature forest ecosystems can be reduced by the rapid revegetation of disturbed sites. Establishment of vegetation on recently disturbed bare soil is often complicated by harsh site conditions and lack of plant available nutrients. Nitrogen fixing plant species are often important components of early succession increasing the absolute amounts and availability of soil nitrogen and soil organic matter content (Tarrant & Miller 1963, Youngberg & Wollum 1968). Carbon to nitrogen ratios of above and below ground litter components are narrowed by nitrogen fixing species (Cromack & McNabb 1979).

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The below ground component of forest ecosystems is an important current area of research in nutrient cycling and decomposition. In many forests, most energy utilization and nitrogen transformations of carbon components occur below ground (Harris et al. 1980; Fogel 1980). This is true throughout secondary succession. Above ground patterns of changes in species composition and vegetative structure with forest succession are accompanied by major qualitative changes below ground. One stage of succession is affected by prior stages that occur below ground. Symbiotic soil microorganisms play a key role in the formation of these below ground ecosystems.

Two types of organisms fix atmospheric nitrogen to a plant available form in association with vascular plant roots. Bacteria of the genus Rhizobium form nodules in relationships with legumes. A group of woody shrubs and trees form root nodules with Actinomycetes. One such associate is red alder, annually fixing as much as 320 kilograms per hectare in the coast rages of Oregon (Newton et al. 1968). These relationships provide large quantities of nitrogen the nutrient most commonly limiting in disturbed forest soils.

Mycorrhizal relationships of two basic types occur on most species of vascular plants. Ectomycorrhizae form between fungi and the roots of most conifers and broad-leafed trees as well as many woody shrubs. Endomycorrhizae are relationships between fungi and most herbaceous plants, some conifers and woody broad-leafed plants. Both associations aid the vascular plant symbiont by increasing effective surface area for absorption, increasing ability to take up P, N, and cations (Melin et al. 1950, 1952, 1958). Resistance to some serious diseases is increased by the production of antibiotics (Marx and Davey 1968). Fungi obtain habitat and carbohydrates from their photosynthetic symbionts (Melin and Nilsson 1957). The specific characteristics of mycorrhizal associations vary with the species forming them.

In Redwood National Park (Table A) and the western states (Klemmedson 1979, Rose 1980), many important woody plants invading freshly disturbed sites are nitrogen fixing as well as mycorrhizal. Nitrogen fixation enables rapid growth due to increased nitrogen availability. Mycorrhizae increase the uptake of other nutrients, reducing their tendency to become limiting with increased growth due to nitrogen availability. Plants forming both these relationships can thrive in conditions of low soil nutrient levels. With attempts to reestablish vegetation on disturbed sites, the importance and potential benefits of these relationships are being recognized. Utilization of these organisms holds great potential and is an integral part of any complete natural vegetation system restoration.

The Redwood National Park watershed rehabilitation program includes revegetation of areas immediately following heavy equipment work. These sites contain the most highly disturbed vegetation systems in the Redwood Creek basin. Soils consist largely of loose, subsoil fill or ripped road surfaces, often deficient in plant available nutrients. Decomposition of mulches applied to minimize surface erosion initially reduces plant available nitrogen. Recently excavated soils are typically deficient in microbial flora, reducing potential for rapid formation of mycorrhizal and nitrogen fixing relationships (Wilson 1965). Proper establishment of microflora on planting stock can have significant impact on the success of this or any large scale revegetation effort.

TABLE A. SYMBIOTIC ASSOCIATIONS OF PLANT SPECIES USED IN THE REDWOOD NATIONAL PARK REVEGETATION PROGRAM

Species	Nitrogen Fixing		Mycorrhizal	
	actinomycete	Rhizobium	ecto-	endo-
Acer macrophyllum	0	0	+[1]	+[1]
Alnus oregana	+	0	+[2]	+[3]
Arbutus menziesii	0	0	+[4]	0
Baccharis pilularis var. *consanguinea*	0	0	0	+[1]
Carex spp.	0	0	0	+[1]
Ceanothus thrysiflorus	+	0	0	+[3]
Corylus cornuta var. *californica*	0	0	+[5]	0
Gaultheria shallon	0	0	+[4]	+[4]
Grasses	0	0	0	+[1]
Juncus spp.	0	0	0	+[1]
Legumes	0	+	0	+[1]
Lithocarpus densiflora	0	0	+[5]	+[1]
Pseudotsuga menziesii	0	0	+[5]	0
Rhododendron macrophyllum	0	0	+[4]	0
Rubus parviflorus	0	0	0	+[1]
Rubus spectabilis	0	0	0	+[1]
Rubus vitifolius	0	0	0	+[1]
Salix spp.	0	0	+[5]	+[1]
Sambucus callicarpa	0	0	0	+[1]
Sequoia sempervirens	0	0	0	+[1]
Vaccinium ovatum	0	0	+[4]	+[4]
Whipplea modesta	0	0	0	+[1]

[1]Data obtained from material collected in Redwood National Park.

[2]Molina, 1980.

[3]Rose, 1980.

[4]Largent, *et al.*, 1980.

[5]Trappe, 1962.

To determine the status of commercially available planting stock, a survey of symbiotic relationships was conducted (Table B). Roots of seedlings were stained with trypan blue and examined for endomycorrhizae. Other rootlets were sectioned and examined for the Hartig net and mantle which are diagnostic of ectomycorrhizae. Root systems of plant species known to form associations with nitrogen fixing organisms were examined visually for evidence of root nodules.

TABLE B. SYMBIOTIC RELATIONSHIPS PRESENT ON NURSERY STOCKS USED BY REDWOOD NATIONAL PARK

Plant Species	Age	Type	Associations	Percent Infection	Symbiont
Redwood	2.0	BR*	endomycorrhizal	100%	unidentified
Redwood	1.0	SB**	none	0%	---
Redwood	1.0	PT***	none	0%	---
Douglas-fir	2.0	BR	ectomycorrhizal	99%	*Laccaria lacata* and *Telephora terrestris*
Douglas-fir	1.0	SB	ectomycorrhizal	95%	*T. terrestris*
Douglas-fir	1.0	PT	none	0%	---
Red alder	1.0	PT	none	0%	---

* BR: Bare Root Seedlings; outdoor field grown.

** SB: Containerized seedlings in styroblocks; greenhouse grown.

*** PT: Containerized seedlings grown in plastic tubes; greenhouse grown.

MYCORRHIZAL ASSOCIATIONS

Virtually all of the bare root seedlings had formed extensive mycorrhizal associations. *L. lacata* and *T. terrestris* were present in large quantities in association with Douglas-fir. Both of these species are common to nursery beds.

Redwood seedlings in nursery beds were heavily infected with endomycorrhizal fungi. The identification of these fungi is pending spore production. All bare root seedlings were grown outdoors in plowed, fumigated fields.

Douglas-fir seedlings grown in styrofoam blocks (styroblocks) were the only containerized seedlings found to be forming any mycorrhizal associations. Seedlings grown in plastic tubes under very similar conditions were devoid of ectomycorrhizae. *T. terrestris* was the fungal symbiont of all 95 percent of the Douglas-fir found to be ectomycorrhizal. All containerized seedlings were grown in greenhouses or under shade frames.

Ectomycorrhizae

Controlled greenhouse studies investigated the ability of *T. terrestris* to survive in and around styroblocks. Douglas-fir seedlings were grown in new and used blocks placed directly on the surface of a wooden table. Containers were isolated from each other to prevent spread of infection. An average of 4.3 percent of the seedlings were ectomycorrhizal in new blocks while 82.8 percent of the seedlings in recycled styroblocks formed mycorrhizae with *T. terrestris*. The large difference in the rate of infection suggests that the source of inoculum is related to the recycling of the containers. This was not unexpected due to the presence of abundant *T. terrestris* mycelia and fruiting bodies on the surface of the containers. To function as a source of inoculum, fungal hyphae would be required to survive the washes of water and dilute bleach solutions intended to sterilize the blocks.

To determine the ability of the *T. terrestris* to spread between styroblocks another groups of seedlings was grown. New and recycled blocks were placed adjacent to each other in an alternate pattern on the table. Another set of new blocks were placed adjacent to the previously used ones but elevated to prevent direct contact with the table. Rate of infection in new styroblocks placed adjacent to recycled was greatly increased over the rate in isolation. Elevated containers had the lowest infection rate of any treatment (3.4%). Observation of the underside of the containers revealed mycelia growing out of the bottoms of containers, spreading to other chambers and adjacent blocks in the space between the containers and the table. In this manner the mycelium spread rapidly through the nursery and provided inoculum for the following year.

Endomycorrhizae

Coast Redwood, unlike most conifers, forms endomycorrhizae and not ectomycorrhizae. Available field grown bare root seedlings had uniformly heavy infections. Containerized seedlings grown in greenhouses or under shade frames were all sterile (Table B).

Little information is available on the endomycorrhizae formed by redwood. Inoculations performed on one year old redwood seedlings, with *Glomus fasiculatus*, produced some infections but no growth response. Endomycorrhizae formed displayed good vesicles and arbuscles but did not become widespread on the root systems. This study is being conducted under greenhouse conditions using containerized redwood stock.

NITROGEN FIXING ASSOCIATIONS

Rhizobium Nodulated

Legumes are commonly utilized for their ability to fix nitrogen. Commercial inoculum is available for many species. Legumes were inoculated and seeded on rock subsoils producing dense stands without fertilization. The ability to grow rapidly and add nitrogen and organic matter to the soil makes these plants valuable in restoring disturbed areas.

Actinomycete Nodulated

The revegetation program in Redwood National Park emphasizes the establishment of successional plants as well as potential canopy species. On moister slopes red alder is the most effective native woody plant colonizing bare soil, rapidly forming dense stands over large areas following any ground disturbance. C. thrysiflorus is adapted to colonization of sites following fire, forming dense stands following slash burning (Muldavin et al., 1981). Due the their ability to form associations with nitrogen fixing actinomycetes these species are important in soil restoration and nutrient enrichment. For this reason red alder is being used as a primary species where the rapid establishment of vegetation on a moist slope is required.

For slope stabilization it is important to maximize initial survival and growth rates. Large scale red alder plantings warranted investigation of the effects of nitrogen fixing actinomycetes on survival and initial growth after outplanting. No evidence of nodule formation was found on the seedlings available for purchase. After one season of growth unnoculated, outplanted seedlings averaged 93 percent increase in top height. A test of nodulated seedlings averaged 526 percent increase. Initial height and site conditions were similar for the two samples. Following the first growing season after outplanting, all seedlings were nodulated. Size advantage gained from the increased initial growth, enables greater initial growth and vigor the following year.

The 1980 revegetation program included the development and implementation of inoculation procedures for actinomycetes on containerized alder seedlings. Sterile one year old seedlings were transplanted into glass sided containers to observe root development and nodulation. Half of the seedlings were inoculated with an aqueous suspention of ground nodules. Dosage was 0.50 grams of nodule per container. Seedlings were grown under greenhouse conditions. Root and shoot growth were carefully monitored.

Twenty-eight days after inoculation, all treated seedlings showed signs of nodulation while the controls did not. Fourteen days later, leaves begun to rapidly increase their size and darken in color. A rapid increase in growth rate followed immediately. Control plants gradully become chlorotic, leaf size decreased and no top growth was observed. During the first growing season following inoculation, caliper and top height were increased by 325 percent and 1257 percent respectively, over the control plants.

Practical use of this technique for large scale inoculations of nursery stock requires more precise knowledge of the minimum inoculation dosages required to achieve a high rate of nodulation. Seedlings were inoculated at rates ranging from 0.001 to 0.250 grams nodule per container and grown under greenhouse conditions. At 0.080 grams per container and above, 100 percent nodulation was achieved. Gradual reduction occurred form 0.003 to 9 percent at 0.001 grams per container. Inoculation at the rate of 0.003 grams per container produced higher rates of nodulation when seed, rather than one month old seedlings, were inoculated.

Fifty thousand containerized red alder seedlings were inoculated one month after seed was sewn for the 1980 planting season. Inoculum was prepared by masceration of field collected nodules in a blender at high speed in sterile water. The solution was strained and diluted to a concentration of

0.080 grams nodule per mililiter to simplify inoculation procedures. Treatment was at a dosage rate of 0.080 per gram, or one mililiter per container. Inoculations were performed by spray misting 10,000 seedlings and with the use of a repeating pipetter for the remaining 40,000. Seedlings were otherwise grown under normal nursery conditions until outplanting.

Prior to the dropping of the leaves, the inoculated areas of the greenhouse were visually distinct from the uninoculated areas. Nodulated plants appeared taller with darker, larger leaves and were readily distinguished from unnodulated plants. Distinct lines were apparent between the inoculated and uninoculated groups of plants adjacent to each other. After plants were dormant, random samples were removed and root systems examined for the presence of nodules. The abundance and relative stage of nodule development displayed by the individual seedlings was noted. Nodulation rate varied from 60-95 percent in different samples with no difference observed between the two methods of inoculation. This rate of nodulation is appreciably reduced from the small scale preliminary tests. This is attributed to reduced precision and accuracy of the large scale inoculations and to application of fertilizers and pesticides used in commercial nurserys. These factors were not included in the preliminary tests.

At the time of outplanting the size and development of seedlings was improved. Nodulated seedlings averaged 20.3 percent increase in top height and 16 percent increase in caliper over the unnodulated trees. The seedlings with well developed nodules had 32 percent and 41.7 percent increases respectively, over the unnodulated. The overall vigor of seedlings was improved.

An outplanting test plot was established to monitor the effects of nodulation after outplanting. Nodulated and unnodulated seedlings were planted in alternate rows. Initial growth for the nodulated trees was rapid with lush green foliage, large leaves and green stems. The uninoculated seedlings uniformly displayed slower growth much smaller chlorotic leaves and red stems. After twelve weeks all trees appeared healthy, dark green and robustly growing. Six months after planting, top heights were measured. An average increase of 63.7 percent was obtained for nodulated seedlings over unnodulated. The inoculations appeared to have reduced planting shock and seedlings appeared much more robust with more and stouter lateral branches. Mortality rate was lower in the nodulated sample and recovery from wildlife browsing was much more rapid.

DISCUSSION

Establishment of vegetation on recently disturbed bare soil is made difficult by the lack of plant available nutrients. Without nitrogen fixing and mycorrhizal symbionts, growth and survival rates are poor for planted seedlings, even for species well adapted to planting sites. The obvious increase in vigor, due to establishment of nodules on nursery grown red alder, shows high potential in establishment of these relationships on seedlings. Rate of nitrogen fixation and growth response are known to be even higher, with the additional presence of mycorrhizae. More effective use of nitrogen fixing species for slope stabilization, and as a nitrogen source in reforestation, can be achieved with establishment of symbiotic relationships prior to outplanting.

Establishing mycorrhizal associations on nursery seedlings increases survival, growth and resistance to pathogens. However, work with T. terrestris exemplifies the complex nature of establishing mycorrhizae on nursery stock. Though abundant on nursery stock, it is not always easily established or controlled if another species is determined more desirable. The ability of this fungus to produce antibiotics is well documented, but planting tests confirmed those of Marx (1975) which obtained no effect on initial survival rates. Survival and vigor at another stage may be influenced. To achieve maximum results, techniques must utilize a wide range of mycorrhizal species. The information concerning growth and spread of T. terrestris in nursery situations, will probably be most applicable to the establishment of other species.

The utilization of symbiotic soil microorganisms in revegetation of disturbed areas holds great promise. Naturally occuring vegetation is reliant on microorganisms for nutrient availability and rapid growth. We must also rely on these relationships. Without them, many invading species would not approach the success they display in colonizing disturbed sites.

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EFFECTS OF GRASS-SEEDING, FERTILIZER AND MULCHES ON SEEDLING PATTERNS AT THE COPPER CREEK WATERSHED REHABILITATION UNIT

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Abstract. Several experimental combinations of grass seed, fertilizer and organic mulches were tested on newly reshaped ground in Redwood National Park. Results were monitored for two years. Total vegetative cover increased with rate of seed or fertilizer application, but decreased under mulches. Species composition was as follows: control areas were colonized by ruderal herbs and the native shrub, Baccharis pilularis var. consanguinea. When fertilized and seeded with perennial grasses, the seeded grasses dominated, ruderals decreased in number and Baccharis was absent. When fertilized and seeded with barley, ruderals dominated and a few Baccharis appeared the second year. Ruderals were less vigorous in treatments using straw or Monterey pine mulch and no fertilizer, but Baccharis seedlings were more numerous.

INTRODUCTION

In 1978 Redwood National Park was expanded to provide additional protection for irreplaceable resources within the Redwood Creek drainage. The new park lands contained much cutover forest. Disturbed areas threatened to discharge voluminous sediment into tributary basins of Redwood Creek in the event of major winter storms. Congress authorized the park to develop a rehabilitation plan for its portion of the watershed to minimize man-induced erosion and to encourage return of a natural pattern of vegetation. In 1979 the program was still in a developmental, primarily experimental phase. Many techniques were being tested for evaluation and potential incorporation into the rehabilitation plan. This paper is based on the monitoring of one set of revegetation experiments at one unit that year.

Experiments at Copper Creek were planned to answer a number of practical questions: How well do mulches and/or grass control erosion? To what extent do mulches interfere with or bolster efforts at revegetation? How much does grass compete with and suppress natural revegetation? How much fertilizer is needed to establish a good stand of grass? My task was to monitor and

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evaluate the vegetation. I felt it was important to evaluate recovery in the context of the natural system. Revegetation is rapid in the redwood region. Since natural processes would play the largest role in the recovery of the ecosystem, monitoring needed to include:

1) natural revegetation independent of the park's effort to plant bare ground (controls), and
2) the effect of park treatments on the course and rate of revegetation as a whole.

The Study Area

Copper Creek is a major tributary stream to Redwood Creek 20 km southeast of Orick, California. It drains about 730 ha and, for planning purposes, the basin was subdivided into several units to be restored over a period of years. Copper Creek Watershed Rehabilitation Unit 79-4 is south of Copper Creek in Section 26, T.9N., R.2E., Humboldt B.L. & M. The area of study is a portion of former logging road "1930" and its associated landings.

The climate is mild year round with strong marine influence. Mean annual precipitation is about 200 cm and mean annual temperature is about 12°C. Elevations in the study area range from 500 to 700 m and slopes are predominantly 30 to 50 percent. The unit faces generally northwest toward Copper Creek, but is dissected by many small tributary streams. There are sites with SW, W, NW, N and NE aspects. On former roads and landings, slopes range from 2 to 30 percent.

The unit was logged from 1959 to 1971. Prior to logging the principle overstory species included *Sequoia sempervirens*,[2] *Pseudotsuga Menziesii*, *Lithocarpus densiflora*, *Acer macrophyllum* and *Arbutus Menziesii* with an understory of *Vaccinium ovatum*, *Rhododendron macrophyllum* and *Gaultheria shallon*. Following logging the pioneer shrub, *Baccharis pilularis* ssp. *consanguinea*, and subshrub, *Whipplea modesta* have become prominent in the area. These two species dominate and are associated with lesser numbers of herbaceous pioneers, including *Lathyrus Torreyi*, *Trientalis latifolia* and *Iris Douglasii* where surface soil is present. On abandoned skid trails, roads and landings without surface soil the vegetation is dominated by ruderal herbs and *Baccharis*. Sprouts and seedlings of former forest species are gradually becoming established throughout the area under all but the worst soil conditions.

Soils of the unit are youthful, most colluvial Inceptisols in fine-loamy and loamy-skeletal families. Depth to the C horizon is usually one to two meters and depth to bedrock usually exceeds two meters. Roadbed material is loam or light clay loam in texture with 20 to 75 percent rock fragments and pH 5 to 6. Levels of nutrient elements in the roadbed average near those in the upper B horizon of a typical profile adjacent to the road.

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[2]Plant names follow Munz and Keck (1968).

METHODS

Heavy equipment work was done in July and August 1979. The unit was seeded, fertilized and mulched on August 30 to 31. The first significant storm was on September 4, with 2.5 cm of rain. Seedling emergence was observed on September 12, and thereafter enough rain fell to sustain seedlings through the winter. A mixture of perennial grass seed called "RNP mix" was applied on many sites. The mixture contained equal parts by weight of *Agrostis tenuis*, *Dactylis glomerata*, *Festuca rubra* and *Lolium perenne*. Common barley (*Hordeum vulgare*) was seeded on some other sites. The type of fertilizer used was ammonium phosphate/sulfate (16-20-0). Mulch types tested included straw, chipped Douglas-fir and chipped Monterey pine. The pine chips contained a much higher proportion of needles and smaller proportion of woody branches than the fir chips. Straw mulch was applied at rates of zero and 2240 kg/ha (0, 2000 lbs/acre). The Douglas-fir mulch was applied at a heavier, less controlled rate. Rates of grass seed application were zero, 34 and 56 kg/ha (0, 30, 50 lbs/acre). Fertilizer was applied at rates of zero, 280 and 560 kg/ha (0, 250, 500 lbs/acre).

I monitored from June 3 to June 19, 1980, and from June 18 to June 19, 1981. My objective was to evaluate and compare treatments in terms of how each was meeting rehabilitation goals. Sampling had to include two kinds of data: an index of erosion-control effectiveness, and an index by which to measure return of a natural pattern of vegetation. C values (fluvial erosion rates relative to fallow ground) have been shown to lower with increasing surface cover for a wide range of surface treatments (Darrach, 1978). Therefore, I measured cover as an index of erosion control effectiveness.

Depth of soil removal accounts for much of the variation in early floristic composition of types within logged units (Muldavin, et al. 1981). Former roads, landings and skid trails generally lack O and A horizons and rate near maximal disturbance on the authors' scale. The freshly ripped or reshaped surfaces may offer a seedbed to light-seeded species, but one would expect poor representation from species that reproduce by sprouting or from buried seed (Bormann and Likens 1979). When openings occur in a redwood forest, I suspect that *Ceanothus*, *Lathyrus* and *Whipplea* pioneer mostly from buried seed. Species of the forest floor which sprout from bulbs, rhizomes or tubers include *Gaultheria*, *Iris* and *Trientalis*. Species above seem poorly adapted for dispersal onto broad, open disturbed areas. It is likely that species with winged or plumed seeds would quickly colonize newly reshaped ground, including *Baccharis*, *Acer*, *Alnus*, *Pseudotsuga* and *Sequoia*. And since *Arbutus* and *Lithocarpus* are prevalent at Copper Creek and were not harvested, their less mobile seeds could fall directly onto roadbeds as well. Non-native species are conspicuous on former logging roads. Short-lived ruderals established populations during the years since harvest. Other non-natives were introduced with rehabilitation in the form of grass seed treatments and seed in purchased straw. Some of these species might compete aggressively with natives under the open site conditions. Treatments could affect survival of seedlings from various sources differentially in initial years. While most seedlings would be pioneer herbs, presence of woody seedlings would demonstrate the potential for those woody species to dominate in years to follow. This was my reasoning and why I used the composition and density of species as an index of the potential of the system to recover toward a more natural pattern of vegetation.

I sampled with a 50 cm x 50 cm square frame split into four quarters. All seedlings were monitored, without regard to source. Quadrat sample area was reduced to 25 cm x 25 cm quarter if the sample would include a count of more than 50 for a given species. If not, the area was increased to 25 cm x 50 cm, 50 cm x 50 cm, 50 cm x 100 cm, and up to 50 cm x 200 cm on sites with low plant densities. This enabled sampling of densities that ranged from about 2 to 2000 per m^2. Counts were made of inflorescences, by species or of individuals, if plants were large enough to be recognized by species and they were not flowering. Cover was recorded in cover classes of 0-1, 2-4, 5-10, 11-20, 21-33, 34-50, 51-75, 76-90, and 91-100 percent. Sampling intensity ranged from three to six samples per treatment at one or two sites.

RESULTS

Total plant cover and the composition of seedlings in terms of ecological classes is depicted for selected treatments in Table 1 and figure 1.

Table 1. Average total plant cover the first spring. Cover was essentailly unchanged the second spring for all treatments except straw mulch sites. On straw mulch sites the cover of Baccharis seedlings increased the second year to 2 - 4 percent.

Grass Seed type-rate (kg/ha)	Fertilizer rate (kg/ha)	Mulch type	Average vegetative cover class percentage
None	None	None	5 - 10
RNP - 56	None	None	5 - 10
None	None	Straw	2 - 4
None	None	Pine	0 - 1
None	None	Fir	0 - 1
Barley - 34	280	None	34 - 50
Barley - 56	280	Straw	11 - 20
Barley - 56	560	Fir	0 - 1
RNP - 34	280	None	21 - 33
RNP - 34	280	Straw	34 - 50
RNP - 56	280	None	51 - 75
RNP - 56	560	None	76 - 90

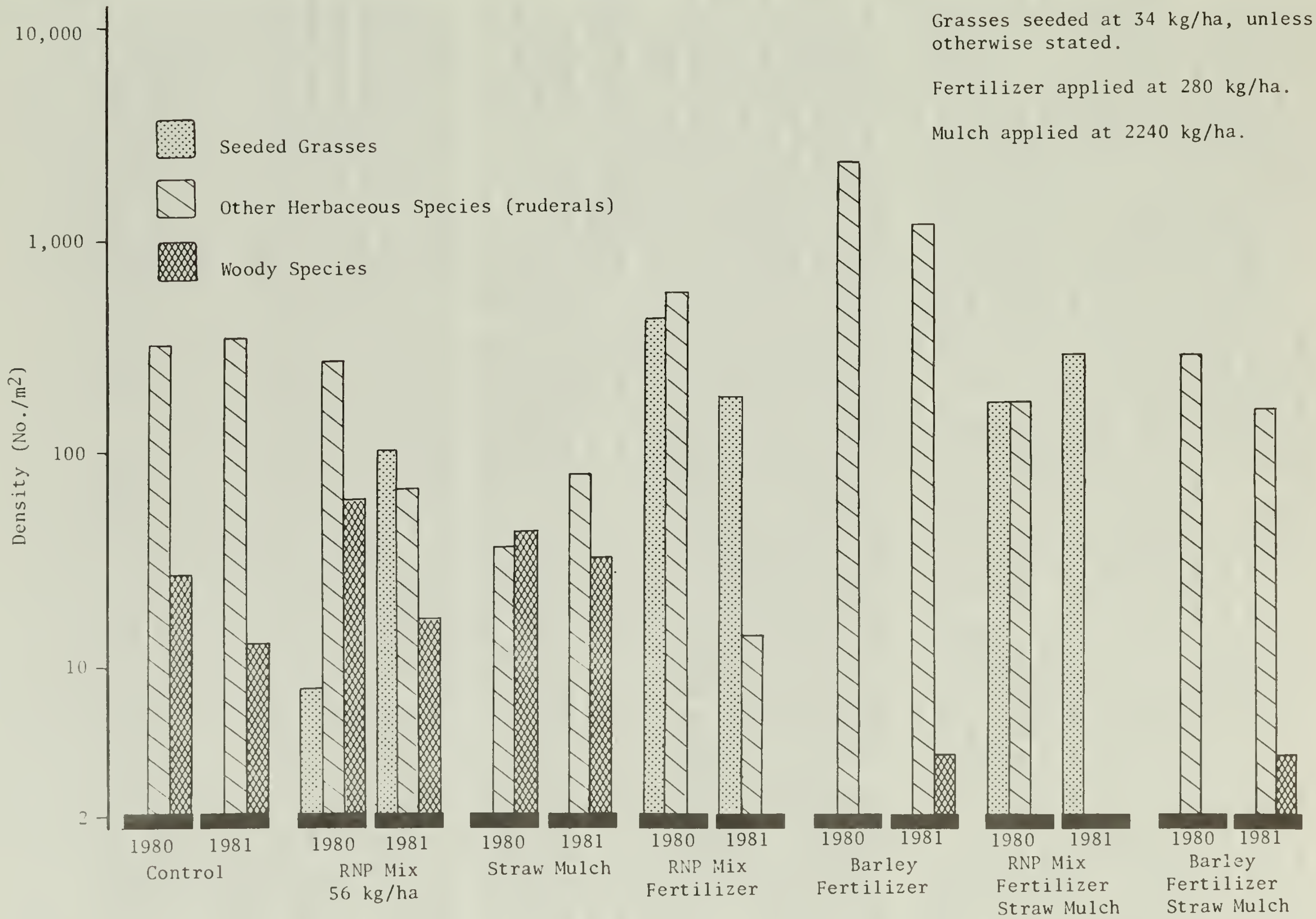

Fig. 1. Seedling Densities at Copper Creek (79-4) under different vegetal treatments.

Of the species introduced in grass seed treatments, only Lolium and Agrostis produced appreciable cover. Lolium was dominant the first spring but was largely replaced by Agrostis during the second year. Festuca averaged 5 to 10 percent in stands the first year with only scattered individuals remaining in the second. Lolium probably gained a head start the first year by virtue of its larger seeds. Given time, Agrostis outcompeted Lolium. Based on a previous study by Dyrness (1975), Agrostis is expected to persist for several years with Lolium gradually decreasing. The other seeded grasses, Hordeum and Dactylis, were observed only as widely scattered individuals. H. vulgare seed was contaminated, as evidenced by the presence of scattered first year seedlings unique to this treatment. Seedlings included Amsinckia intermedia, Avena fatua, Bromus diandrus, Hordeum leporinum, and Raphanus sativus. Careful observations were made the second year to see if any of these species would persist, spread or begin to compete with other vegetation during the second year. However, only one individual of B. diandrus was found the second spring.

The dominant ruderals were grasses, including Festuca megalura, Aira caryophyllea, Deschampsia elongata, Holcus lanatus and Bromus mollis. Seeds of these grasses would have been present in the roadbed prior to rehabilitation. Forbs with plumed, wind-dispersed seeds were present in smaller numbers than the grasses. These included Epilobium, Erechtites and Gnaphalium species. A tarweed, Madia gracilis became important the second year, probably due to late rains. Another ruderal which increased the second year was the rosetted perennial, Hypochoeris radicata. Hypochoeris was consistently present under all kinds of treatments the second year at densities of 1 to $10/m^2$ and some individuals were up to 10 cm across. Except for Madia and Hypochoeris, the proportions of different ruderal species were generally unchanged the second year on unfertilized areas. With fertilizer, Agrostis outcompeted and at least partially excluded ruderals during the second year. In the fertilized barley treatment, the perennial, Holcus, increased at the expense of other, smaller, mostly annual species. With fertilizer, Deschampsia elongata, a native bunchgrass, flowered prolifically the first year and then died.

Woody species encountered include Baccharis, Acer, Arbutus, Alnus, Lithocarpus and Pseudotsuga. Baccharis was, by far, the dominant woody species and the combined density of all others was generally $2/m^2$ or less. Baccharis survived in greatest numbers under straw or pine mulch treatments where herbaceous vegetation was held in check. Compared to controls, mulch treatments had more Baccharis seedlings the first year, a higher proportion of first-year seedlings which survived until the second year, and more new, second-year seedlings, too. When fertilizer was applied, sown grasses or ruderals increased at the expense of Baccharis.

Although common in the clearcuts all around, none of the species which I hypothesized might arise from forest floor seeds and tubers was encountered in a sample. Population levels of Ceanothus, Iris, Lathyrus, Trientalis and and Whipplea were essentially zero on former roads and landings at Copper Creek.

DISCUSSION

Cover and Erosion Control Effectiveness

Grass was tested as a temporary erosion-control cover, not to restore a natural pattern of vegetation. Based on spring cover, I would have predicted 56 kg/ha RNP mix with 560 kg/ha fertilizer to be as effective at controlling erosion as even the heaviest mulch. However, observations made during the course of this study show that timing is of at least as much importance as the final cover. For grass, what are measured as vegetative cover and erosion-control effectiveness will vary from year to year. Grass may form a near-perfect cover in years with early gentle rains, but very little cover in years that begin with heavy rains, especially on steeper slopes. Until the soil has settled, reworked ground is loose and highly vulnerable to erosion. Grass can be washed away before it forms a sod, or even before it germinates. Although the 1979 grass had good coverage in spring, there was evidence of sheet erosion and rilling. While the majority of rills were no longer active, grass alone had simply failed to produce ground coverage early enough to control erosion during the critical early part of the season. To really control erosion, there should be good cover right after ground disturbance, prior to the first rains. Mulches provide this timely cover. According to Dyrness' measurements in western Oregon, more soil loss occurred from grass plots in the first year than from mulch plots in five years, regardless of the fact that the mulches had less cover. In Redwood National Park, mulching bare soil areas with straw has proven to be the most effective erosion-control technique (Weaver and Seltenrich, 1981).

Mulches and Revegetation

Mulches inhibited development of plant cover but seeded grasses and ruderals were more affected than Baccharis and chipped Douglas-fir was much more inhibitory than chipped pine or straw. Each of the mulches appears to have had a strong effect upon the seedbed environment.

2240 kg/ha straw just slightly filters and diminishes sunlight striking the ground. It may have had a greater effect on moisture retention and soil chemistry. Fresh straw has a C:N ratio of approximately 100:1. During initial stages in decomposition of mulches, there is a rapid increase in decomposer organisms. These microbes take up nitrogen from soil near the ground surface and make it mostly unavailable to seedlings. As decomposition proceeds, the most easily decomposed organic material is consumed. With a reduced food supply, some of the microbial population dies off, and there is a release of mineral N back into the soil (Tisdale and Nelson, 1975). Depletion of available N during fall would account for the reduced success of fall-germinating species: species in grass seed treatments and volunteer ruderal grasses and forbs. Release of N in spring may have contributed to the success of species which germinate in winter, particularly the native woody species, Baccharis. In short, straw mulch proved to be valuable in two ways. In controlled erosion and it favored establishment of native species through its modification of the seedbed environment.

There was practically no vegetation under the Douglas-fir mulch. It was applied heavily and light may have been limiting for seedlings of some species. In addition, Douglas-fir branches have a C:N ratio greater than 400:1. Wood chips immobilize nitrogen at the soil surface more strongly than straw and their larger particle size results in slower decomposition. Wood chips suppressed new seedlings too much for use as a broadcast mulch, but they would be valuable around individual planted trees and shrubs to suppress weeds and conserve soil moisture. The chipped pine, with more needles and less wood, had an abundance of _Baccharis_ seedlings, a result more like that under straw than under the Douglas-fir chips.

Fertilizer and Revegetation

Fertilizer increased overall plant cover but, as with mulches, the seeded grasses and ruderals responded most strongly. Since the fertilizer was applied in fall, it would have been most available at that time, just when the seeded grasses and ruderals were germinating. The fertilizer speeded establishment and led to a rapid increase in the size of individual plants. By winter, fall-germinating species had preempted nearly all the available space, largely excluding later germinating species. _Baccharis_ was the most obviously excluded species at Copper Creek. It was present in the largest numbers in areas left unfertilized. Fertilized areas had less than one percent as many seedlings per unit area as those without fertilizer, although the huskiest individuals were the few in openings on fertilized sites. _Baccharis_ seeds are wind-dispersed during winter. Emerging seedlings probably cannot survive amidst vigorously growing grass, whether weedy or introduced.

If the competitive exclusion of _Baccharis_ with fall fertilization is typical of native woody species, then this treatment is inimical to re-establishment of the natural vegetation. Herbaceous competition is very important in parts of the redwood region. Fritz and Rydelius (1966) observed lower survival rates of planted _Sequoia sempervirens_ and _Pseudotsuga menziesii_ with broadcast fertilizer than without it. They observed higher survival rates when grass was scalped away around trees than when it was not. Results of recent studies initiated within the park support these findings.

Summary of Findings and On-going Research

Experimental treatments at Copper Creek were intended to provide immediate erosion control. Mulches controlled erosion more effectively than grass. Straw was the most available and least costly of the mulches. Straw and Monterey pine mulches favored invasion of many light-seeded native woody species. Seedlings of some other natives were absent or poorly represented. Prescriptions need to go beyond reliance on natural seed dispersal to restore such species. Currently, of these, _Sequoia_ and _Whipplea_ are established by outplanting. Widely spaced conifers can be established at modest cost. However, since _Whipplea_ requires dense planting, costs would be reduced substantially if success were achieved with seed. I am investigating ways to reestablish _Whipplea_ and other species which may arise from buried seed or vegetative parts. In plots spread last year with topsoil from adjacent to roads, there are now many _Whipplea_ seedlings. Fertilizer timing is also important. In plots straw-mulched in fall and fertilized in early spring, Baccharis are just as numerous and more robust than Baccharis in unfertilized plots. By making use of the population processes and phenology of native species, more natural and lasting patterns of vegetation may be encouraged. I trust that as hypotheses are tested and a better ecological foundation developed, the revegetation program in Redwood National Park will continue to move forward.

ACKNOWLEDGEMENTS

I wish to thank Mary Hektner, Lee Purkerson and Lois Reed for their review and comments. Mary Hektner planned the experimental prescriptions before I came to work in Redwood National Park. Danny Hagans shared his notes on treatments, early rainfall and seedling emergence. Susan Birch and Lois Reed participated in vegetation monitoring, Esteban Muldavin and Bonnie Griffith helped describe and sample soils, and Dennis Davenport and Gary Lester assisted in plant identifications.

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VEGETATIVE PROPAGATION OF BLUE BLOSSOM

David Axelrod*

ABSTRACT

Stem cuttings of Ceanothus thyrsiflorus Esch. were propagated in a greenhouse to compare six soil media and three collection times for relative rooting success. Spring/summer cuttings rooted far more readily than those taken in fall or winter. Sand and sand/perlite were found to be superior to other media. The use of peat moss appeared to discourage rooting.

INTRODUCTION

The rehabilitation of disturbed wildlands is often assisted by woody shrub pioneers. A successful brush cover can mitigate erosion in the absence of rapid natural forest regeneration.

Vegetative propagation by stem cuttings may have specific advantages over seed propagation for certain taxa of native plants in wildland rehabilitation prescriptions. Vegetatively-generated stock of some species may, under given circumstances, be produced more rapidly, cheaply or reliably.

Since rooted sprigs are genetic clones of their parent stock, they can be reintroduced to their original native habitats without any fear of transforming gene pools, causing unintended hybridization, or unleashing potentially invasive exotic strains. Moreover, viable cuttings may be taken virtually year-round, whereas mature seed is typically available for a relatively short period of time.

Blue blossom (Ceanothus thyrsiflorus Esch.) has characteristics that make it useful for revegetation at disturbed sites in north coastal California. It forms root modules with a nitrogen-fixing symbiont and can thus grow rapidly on nitrogen-poor sites (Rose, 1976). Its attractive blossoms make it useful for environmental purposes where native plants are desired. The development of rapid techniques of propagation would increase the usefulness of blue blossom in revegetation and rehabilitation programs.

The purpose of this study was to determine the influence on rooting of blue blossom stem cuttings attributable to 1) propagation medium and 2) season of collection and propagation.

METHODS

The vegetative propagation experiment was conducted on a propagation bench along a white-washed, south-facing window of a forestry greenhouse at Humboldt State University, Arcata, California.

Six wooden propagation flats (approximately 46 x 46 x 8 cm) were divided into four equal quadrants and planted with 16 cuttings in each quadrant.

Table 1 shows the propagation media used. Table 2 shows the pH of materials used in the media.

* Article based on Master's thesis in forestry submitted June, 1981 to the School of Natural Resources, Humboldt State University, Arcata, California.

Table 1. Media Used in the Propagation Experiment.

Flat Number	Medium
1	100% Perlite
2	50% Vermiculite; 50% Perlite
3	50% Peat moss; 50% Perlite
4	50% Dune Sand; 50% Perlite
5	25% each: Perlite, Vermiculite, Dune Sand, Peat moss
6	100% Dune Sand

Table 2. pH of Materials Used in the Propagation Media.

Material	pH
Perlite	6.8
Vermiculite	6.7
Peat Moss	3.5
Dune Sand	6.0

Cuttings were collected in Redwood National Park, Humboldt County, at an elevation of 600 meters. Associated plants at the collection site included *Baccharis pilularis* DC. ssp. *consanguinea* (DC.), *Pseudotsuga menziesii* (Mirb.) Franco, *Lithocarpus densiflora* (H. & A.) Rehd., *Quercus garryana* Dougl., and an occasional *Abies grandis* (Dougl.) Lindl. or *Arctostaphylos columbiana* Piper. Groundcover consisted of *Iris douglasiana* Herb., *Sisryinchium bellum* Wats., *Whipplea modesta* Torr., *Rubus* species, grasses, rushes, sedges, and various annual wildflowers.

The three collections were taken, respectively, on 20 June, 1980 (from bushes 1 through 5), on 22 October, 1980 (bushes 1, 2, 3, 6 and 7), and on 20 February, 1981 (bushes 1, 2, 3, 8 and 9). In each of the three collections, half the material was derived from the same three bushes; half was derived from two bushes unsampled in any other collection.

Samples from two newly-selected shrubs at each collection assured fresh, high-quality material, but introduced the possibility of minor genetic or environmental differences. Samples from the same three shrubs each time provided genetically identical material for each season, but introduced the unknown influence of previous pruning and removal of choice material.

Each collection was made at 6 p.m. and consisted of 384 cuttings. All sprigs were terminal stem shoots trimmed 12 to 15 cm. long, bagged in plastic, and stored under refrigeration within about three hours.

All cuttings were implanted on the second day following collection. Although a shorter lag time might have yielded higher rooting percentages, the delay more realistically approximated the practical circumstances of a large-scale propagation effort.

In the greenhouse, all flowers, flower buds, side shoots, lower leaves, and excess or damaged leaves were removed. The sprigs were recut diagonally at the second or third node above the stub.

No root-stimulating chemical treatment was employed. Limited trials during the preliminary phase of the study demonstrated that blue blossom cuttings treated with "Rootone" powder (containing naphthylacetamide) rooted somewhat less often than identical cuttings left untreated.

The cuttings were watered by an automatic overhead mist system of timed duration and frequency. Misting was applied equally in all seasons, hourly during daytime with two additional bursts around midnight. Air temperature within the greenhouse was thermostatically controlled at 21.1°C by forced-air heating and mechanically-operated overhead ventilation. Insulated electrical wires running directly under the flats provided bottom heat thermostatically set at about 21°C.

Duration of the propagation period for each batch was 90 days, after which the cuttings were lifted and examined. Any root formation whatsoever was considered a positive result. Any cutting which lacked roots, whether alive or dead, calloused or not, was considered a negative result.

In order to supplement the basic results, data on root quality were also recorded. Length of longest or lead root and length of new top growth was examined for each rooted slip. A subjective root grading system was also developed in order to score the overall density and vigor of each incipient root system.

RESULTS

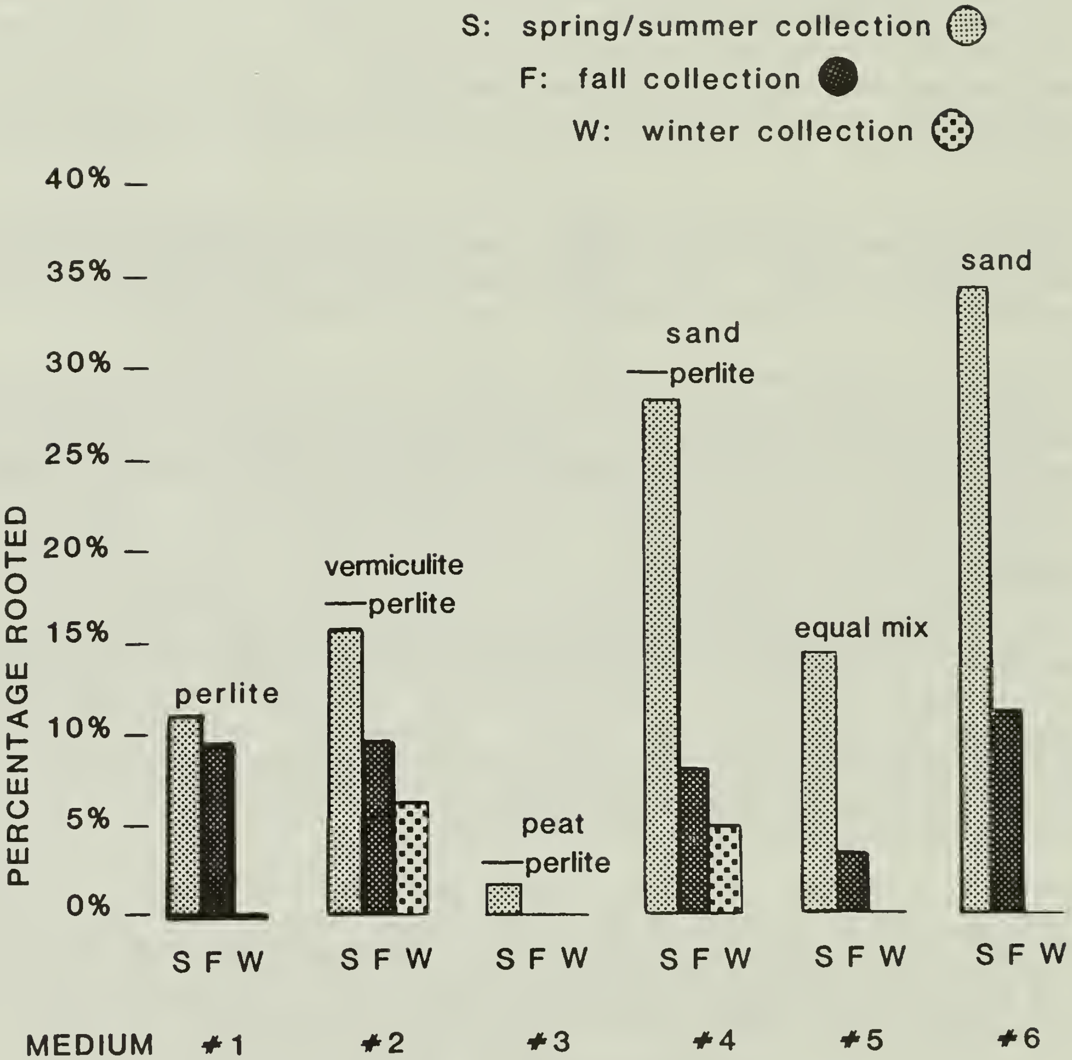
Results of the propagation trials are expressed in Figure 1. Pure dune sand achieved the highest total production for all seasons, with 29 rooted cuttings (15.1% rooting success). Sand was closely followed by sand/perlite, which produced 26 rooted cuttings (13.5%). Success was lower for vermiculite/perlite with 20 rooted (10.4%); pure perlite with 13 rooted (6.8%); and the equal mix with 11 rooted cuttings (5.7% success). Peat moss/perlite managed only 1 rooted cutting out of 192 tried (0.52%).

Not much difference was evident among the media with regard to the quality of rooting, except in terms of mean root-leader length. Pure dune sand had the longest roots, with a mean of 14.4 cm. Sand was closely followed by the equal mix with 13.9 cm.; vermiculite/perlite with 12.0 cm.; sand/perlite, with 9.7 cm.; pure perlite, with 7.7 cm.; and finally, peat/perlite with 1.0 cm.

It was noted that no root nodules were observed on any roots which formed in these sterile media. Evidently, nodulation requires innoculation with symbiotic nitrogen-fixing soil organisms (Rose, 1976,1980).

The spring/summer collection produced the most rooted cuttings, with 67 rooted out of 384 attempted, or 17.4% rooting success. The autumn collection produced 26 rooted cuttings, or 6.8% success. The winter collection produced only 7 rooted cuttings, or 1.8% success.

FIGURE 1: Histogram of Rooting by Medium



It had been assumed that a slip would either strike roots or die. Not all, however, could be so neatly categorized. When the first (spring/summer) batch was uprooted, five cuttings were green, calloused and apparently alive, yet devoid of roots. One or two others had developed roots, but had died.

A surprising result of the second batch, collected in fall, was that 45 sprigs were green and calloused, but had not in fact rooted. The 26 cuttings that had sprouted roots were outnumbered nearly two to one by those that had apparently gone dormant, while still alive.

Almost all cuttings from the third batch died fairly early in the winter. The seven which did survive produced roots that were, on the whole, equal or superior in form to those of either previous collection.

The spring/summer collection accounted for the longest mean root-leader (the greatest mean length of the longest roots of all of a season's rooted cuttings), which was 14.0 cm. Mean root-leader for autumn was 5.5 cm.; for the winter collection it was 8.7 cm.

ANALYSIS AND INTERPRETATION

A statistical analysis of the results was carried out by means of two-way analysis of variance (ANOVA) with an arcsine transformation (Sokal & Rohlf, 1969). The significance of differences between propagation media, for each of the three collections and overall, was determined by the Studentized Range test (Goldstein, 1964). The media are ranked below in descending order, left to right. Flat numbers joined by the same underline represent media which were not significantly different from each other at the 5% level:

Flat Nos. 6 4 2 1 5 3

Thus, dune sand (flat #6) and sand/perlite (#4) were significantly superior to perlite (#1), equal mix (#5) and peat/perlite (#3); and all media were superior to peat/perlite (#3) at 5% significance.

Rankings of the media (utilizing the arcsine transformation) are broken down by season as follows:

SPRING/SUMMER -- Nos. 6 4 2 5 1 3

AUTUMN --------- Nos. 6 2 1 4 5 3

WINTER --------- Nos. 2 4 6 5 1 3

The Studentized Range test revealed the significance, at the 5% and 1% levels, of all differences between each of the three seasons of collection. Additionally, the <u>interaction</u> between the factors of medium and season was found to be significant at the 1% level, through the analysis of variance. Pure sand was significantly superior to other media in the summer but lost its advantage for fall and winter propagation.

The interaction effect may be due to the differing characteristics of grain size. The superior moisture-holding capacity of finer-grained materials (dune sand and peat moss) is more crucial in summer; whereas, the superior drainage and gas-exchange qualities of coarser materials (perlite and vermiculite) would have greater advantage in winter.

Rooting success for the intermediate (mixed-grain) media may have been depressed somewhat by the apparently deleterious effects of peat moss. The relatively poor rooting response to the equal mix (#5) and especially to the peat/perlite blend (#3) was probably due to the low pH of natural peat moss (3.50). Hitchcock (1928) reported that best rooting for most species occurred at pH 4.5 to 7.0. Below pH 4.1, root formation was curtailed.

DISCUSSION AND CONCLUSION

Results of the present study do not necessarily contradict the diverse findings of other workers. Coate asserts (personal communication, 1981) that choice of medium and season depends in large measure on the location and circumstances under which propagation is conducted. Clearly, frequency of irrigation, humidity (Chadwick, 1944), ventilation (Laurie & Ries, 1950), temperature (Kramer & Kozlowski, 1979), season, weather, latitude, aspect, species and other factors must be taken into account in determining the water-holding characteristics and qualities which will be required of the optimum propagation medium.

Presumably, some of the calloused-but-unrooted cuttings from the autumn collection may eventually have struck root, had they been sustained through the onset of spring and beyond the arbitrary 90-day propagation period allowed each seasonal batch of cuttings.

The factor referred to as "season," moreover, was actually a composite of at least two major variables:

1) Physiological nature of the cutting material itself, determined by the individual parent plant's yearly cycle and response to environmental stimuli up until the moment of cutting.

2) Uncontrolled seasonal influences on the cuttings during propagation in the medium, particularly diurnal period and light intensity, beginning at the moment of implantation.

These intervening variables were inseparably linked within the design of the study. As a practical matter, this linkage occurs whenever cuttings are collected and promptly propagated in a greenhouse. Nevertheless, there may be circumstances under which these two variables should be separated: for propagation under controlled sunlight or artificial illumination, when planning longterm storage of cutting material, or when transporting cuttings great distances north or south. In physiological research, it may be desirable to separate these factors. Controlled growth chambers can be used in order to discriminate among the variables which comprise the "season" factor.

Further investigation should also be undertaken to test other media and collection times. The technology of innoculating rooted cuttings of blue blossom with its nitrogen-fixing symbiont also remains to be developed.

The optimum combination of medium and season (summer cuttings propagated in dune sand) had a 34% success rate. This rate can undoubtedly be improved. Implications of this study for more cost-effective native-plant propagation await confirmation in repetitive greenhouse trials. However, it is clear that clean dune sand, cheap and plentiful along the North Coast, deserves consideration as an alternative to the exotic and expensive media commonly used today. Time and money might also be conserved through the potential advantages of summer propagation, over the more traditional dormant-season practice.

Controlled and systematic study of these matters, broadening the present work to encompass many diverse species and varieties, may one day lead to reliable predictability of the rooting characteristics of untested taxa, fuller understanding of the physiology of plant propagation, and higher standards of wildland rehabilitation.

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Analysis and Guidelines for Watershed Rehabilitation

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ABSTRACT

Analysis of gully networks and subsequent ranking of the network gullies for treatment priority leads to highest benefits for least cost. Ranking is suggested as a stepwise process consisting of determining stream order, number of tributaries, and stages of development. Development stages are interpreted in terms of present and expected future erosion rates.

INTRODUCTION

Since the 1930's and 40's, how to rehabilitate watersheds has been the subject of controversy. For some land managers, these controversies still exist, because they are unaware of the dynamics of the system.

Geomorphologic concepts can enhance our understanding of watersheds as dynamic systems in which all parts are interrelated, whether the fluvial system is perennial or ephemeral (whether flows run yearlong or during part of the year only).

Watershed rehabilitation efforts must consider the dynamic interrelationships, not only to be effective, but also to save money. Certainly, it is cheaper to work with the mechanics of a system than against it. For instance, the knowledge that aggradation in a master gully induced by check dams can lead to aggradation in its tributaries, may save the construction of unnecessary additional dams. Conversely, controlling only the headcut of a discontinuous gully, whose local base level dropped, eventually will lead to loss of the structure because future gully cuts will migrate upstream.

This paper will address some of the old controversies in light of more recently developed knowledge. It will demonstrate further how gully networks with confusing appearance can be deciphered for control purposes, and how rehabilitation funds can be saved by utilizing the dynamic interrelationships among gullies, i.e., working with gully dynamics.

Watershed rehabilitation problems are similar among different regions of the West, but the severity of the problems changes. The principles that will be discussed in connection with gully dynamics and control applications are valid regardless of physiographic region. Thus rehabilitation efforts in the Redwood National Park, other Pacific coastal regions, or watersheds of the interior West can be guided by these universal principles.

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WORKING WITH THE PROCESSES TOWARD REHABILITATION AND EROSION CONTROL

UPSTREAM VERSUS DOWNSTREAM CONTROL

A frequently heard issue in watershed rehabilitation is whether control should start and concentrate on the headwater area or the lower land. The argument for upstream control is that runoff originates in the high elevations, and if it is prevented from reaching the low land, the problems of erosion are solved.

First, this approach relies on the validity of Horton's overland flow model, and second, it neglects the geomorphologic processes. The Horton model differentiates only between above-surface and vertical (infiltration) flows, but does not include lateral flow. My observations and preliminary research suggest that lateral flow must be included as a possible source for above-surface flow. Indeed, it should be recognized that flow may alternate among the three components; i.e., overland flow may convert to lateral flow and the latter back to overland flow. Also, the vertical flow component, infiltration, may change to lateral and back to above-surface flow under certain conditions. This was also suggested by Zaslavsky and Sinai (1981) who described above-surface flow even on sand dunes in the Negev desert.

Thus water retained in the headwaters of a watershed by trenches, conversion ditches, or other structures, if not consumed in place, may reappear as overland flow at some location downstream.

The second and more serious argument against controls limited to headwaters, are the geomorphologic, dynamic relationships among the individual parts of a watershed. These are best illustrated by the base level concept. Assume that a stream cuts its bed deeply at the mouth due to deepcutting of the master stream or tectonic movement. As a result, a bed scarp will advance upstream and thereby lower the streambed. Eventually, the deepcutting will reach the headwaters and destroy the treatment, unless the bed scarp advance is controlled naturally by a bedrock outcrop or artificially by a gradient control structure (check dam). Thus, headwater control without downstream control cannot be successful. It also follows that channel system control work should proceed upstream to protect the local base level of the project area. Conversely, areal land treatments must proceed from the headwater area of the basin downslope to insure control of runoff. The issue is control of channel base level, which must be accomplished before on-site runoff and erosion control can proceed. Generally, this means successful treatments begin at the watershed mouth, unless substantial controls provide treatment starting points elsewhere.

HIGH DAMS VERSUS LOW DAMS

Another old erosion control issue is the question of whether to build a few high check dams or many low ones. Costs, sedimentation, structural stability, etc., were considered, but research results were not available to clarify the issue.

At the outset, it must be stressed that aspects of costs and sedimentation should be considered individually, because they cannot be lumped for determinations of effectiveness. For example, cost effectiveness may not be identical with sediment catch effectiveness.

A research watershed on the western flank of the Colorado Rocky Mountains, treated for rehabilitation for more than a decade, revealed functional relationships in structural gully control (Heede 1978). These relationships show that the answer to the question of high versus low dams depends on the specific objective of the treatment.

Furthermore, the project demonstrated that sediment is deposited above check dams on an upslope gradient. Sediment catch increases much faster than dam height. For example, the volume of sediment deposits behind a 1.2-m dam is seven times larger than behind a 0.3-m dam, or a four-fold increase in dam height causes a seven-fold increase in deposits (fig. 1).

During the large-scale pre-World War II rehabilitation efforts, zero sediment deposit gradients were assumed. Not only did this lead to overdesign in numbers of structures, but also to wasted sediment catch capacity of the dams, because upstream dams stopped the upstream extension of deposits.

We are able now to resolve the old issue as follows: Since high dams catch more sediment than low dams, the highest possible dams should be installed if sediment catch is the primary objective. Depth of streambed or stability considerations will set an upper limit for dam height.

Maximum possible dam height should also be selected in gully control where the number of dam sites must be limited, because the projected upstream extent of the sediment deposits above a dam determines the location of the next upstream dam. Increasing the dam height reduces the number of dam sites more in steep than in low-gradient gullies.

In the Colorado research project, loose rocks, wire mesh, and steel posts were the main construction materials. The functional relationships showed that, regardless of gradient or dam type, at a certain dam height material and cost requirements are lowest (fig. 2). Dams lower or higher than this optimum height have higher requirements of both. Under some conditions, other design factors such as structural stability and landscape aesthetics may override cost and material considerations.

ENGINEERING VERSUS VEGETATIVE MEASURES

An issue often raised by watershed managers is the choice of engineering versus vegetative measures in rehabilitation projects. The watershed manager must first evaluate the erosion potential of the area in question. Oversteepened slopes, high rainfall, and weak vegetative cover may indicate very high potentials for erosion. An example is found on the Redwood National Park, as well as many other Pacific coastal areas where plant growing conditions per se are excellent, but once the vegetative cover is disturbed, erosion rates are unusually high. Redwood Creek watershed in the Redwood National Park loses in excess of 2,800 metric tons of sediment per square kilometer per year (Redwood National Park 1981). On the Redwood

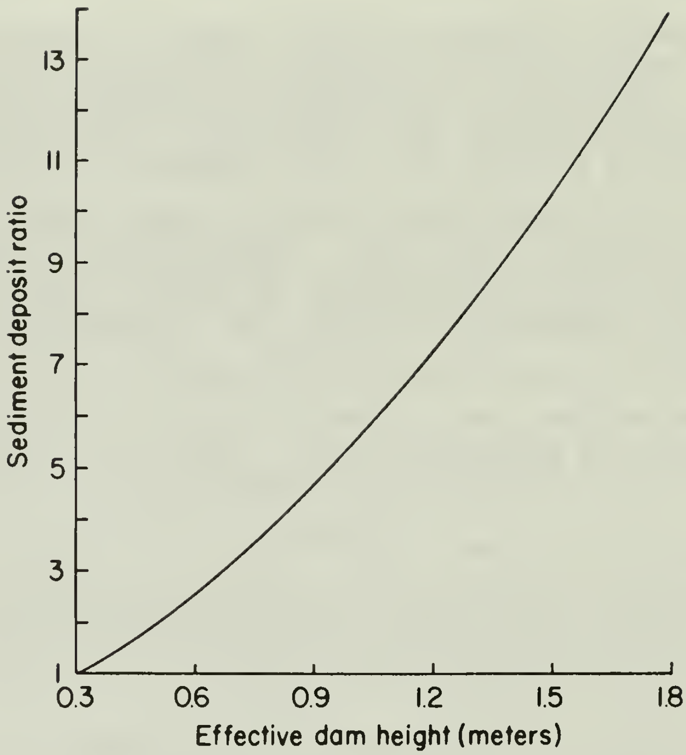

Figure 1. "Analysis and Guidelines for Watershed Rehabilitation" by Burchard H. Heede.

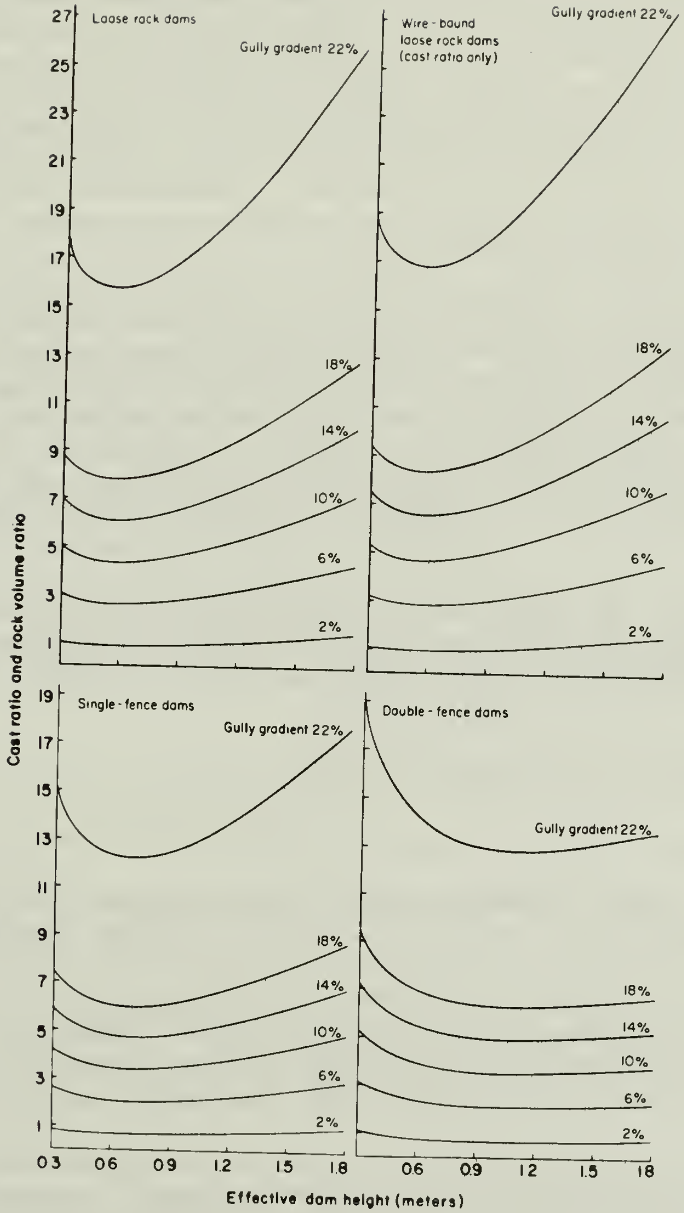

Figure 2. "Analysis and Guidelines for Watershed Rehabilitation" by Burchard H. Heede.

Creek watershed, 90 percent of the forests have been removed. This removal resulted in severe ground surface disturbances due to harvest methods in some areas, aggravating the problems of rehabilitation.

Based on rehabilitation projects in the Redwood National Park and in the Colorado Rocky Mountains, the issue of engineering versus vegetative measures can be resolved as follows: Where growing potentials are high and erosion potentials excessive--Pacific coastal areas--or where growing potentials are moderate and erosion potentials high--arid and semiarid interior West--engineering measures must be used to stabilize the ground surface; vegetation will enhance and perpetuate this stabilization. As will be shown in the second part of this paper, engineering works can be applied sparingly, if used at strategically important locations and in combination with vegetative measures.

For purposes of rehabilitation, engineered measures can be either structures or topographic reshaping. Both were successfully used in the Redwood National Park. Vegetative measures could be classed into three broad groups: 1) Improvement of existing cover by grazing reduction, enhancement of soil nutrients by fertilization, introduction of mulches, or other measures. 2) Planting of vegetation by seed or seedlings. 3) Establishment of wattles, representing a vegetative structure. These three groups were beneficially used in the Redwood Park rehabilitation projects.

Engineering structures are expensive. A methodology is therefore needed to determine which gullies require check dams, and to select those gullies where structural treatment will give greatest results. Such a methodology will be discussed in the following section.

RANKING NETWORK GULLIES FOR TREATMENT PRIORITY

GULLY NETWORK TYPES

Gully networks may appear confusing to the rehabilitation project planner, and questions arise such as: must all network gullies be structurally controlled? Or, which gully, when treated, offers greatest return? A systematic approach is therefore required that makes it possible to decipher gully networks and allow application of a process of elimination. The latter is important, if funds are a severely limiting factor. Generally, engineering measures require more funds than vegetative approaches.

Before considering the interdependencies in a network hierarchy, the types of gullies making up the network should be determined. Two types of gullies exist: continuous and discontinuous. Geomorphic gully processes differ with gully type and lead to different critical erosion locations within the gullies. Recognition of these critical locations is basic to a successful treatment design.

Critical locations are identified by a condition that not only induces instability at the location, but also transmits it into adjacent gully reaches and/or into the undissected watershed.

Continuous gullies begin their course in the headwater area with a gentle transition into the channel. At the gully mouth, where the bed gradient is low, flow velocities decrease and sediment is deposited. With time, this leads to gully widening at the mouth to convey larger flows through the gully cross section. Deposition and widening cause decreases in flow depth and increases in bed roughness (increased wetted perimeter). These in turn lead to further losses of flow velocities. At some point in time, deposits become excessively large, restricting high flows. Deep cutting of the bed at the gully mouth follows, which lowers the local gully base level. As a result, the whole gully will be deepened and ultimately widened. The mouth of a continuous gully is therefore its critical location.

Discontinuous gullies begin their course with an abrupt headcut that may be situated at any location on the watershed. This headcut advances toward headwaters and therby extends the gully upstream. Generally, discontinuous gullies begin their course at some point on the watershed, and an alluvial fan forms downstream from the gully mouth. Oversteepening of the fan by periodic sediment deposition causes the formation of a new discontinuous gully on the fan (Patton and Schumm 1975). This gully progresses upstream by headcutting into the pre-existing discontinuous gully, deepening and widening it. Thus the headcut and alluvial fan at the gully mouth are both critical locations in discontinuous gullies.

The compilation of aerial photograph overlays is very helpful in the determination of network types, because the images of independent discontinuous gullies, headcuts, and fused continuous gullies appear unobstructed by other terrain features. Based on gully types, four network types can be found:

- continuous gullies only;
- discontinuous gullies only;
- continuous and discontinuous gullies, the latter not fused with the network;
- continuous and discontinuous gullies of which some or all are fused with the network.

If a watershed has discontinuous gullies only, there is no network in the true sense of the term. The gullies may be located on the valley floor, resembling pearls on a chain, or they may occupy subdrainages adjacent to each other. If discontinuous gullies follow each other, they will eventually fuse (Heede 1967).

Discontinuous gullies that have fused with the network can be recognized by their headcut. Network fusion was attained by periodic gully processes on the alluvial fan, as described previously. At the location of fusion, a headcut develops, if a water overfall from the discontinuous into the network gully existed. Adjustment of the discontinuous gully to its new base level (network gully) follows by deep cutting. This may result in accelerated upstream advance of the main headcut. With time, the headcut may be eliminated by a gentle transition and a new continuous network gully is established.

STREAM ORDERING

Horton's (1945) stream order analysis demonstrates the relationships between network streams by assigning numbers (orders) to the individual streams, based on their network importance. The smallest streams, having no tributaries, are order (1), the next larger, having one or more tributaries of order (1), are order (2), etc., and the master stream of the network receives the highest order. This analysis is also well suited to gully networks with the exception that discontinuous gullies not fused with the network must be considered on their own, without an order, because interaction with other gullies cannot be established.

In gully ordering, we go one step beyond Horton's analysis, because for control objectives, it is important to know the number of tributaries dependent on a gully of a given order. We designate therefore each network gully by a letter, and use the number of tributaries as subscript (fig. 3). Examples of Figure 3 are gullies D and B_6, signifying that gully D has no tributary, while gully B_6 has six. Obviously, considering the local base level concept, gully B_6 has greater importance in the network hierarchy than gully D. A table should be established, separating the network gullies by stream order (Table 1).

Table 1.--Stream orders of gullies shown in Figure 3.

Stream orders				
1	2	3	4	0*
A	F_3	B_6	K_{14}	I
C	N_1			Q
D	P_1			
E				
G				
H				
J				
L				
M				
O				

Subscripts indicate number of tributaries.

*Gullies not fused with network.

STAGES OF DEVELOPMENT

For control purposes, the importance of a gully in the network hierarchy is also given by its erosional stage, accelerating or inactive in extreme cases. Erosion may not be limited to the gully in question. By geomorphologic chain reaction, it may advance through the network. The next step in the network analysis will therefore consider stages of gully development.

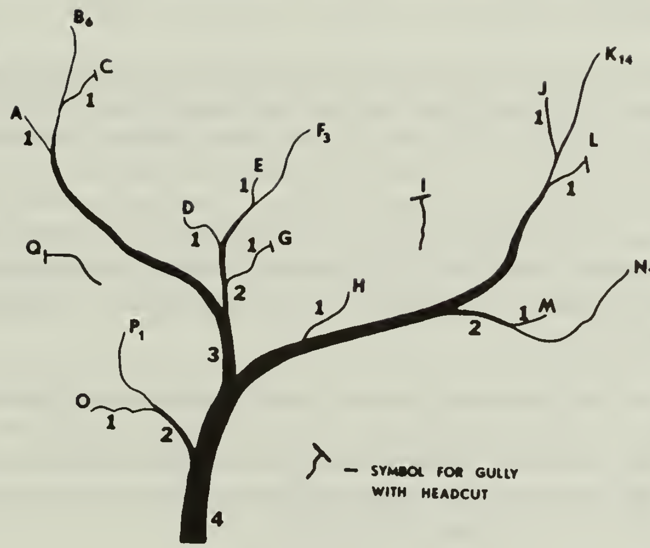

Figure 3. "Analysis and Guidelines for Watershed Rehabilitation" by Burchard H. Heede.

Stage designations should be based on erosional development alone, and should not necessarily represent the age of a gully. Thus, borrowing terms from classical geomorphology, an early erosional development is called young stage, a progressive development, mature stage, and the end stage of erosional development, old stage.

It is conceivable that network gullies are predominantly of one stage of development. In such a case, it may be desirable for purposes of differentiation to subdivide the proposed stages. An example is: early mature and late mature.

The proposed terminology also reflects the fact, suggested before, that gully age is not necessarily synonymous with development stage. A gully may be youthful by age but old in terms of development, or vice versa. For example, an unusual storm may create a gully, cut its bed down to hard bedrock, and leaves banks close to their angle of repose. Not much more future erosion could be expected, and old stage of development would be the correct designation.

On the other hand, a gully of old stage may cut through relatively hard bedrock, exposing soft bedrock in the geologic strata below. Accelerated erosion may begin, leading to processes that deepen and widen the formerly existing old stage gully. It has become youthful in its development.

These examples not only illustrate the dynamics of gully systems, that stages of development may not follow each other in sequence, but they indicate also that much knowledge can be gained by comparing the network gullies with each other.

Other examples of development stages are continuous gullies that adjust to base level changes. The adjustments will be indicated by frequent erosional scarps on the bed, often accompanied by channel widening at the location of the scour hole (plunge pool). The bedscarps advance upstream, deepening and widening the gully. It is youthful.

If a continuous gully has infrequent bedscarps and parts of the banks are stable, mature stage has been reached. Further development may lead to vegetation-lined gully bottoms, a few inconsequential bedscarps, and most banks in stable and vegetated condition. Old age is attained.

Table 2 presents commonly found indicators for determining stages of development. This table should not be taken as all-encompassing, because different indicators may exist as well as different combinations of them.

Table 2.--Commonly found indicators of stages of gully development.

Stage of development	Indicators
Young	Discontinuous gullies not fused with the network.
	Discontinuous gullies fused with the network. Their headcut

	is located far below the watershed divide or other control point. The bed shows frequent erosional scarps. The farthest downstream bedscarp is close to the location of fusion with the network.
	Continuous gullies with frequent erosional scarps on the bed, raw banks, and vertical incisons of at least 1 m depth, even if the remaining cross section is trapezoidally or semi-spherically shaped.
Mature	Discontinuous gullies joined with the network. Erosional bedscarps are infrequent but deeper than 0.6 m. The head-cut still has to advance a substantial distance before a natural control is reached.
	Continuous gullies with infrequent bedscarps. Half of all bank length is stable as indicated by an advancing vegetative cover. The bed shows signs of vegetation cover establishment.
Old	Discontinuous gullies fused with the network. The headcuts reached the watershed divide or any other natural or man-made control. Bedscarps are practically absent.
	Continuous gullies with bed and banks well vegetated, or the bed rests on hard bedrock, or may consist of an armor of predominantly large loose rock. In the latter case, it is especially important that bedscarps are practically absent.

Table 3 presents development stage for the sample network in Figure 3.

Table 3.--Stages of development of gullies shown in Figure 3.

Young	Mature	Old
I	B_6	K_{14}
Q	C	A
	F_3	D
	G	E
	H	J
	N_1	L
	P_1	M
		O

TREATMENT PRIORITIES

The proposed method of ranking network gullies for treatment priorities assumes that the treatment approach combines structural and vegetative measures. The Colorado rehabilitation project has shown that not all gullies require check dams, if the vegetation on the watershed is managed for rehabilitation.

If check dams are built in a network gully, the base level of its tributaries will be maintained or raised. In either case, deepcutting is eliminated in the tributaries, vegetation cover can become established and the gullies stabilize with time.

On the Colorado research watershed, subsequent analysis showed one third of all gullies treated with check dams (expressed as total gully length) would not have required dams. Thus ranking network gullies for structural treatment priorities is an important tool for avoiding overdesign.

The stepwise approach to the analysis of gully networks for control and rehabilitation purposes has two major objectives. The first is to define the critical erosion locations within the individual network gullies. This is achieved by delineating the types of gullies that make up the network. The second objective is to determine the importance of the individual gullies in the hierarchy by establishment of stream order, number of tributaries, and stage of development. All these criteria must be considered in the final ranking for treatment priority. Regarding development stage, it must be emphasized that this stage not only expresses present but also the future erosion rates, and hence, it is an expression of expected returns from treatment.

Tables 1 and 3, based on the network schematically illustrated in Figure 3, will be used to demonstrate the final ranking step. We start with the main gully of the network K_{14}. Stream ordering showed that it has the highest order in the system, thereby controlling all other network gullies, a total of 14. Table 3 indicates an old stage of development, because the gully had reached bedrock in some places and was well vegetated in others. Also, the banks were predominantly stable as shown by plant invasions. If we would evaluate this gully as an entity by itself, we would assign the lowest treatment priority. But, of course, we have to evaluate this gully also in terms of its network importance, expressed by its control of 14 gullies. If the old-stage main gully remains stable in the future, and check dam installation can even raise the base levels for the other gullies, future benefits will be large. Table 4 shows that the designer ranked the main gully therefore as priority 1.

Table 4.--Ranking of gullies by treatment priorities

Priority 1	Priority 2	Headcut treatment only
I	F_3	C
Q		G
K_{14}		L
B_6		

Because gully B_6 has a high order, controls the second highest number of tributaries (Table 1), and is of mature development stage, (higher future erosion rates must be expected), it was also assigned priority 1.

The final ranking of discontinuous gullies I and Q offers no problems. Being without stream order because of network independence, and located on the watershed in locations that indicate large future headcut advances (young development stage in Table 3), they are ranked priority 1 (Table 4).

Within the priority classes of Table 4, ranking is also applied from top to bottom. Thus gullies I and Q rank before gully K_{14}, and that, in turn, before gully B_6. This means, if funds are severely restricted, the discontinuous gullies would be treated. But it is not advisable to consider gully control as a "one-shot" approach. Gully control activities can be spread out over time, if the concept of base level control is adhered to.

Table 4 shows gully F_3 ranked as priority class 2. The reason is that this gully controls the third highest number of tributaries. Structural treatment of all other gullies, with exception of the discontinuous gullies fused with the network, is judged to offer only small returns. Additionally, the watershed was evaluated to have high plant growth potentials, making effective ground cover establishment possible, once the main local base levels are stabilized.

The headcuts of the discontinuous gullies (C, G, L) that fused with the network must be treated, otherwise future headward extension of these gullies will take place. Generally, control of abrupt headcuts requires structures. Plants invade, after stabilization has been achieved, by selecting sediment deposits within and alongside the structure.

The examples discussed demonstrate that, in some cases, a step may be neglected for final ranking of treatment priority. Hence the question arises, could the stepwise approach sometimes be shortened? This is not advisable, because the information gained in each step must be established first, before its importance within the totality of all aspects can be determined.

SUMMARY AND CONCLUSION

Effective erosion control and watershed rehabilitation designs must recognize the dynamic interactions within the natural systems. Base level interactions tell us to proceed with a treatment from downstream toward upstream, to start at a location with a stable elevation that will not be lost during treatment life, and to omit certain network gullies from structural treatment, if the watershed vegetation is treated for rehabilitation. Land and vegetative treatments are the second step, and should proceed from headwaters downward to assure their functional integrity.

Where sediment catch is the prime objective, maximum possible dam height should be used. But if cost is the major constraint, the dam height that minimizes costs should be selected.

A treatment approach that combines engineering and vegetative measures not only hastens rehabilitation processes in many cases, but also reduces the number of structures required. Obviously, the Redwood National Park as well as other Pacific coastal areas, and the arid and semiarid watersheds of the interior West, fall into this category.

Networks can be differentiated by the type of their gullies: continuous, discontinuous, or mixtures of both. This network classification points to the main critical erosion locations within the individual gullies that must be recognized for control.

For treatment selection, gully networks must be further described by stream order, number of tributaries, and stage of development (treatment return expectancy). Establishment of treatment priorities can be summarized in general terms:

First priority--
- discontinuous gullies;
- main-stem gully;
- tributary gullies with largest number of tributaries of their own.

Second priority--
- tributary gullies controlling smaller numbers of tributaries.

Third priority--
- tributary gullies with excessive erosion rates.

The proposed systematic approach to ranking of network gullies for treatment priorities assures that, regardless of funding level, the highest return will be obtained for the least cost.

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Figures

Figure 1.--Expected sediment deposits retained by check dam treatment as a function of dam height. The sediment deposit ratio relates the volume of sediment deposits to the volume of sediment deposits at dam height of 0.3 m.

Figure 2.--Relative cost of installing check dam treatments and relative angular rock volume requirements in gullies with different gradients as a function of dam height. The cost and rock volume ratios relate the cost of a treatment to those of a treatment with loose rock dams 0.3 m high installed on a 2% gradient.

Figure 3.--A schematic gully network consisting of continuous gullies, independent discontinuous gullies I and Q, and discontinuous gullies fused with the network C, G, and L. Fused discontinuous gullies are indicated by the headcut symbol.

Erodibility of Forest Soils -- A Factor in Erosion Hazard Assessment

Philip B. Durgin and Jeffrey E. Tackett[1]

ABSTRACT

Surface erosion is a function of two opposing forces--driving force and resisting force. Analysis of surface erosion hazards at a site should consider the resource at risk, the duration of hazard, and the site characteristics. Soil erodibility is an important site characteristic determining resisting force. To evaluate erodibility, soil samples were collected from 36 cutblocks in Redwood National Park, California. Soil series represented were Masterson, Orick, Sites, Atwell, Hugo, and Melbourne. Samples were analyzed for size distribution and indexes of erodibility. Atwell, the least oxidized soil, had significantly higher erosion indexes than Sites, the most oxidized.

INTRODUCTION

Surface erosion is a major contributor of sediment to Redwood Creek and other disturbed streams in the north coastal region of California. Logging has generally accelerated surface erosion much more than mass movement in the Redwood Creek basin (Janda and others 1975). With better understanding of the processes of surface erosion, erodible soils can be more easily identified, rehabilitation sites can be selected, and appropriate methods of erosion control can be prescribed.

Surface erosion is a function of two opposing forces--driving force and resisting force. The resisting force is the result of conditions that protect soil particles from being detached; the driving force is the kinetic energy of rainfall and runoff.

The processes of surface erosion can be quantified for inclusion in the following factor of safety (FS) equation:

$$FS = \frac{\text{Resisting force}}{\text{Driving force}}$$

Surface erosion occurs when $FS \leq 1$.

Undisturbed forest soil has a strong resisting force because the mineral soil is overlain by a protective layer of litter; the driving force is weak because the soil has abundant macropores, infiltration rates are high, and overland flow is limited. Consequently, surface erosion tends to be low in undisturbed

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forests. It has been reported to be surprisingly common, however, in the Redwood Creek basin (Janda and others 1975).

Logging activities such as roadbuilding and tractor yarding expose soil and can lower the factor of safety by altering the resisting and driving forces. Disturbance by tractors may remove the litter layer, destroy soil structure, and bring the less aggregated subsoil to the surface. As a result, the soil has less ability to resist erosion by raindrops or runoff. Disturbance may also compact soil and thereby decrease infiltration and percolation rates, causing more overland flow or a greater driving force down the slope. The extreme case occurs with inboard road ditches that concentrate runoff.

Most of the research in predicting surface erosion has been conducted on agricultural land that is in sharp contrast to forest land. Farm land commonly has disturbed, unprotected soil readily available for transport, and erosion occurs in proportion to the driving force, the variable energy of the runoff. Because forest lands of the Pacific Northwest are characterized by steep slopes, runoff tends to be high in energy and has the capacity to transport much more material than is available. As a result, the resisting force, as the variable supply of detachable soil, is of greater importance.

Studies of bedload transport and suspended sediment in steep mountain streams (Nanson 1974, Paustian and Beschta 1979) have documented that the sediment loads are more closely related to the available supply (resisting force) than to flow conditions (driving force). Investigation of a stream in the Oregon Coast Range showed that following disturbance by logging an armor layer of gravel and cobbles forms and controls the release of the underlying fine sediment (Milhous and Klingeman 1973). A paired watershed study of two north coast streams (North and South Forks, Caspar Creek) found that while logging and roadbuilding had little or no effect on peak flows (driving force), suspended sediment production increased substantially (Ziemer 1981, Rice and others 1979). These studies show that after disturbance the resisting force decreases; a period of recovery follows, during which the channels are rearmored.

Although previous work has focused on perennial streams, field observations suggest that related processes occur in rills and gullies. Site disturbance exposes soil, allowing rills and gullies to form; as erosion continues, coarse fragments left behind accumulate in these small channels and armor the underlying soil against further downcutting. The size of the material needed for armoring depends on the driving force. For example, cobbles may be necessary in stream channels, pebbles in gullies, and granules in rills. Organic debris can also provide the armor for forest drainages.

The surface erosion potential at a site must be evaluated before any rehabilitation steps are taken. Ideally the erosion potential is determined before disturbance occurs, so that measures can be taken to mitigate effects. The following considerations apply to either course of action.

Resource at risk--An important factor in determining the value of rehabilitation is assessment of what is being protected. It may be the fisheries resource, site productivity or simply esthetic value. On the north coast, the fisheries resource is of great importance, and the sediment delivery ratio is thus a major component of the assessment. For example, erosion sites that release sediment directly to channels with spawning gravels would likely rate high as candidates for rehabilitation.

Duration of erosion--Another consideration is whether the erosion problem is short or long term. Short-term erosion hazards occur where disturbance is followed in 2 or 3 years by revegetation or an erosion pavement. This sequence is common on skid roads and main haul roads. Long-term erosion problems occur where the slopes are steep and vegetation or erosion pavements cannot get established. Long-term erosion may be found in landslide scars, road cuts, landings, and failed stream crossings.

Site characteristics--A variety of site variables can influence soil erosion, including topography, vegetative cover, climate, and soil erodibility.

We evaluated one of these site variables--soil erodibility in Redwood National Park. The sites selected included skid roads and other tractor-disturbed areas on recent clearcuts.

EVALUATION OF SOIL ERODIBILITY - REDWOOD NATIONAL PARK

Soil types--In Redwood National Park, several forest soils are associated with different lithologies and weathering stages. On the west slope, underlain by the Redwood Creek Schist, the Masterson Soil Series weathers to Orick and eventually to Sites. On the east side, underlain by the Franciscan Formation, Hugo soil predominates, and weathers to Melbourne and then to Sites. Atwell soil is present on the east side in association with fault gouge material. Masterson and Hugo are inceptisols, Atwell is an alfisol, and Orick, Melbourne, and Sites are classified as ultisols.

Sample collection--Soil samples were collected from Redwood National Park in April 1981. Atwell soils were collected from an area classified as "highly erosive unit confined to southeast corner of the Park ..." on a disturbance map of Redwood Park (National Park Service 1980). The other samples were selected from cutblocks mapped as "recent tractor-yarded units with minimal regrowth; prominent drainage disturbance." The dominant soil type was determined for each of these mapped units from soil-vegetation maps (DeLapp, et al. 1961a, 1961b; Alexander et al. 1960, 1961). Six cutblocks were randomly selected for each of the six soil series. Soil series on each site was verified by examination of relatively undisturbed pedons. Three subsamples were then randomly selected from exposed soil surfaces at each of the 36 sampling sites. The samples may have included soil from any of the horizons, subsoil, slash, or debris. The three subsamples were thoroughly mixed to form a composite sample for each site.

Size distribution--The composite samples were wet-sieved to obtain the fractions at 5.6 mm, 2-5.6 mm and 2 mm. The results (Fig. 1) indicate that Masterson, Hugo, and Atwell soils have the most coarse fragments: more than 35 percent by weight. However, Tukey's test for multiple comparison (Guenther 1964) showed that the only significant differences were between Masterson as compared to Orick and Sites, and Atwell as compared to Orick. The coarse fragments are important in evaluating erosion because they may contribute to erosion pavement formation.

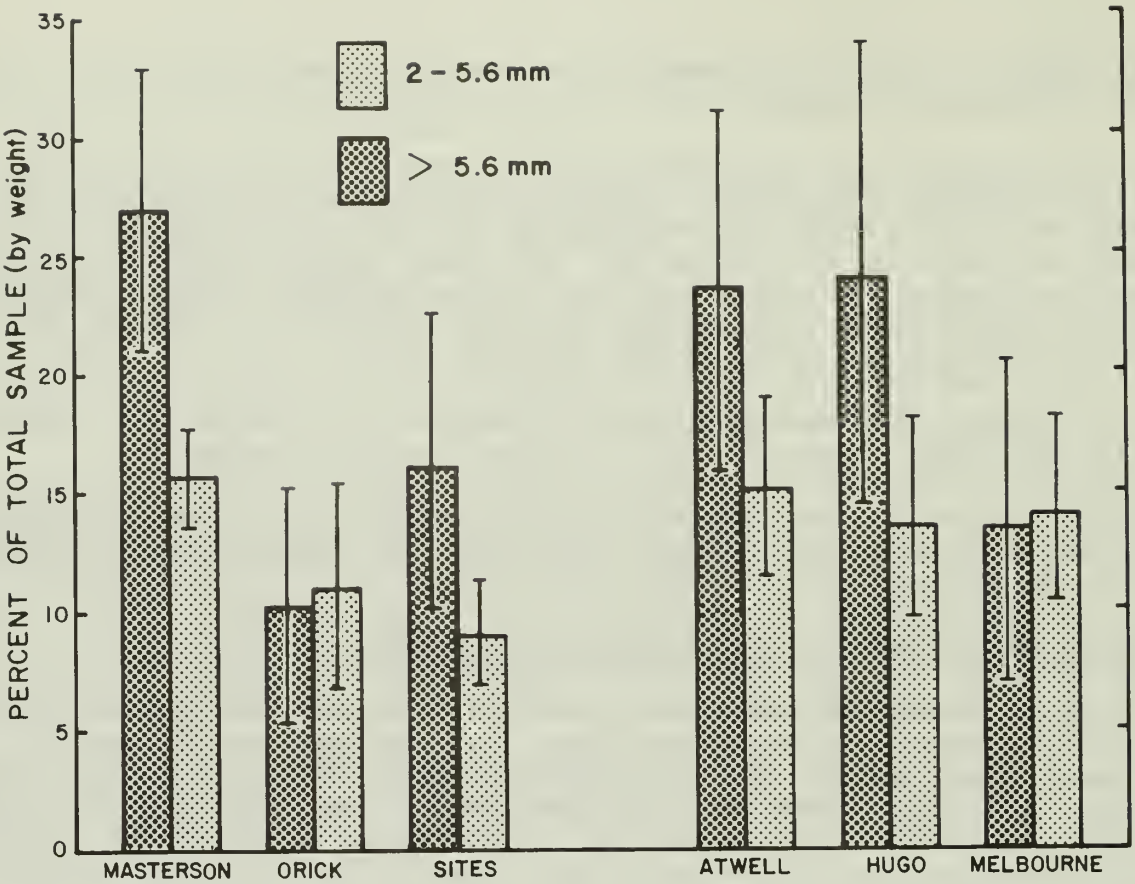

Fig. 1. Percentages of coarse fragments in the composite samples from the six soil series. The columns indicate means and the lines show standard deviations.

The fine grained fractions of soils on both sides of the basin (Fig. 2) show that the soils have substantial amounts of clay. Sites and Orick are classified as clays and the others are clay loams. Tukey's test (Guenther 1964) showed that Sites had significantly more clay than Masterson, Atwell, or Hugo.

Color--The dry composite samples have the following colors according to the Munsell color chart:

Masterson--Light gray to brown. 2.5 Y 7/2, 10 YR 5/4, 10 YR 6.5/4, 10 YR 6.5/3, 10 YR 6/3, 10 YR 5/3.
Orick--Pale yellow to very pale brown. 2.5 Y 7.5/4, 7.5 YR 7/6, 7.5 YR 6.5/6, 7.5 YR 6/6, 7.5 YR 5/6, 10 YR 7/4.
Sites--Reddish-yellow to yellowish-red. 7.5 YR 5/7, 7.5 YR 5/6, 7.5 YR 6/6 (X2), 5 YR 6/7, 5 YR 4.5/6.
Atwell--Light brownish-gray to gray. N 5/0 (X4), 2.5 Y 6/2 (X2).
Hugo--Light gray to pale brown. 10 YR 7.5/2, 10 YR 7/4, 10 YR 7/3 (X2), 10 YR 6/4, 10 YR 6.3.
Melbourne--Yellow to light yellowish-brown. 10 YR 7/6, 10 YR 7.5/3.5, 10 YR 7/4 (X2), 10 YR 6/4 (X2).

The samples tend to range from gray for Atwell, the least developed soil, to a yellowish red for Sites, the most developed.

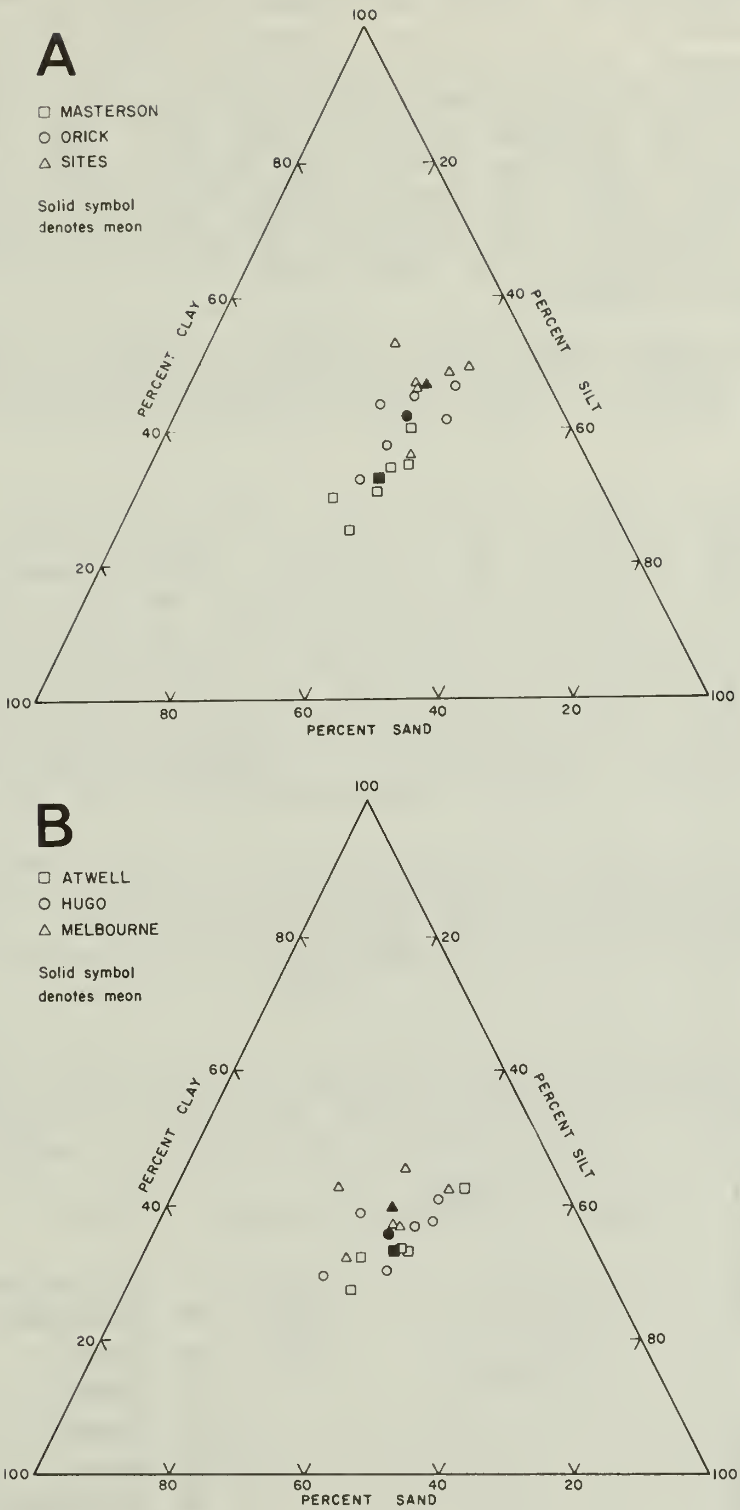

Fig. 2. Particle size distribution of composite samples with mean of the soil series. (A) Soils on west side of Redwood Creek (B) Soils on east side of Redwood Creek.

Erodibility indexes--Some simple laboratory analyses have been designed to evaluate soil erodibility. Middleton (1930) devised the "dispersion ratio" whereby the percent of silt plus clay dispersed by distilled water is divided by the total percent of silt plus clay. Anderson (1951) found that a regression equation using dispersion ratio and percent cover had a correlation coefficient of 0.89 with suspended sediment discharge of Coast Range drainages in southern California. Anderson (1954) later examined soils and sediment discharge from western Oregon watersheds and found that the surface aggregation ratio was an improvement over the dispersion ratio. The surface aggregation ratio is the surface area of sand and coarser particles (> 0.05 mm) divided by the aggregated silt plus clay.

The composite samples were tested for their dispersion ratios and surface aggregation ratios. Our procedures were similar to those described in the

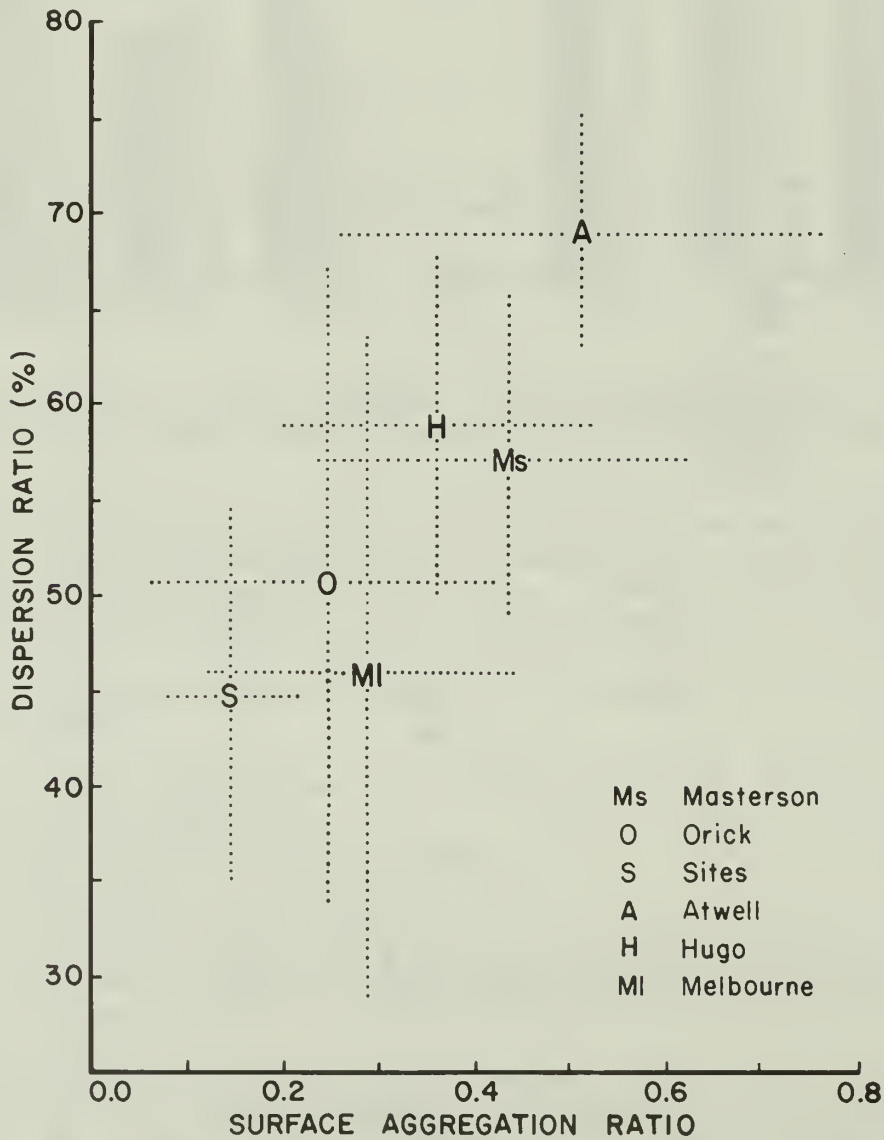

Fig. 3. The surface aggregation ratios and dispersion ratios of the composite soil samples. Letters denote the means and dotted lines indicate the standard deviations.

publications cited above except that the dispersion ratio was determined by hydrometer and the surface aggregation ratio was determined with a 5.6 mm sieve instead of a 5 mm sieve.

The results of these tests (Fig. 3) indicate that there is considerable variation in erodibility in any soil type and consequently there may not have been enough samples to show that some soils are statistically different from others. However, Tukey's test showed that the only significant difference in surface aggregation ratio was between Atwell and Sites. The most apparent difference between these two soils is their range of oxidation. Atwell primarily contains reduced iron whereas Sites is dominated by oxidized ferric hydroxide ($FE(OH)_3$). Orick and Melbourne are difficult to differentiate and are more oxidized than Hugo and Masterson. Although Atwell is classified as being more mature than Hugo and Masterson, the Atwell samples were generally collected from the poorly weathered subsoil that is exposed on the Copper Creek drainage in the southeast portion of the Park.

The most widely used erosion index is the universal soil loss equation. The soil factor (K) in this equation is derived from a combination of 24 variables (Wischmeier and Mannering 1969). Since K is too difficult to determine under most circumstances, simpler methods have been devised. For example, the Pacific Southwest Region (R-5) of the Forest Service has prepared a guide (R5-2500-14) which approximates the soil factor by evaluating soil detachability, infiltration, permeability, and depth. Soil detachability is measured by the response when water is applied to an aggregate with a squirt bottle (with a modification for coarse fragments). This technique is intended to give some idea of the amount of water-stable aggregates in soil.

Detachability was measured on air-dried composite samples according to the R-5 method. The results show no correlation (r^2 = 0.0087) with the surface aggregation ratio. These findings indicate that the detachability index needs further critical evaluation to determine whether it is of value in erodibility predictions.

The relative erodibilities of soils as measured by two erosion indices and as determined through observations by the soil-vegetation survey (DeLapp et al. 1961a, 1961b; Alexander et al. 1960, 1961) are compared in Table 1. The most erodible soil is given a value of 1.0 in these indexes.

Table 1 - Relative erodibility indexes

Soil series	Mean percent slope	Detachability index (R-5)	Surface aggregation ratio (Anderson)	Soil-vegetation survey
Atwell	39	0.8	1.00	Moderate to high
Masterson	39	.9	.84	Moderate to high
Hugo	35	1.0	.71	Moderate to high
Melbourne	30	0.9	.55	Moderate to high
Orick	33	1.0	.47	Moderate
Sites	23	0.9	.28	Slight to moderate

Relation to slope--Determination that a site is highly erodible cannot be made from data on relative soil erodibility only. Slope, disturbance, and other conditions must be considered in the hazard evaluation. In Redwood National Park, soil erodibility is not independent of slope (Table 1). The older, less erodible soils are on the gentler slopes. In contrast, Atwell and Masterson are on the steeper slopes and because of their poor physical properties, are associated with slumping and sliding.

Causes of erodibility differences--The dominant conclusion from the data is that the young Atwell soil is more erodible than the strongly developed oxidized Sites (Fig. 3). Weathering produces iron oxides that improve a soil's physical properties by promoting aggregation and higher porosities (Arca and Weed 1966, Lutz 1936). Sites also has a higher percentage of clay, a trait associated with lower erosion rates (Buoyoucos 1935). The cohesive clay resists detachment of the soil particles.

The type of clay may also contribute to differences in erosion rates. Clay mineralogies were determined by x-ray diffraction on random samples from four of the soil series. The Hugo and Masterson were similar and contained vermiculite, intergradient chlorite-vermiculite, and chlorite. Atwell was dominated by authigenic chlorite but contained mica as well. The x-ray analysis verified the existence of chlorite in Sites but could not determine if kaolinite was also present. There is some agreement between these findings and a study by Winzler and Kelly (1975). However, we found vermiculite to be more common than they reported. The number of samples we tested was insufficient for statistical reliability.

The relation between clay mineralogy and soil erodibility has not been documented, although Singer and others (1978) studied the erodibility of some California soils and found that the smectite clays were more erodible than vermiculite. Both the most and least erodible soils of Redwood Park had chlorite as a primary constituent. The major difference between the clays we identified is their cation exchange capacity (CEC). Vermiculite has a CEC of 100 to 150 meg/100αg of dry soil compared to 10 to 40 for chlorite and 3 to 15 for kaolinite (Birkeland 1974). Vermiculite has a much greater negative charge and therefore more potential for dispersion. However, this negative charge is offset by the clay's exchangeable cations. The type of exchangeable cations can also influence erodibility (Wallis and Stevan 1961) but their determination was outside the scope of this study.

IMPLICATIONS FOR MANAGEMENT

Rehabilitation should either decrease the driving force or increase the resisting force. The change may be accomplished by common methods, such as mulching, revegetation, or creating an erosion pavement. Natural erosion pavements can occur on any of the Redwood Park soils provided the gradient is not too steep. Erosion pavements are most likely on the young skeletal soils where they are also most needed.

This study suggests that rehabilitation efforts should be concentrated in areas with highly erodible soils such as Atwell. The Atwell soils are commonly underlain by fault gouge or melange and are associated with seeps and slumps. It is difficult and expensive to retard slumping but revegetation will at least decrease the active surface erosion of Atwell soils, as in the Copper Creek drainage.

The goal of earth science specialists should be to identify highly erosive sites before logging so that mitigation measures can be taken and the need for rehabilitation avoided. The best method at this time is field observation of disturbed sites on terrain similar to the area proposed for logging. This will define the important variables better than any rigid scheme. There are several disadvantages to this approach, however, the most important being that it depends on subjective evaluation. The demand is for an objective, quantitative approach that can be widely used and will hold up in court if necessary. Several erosion hazard rating schemes are available but none have a high success rate. They can be helpful as guidelines but should not be followed dogmatically.

Although mapping of soil series is based on such factors as bedrock, vegetation, and slope, rather than soil characteristics these maps can provide some help in predicting soil erodibility. However, this study suggests that even with more samples there probably would be no significant difference in erodibility between the Orick and Melbourne or the Hugo and Masterson. In field observations, Popenoe[2] has found no practical differences and thinks these soils should be grouped. On the other hand, Hugo and Masterson have skeletal and nonskeletal phases and that differentiation would be helpful for soil management.

The trend in soil mapping is toward less reliance on bedrock as a basis for classification. Therefore soil mapping of National Park lands today would group some soils and more closely reflect soil erodibility. Specific sites could be evaluated by quantification of coarse fragments, free iron oxide and organic matter. Soil color reflects free iron oxide content. We are now conducting a study to determine if color is a useful prediction tool that has as good a correlation with erodibility as the surface aggregation ratio.

2 Personal communication, J. Popenoe, Soil Scientist, Redwood National Park, Orick, Calif. 1981.

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BIOTECHNICAL SLOPE PROTECTION AND EARTH SUPPORT

Donald H. Gray[1]

ABSTRACT

The combined or integrated use of vegetation and structures provide an attractive and cost effective method of supporting earth masses and preventing erosion and shallow slope failures. This combined approach is termed biotechnical slope protection. Biotechnical measures include contour-wattling, brush layering, staking of unrooted cuttings, reed-trench terracing, brush matting, and conventional slope plantings in combination with breast walls or other low structures at the toe of slopes. Vegetation can be grown in the interstices of porous revetments where plant roots are able to permeate and indurate the soil beneath. Vegetation can likewise be planted and established on the benches of tiered retaining wall systems or in the vertical faces of porous retaining structures.

INTRODUCTION

Biotechnical slope protection entails the use of both mechanical elements (or structures) in combination with biological elements (or plants) to support earth masses and to arrest or prevent shallow slope failures and erosion. Both biological and mechanical elements must function together in an integrated and complementary manner. The principles and general approach of biotechnical slope protection are outlined in this paper. Detailed guidelines and specifications for design and implementation of various biotechnical measures can be found elsewhere (Schiectl, 1980; Gray and Leiser, 1981).

There are a number of advantages or reasons for a biotechnical approach to slope protection. Actual field studies (White, 1979) have shown that in many instances combined structural-vegetative slope protection systems are more cost effective than the use of either vegetation or structures alone. Vegetative treatments are usually much less expensive than earth retaining

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structures or other constructed protection systems. On the other hand, their effectiveness in terms of preventing soil loss or arresting slope movement under severe conditions may also be much lower.

Biotechnical slope protection systems blend into the landscape. The structural or mechanical components which are typically used do not visually intrude upon the landscape as much as conventional earth retaining structures. Examples of such structures include log or timber cribs; welded wire walls; gabion and rock breast walls; and reinforced earth. In addition, opportunities arise to incorporate vegetation into the structure itself. This is done either by planting in the voids or interstices between structural members or upon the benches purposely designed into a structure.

Biotechnical slope protection systems emphasize the use of natural, locally available materials - earth, rock, timber, vegetation - in contrast to man-made artifical materials such as steel and concrete. The distinction here is one of emphasis. In many instances or critical situations an effective design may require the use of steel and concrete. But even in this case opportunities for biotechnical design still exist. A good example is a porous or open face crib retaining wall whose front face can be vegetated with a variety of plants and vines. Such retaining walls not only support but also lend an attractive appearance to cut slopes and embankments as shown in Fig. 1.

Biotechnical slope protection measures and systems tend to be more labor-skill intensive as opposed to energy-capital intensive. The nature of biotechnical slope protection systems is such that well supervised, skilled labor can often be substituted for high cost, energy intensive materials. A good example would be slope protection by willow wattling (see Fig. 2).

A variety of situations and examples can be cited where biotechnical slope protection methods have been applied successfully and effectively. These include stablization of cut and fill slopes along major highways (Bowers, 1950; Leiser et al., 1974; and Schiechtl, 1978) and secondary roads (Kraebel, 1936). The latter included access or timber haul roads in forested areas. With the exception of Schiechtl's work all these examples are drawn from California.

Rehabilitation of slopes and watersheds severely damaged by resource exploitation, e.g., mining or timber harvesting, is an important application. Rehabilitation work in Redwood National Park (Madej et al., 1980; Kelsey and Stroud, 1981) provides a good example. Severe constraints may operate in this case to limit the type of slope protection measures that can be employed, viz., cost limitations, requirements for use of labor-skill intensive measures, prohibition against use of stark or massive retaining structures, etc. In such cases biotechnical methods are particularly attractive alternatives.

Biotechnical slope protection measures can be employed in the coastal zone for relatively low cost protection of backshore slopes against the ravages of both erosion and mass-movement. Some interesting and successful examples of biotechnical protection of slopes in the coastal regions of

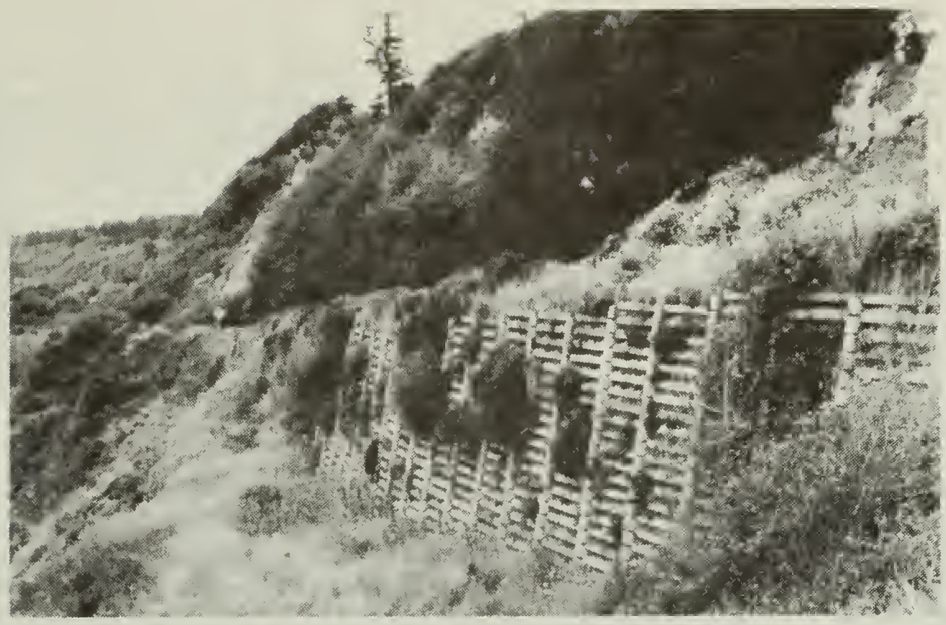

Fig. 1. Vegetated, open-front crib wall supporting coastal roadway. Colorful native shrubs and plants have become established in the openings between structural members at the face of the wall. Trinidad Beach, California.

Fig. 2. Slope protected by contour wattling. Partially buried and staked willow wattles protect slope against erosion. Wattles root and sprout thus further stabilizing slope. Redwood National Park, California.

the USA have been documented in the literature (USDA, 1940; Reid, 1969; Knutson, 1977). Biotechnical methods can also be employed to protect streambanks and channels against bank erosion primarily through use of vegetated, porous or cellular revetments (U.S. Army Corps of Engineers, 1978).

Control of gully erosion provides yet another instance where biotechnical methods are appropriate and effective. The long-term goal of gully control is establishment of vegetative cover. This can seldom be accomplished, however, without short-term assistance from various structural-mechanical measures (Heede, 1976).

ELEMENTS OF BIOTECHNICAL PROTECTION

Biotechnical slope protection systems consist of both structural-mechanical and vegetative elements working together in a complementary or integrated manner. This approach can be viewed and understood best by placing it in a spectrum of different approaches to slope protection and erosion control as shown in Table 1. Basic approaches are divided into three major categories according to type of construction which is involved, viz., live, mixed, or inert construction. Live construction entails the use of conventional plantings along, e.g., grasses and shrubs. Vegetation in this case is used mainly to prevent surficial erosion by providing a good ground cover. At the other extreme is inert construction, which entails the use of conventional structures alone, e.g., gravity and cantilever retaining walls. These type of structures are required when slope movement is deeper seated or lateral earth stresses high. The role of vegetation in this case would be mainly decorative.

Biotechnical methods fall into the middle category of mixed construction. In this case plants have multiple and important functional roles to play; they should not be regarded as cosmetic adjuncts to the structure. Vegetation may be planted on the face of a slope above a low toe wall (Fig. 3). Alternatively, the interstices of the structure may be planted with vegetation whose roots ultimately will permeate and indurate the soil or backfill within or behind the structure. Vegetated rock breast walls, crib walls, gabion walls, and welded-wire walls fall into this category (Figs. 3 and 4) as do vegetated grid or cellular revetments (Fig. 5). Another combination consists of planting vegetation on the steps of a tiered, retaining wall system (Fig. 6). Procedures for designing, constructing, and vegetating these structures are described by Gray and Leiser (1981).

Contour-wattling and brush-layering can be viewed as either quasi-vegetative or quasi-mechanical means of slope stablization (Figs. 7 and 8). In both cases parts of woody shrubs are used as the soil stablizing and reinforcing material. Although natural vegetation is used for the most part, the stablizing mechanism is largely of a mechanical nature particularly in the case of brush layering.

Wattling consists of tied bundles of plant stems or branches, usually willow or other easy to root species. The bundles are laid in trenches on contour along the slope face (Fig. 7) and staked into position, then the trenches are backfilled. Construction stakes are commonly used for this

TABLE 1 APPROACHES TO SLOPE PROTECTION AND EROSION CONTROL

CATEGORY		EXAMPLES	APPROPRIATE USES	STABILIZING MECHANISM OR ROLE OF VEGETATION
LIVE CONSTRUCTION Conventional plantings		· Grass seeding · Transplants	- Control of surficial rainfall & wind erosion - Minimize frost effects	- bind & restrain soil particles - filter soil from runoff - intercept raindrops - maintain infiltration - change thermal character of ground surface
MIXED CONSTRUCTION	Woody plants used as reinforcement & as barriers to soil movement	· Live staking · Contour wattling · Brush layering · Reed-trench terracing · Brush mats	- Control of surficial rainfall erosion (rilling & gullying) - Control of shallow (translational) mass movement	Same as above...but also reinforce soil & resist downslope movement of earth masses by buttressing & soil arching action
	Woody plants grown in interstices of low, porous structures or benches of tiered structures	· Vegetated <u>revetments</u> (riprap, grids, gabion mats, blocks) · Vegetated <u>retaining walls</u> (open cribs, gabions, stepped-back walls, & welded-wire walls)	- Control of shallow mass movements & resistance to low-mod. earth forces - Improvement of appearance & performance of structures	- reinforce & indurate soil or fill behind structure into monolithic mass. - deplete & remove moisture from soil or fill behind structure.
	Toe-walls at foot of slope used in conjunction w/ plantings on the face	· Low, breast walls (stone, masonry etc.) with vegetated slope above (grasses and shrubs).	- Control of erosion on cut & fill slopes subject to undermining at the toe	- stop or prevent erosion on slope face above retaining wall
INERT CONSTRUCTION Conventional structures		· Gravity walls · Cantilever walls · Pile walls · Reinforced earth walls	- Control of deepseated mass movement & restraint of high lat. earth forces - Retention of toxic or agressive fills & soil	mainly decorative role

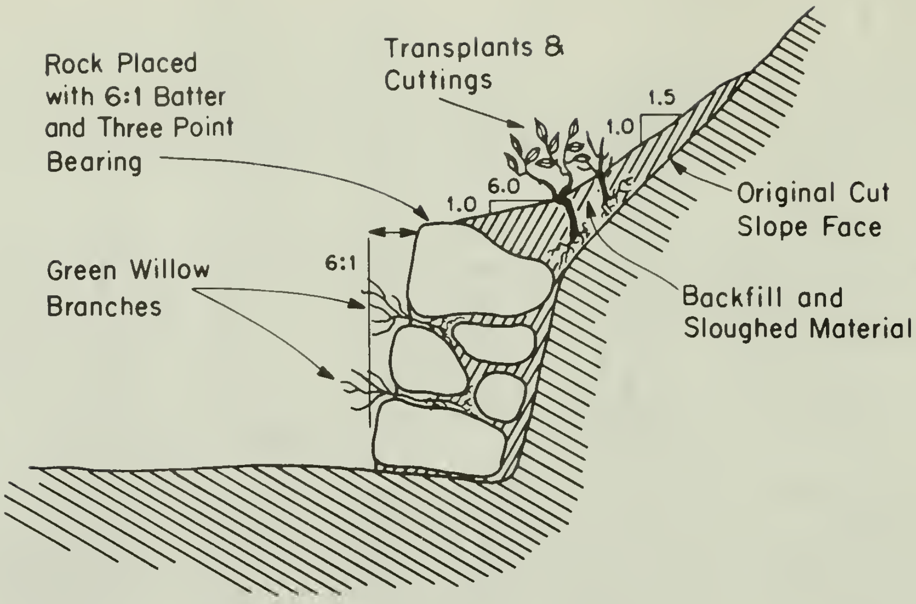

Fig. 3. Vegetated breast wall design for protecting the toe of an earth slope. Plants and live cuttings are placed on the bench or backfill above the wall. Green willow branches or other live cuttings can also be inserted into the backfill through openings between rocks as shown. Plant roots eventually permeate the backfill and help to anchor and reinforce the breast wall.

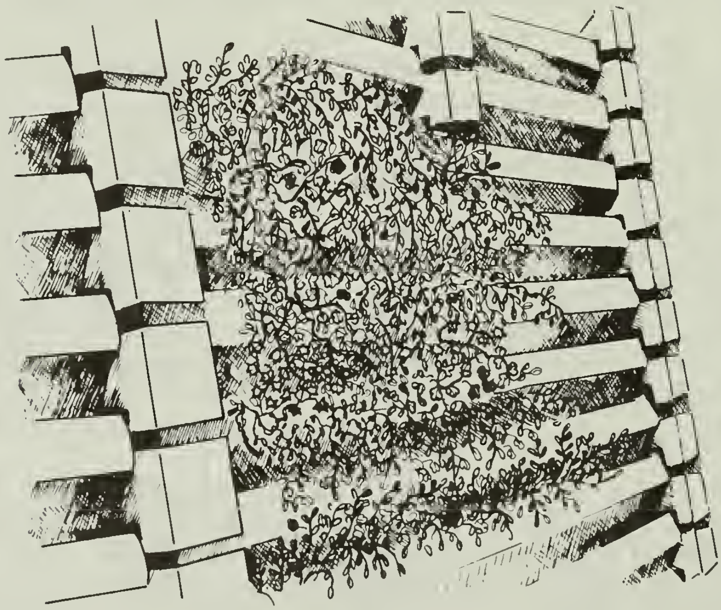

Fig. 4. Vegetated, open-face crib wall design. Cribbing is erected "log cabin" fashion with a batter of 1:6. Suitable vegetation is planted in the open bays between structural members at the front of the crib wall. This procedure not only provides secondary reinforcement of the cribfill (via plant roots) but also opportunities for imaginative landscaping on near vertical surfaces.

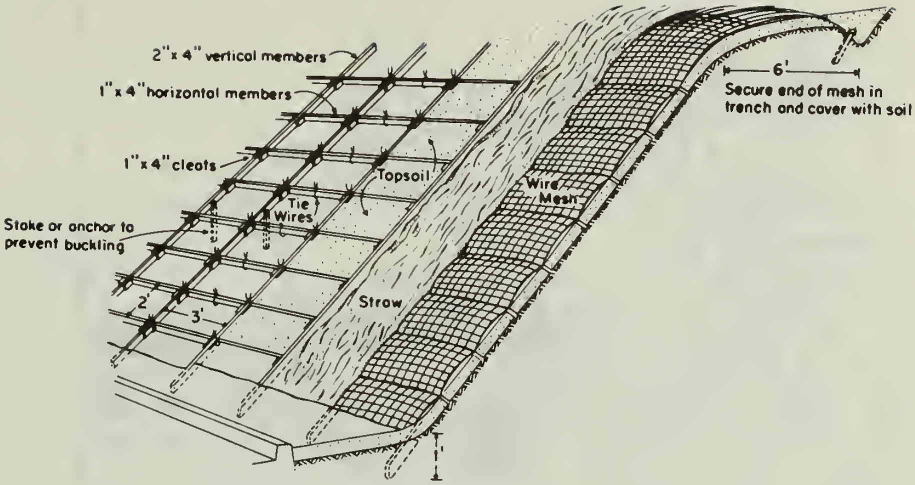

Fig. 5. Cut slope stabilization using an anchored timber grid to hold topsoil and slope plantings in place. Structural grid provides temporary slope protection and permits establishment of vegetation. Once established the plants provide long term slope protection and erosion control.

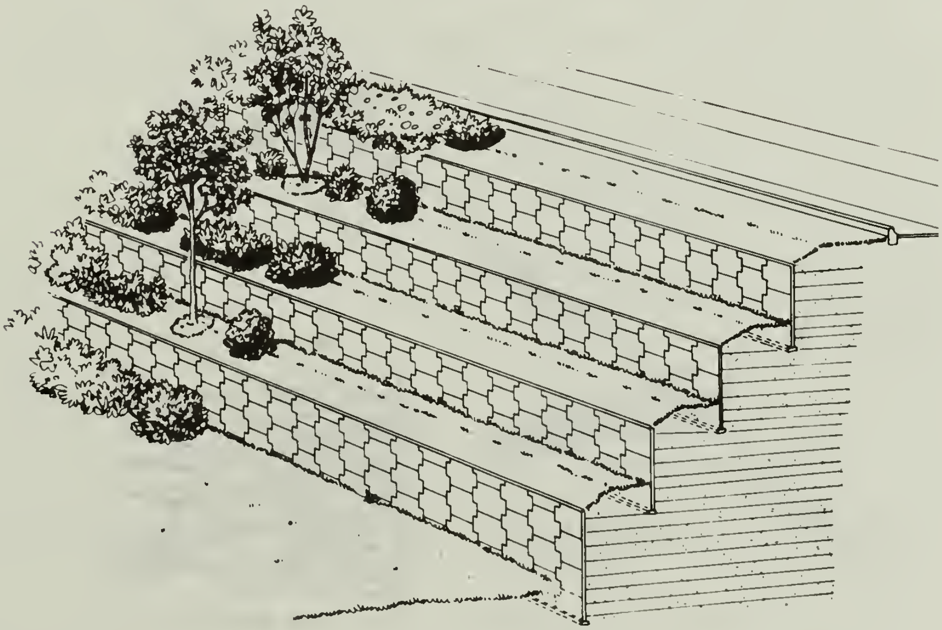

Fig. 6. Tiered, Reinforced Earth wall design with landscaped benches. Lateral earth support is provided mainly by metallic strips which extend back into the slope and which are connected to thin facing elements at the front of the wall. Roots of vegetation growing on the benches provide secondary reinforcement.

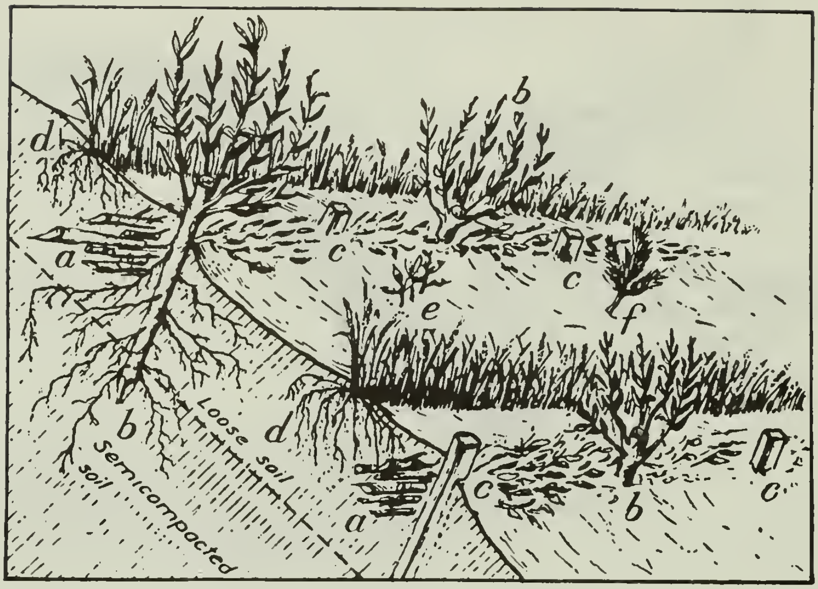

Fig. 7. Fill slope protected by contour wattling. Shown schematically are (a) stems of cut brush "wattles" (b) live willow stakes which have rooted (c) inert construction stakes driven through the wattles (d), (e), and (f) vegetation (grasses, shrubs, and trees). The wattles of bundled brush are laid in shallow trenches on contour and partially backfilled as shown (from Kraebel, 1936).

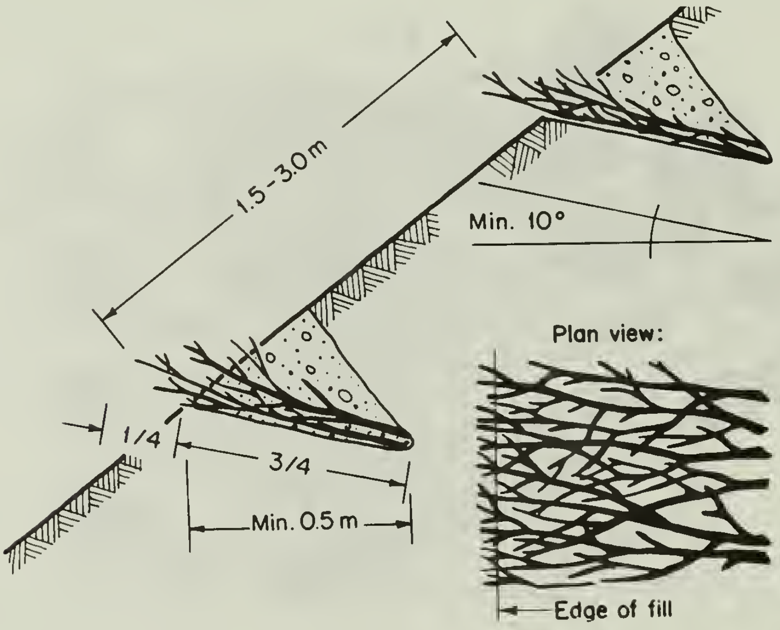

Fig. 8. Fill slope protected by brush layering, Green cuttings and branches of sprouting shrub and tree species are "layered" between successive lifts of fill in horizontal rows at the face of the slope. The branches are placed randomly with some criss crossing of stems. Buttends angle down slightly into the slope and the tips are allowed to protrude slightly beyond the face of the slope as shown (adapted from Schiechtl, 1978).

purpose; these are driven through the wattles into the ground. The stakes act as "dowels" and help anchor the soil to the slope, thereby minimizing shallow debris slides. Alternatively, live willow stakes may be used. These are more difficult to drive in hard ground but provide the additional advantage of rooting and sprouting which will further enhance stability of the slope.

Countour brush-layering consists of imbedding green branches of shrub or tree species, preferably those which will root, on successive horizontal rows or contours in the face of a slope. Rooted cuttings have also been used in lieu of brnahces. The method is schematically illustrated in Fig. 8. Brush-layering may be incorporated for slope protection purposes, during construction of a fill or embankment or alternatively used as a rehabilitation measure for seriously eroded and barren slopes. Brush layers have been incorporated into embankments during construction to stabilize erodible slopes along highways in California (Bowers, 1950). The function of the brush layer in this case was primarily to minimize formation of gullies, in event the surface protection on the slope face should fail. Brush layering is similar to contour wattling in its function and purposes but there are some important differences and advantages, viz.,

(a) It lends itself more readily to partial mechanization. There are no willow bundles to tie and the benches can be excavated with a small tractor.

(b) The branches are inserted into the slope (perpendicular to the strike) rather than parallel. The reinforcement is better oriented, therefore, to resist shallow shear failures or slipouts.

(c) The need for staking is eliminated.

(d) It may be reinforced with wire mesh or other materials.

Brush matting is essentially a mulch of hardwood brush fastened down with stakes and wire (Fig. 9). This measure is used to protect streambanks. The brush is laid shingle fashion with the buttends pointed upstream. Speckled alder and purple-osier willow are ideal species for this purpose, but any convenient streamside brush may be used. Brush matting is employed primarily in conjunction with other stream bank protection measures. Used alone it provides a certain amount of bank protection and erosion control; it can resist temporary inundation, but not scour and undercutting. Structural measures such as groins and revetments are necessary if the bank undercutting is a problem.

Brush matting was employed very effectively for steambank erosion control work along the Winooski River in Vermont (Edminster, et al., 1949). It was an integral component of a combination of measures which were found the most successful on the Winooski project. Thse measures included bank sloping, riprapping at the toe, brush matting, and planting.

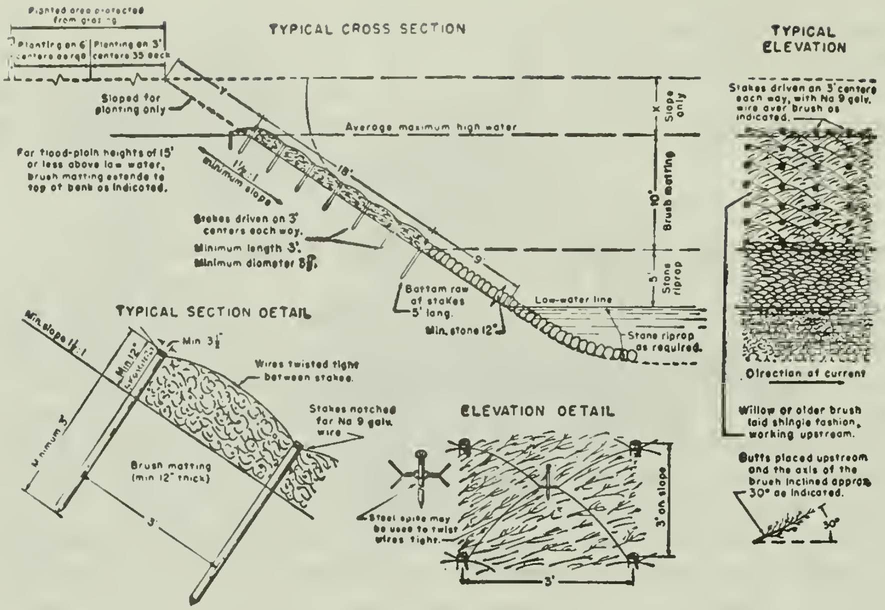

Fig. 9. Construction procedure and details for streambank protection using brush matting. The brush is laid shingle fashion with the butt ends pointed upstream and is fastened down with stakes and wire (from Edminster et al., 1949).

Fig. 10. Steep slope in granitic terrain stablized by willow staking and wattling. Unrooted willow cuttings were planted on two-foot centers. This previously denuded highway cut, about one acre in area, was producing over 100 cu. yds. of sediment per year. Erosion and bank sloughing problems have been virtually eliminated at this iste. State Highway #89, near Luther Pass, California.

Live staking is a quick and effective method of securing a vegetative cover for control of soil erosion and shallow sliding. Live staking, also known as sprigging, consists of planting or driving unrooted cuttings from a live tree or bush. Species which root easily such as willow, poplar, and cottonwoods should be used. These species will grow readily from cuttings set in moist soil. Several species of willow will also grow from cuttings in much less favorable soils, e.g., road cuts and gullies in bare denuded land. Even in very unfavorable sites willow cuttings will often grow vigorously for a few years before they die out. In the meantime they will have served the important function of stabilizing and modifying the soil so that other plants can become established.

Live staking has been used to help stablize shallow slope failures where excess soil moisture is a problem. It has also been used: (a) to establish a vegetative cover on barren, highly erodible highway cuts or fills (Fig. 10), (b) to vegetate porous revetments, (c) as an adjunct to contour wattling, and (d) to provide secondary protection to gully control structures, e.g., check dams and gully head plugs.

Care and attention are required in the selection, sizing, handling, and placement of live materials in all these methods. The same attention that is applied to design standards and specifications for structures also applies to plants. Gray and Leiser (1981) provide guidelines and specifications in this regard.

ROLE OF VEGETATION AND STRUCTURAL ELEMENTS

Vegetation and structures have mutually reinforcing and complementary roles in biotechnical slope protection systems. It is instructive to examine their respective roles and function.

Role of Vegetation: Vegetation offers the best long term protection against surficial erosion on slopes and provides some degree of protection against shallow mass-movement. The stablizing mechanisms and role of vegetation in each case are summarized in Table 1. A detailed review of this topic has been given by Gray (1978).

Vegetation is self regulating and self repairing to a certain extent. Vegetation slope protection measures are also less costly *per se* than structural measures (White and Franks, 1978). On the other hand, vegetation suffers from several limitations and disadvantages. It is of little use for preventing deep seated, rotational slope failures and it is vulnerable to disease, drought, browsing, trampling, and erosion from wave action or stream bank scour. Vegetation may also be difficult to establish on steep slopes. Many of these limitations can be overcome, however, by (a) selecting the right type of vegetation, (b) planting and maintaining the vegetation correctly, and (c) using the vegetation in combination with structural-mechanical elements.

Role of Structure: Properly designed structures help to stablize a slope against mass-movement and they protect the toe or face of a slope against scour and erosion by running water. Structures are generally capable of resisting much higher lateral earth pressures and shear stresses than vegetation. Structures can also be used to divert and convey running water away from critical areas or dissipate the energy of flowing water in a defended area within the structure.

Structures can be built from a number of materials both natural and artificial. Natural materials include earth, rock, stone, and timber. These materials normally cost less, are environmentally more compatible, and better suited to vegetative treatment or modification. Artificial materials include steel and cement. Structures made from the latter materials are stronger and generally more durable, but also more energy and capital intensive. Some structures are comprised of both natural and artificial materials; examples include concrete crib walls, steel bin walls, gabion walls or revetments, welded-wire walls, and reinforced earth. Steel and concrete in this case mostly provide the rigidity, strength, and reinforcement while stone, rock and soil provide the mass. These type of structures can often be planted or vegetated using techniques alluded to previously.

A retaining structure of some type will usually be required to protect and stabilize oversteepened slopes. A low toe-wall or retaining structure at the foot of a slope permits oversteepening of the slope at its base and flattening above. The latter makes it possible to establish vegetation on the slope and the former reduces the amount of clearance required between the base of a slope and an adjacent right-of-way or existing use. This advantage and other applications of retaining structures and toe-walls in combination with vegetative treatments are discussed by Gray and Leiser (1981) and Gray *et al*. (1980).

Revetments and grade stabilization structures are used where protection is required against scour and erosion by running water. A revetment is a structural armoring on a slope. The weight or mass of revetment may also buttress the slope to some extent and increase its resistance to mass-movement. Revetments may consist of a variety of different materials including dumped rubble rock, concrete facings, slotted or cellular concrete grids, articulated blocks, rubber-tire mats, or gabion mattresses. Revetments are commonly used to protect streambanks and channels where water velocities are high and bank materials, weak.

A grade stablization structure is used to reduce grade and dissipate the energy of flowing water within the structure itself or nearby defended area. Debris and sediment tend to be deposited and trapped upstream of the structure which further stablizes the ground. Grade stabilization structures may range from a series of simple, board check dams to earth enbankments with pipe spillways. Mechanical box structures of concrete, masonry, steel, treated wood or gabions have also been used. Grade stabilization structures or check dams as they are commonly known are often employed in gully control work. Effective and inexpensive check dams can be constructed from loose rock in combination with wire mesh fencing and steel posts (Heede, 1976).

Gully control provides a good example of the combined use of structures and vegetation. The long term goal of gully control is establishment of a vegetative cover. This goal can seldom be realized unless severe gully conditions can be altered first. Vegetation alone, for example, will rarely stabilize headcuts because of active piping and concentrated flow of water there. The immediate or short term objective, therefore, is to stabilize critical locations with structural or mechanical measures. Critical locations where structural measures may be required include nick-points on the gully bed, headcuts, and gully reaches close to the gully where deepening, widening, and deposition alternate frequently with differing flows. The ultimate function of these structural-mechanical measures, however, is to help establish and rehabilitate vegetation which provides long term control and protection. Effective gully control requires in short a "biotechnical" solution to the problem. Various gully control systems and structures are described in considerable detail by Heede (1976).

COMPATIBILITY BETWEEN ENGINEERING AND BIOLOGICAL REQUIREMENTS

At first glance biotechnical construction methods may seem unworkable because of compatibility problems, i.e., engineering requirements or conditions imposed by the structure may clash with biological requirements of the vegetation. While indeed some difficulty with incompatibility does exist, much of this concern is either misplaced or can be mitigated. Part of the problem arises from a lack of understanding on the part of both engineers who design the structure and horticulture specialists who design plantings as to each other's design requirements and constraints. An example will serve to illustrate these points.

The backfill or cribfill behind a retaining structure should have certain specified mechanical and hydraulic properties if the structure is to perform properly. Ideally the fill should be coarse grained, free draining, granular material. The presence of excessive amount of clay, silt, and organic matter is not desirable. Gabions should be filled with rock no smaller than 4" in diameter. Reinforced earth structures have very tight specifications on allowable amount of fines in the backfill; the pH is also of concern because of possible corrosion problems with the ties.

The requirement of free drainage - so essential to the mechanical stability of an earth retaining structure - is also important to vegetation, which cannot tolerate water logged soil conditions. Establishment of vegetation, on the other hand, usually requires the presence of fines in the soil in order to provide some moisture and nutrient retention. In many instances these biological requirements can be satisfied without compromising engineering performance by incorporating minor amounts of fines or other amendments in the backfill. These fines or other soil amendments can be put in the backfill either in a surface layer at the top or in small scattered pockets near the face. The former approach would be used in the case of a tiered or bench structure where the objective is to vegetate the horizontal steps; the latter in an open crib structure (timber or concrete) where the objective is to vegetate the face. In the case of gabions, soil can be drifted into the gabion after they are already filled with rock in order to facilitate growth of vegetation. Conversely, cuttings of sprouting plant species (e.g., *Salix*) can be inserted through the baskets during filling into the soil or backfill beyond.

A frequently voiced concern or fear about the use of plants in conjunction with structures is that the roots will pry and tear the structure apart. The evidence for this is scant. The opposite is more likely. Over time the roots will permeate and bind the fill together into a monolithic mass, thereby improving its internal stability. Furthermore, plant roots exhibit a property termed "edaphoecotropism" (Vanicek, 1973) or simply, stress avoidance. This means that plant roots will tend to avoid the face of a porous, open retaining structure because of phototropic response in the roots and because of high soil moisture tensions (moisture deficiencies) in this zone. The main danger from prying or wedging would most likely arise instead from species with trunks or stem sizes which exceed the diameter or size of openings in the face of structures or revetments. It is important, therefore, not to plant seedlings which will mature into large diameter trees in the frontal interstices of a structure.

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LANDSLIDE TERRAIN MANAGEMENT USING HAZARD ZONATION AND RISK EVALUATION

B. G. HICKS*

ABSTRACT

A technique for the assessment of risk of landslide activation due to impact generated by road building and logging is presented. This technique involves assignment of activity levels and influence zones to all landslides and subsequent determination of hazard levels. These data are used to develop qualitative risk tables and quantitative estimates of potential impact in both cubic yards of sediment produced and acres of surface area lost. The technique produces valuable input for land management decision making. In addition, the technique can be used to gain access to some basins previously inaccessible due to stability problems, plus will allow unstable land to be easily identified and protected.

INTRODUCTION

The technique of landslide risk evaluation outlined in this paper has been developed in order to present landslide stability data in a form that can be readily assimilated into the interdisciplinary decision-making process. Using this technique, alternative proposals for an area can be compared with minimum effort. It should be stated that the technique is continuing to develop and evolve. As specific projects arise and the technique is applied to them, improvements in the use or application develop as the actual "problem solving" progresses.

Field and aerial photograph inventories of existing active and old landslides provide the principal data on which the zoning and hazard evaluation are based. The topographic map base must be sufficiently detailed to depict true ground features; a scale of 1 inch = 300 feet with 20-foot contour intervals is commonly used.

Data from which activity levels are developed is recorded on a field form for each landslide which includes: (1) failure and deposit volumes; (2) dimensions and form in long and cross-profile; (3) scarp elevation, height, aspect and degree of weathering; (4) character of material at slide surface; (5) strike and dip of strata or other planar structures; (6) slope gradient; (7) vegetation size and type; and (8) evidence of distorted tree growth. Subjective estimates of the availability of surface and subsurface water, and of the relative stability of the surrounding area, are recorded for evaluation of reactivation risks.

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Although not developed in this paper, semi-quantitative methods of activity level assignment have been made by rating the above factors on a 1 (least stable) to 3 (most stable) scale and then summing up and dividing (by the number of factors) to get a sensitivity (to instability) number (D'Allura 1980). The procedure for full quantitative derivation of the factors of safety vs activity levels has been developed but not employed to any great extent. The generalized procedure is described in the Road Investigation and Design section of this paper. Position on the slope and the slope form below the failure relate to the estimated proportion of the failed material reaching a stream channel. These factors are noted for potential impact evaluation. Stream channel is also noted where debris has reached or may reach a channel. If further failures are deemed likely at the site, the probable volume is also estimated from field data.

ZONATION AND RISK EVALUATION

The basic rule in the application of landslide hazard zonation principles is that any forest management activity (road building, logging) which increases the ground water or surface water entering landslide terrain or potentially unstable slopes, increases the risk of failure or reactivation. The landslide hazard zonation map is a tool which can be used to minimize unwanted environmental impacts associated with timber harvesting and road building. The technique (see Figure 1) involves: (1) stratifying the landslides into their individual "activity levels", (see Table 1 and Figure 2); (2) outlining the surface water and ground water influence zones of landslides, using upslope surface water drainage boundaries (see Figure 3); and (3) assigning hazard levels (potential for failure) due to specific land management impacts; i.e., clear-cutting, partial cutting, road contributed water, etc. (see Table 2 and Figure 3). The technique develops sufficient ground data so that terrain with failure potential, but not containing mappable landslide forms, can be readily assigned "activity levels" from which hazard levels can be assigned. Hazard levels are strongly influenced by the activity level assigned to landslides within any piece of terrain, but many other factors are also taken into account in assigning the hazard level. These include:

- Slope angle and changes in slope angle - upslope and downslope;
- Shape of the upslope area contributing surface and ground water - i.e., V-shaped, A-shaped or H-shaped (converging, diverging, or parallel flow paths);
- Size of the upslope area contributing water to potentially active zones;
- Concentration of surface and ground water by roads, skid trails, etc.;
- Position of the potentially active area along the slope profile, lower slope positions being rated more hazardous then otherwise similar upper slope positions;
- Effects of other geomorphic processes; e.g., stream undercutting;
- Character of regolith material; e.g., clay-rich regolith rated as higher hazard;
- Slope aspect, with north and east facing slopes rated as higher hazard;
- Bedrock geology and structure; e.g., sheared serpentinite, graphite schist, highly foliated and jointed rocks form surfaces prone to failure.

Risk evaluation is presented in the form of a table (Table 3) showing the various hazard levels of the terrain rated against logging and road building impacts. The table prepared shows estimated natural risk of failure to use as a comparison with estimated risk of failure due to man's impact. Simplifying assumptions are presently required to develop the various failure risk percentages (i.e., percent of risk of failure of the various hazard level terrains). At present, the highest risk (100%) is assigned to the most severe hazard level terrain (e.g., active and subactive landslides) receiving the maximum planned impact (e.g., clear-cutting). The minimum risk (generally 0-20%) is assigned to the least hazard level terrain receiving the minimum planned impact (e.g., 50% vegetation removal in partial cutting). All terrain falling between these two extremes is then assigned risks that decrease from the maximum down to the minimum risk.

In order to evaluate the potential for activated landslides to affect downstream structures, land values, reservoirs, fisheries, etc., a simple semi-quantitative technique is used. Landslides which have a high likelihood of reaching a flowing stream are indicated on a separate map or overlay. The volume of material potentially involved is shown on a table relating percentage risk of arrival (at the stream) versus activity level of landslides. This procedure provides an additional weighing factor for use in the selection of logging units for a particular project and for assessment of the environmental risks.

Estimation of some environmental and loss-of-production costs is possible using the landslide area and volume figures for potential impact in Table 3, pro-rated by the percentages shown for various levels of cutting and converted to costs with appropriate multipliers. For hazard zone 1 in the example shown, the potential volume impact is 10,000 cubic yards of landslide debris; multiplication by the estimated costs of removal from downstream reservoirs ($8/yd^3) provides an estimate ($80,000) of one environmental cost of clear-cutting. The area lost from production for hazard zone 1, in this example, is estimated as four acres. If production is lost for three rotations of 20,000/MBF, the total cost of lost production is estimated to be $48,000. Other costs may be semi-quantitatively estimated in like fashion, using appropriate multipliers.

ZONATION IN VARYING TERRAIN TYPES

The identification of areas of active or potential landsliding is relatively simple in areas underlain by cohesive soil mantle material; e.g., where slump/earthflow type landslides have developed in soil mantles derived from serpentinite, metamorphic rocks, clay/silt sedimentary rocks, etc. In such terrain, landslides of widely varying sizes and ages are easily mappable because the zonation technique commonly uses maps at a scale of 1 inch = 300 feet with 20-foot contour intervals. Designation of activity levels and influence areas, and development of hazard level zones and accompanying risk of activation, present no problem in such areas. However, in terrain composed of non-cohesive soils (e.g., weathered granitic rock areas), the sites of potential failures cannot always be identified by surface form alone, and special techniques are required. These procedures include study of old failures to determine the ground conditions contributing to failure and field investigations using hand auger holes and resistivity and electro-magnetic surveys.

ROAD INVESTIGATION AND DESIGN*

In addition to evaluating the effect of logging on slope stability, the effect of the roads proposed to access the timber sale for logging equipment and trucks

* This phase of the process is shown on Figure 1 in STAGES V and VI.

must be studied. Cut and fill slope design are part of the work accomplished, but this paper will only focus on the effect of the road on landslides crossed (or impacted) by a road. Landslides are primarily impacted by road construction excavation and by increasing the volume (and change of timing) of water flows to the landslide.

The detailed landslide mapping completed for the zonation process is usually sufficient to delineate and describe the aerial (plan) view of the landslides. However, in order to obtain the surface and subsurface geometry of the landslide for use in stability analyses, substantially more detail is required. The technique used is described as the "field-developed cross section" method, as described by Williamson and Neal (1980). The field-developed cross section, the landslide mapping completed for zonation, commonly subsurface exploration and, as needed, soil testing allows the stability of specific landslides to be quantitatively analyzed. In addition, changes in road alignment and design can be made, if needed, to reduce impact of the road on the landslide.

The above described landslide analysis method can be used to further quantify the zonation process. It requires the selection of representative landslides which are then analyzed. The factors of safety developed are combined with activity level groupings and used to quantify the impact of logging and road construction on specific terrain.

SUMMARY

The hazard zoning and risk evaluation technique presented here is based on detailed inventorying of active and formerly-active landslides. Qualitative assessments of risk of failure are presented to the land manager in a map of hazard zones and quantitative estimates of the area and volume impacts of landslides in those zones. Failure risks are estimated for a range of management activities, and the estimated volume and area impacts (which may be used to estimate some direct costs of various management operations) provide valuable background data for the interdisciplinary decisions by land managers and land-use planners. The technique allows the potential road-generated impacts to be integrated into the full assessment of risk of entry.

ACKNOWLEDGMENTS

A number of associates aided in the development of details of this technique. Most notably, Richard D. Smith, who was intimately involved in the first sequence of projects utilizing the technique.

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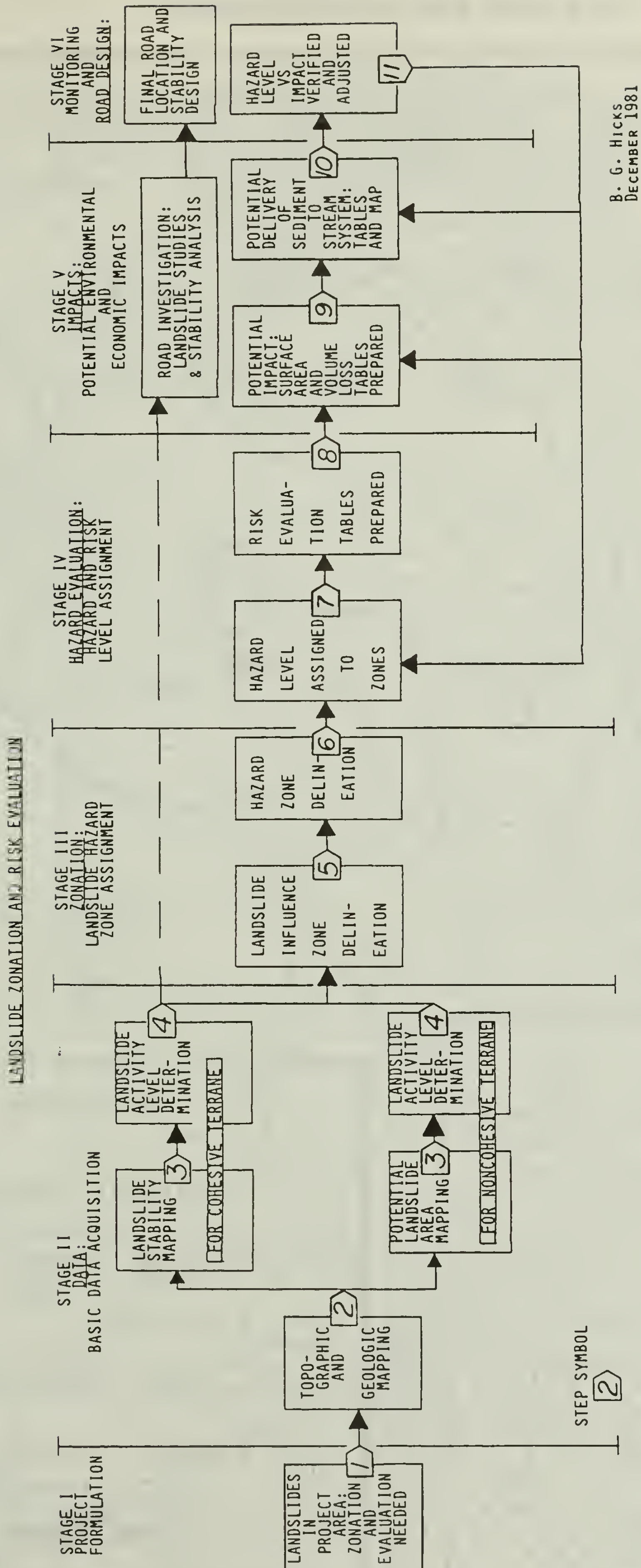

FIGURE 1 FLOW CHART: LANDSLIDE ZONATION AND RISK EVALUATION.

LANDSLIDE ACTIVITY MAP

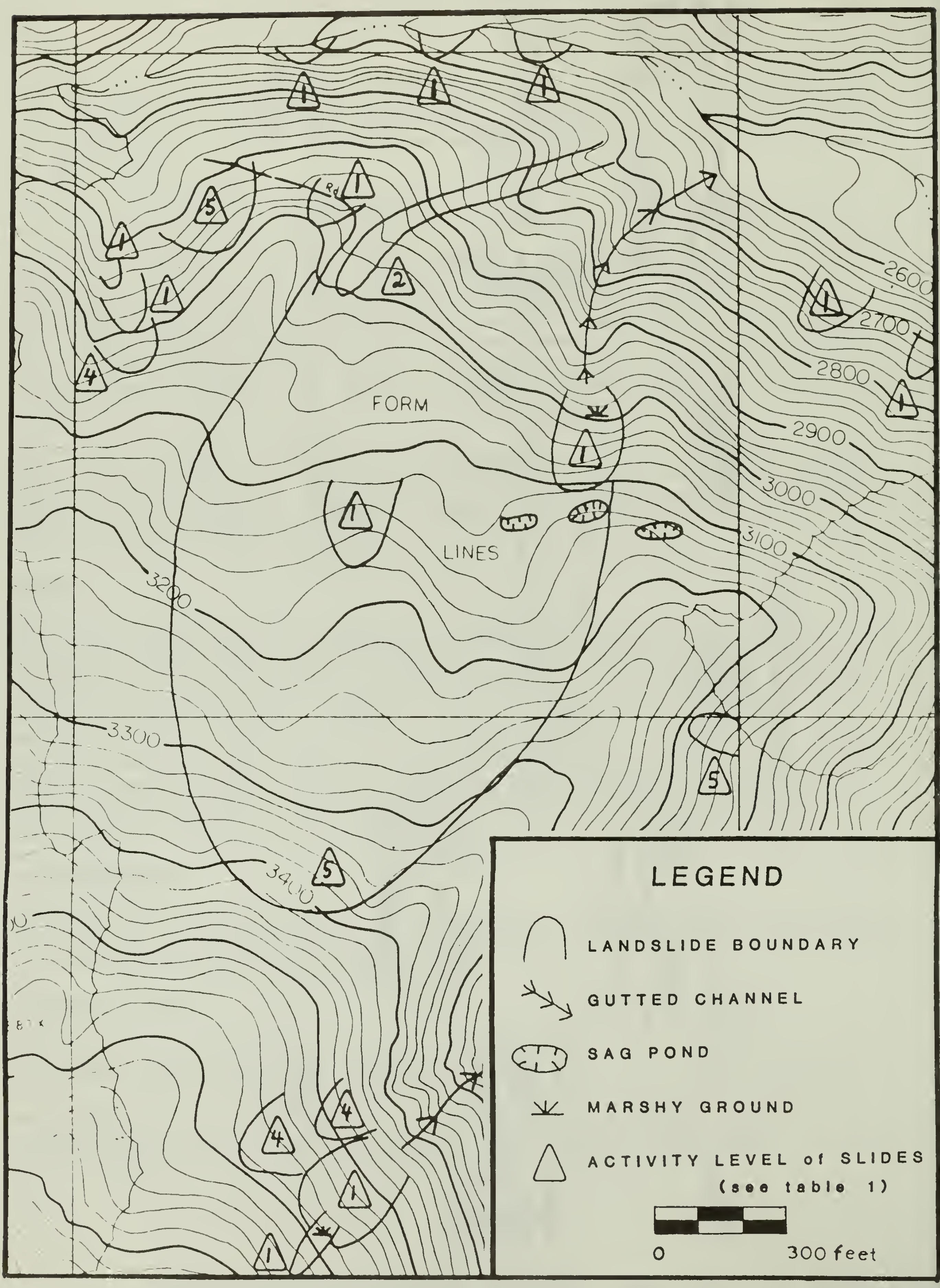

FIGURE 2

HAZARD ZONATION MAP

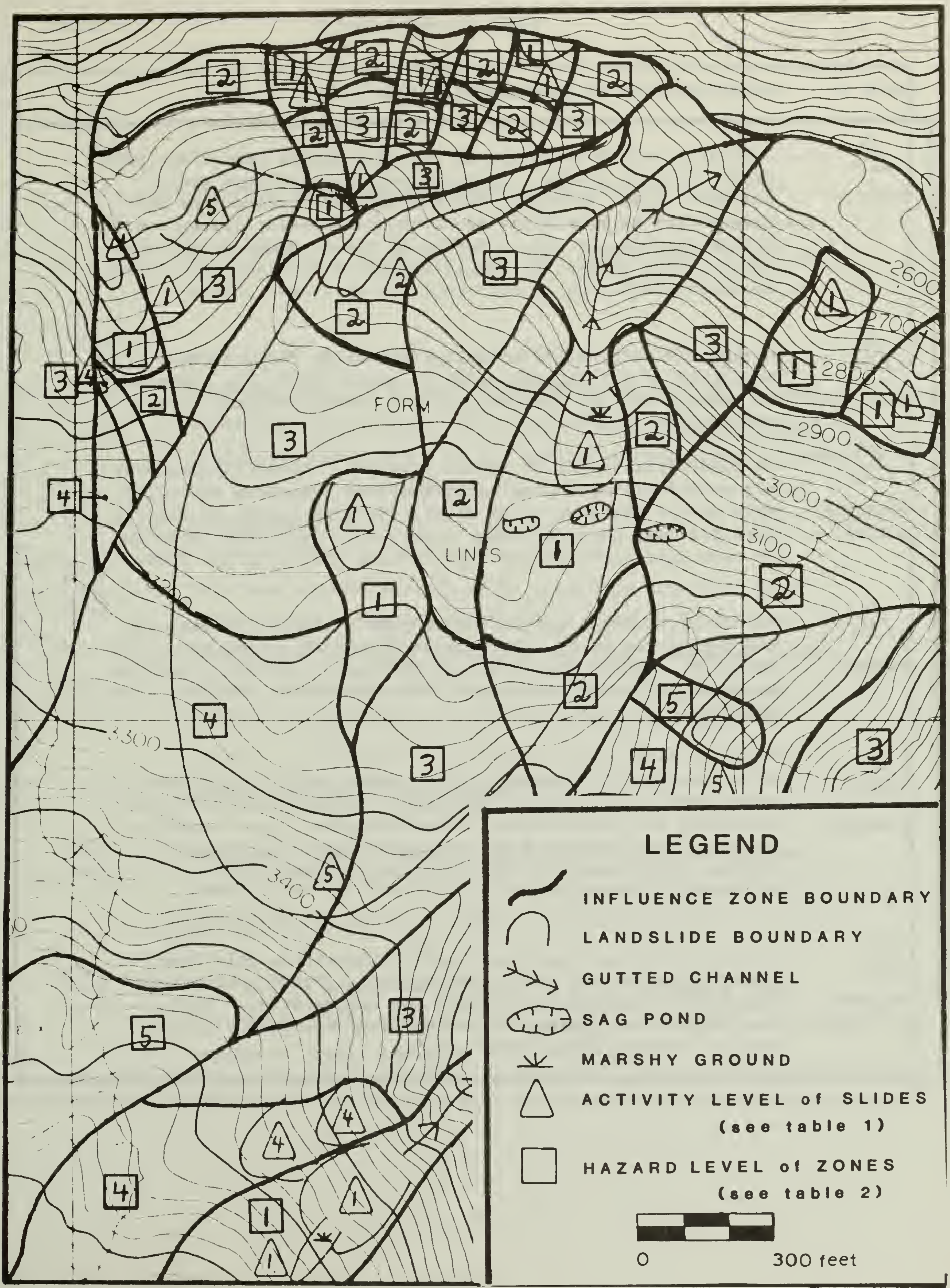

FIGURE 3

NOTE: Activity levels shown for clarity, actual technique uses overlays

TABLE 1: LANDSLIDE ACTIVITY LEVEL DESCRIPTIONS

△1 ACTIVE	Currently active or active in the very recent past. May have fresh scarp or cracks. Leaning trees may indicate recent movement; i.e., straight, healthy conifer leaning from the base indicates recent movement. Broadly-bowed, living conifer indicates movement over a period of time. Hummocky terrain, terrace-like slopes not deeply weathered may indicate recent movement.
△2 SUB-ACTIVE	Movement occurring periodically, landslide features more weathered (e.g., flatter slope to scarp) than △1. Leaning or bowed trees may indicate no very recent movement; i.e., temporarily dormant.
△3 POSSIBLY ACTIVE	No clear indications of recent movement. Landslide features not so heavily weathered as to indicate long-term stability. More subtle features often without obvious scarps or cracks. Possible low, constant creep rate; i.e., currently creeping at rate sufficiently slow that obvious cracks do not form.
△4 DORMANT	No active movement within recent past. Landslide features moderately weathered. Only larger trees show indications of movement. Conditions (i.e., parameters of stability such as slope angle, shape and area of influence zone) make reactivation possible.
△5 INACTIVE	No indication of movement within recent past. Only oldest trees show indications of movement. Landslide features well weathered and revegetated. Interpretation (i.e., location and form) may be only from topographic map or aerial photographs. Field evidence for this type of landslide is difficult to interpret.
△6 ANCIENT INACTIVE	Ancient features, which are easily discernible only from topographic map and aerial photographs. Field indications obscured by weathering, erosion and revegetation. Very low risk of reactivation. Creep rate, if present, is too slow to visibly affect tree growth.

TABLE 2: HAZARD LEVEL OF ZONES

1	Zone which includes active landslides or actively gutting channel and/or includes the portion of the influence zones directly impacting the landslide or channel; i.e., the portion of the influence zone believed to require as much caution as the landslide or gutted channel due to instability and/or impact on the landslide or gutted channel.
2	Zone which is slightly less sensitive than the 1 zone. Often adjacent to or within the influence zone of an area of active landsliding. This hazard level used for type 2 landslides and portion of the influence zone directly impacting the landslide when other factors do not indicate greater instability.
3	This zone may be determined by proximity to active landslides or by potential for impacting active landslides. It is used for type 3 landslides and their immediate impact zones. Additional key parameters are percent slope and position of the zone on the slope (i.e., proximity to creeks or drainages). Some zones delineated by specific combinations of hazard parameters.
4	This zone usually does not impact active landsliding area except from considerable distance upslope. Applies to type 4 landslides and their immediate impact zones.
5	Most stable zone. Rarely located in an influence area of active landslide. Applies to type 5 landslides and their immediate impact zones.

TABLE 2

LE 3 EXAMPLE RISK EVALUATION AND POTENTIAL IMPACT

HAZARD ZONE (LEVEL) ↓ / % CUT (LOGGING) ---->	0% (NATURAL CONDITIONS)	50% (SELECTIVE, ETC., CUT)	100% (CLEAR-CUT)	POTENTIAL (2) IMPACT: CUBIC YDS. / ACRES
1	50 - 80% (1)	80 - 90%	90 - 100%	10,000 / 4
2	40 - 60%	60 - 80%	80 - 90%	5,000 / 2
3	30 - 40%	40 - 50%	60 - 70%	2,000 / 1
4	15 - 25%	20 - 30%	40 - 60%	5,000 / 2
5	10 - 20%	15 - 25%	20 - 30%	8,000 / 3
----> TIME	50 - 500 Years	5 - 10 Years	5 - 10 Years	

(1) 50 - 80% risk of landslide activation; under natural conditions activation may not occur for a long time period, or may occur during a long time period (50-500 years) but with impact can occur post-cutting and pre-regrowth (5-10 years)

(2) Impact listed if for one alternative only

TABLE 3

CHANNEL RECOVERY FROM RECENT LARGE FLOODS IN NORTH COASTAL CALIFORNIA: RATES AND PROCESSES

Thomas E. Lisle [1]

ABSTRACT

Stream channel recovery from recent large floods in northern California involves a sequence of processes, including degradation of streambeds to stable levels, narrowing of channels, and accentuation of riffle-pool sequences. Most channels have degraded but remain widened because hillslope encroachment and establishment of riparian groves conducive to sediment deposition have not yet caused streambanks to accrete. The deepening of pools depends on streambed degradation, channel narrowing, and introduction of scouring agents, such as large organic debris, that were removed by floods. The treatment of riparian vegetation and organic debris may be the most effective and economical means of hastening channel recovery.

INTRODUCTION

Recent floods and accelerated mass erosion in north coastal California have caused substantial changes in stream channels--changes that have persisted for many years. The consequent alteration of anadromous fish habitat is considered to be partially responsible for the decline in fish populations over the last two decades (Rankel, 1979). The duration of these channel changes is determined by the rate at which channels recover to their former condition. To plan for the future management of fish habitat, managers need to know and understand the changes stream channels have undergone. A better understanding would enable them to suggest ways to hasten the recovery process.

This paper describes changes in the condition of stream channels in north coastal California as a result of recent floods--particularly the destructive flood of December, 1964. It details changes in the characteristics of channels, including bed elevation, channel width and riffle-pool sequences.

CHANNEL BED AGGRADATION AND DEGRADATION

Large storms caused regional flooding in northern California in 1953, 1955, 1964, and 1972, and 1975 (Harden, et al., 1978). The flood of 1964, in particular, resulted in great volumes of hillslope material being eroded and delivered to channels, causing widespread channel aggradation (Waananen, et al., 1971; Hickey, 1969). Excess sediment in stream channels can harm fish habitat by filling pools and widening channels. Channels can begin to recover only after excess sediment has been removed and the bed degrades. The

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rise and fall of bed elevation marks the downstream passage of flood debris through a particular reach of channel.

An episode of aggradation consists of an initial period of relatively rapid channel filling, followed later by progressive scour or degradation to a nearly constant bed level (Figure 1).

Streamflow measurements at permanently located stream gaging stations provide an annual record of bed elevation changes from which the period of episodes of aggradation at specific locations can be determined (Lisle, 1981). These sections are usually located at the tails of pools in straight reaches. Their consistency of location permits the documentation of changes in channel morphology in a variety of streams.

At some stations bed elevation returned to preflood levels at the end of episodes of aggradation--a period lasting a few years or more. At other stations bed elevation stabilized at a level higher than that before the flood. Data from the Smith River show three episodes of aggradation associated with floods in the early 1950's, 1964, and 1972 (Figure 2). An important factor affecting the duration of the aggradation episodes was the post-flood sequence of flows. Moderately high flows are effective in transporting sediment out of main channels. However, large floods which contribute additional sediment to channels may prolong episodes of aggradation. In the Smith River, new episodes of aggradation were started before previous episodes had ended. Recovery of stream channels from aggradation, therefore, depends on long periods without large storms as well as the absence of new sediment. Records from 13 stream sections in northwestern California indicate that most fourth order or smaller stream

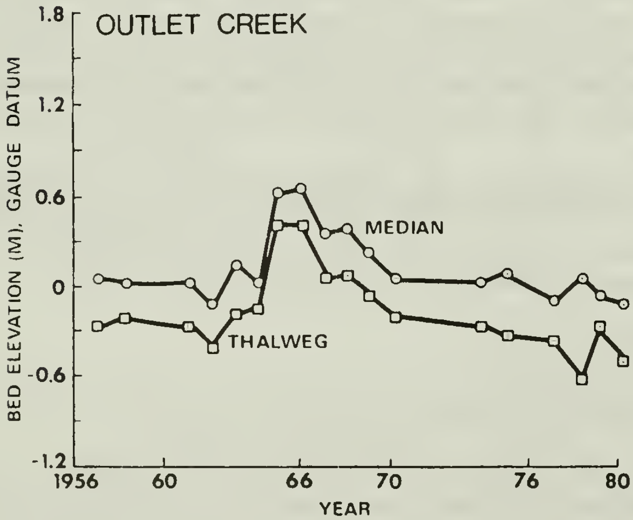

Figure 1--Changes in bed elevations of the Outlet Creek gaging section (Lisle, 1981).

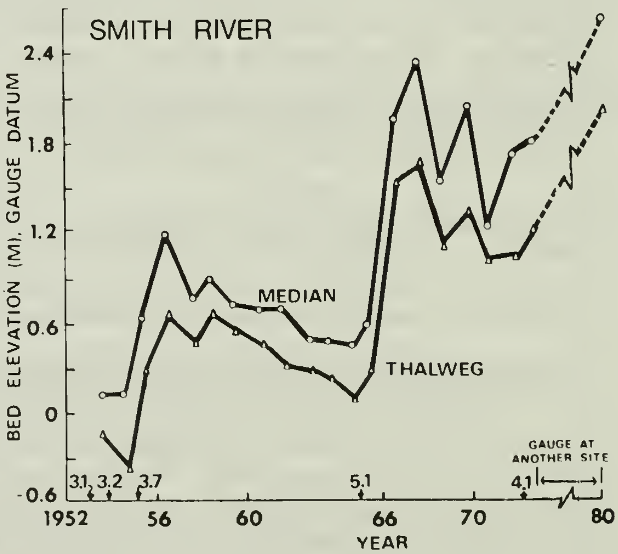

Figure 2--Changes in bed elevations of the Smith River gaging section (Lisle, 1981). The gage was located elsewhere from 1972 to 1979. Numbers above abscissa are runoff values (m^3/s - km^2) for floods.

channels have degraded to stable levels since the flood of 1964 (Kelsey, 1980; Nolan and Janda, 1979; Lisle, 1981). Reaches where large volumes of sediment have been stored along main stem channels, such as in Redwood Creek, the Van Duzen River, and the South Fork Trinity River, will however, remain aggraded for one or more decades (Nolan and Janda 1979; Kelsey, 1980; Haskins, 1981).

RECOVERY OF CHANNEL WIDTH

Channel widening often leads to a deterioration of anadromous fish habitat. Food sources are reduced by the destruction of the riparian zone and its isolation from the stream during low flow, and by the seasonal dessication of wide areas of substrate. Channel widening also increases solar insolation, and reduces the number and quality of riffle-pool sequences needed for diverse habitats.

Channel widening was a widespread result of flooding and aggradation (Waananen, et al., 1971; Lisle, 1981). An effect of voluminous bedload sediment is the widening of stream channels; conversely, the onset of channel narrowing depends upon a depletion of sediment. Channel streambeds represent the interface between hillslope and fluvial processes, and their formation is strongly influenced by biological processes. Thus the rate of streambank recovery depends upon the rates of the dominant processes forming streambanks along a particular reach.

Because of rapid tectonic uplift, most stream channels in northern California are contained in narrow valley bottoms bounded by hillslopes. From records of nine gaging sections (Lisle, 1981), it appears that such channels widened no more than 20 percent, but did not narrow along high portions of their banks after degradation of the channel bed (Figure 3). Mass movement contributes material to the channel margins at widely varying rates, thereby contributing to channel narrowing, but mass movement is usually so slow that most channels bounded by hillslopes do not show evidence of narrowing (Figure 4; Lisle, 1981). The processes of channel widening and narrowing in this situation represent a dynamic equilibrium between episodic bank erosion and more gradual bank construction by hillslope encroachmant.

Alluvial channels (bordered by river-borne sediment) widened as much as 100 percent (Lisle, 1981). Channel narrowing was accomplished in the Black Butte cross section, for instance, by erosion into flood deposits (Figure 5). This fluvial process coincided with the degradation of the elevated streambed (Figure 6). Streambanks may also be gradually constructed by the deposition and stabilization of alluvium--a relatively slow process that depends largely on the spread and growth of riparian vegetation.

RECOVERY OF RIPARIAN VEGETATION

One of the most crucial problems of channel bank recovery is the stabilization of newly deposited stream bank material. With or without producing large volumes of sediment, large floods characteristically cause channels to widen, although most will narrow afterwards. Rates of bank recovery depend on annual precipitation, which governs the rate of growth and colonization of riparian vegetation (Wolman and Gersin, 1978). In humid climates, channels often narrow within a few months to several years after a large flood; in arid climates this process may take several decades or longer.

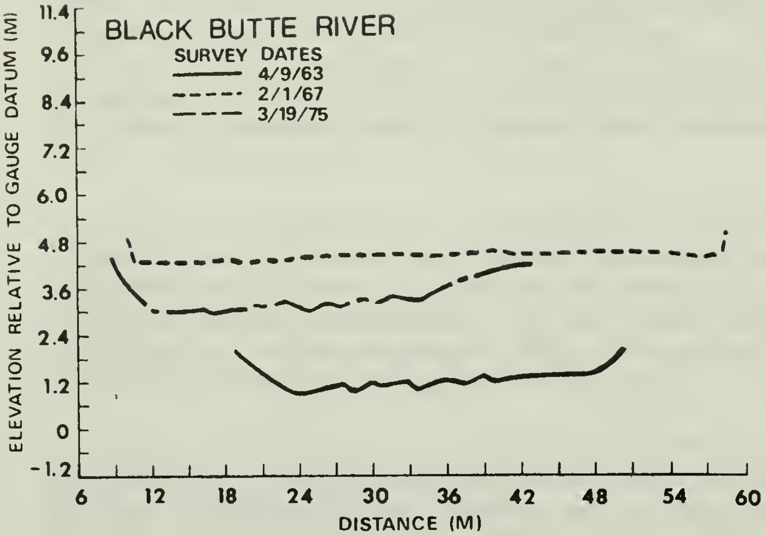

Figure 3--Soundings of the Black Butte River gaging section near Covelo.

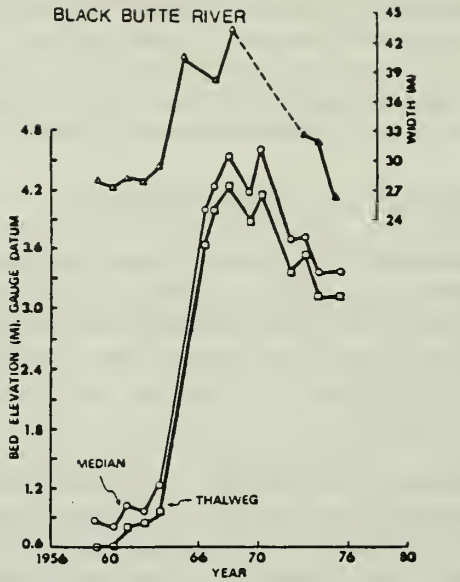

Figure 4--Changes in bed elevations and channel width of the Black Butte River gaging section near Covelo (Lisle, 1981).

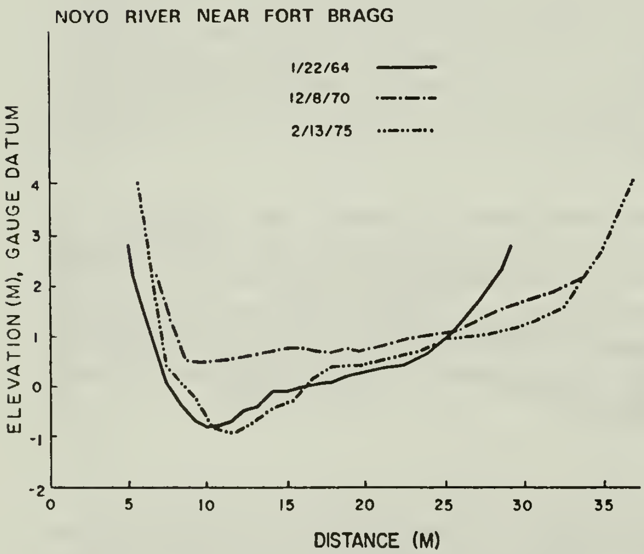

Figure 5--Soundings by the U.S. Geological Survey in the Noyo River gaging section before, during, and after an aggradation episode. After aggradation peaked in 1970, the channel degraded to its preflood level by 1975, when it maintained its maximum width.

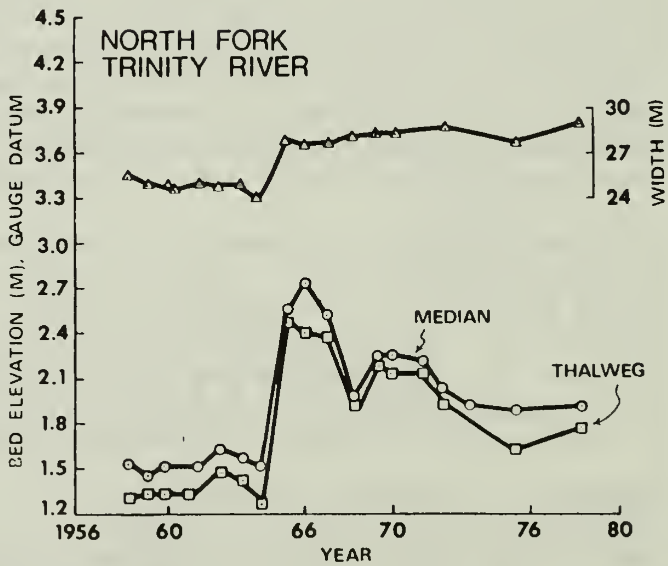

Figure 6--Changes in bed elevations and channel width of the North Fork Trinity River gaging section at Helena (Lisle, 1981).

The following scenario decribes the recovery of riparian vegetation along north coastal streams after the 1964 flood. Narrow valley bottoms and a highly seasonal period of runoff have retarded the recovery of riparian vegetation along channels widened by the 1964 flood. Flood bars and streambanks tend to become extremely dry during summer. This dryness retards the growth of riparian vegetation. Newly-established deciduous trees and brush species, such as red alder and willow, are often concentrated along the summertime flow margins of widened channels where moisture is abundant. Vegetation along stream channels decreases the velocity of flows carrying moderately high concentrations of sediment, thereby promoting deposition of silt and fine sand. Rich in nutrients, these new deposits encourage plant growth. Consequently this process is self-perpetuating. During the winter rainy season, however, coarse sediment and large organic debris carried by high runoff contained entirely within channels bounded by valley walls may destroy young plants growing in the active channel.

Because larger trees can better withstand the effect of such flows, the survival of riparian communities and the subsequent growth of streambanks depend on the postflood sequence of flows and the rate of growth of riparian trees. Suppose that a streamside grove of alders established immediately after a large flood could barely withstand (a) at age 4, floods of a size that recur on the average every 2 years; (b) at age 7, floods of a size that recur on the average of every 5 years; and (c) at age 10, floods of the size that recur on the average of every 10 years (Figure 7). On the basis of these assumptions, the rate of increasing stability of the grove would outstrip the likelihood of occurrence of a sufficiently destructive runoff event. The probability of survival of the grove would, therefore, increase with age. Because no large flows have occurred in most streams since 1975, the recovery of riparian vegetation and the growth of streambanks may be well underway.

RECOVERY OF RIFFLE-POOL SEQUENCES

Fishermen lamented the filling of pools after the 1964 flood, but many now have observed renewed scour. The timing of this apparent recovery in relation to bed degradation and possible channel narrowing can be inferred from hydraulic data from 13 gaging stations (Lisle, in prep.) Gaging stations in pools became more riffle-like with aggradation. That is, pools became faster and shallower at a particular flow (Figure 8). Some recovery of pool characteristics accompanied degradation, but full recovery seems to depend on a narrowing of the stream channel. Rifle-pool sequences are accentuated by channel degradation and narrowing. Further scour of pools accompanies the replacement of scour-causing roughness elements, such as large organic debris.

LARGE ORGANIC DEBRIS IN CHANNELS

One of the most important roles of riparian vegetation in the natural recovery of anadromous fish habitat is to introduce large organic debris into stream channels (Swanson and Lienkaemper, 1978). This debris is often swept away by large flood flows and deposited on gravel bars, flood plains, and in large concentrations such as debris jams. It may take a period measured in decades for higher concentrations of debris to become relatively evenly distributed along a stream course. In many north coast streams, future sources of large

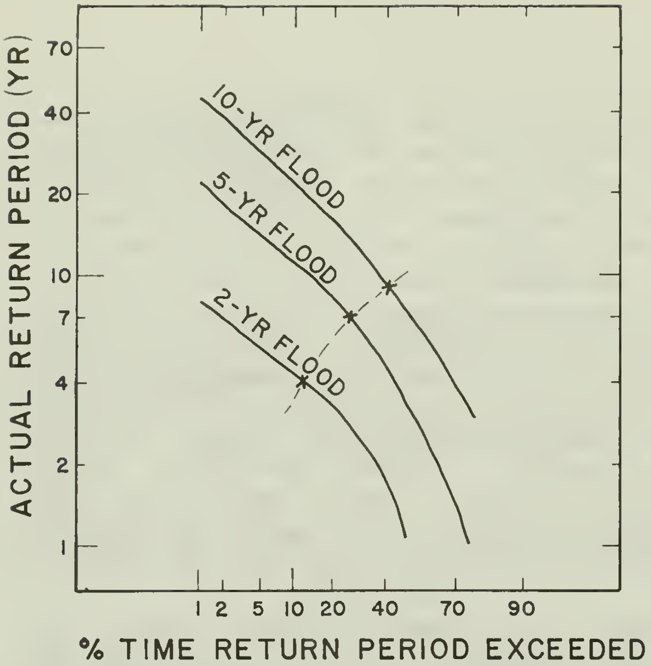

Figure 7--Probability of having a given time period ("actual return period") pass between the recurrence of a flood of a given magnitude or greater (Linsley , et al., 1949, p. 550). Flood magnitudes are given by their average return period.

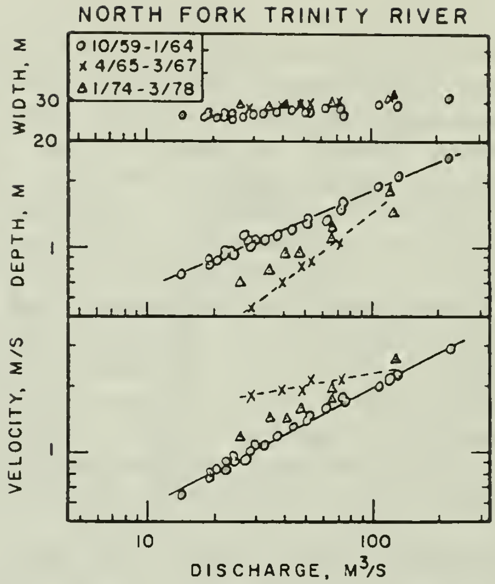

Figure 8--Variations in width, depth and velocity with discharge for periods before and at the peak of aggradation, and after degradation in the North Fork Trinity River gaging section near Helena.

organic debris have been depleted by widened channels, by timber harvesting in the riparian zone, and by present management policies that call for the removal of debris from stream channels.

Large organic debris usually enters stream channels along eroding banks. As a principal pool forming agent in forested streams (Keller, these proceedings), debris offers roughness elements to the flow which, in turn, cause scour. Therefore, the natural replacement of debris in stream channels may constitute a third phase of the recovery of riffle-pool sequences. The introduction and manipulation of large organic debris, as well as other natural roughness elements, such as boulders, offer numerous opportunities for enhancing stream channels for fish habitat. Favorably located elements may be tied in, unfavorably located elements may be relocated, new material may be added, and riparian vegetation may be managed to ensure a continuous steady supply of large organic debris. The trade-off of introducing or manipulating organic debris is often a short term mobilization of sediment. An overall lessening of pool volumes is probably caused more by absence of scour than by the displacement of minor quantities of sediment.

CONCLUSIONS

The recovery of stream channels from recent floods involves a sequence of many processes. Excess sediment has been transported out of most stream channels since the 1964 flood, and fluvial, hillslope, and biological processes may now begin to shape stream channels to their pre-flood condition. Channel narrowing, for most channels, is a slow process because of the gradual movement of hillslope material to channel margins, the vulnerability of streambank deposits to erosion, and the difficulty of establishing riparian vegetation. Methods for rehabilitating stream channels are most effective when they mimic natural processes and are carried on along with the sequence of recovery processes. The mechanics of recovery suggests that the greatest potential for economical stream enhancement lies in the protection and reestablishment of riparian vegetation and in the introduction and manipulation of organic debris and other natural roughness elements.

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STREAMS IN THE COASTAL REDWOOD ENVIRONMENT: THE ROLE OF LARGE ORGANIC DEBRIS

* E.A. Keller and Anne MacDonald
** Taz Tally

ABSTRACT

Large organic debris (greater than 10 cm in diameter) has a major control on channel form and process (and thus anadromous fish habitat) in streams of the coastal redwood environment. Several lines of evidence support this conclusion: first, large organic debris may reside in the stream channel for centuries and, therefore, is a permanent part of the fluvial system; second, large organic debris exerts considerable control over channel morphology, particularly in the development of pools; third, large organic debris produces numerous sediment storage sites, supporting a sediment buffer system that modulates the routing of sediment through the fluvial system; and fourth, large organic debris in steep streams significantly effects the way potential energy is expended by concentrating energy expenditure over short reaches where organic steps or other accumulations of debris exist.

Large organic debris in streams is pertinent to two interrelated management problems in northwestern California: restoration and enhancement of anadromous fish habitat, and reduction of sediment pollution. Management of streams to maximize production of anadromous fish in the coastal redwood environment should consider the entire fluvial system, including the role of large organic debris. Large organic debris in unusually large amounts may block fish migration and cause adverse channel erosion. However, within limits, large organic debris is probably necessary for many streams sustaining anadromous fisheries. Therefore, stream clearing operations must carefully weigh the benefits of locally stabilizing stream banks, opening up stream anadromous fish habitat, or marketing merchantable timber with potential dangers in losing hydrologic variability and mobilizing large quantities of sediment stored in conjunction with large organic debris.

INTRODUCTION

The purpose of this paper is to, first, discuss the role of large organic debris (logs, stems, limbs and rootwads greater than 10 cm. in diameter) in the formation and maintenance of anadromous fish habitat and, second, discuss implications for stream management.

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Large organic debris in the active stream channel has a major control on channel form and process and thus anadromous fish habitat in streams of the coastal redwood environment. Large organic debris resides in the channel for centuries, facilitating the storage of considerable bed load while providing a natural buffer that modulates the routing of sediment, influencing the development of pools, riffles and channel bars, and locally concentrating much of the drop in channel elevation at organic steps or other accumulations of large organic debris. Thus, debris is pertinent to the solution of two interrelated management issues in northwestern California: restoration or enhancement of anadromous fish habitat, and sediment pollution associated with timber harvesting or other land use changes that adversely effect fish habitat.

The decline in recent years of anadromous fish along the north coast is well documented; many rivers and streams that once supported relatively large fish runs of salmon and steelhead trout now have significantly smaller runs (Denton, 1974). Causes for the decline in numbers of anadromous fish are multiple and complex, but most likely are related to human use of hillslopes adjacent to stream channels rather than natural processes, such as floods, or human activity not related to the stream environment, such as overfishing in the ocean.

A generalized life cycle for anadromous fish is shown on Figure 1. Two stream environments are emphasized: pools and riffles. Pools and riffles are formed and maintained by a complex scour-fill sequence related to the morphology of the stream and the interactions between flowing water and moving sediment (Keller, 1972; Keller and Melhorn, 1973 and 1978). Pools are topographic low areas in streams produced by scour during relatively high channel-forming flows that occur every year or so. Riffles are topographic high areas in streams produced by deposition during relatively high channel forming flows. In gravel-bed streams, only the relatively fine sediment may be transported at low flow; the general pattern is for the finer sediment to be transported from riffles into pools.

In many gravel-bed streams that have not been impacted by human use, there is very little fine sediment and so pools are areas of deep slow-moving water during the summer low flow times, providing rearing habitat for juvenile anadromous fish. Land use changes such as timber harvesting and road building that causes an increase in sediment production (particularly fine sediment) may adversely affect pool environments during the summer low flow period by infilling of pools with resulting degradation to the nursery areas for those anadromous fish such as silver salmon and steelhead trout that must remain in the stream for a year or so before migrating to the ocean. An important limiting factor to fish production is, therefore, the pool environment during the summer (low flow) months. In addition, fine sediments fill the interstices of spawning gravels. This prevents aeration necessary to sustain fish eggs and poses a barrier to emerging fry.

The data base upon which inferences concerning the role of large organic debris on stream channel form and process as well as anadromous fish habitat is shown on Table 1. Three of the watersheds, Hayes, Creek, Little Lost Man Creek, and Prairie Creek, are classified as undisturbed because the basins are vegetated with old growth redwood and associated flora. The Casper Creek watershed was logged approximately 80 years ago and now supports an advanced

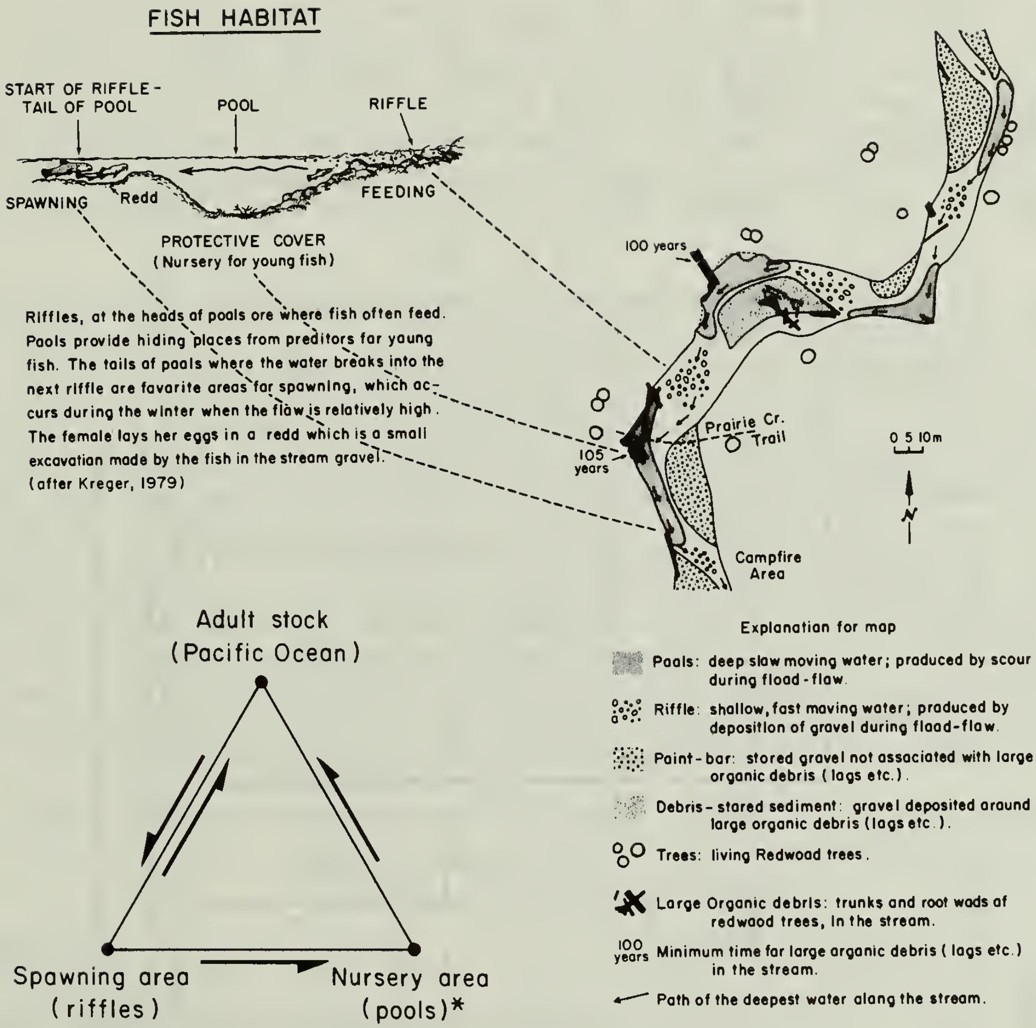

Figure 1. Keller, MacDonald & Talley

Table 1. Comparison of Morphologic Data for Disturbed and Undisturbed Watersheds, Northwestern California (a)

Study Reach	Disturbed: Casper Cr. Upper	Casper Cr. Lower	Lost Man Cr.	Larry Damm Cr.	Undisturbed: Hayes Cr.	Little Lost Man Cr. Upper	Little Lost Man Cr. Lower	Prairie Cr. Hope Cr. Reach	Prairie Cr. Little Cr. Reach	Prairie Cr. Forked Cr. Reach	Prairie Cr. Zig Zag No. 2	Prairie Cr. Natural Tunnel	Prairie Cr. Brown Cr.	Prairie Cr. Campground
Upstream basin area (km^2)	1.6	3.9	1.1	3.7	1.5	3.5	9.1	0.7	3.5	6.6	8.2	11.2	16.7	27.2
Stream order	2	2	2	3	2	2	2	2	2	2	2	2	3	4
Slope	.016	.013	.048	.014	.12	.033	.048	.02	.014	.012	.009	.01	.01	.005
Debris loading (kg/m^2)	21.0	24.0	105.0	76.0	170.0	141.6	49.0	218.0	12.3	13.1	21.7	106	84.8	19.6
Pool to pool spacing (in channel widths)	3.5 (b)	3.8	4.1 (b)	2.2	2.4	1.9 (b)	1.8 (b)	6.2 (b)	4.7 (b)	2.6	6.6	2.7	6.0	4.0
% channel area pool	24	36	33	27	12	22	18	49	34	46	36	41	26	25
% channel area riffle	30	30	25	14	26	15	21	21	46	49	20	15	18	25
% channel in debris stored sediment	44	34	43	59	40	39	39	30	18	30	15	21	29	13
% channel area undercut banks	2	1	4	2	4	3	1	1	4	3	4	1	<1	1
% pool morphology influenced by debris	82	43	79	59	83	100	90	86	71	87	50	80	67	50
Debris controlled drop in elevation of the channel (%) (c)	57	37	69	17	38	59	30	43	27	34	8	<1	18	<1

(a) Total percentages in stream environments may be less or greater than 100% due to overlaps such as pools that contain debris stored sediment or existence of other environments not listed.
(b) Spacing controlled by organic debris.
(c) Ratio of cumulative loss of channel elevation associated with large organic debris to total fall of the stream reach.

second growth redwood forest. It is classified as disturbed, as are the more recently logged Larry Damm Creek and Lost Man Creek watersheds.

LARGE ORGANIC DEBRIS AND ANADROMOUS FISH HABITAT

Residence Time of Large Organic Debris

The amount, arrangement, and residence time of large organic debris in a particular stream reach reflects intimate and complex relations between input and output processes, some of which are shown on Figure 2 (Keller and Swanson, 1978). The dominant process by which large organic debris may enter a stream channel depends on local geologic conditions. For example, on steep gradient sections of Little Lost Man Creek, landslides commonly deliver large organic debris to the channel. On the other hand, where tributaries enter Little Lost Man Creek along relatively low gradient sections or where streamside trees are rooted in thick soils, undercutting of the stream banks may be the dominant process that delivers large organic debris to the channel (Keller and Tally, 1979).

Large organic debris loading measured in kilograms of woody debris per square meter of active channel (kg/m^2), is determined by measuring the length and diameter of all large organic debris found in the active stream channel. In general, there is an inverse relationship between the stream size (drainage basin area) and the debris loading. This results because small streams tend to have small drainage basins, narrow valleys, steep valley slopes, and a relatively high frequency of landslides, all of which tend to increase the debris loading. Examination of Table 1, however, suggests that there is a great deal of variability in the debris loading of a particular stream. Much of the variability can be explained in terms of the proximity of large redwood trees to the stream channel. Where the density of large trees is relatively high the debris loading is higher than along sections of stream where there is a lower density of living redwood trees close to the channel. Data on Table 2 show the good correlation ($r = 0.88$) between debris loading and frequency of large trees within 50m on either side of the channel (Tally, 1980).

Table 2. Debris Loading and Frequency of Trees in the Vicinity of the Channel.

	Debris Loading (kg/m^2)	Tree Frequency	Flood Plain
Hayes Creek	170	68/ha	none
Little Lost Man Creek			
Upper	141.6	52/ha	none
Middle	268	40/ha	none
Lower	49.0	26/ha	none
Prairie Creek			
Hope Creek	218	80/ha	minor
Little Creek	12.3	25/ha	yes
Forked Creek	13.1	21/ha	yes
Zig Zag No. 2	21.7	25/ha	yes
Natural Tunnel	106	41/ha	minor
Brown Creek	84.8	75/ha	none
Campground	19.6	32/ha	yes

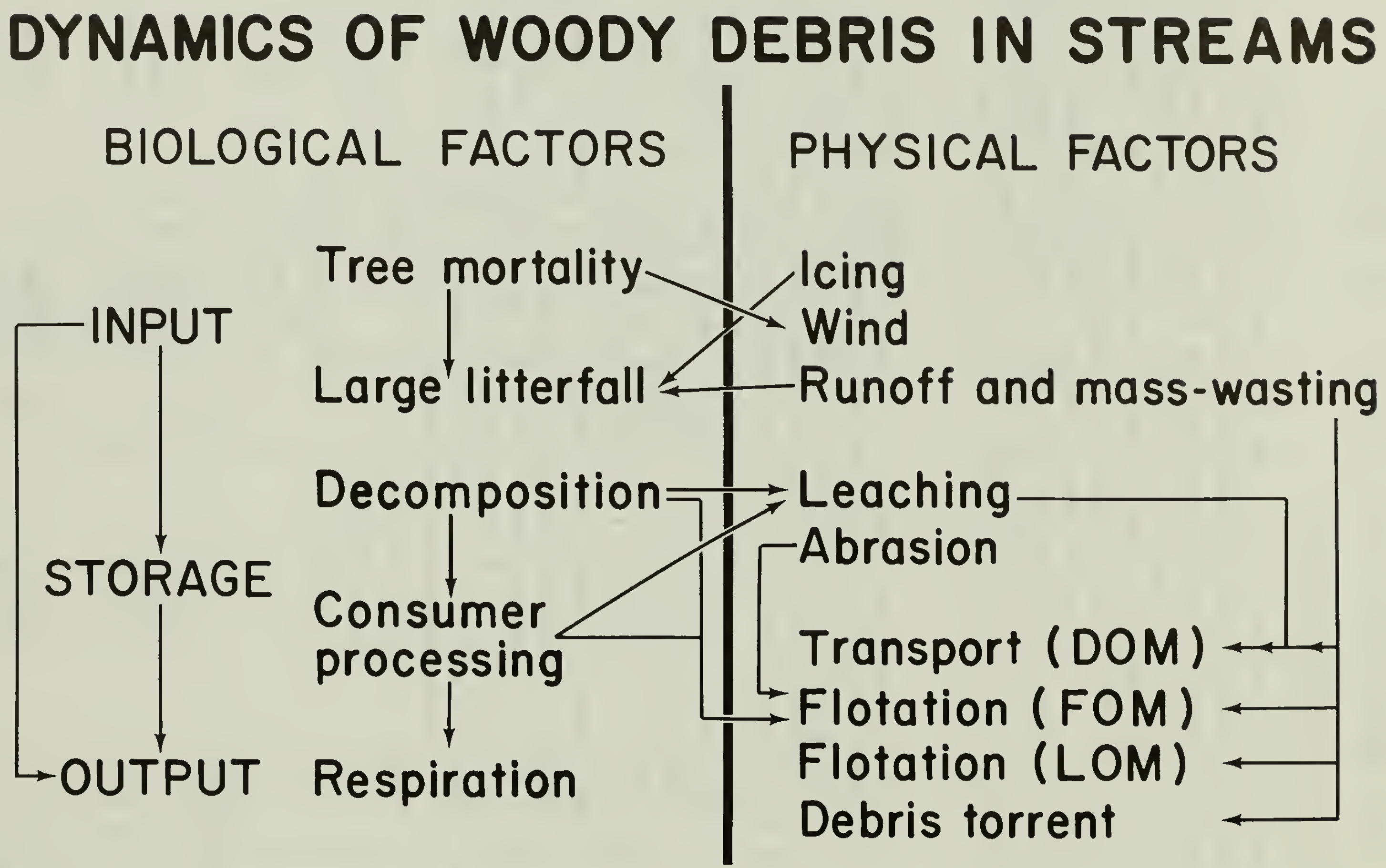

Figure 2. Keller, MacDonald & Talley

Movement of large organic debris through the stream system is primarily by flotation during high flows or perhaps, in very steep sections of the stream, by debris torrents (Swanson and Lienkaemper, 1978, and Keller and Tally, 1979). Large organic debris in streams draining old growth forest, such as Prairie Creek, Little Lost Man Creek, and Hayes Creek, may be very large, often several meters in diameter, and moves only rarely. This was determined by examining "nursed trees" such as hemlock, spruce, and other redwood trees that grow on downed trees. Coring of these "nursed trees" provides a minimum time that the debris has been in the stream channel. Table 3 lists selected examples of residency times in Prairie Creek and Little Lost Man Creek that exceed 100 years. In all, more than 30 pieces of debris have been dated and about half of these exceeded 100 years with the oldest exceeding 200 years. Based on this evidence, it is apparent that large organic debris resides in stream channels for several centuries and, thus, is a permanent part of the fluvial system. In larger streams such as the lower portions of Redwood Creek, there is sufficient water at high flow to float even the largest debris, and therefore the residence time is shorter. However, even here large organic debris greatly influences the formation of large pools and, thus, anadromous fish habitat.

Table 3. Minimum Ages for Large Organic Debris in the Study Reaches of Little Lost Man Creek and Prairie Creek: Selected Examples

Reach	Tree Type	Age (yrs)	Environment
Little Lost Man Creek			
Upper	Hemlock	130	Partial D.D.[(a)]/B.D.Tr.[(b)]
	Hemlock	135	Partial D.D./B.D.Tr.
	Hemlock	150	B.D.Tr. on Debris Stored Sed.
	Hemlock	185	Partial D.D./B.D.Tr.
	Hemlock	175	D.D.[(c)]
	Hemlock	200	D.D.
	Hemlock	105	D.D.
Lower	Redwood	220	B.D.Tr. downed trunk
	Redwood	100	D.D.
Prairie Creek			
Zig Zag No. 2	Sitka Spruce	150	B.D.Tr. with root mat
Brown Creek	Redwood	160	D.D.
	Hemlock	100	D.D.
	Hemlock	100	Partial D.D.
	Redwood	200	B.D.Tr. downed trunk
Campground	Redwood	100	Partial D.D.
	Hemlock	100	B.D.Tr. with root mat

(a) Partial D.D. = debris dam blocking part of channel
(b) B.D.Tr. = bank defending tree
(c) D.D. = debris blocking entire channel

Channel Morphology, Hydrologic Variability, and Anadromous Fish Habitat

Large organic debris in undisturbed streams provide hydrologic variability necessary for maintaining salmonid spawning and rearing habitat, while buffering sediment routing and discharge. Debris control of channel morphology is greatest in steep stream reaches and is most apparent in three categories: percentage of pools influenced by debris, extent of debris stored sediment, and debris control drop in elevation of the stream profile. Examination of Table 1 shows that 50-100% of pools in a given reach are created or enhanced by large woody debris. Examples of debris controlled channel morphology are shown on Figures 3, 4, 5, and 6 for Prairie Creek and Little Lost Man Creek, respectively. Examination of long profiles (Figures 5 and 6) illustrate the hydrologic variability (change in water depth or slope in the downstream direction) for the two study reaches. The ratio of cumulative loss of channel elevation associated with large organic debris to total fall of the stream reach (18% for the Brown Creek reach of Prairie Creek compared to 30% for the lower reach of Little Lost Man Creek, Table 1) is an indicator of potential energy loss (Keller and Swanson, 1979; Heede, 1981). That is, the large organic debris produces a stepped stream profile where a significant amount of a stream's potential energy may be dissipated at debris created falls and cascades which occupy a relatively small percentage of the total stream length. Thus, energy is expended at these locations rather than producing a generally deep incised channel with unstable and eroding channel banks. Little Lost Man Creek, in particular, has a relatively low sediment yield due in part to the existence of large organic debris which tends to preclude high erosion rates by forming accumulations of sediment that armors the stream bed and prevents deep incision. Similar observations by Heede (1981) for streams with smaller caliber large organic debris have been reported in the southern Rocky Mountains of Colorado and the White Mountains of Arizona. Examination of Table 1 reveals that up to about 60% of the drop along the stream profile for undisturbed basins may be due to large organic debris.

Although similar processes are operating in streams draining disturbed and undisturbed basins, the relationship between debris and channel morphology is somewhat different in the two cases. In undisturbed basins, channel morphology is more dependent on the frequency of debris than on the absolute amount. Thus, an old growth log large enough to be stable (generally greater than one bankful channel width and length) has about the same effect on the channel as one twice that size. On the other hand, debris loading in channels impacted by timber harvesting is dependent upon the timber harvesting methods employed rather than intrinsic basin characteristics. As a result, variability in debris loading in disturbed streams may be considerable and if large logs were removed from the channel during timber harvesting, then the caliber of the large organic debris found in the channel will be smaller than that found in undisturbed basins. Examination of Table 1 reveals that debris is only slightly less effective in controlling gross channel form in disturbed channels compared to undisturbed; however, the short-term stability of channel form is decreased in disturbed basins due to the higher percentage of unstable stored sediment.

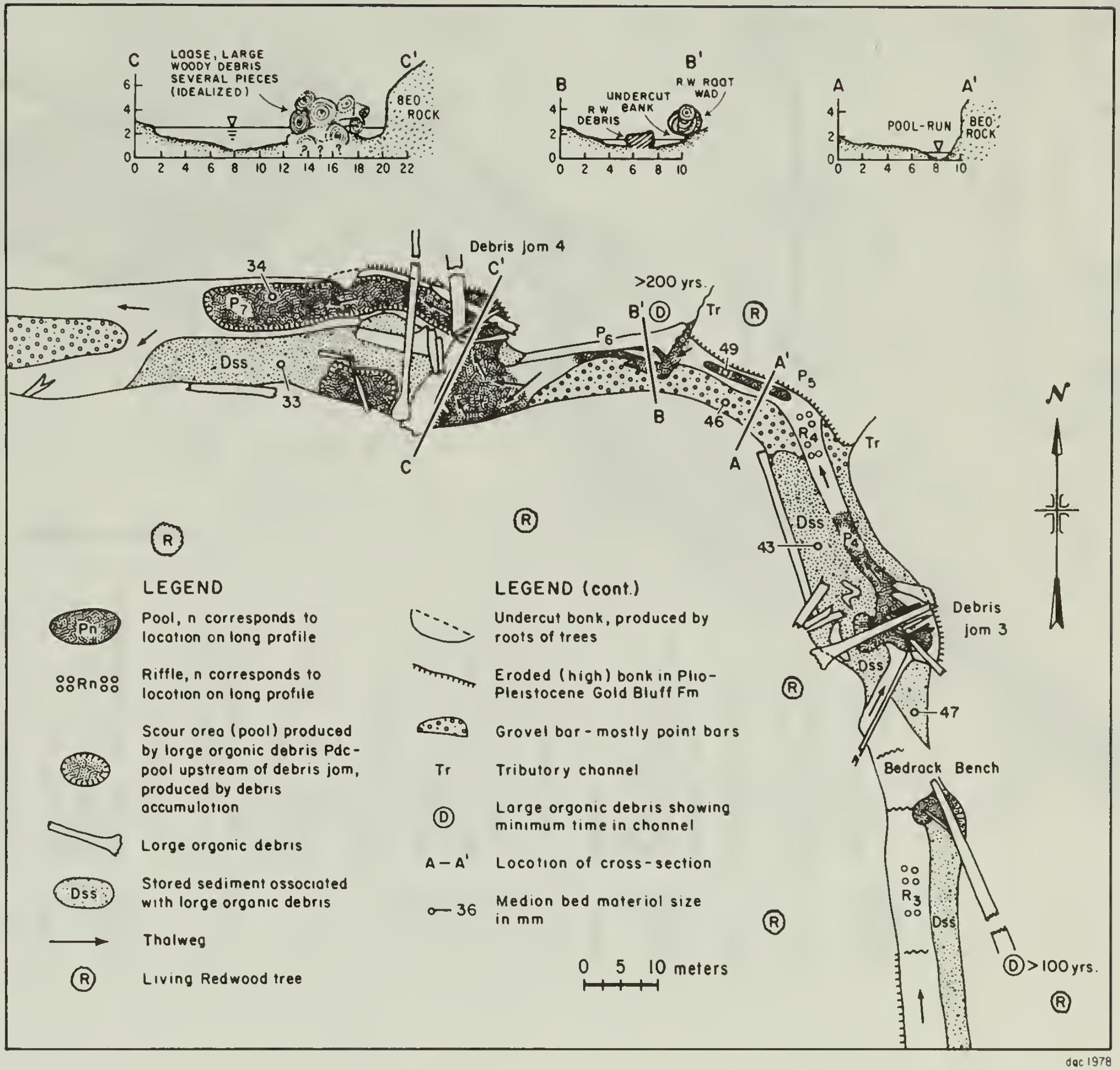

Figure 3. Keller, MacDonald & Talley

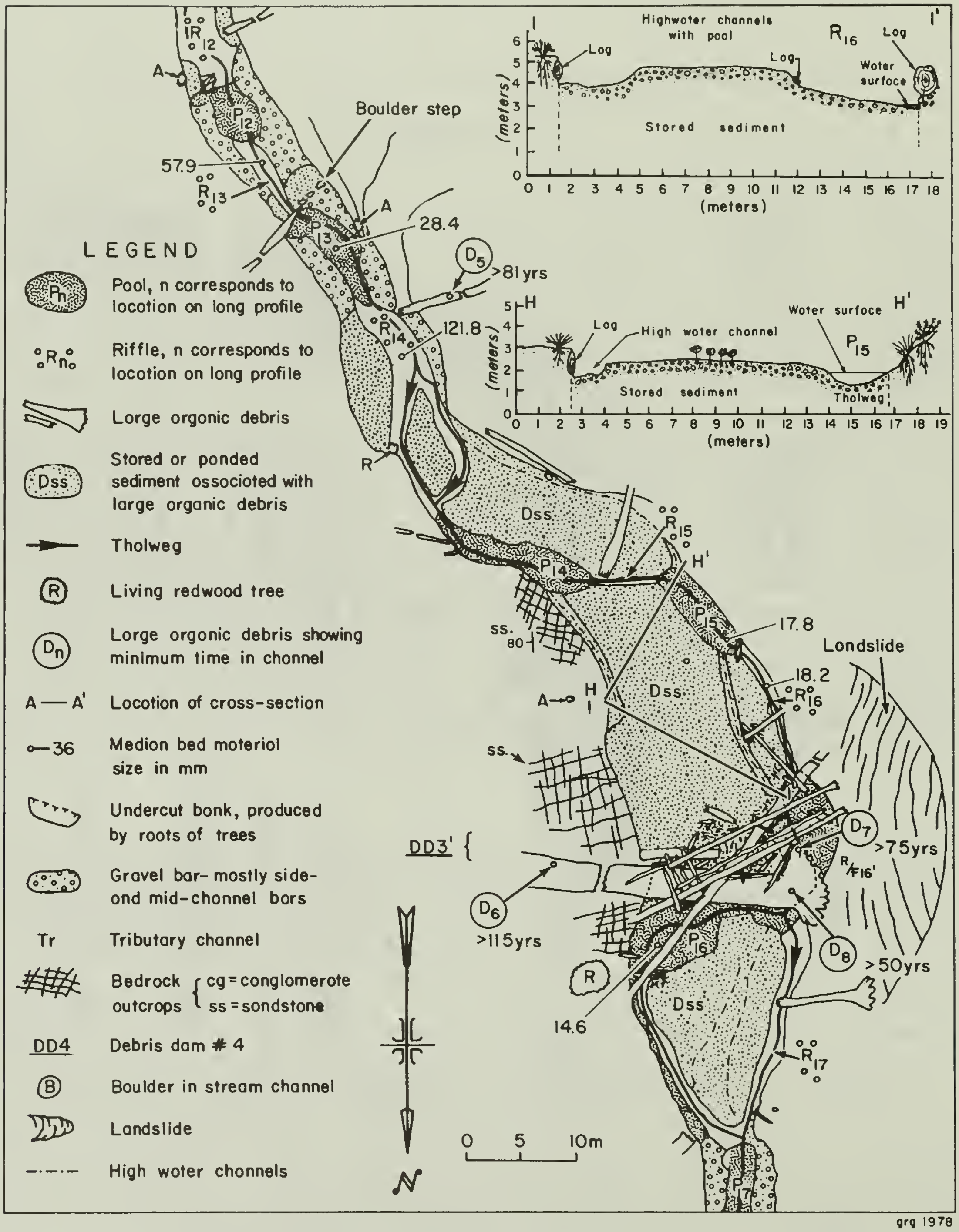

Figure 4. Keller, MacDonald & Talley

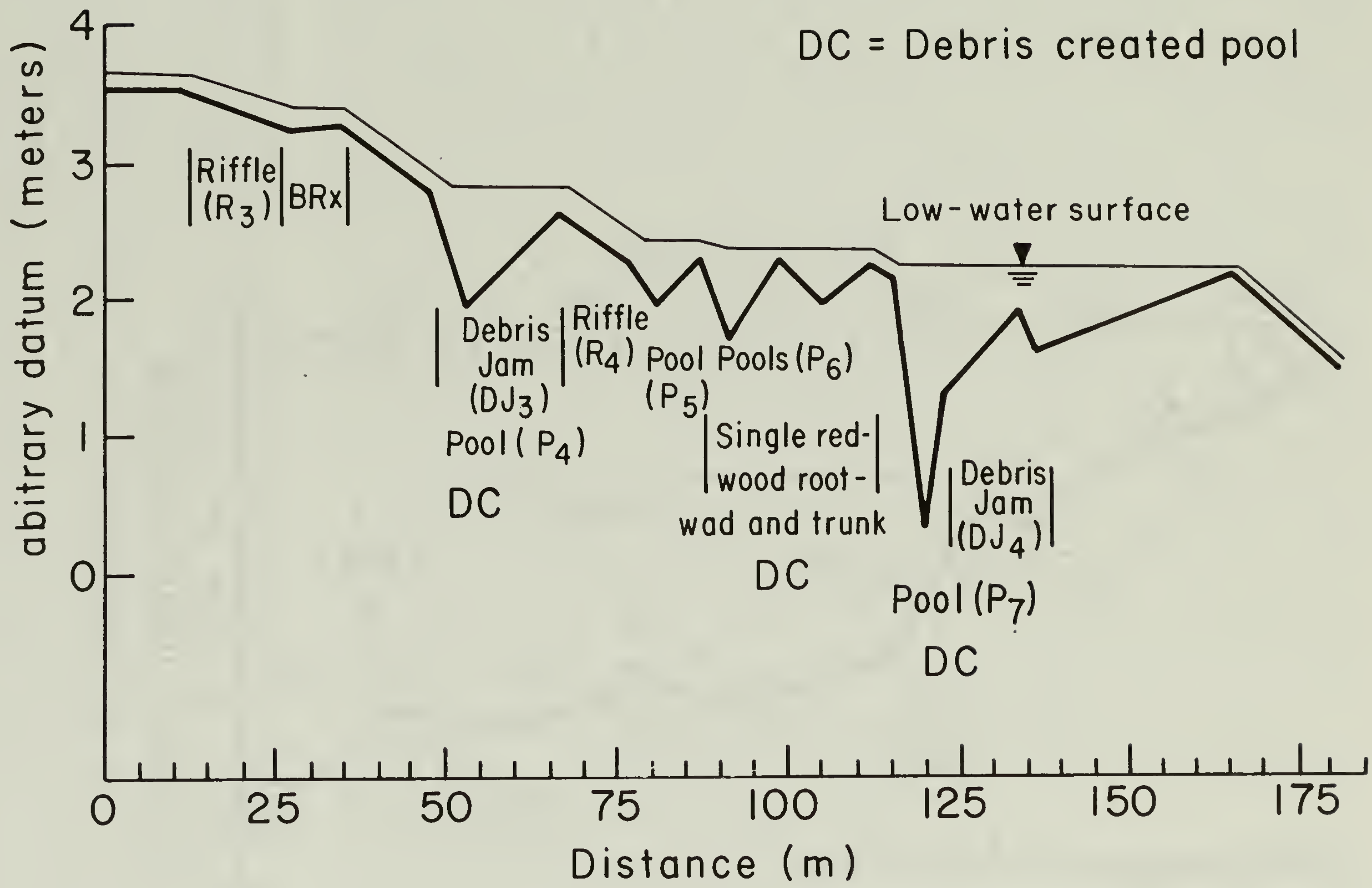

Figure 5. Keller, MacDonald & Talley

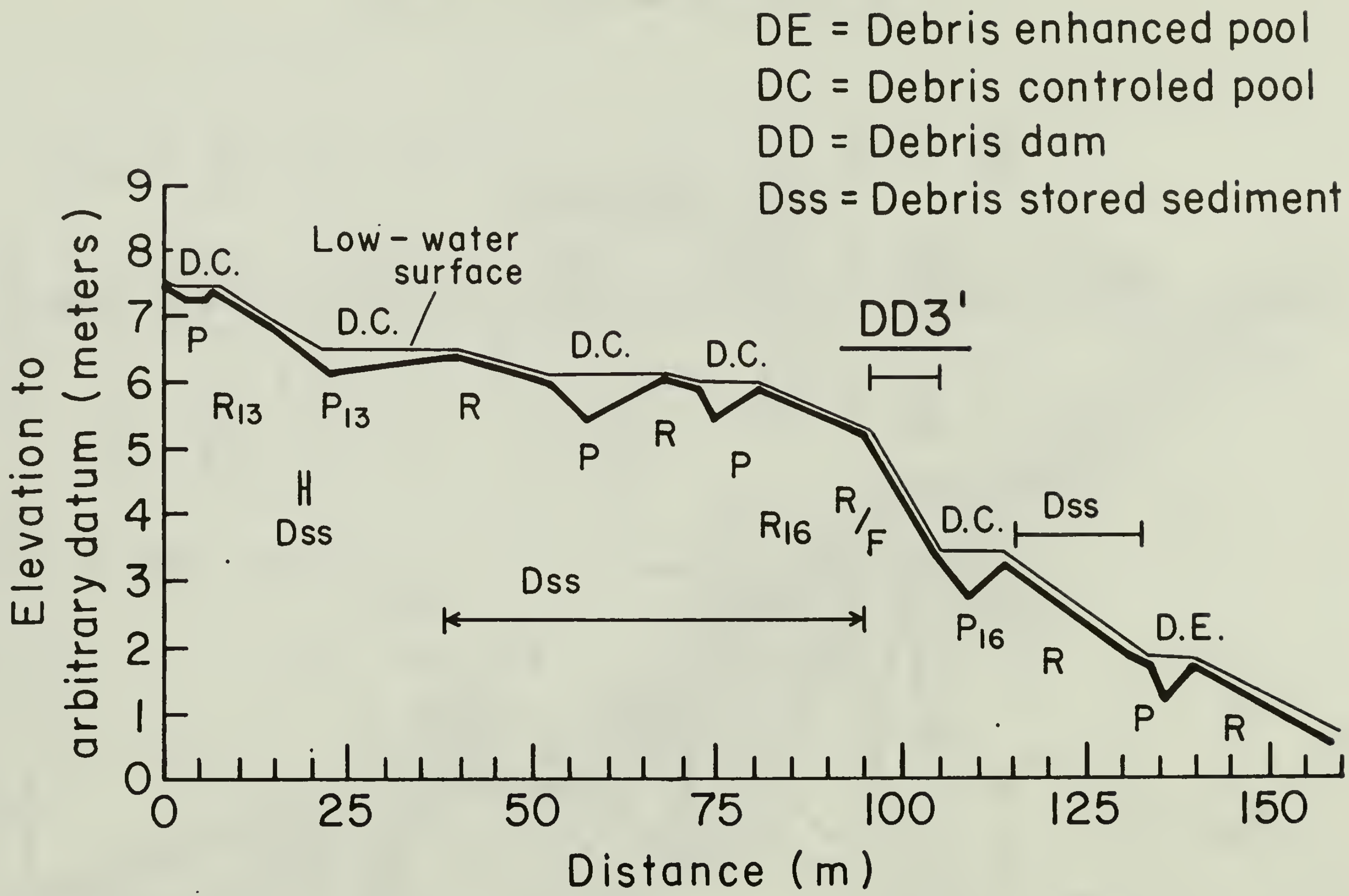

Figure 6. Keller, MacDonald & Talley

Sediment Routing: The Buffer System

Large organic debris plays an important role in the routing and storage of sediment. Debris accumulations such as organic steps produce storage compartments for sediment as ideally shown on Figure 7. Examination of Table 1 suggests that such storage sites account for a significant portion of the total channel area. In comparing disturbed and undisturbed watersheds, disturbed stream systems have a greater amount of debris stored sediment, probably reflecting that a greater portion of the storage compartments are filled. Studies by Megahan and Nowlin (1976) and Swanson and Lienkaemper (1978) suggest that annual sediment yields in small forested watersheds are generally less than 10% of the sediment stored in channels. In comparison, in Little Lost Man Creek, where 40% of the active stream channel is in debris stored sediment, the storage compartments are considerably larger; this probably reflects the difference in size of organic debris producing the compartments. The average annual suspended sediment yield for the Little Lost Man Creek basin is about 450 metric tons and approximately 25% of this is bedload, providing an average annual bedload yield of approximately 116 metric tons. The total debris related sediment volume in Little Lost Man Creek is estimated to be approximately 14,000 m^3 and approximately 64% or 8,950m^3 of this is presently full. Assuming a unit weight of debris stored sediment consisting of gravel and sand to vary between 1.36 and 2.00 tons per cubic meter (Geiger, 1965), approximately 100 to 150 years of average annual bedload sediment yield is stored in debris related sites along Little Lost Man Creek and about 50 to 100 years of average annual bedload yield is available for future storage. Thus, if the storage system were filled to capacity, it would contain from 150 to 250 years of average annual bedload yield. This should not be interpreted to mean that the sediment storage compartments associated with large organic debris effectively trap all of the bedload that moves into a particular reach. In fact, debris stored sediment tends to be significantly finer gravel than that found on riffles on Little Lost Man Creek. Furthermore, because it is finer, it tends to be transported more frequently in response to moderate flow (50% of bankfull, a discharge with recurrence interval of about 1.5 years), whereas coarse material on riffles tend to armor the bed and is probably moved only during extreme events (Tally, 1980). Evidence from streams in New Zealand suggest that sediment that moves out of a debris stored site will usually only move a short distance before being redeposited behind downstream debris accumulations (Mosley, in press).

The important principle concerning debris stored sediment is that the accumulative storage sites define a buffer system that modulates the movement of bedload through the fluvial system. As a result, the output or release of sediment from the watershed which may have been added during an extremely short period of time, will be spread out over a relatively long period. Thus, if a number of landslides develop in response to a high magnitude-low frequency storm, the sediment input from those landslides may take many years to move through the system. This also has important ramifications for watersheds impacted by land use change such as road building or timber harvesting. As the sediment is input into the system, there will be a lag time before the sediment yield or output increases significantly. However, once the storage sites are full, then sediment will be transported more directly down the channel through the full storage sites.

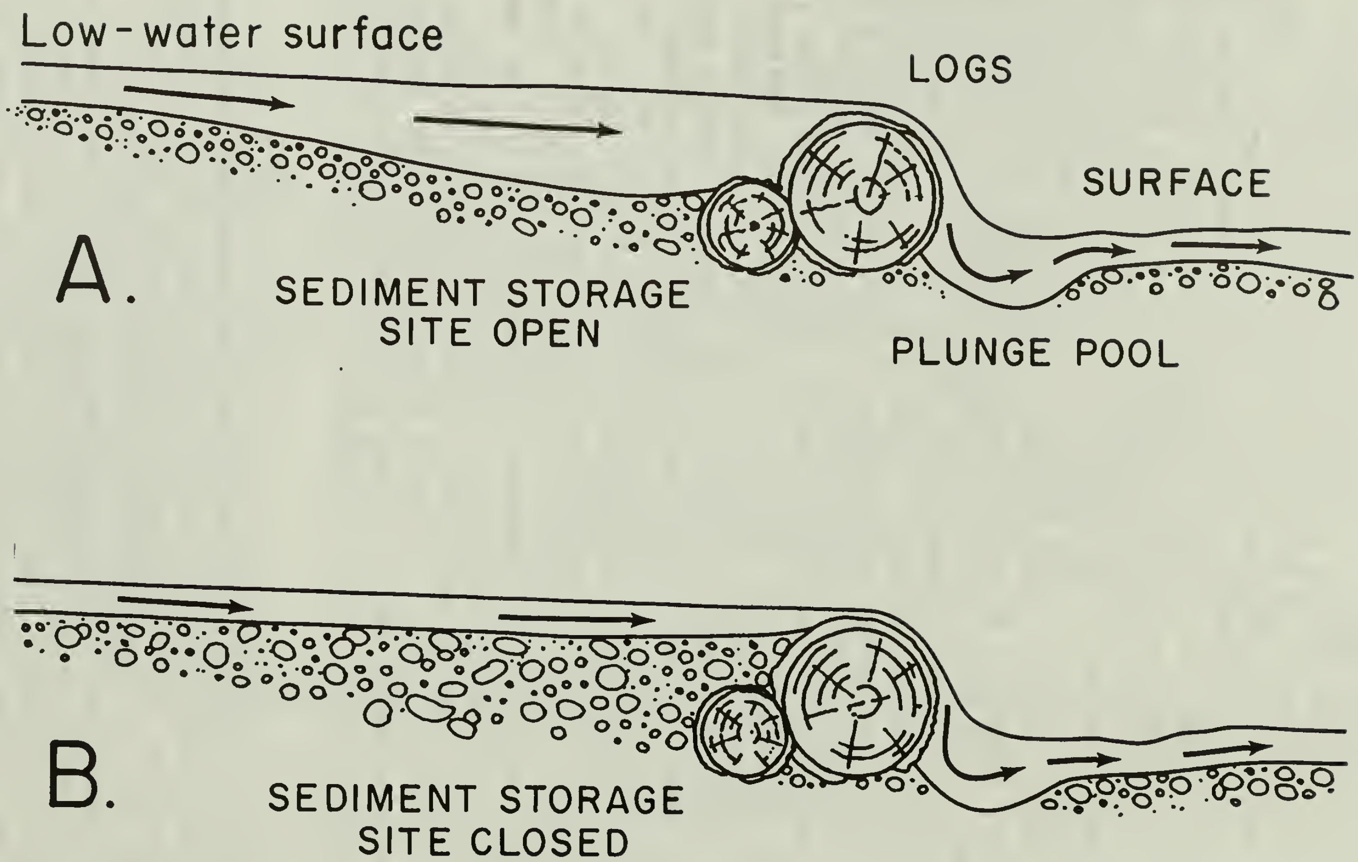

Figure 7. Keller, MacDonald & Talley

LARGE ORGANIC DEBRIS AND MANAGEMENT OF ANADROMOUS FISH HABITAT

Management of streams, to maximize production of anadromous fish in the coastal redwood environment, should consider the entire fluvial system including the role of large organic debris. Occasionally, large organic debris may block fish migration and cause adverse channel erosion. Such accumulations (especially when delivered to the stream channel in response to land use change) should be removed following the development of a specific plan for that site. However, within limits, large organic debris is necessary for a biologically productive stream environment. Therefore, stream clearing operations must carefully weigh the benefits of locally stabilizing stream banks, opening up stream anadromous fish habitat or marketing merchantable timber with potential dangers in losing hydrologic variability and mobilizing large quantities of bed material that has been in storage sites produced by large organic debris.

In dealing with watersheds with old growth timber, it is probably best to not remove large organic debris that falls into the stream channel. There is sufficient evidence to support the conclusion that the debris helps create fish habitat by providing cover and pool environments for juvenile anadromous fish. Furthermore, debris removal is expensive and may damage adjacent areas in the riparian zone.

In managing streams impacted by timber harvesting, removal of large logs and slash introduced by logging may be necessary. Such removal should only involve logs placed into the stream by the logging and should not extend below the level of the natural stream prior to disturbance. Overzealous removal of large organic debris will result in damage to the fluvial system.

Management plans in dealing with large organic debris should strive to duplicate natural processes found in undisturbed basins. This philosophy puts forth a "design with nature" approach recognizing that the natural fluvial system has evolved over hundreds and thousands of years in response to the presence of large organic debris. It also recognizes that removal of the debris may result in problems equal to or exceeding the problems presumed associated with unwanted debris. The more we learn about large organic debris, the more we recognize that it is intimately related to the fish habitat and thus production of anadromous fish. In many subtle ways the debris is interacting in positive ways to produce and maintain desired fish habitat, particularly the low flow summer habitat. Therefore, until we learn even more concerning the role of large organic debris, a very conservative practice conerning its removal should be set forth.

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ACKNOWLEDGEMENTS

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ORGANIC DEBRIS IN TRIBUTARY STREAM CHANNELS OF THE REDWOOD CREEK BASIN

John Pitlick[1]

Abstract. Data from 14 study basins indicates that tributary watersheds are major sediment sources for Redwood Creek. This is a reflection of both the magnitude of point source contributions within these basins and the relative efficiency with which these streams transport the supplied load. The majority of these tributaries are characteristically low order, high gradient streams with narrow, discontinuous flood plains. The accumulation of large organic debris in these streams is common and plays an important role in channel and hillslope processes. The effect of organic debris is most pronounced in the old-growth redwood forests where woody debris remains in the stream channel longer than in a Douglas-fir counterpart. Given the present understanding of basin-wide dynamics, organic debris should be removed from streams only in cases where it presents a barrier to anadromous fish or where it contributes to hillslope failure.

INTRODUCTION

The accumulation of large organic debris (LOD) in low order streams is common to both natural and disturbed watersheds. In a natural system, woody debris is delivered to the channel by a variety of mechanisms including blowdown and hillslope failure. In a logged watershed, additional debris can be delivered to the channel as a direct or indirect consequence of timber harvesting operations. Stream crossings are commonly constructed by placing large logs in the channel, parallel to the flow, and covering with road fill. Known as "Humboldt crossings", they often deteriorate and form a jam. Additional debris such as slash and cut logs often enter streams during or after falling or yarding operations.

Lowest (first and second) order streams lack sufficient power to move most LOD and hence it tends to be randomly distributed. Logs and slash are found within and proximal to the channel in almost any configuration. In third and fourth order streams, logs are mobilized more frequently and there is a tendency for debris to accumulate in jams comprised of several to hundreds of logs. Jams are commonly oriented perpendicular to flow and often span the entire width of the channel. Higher order streams, such as the mainstream of Redwood Creek, have sufficient power under high flow conditions to move

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even the largest debris and hence LOD accumulation tends to be negligible and often confined to channel margins.

The effects of LOD on channel morphology has been studied in detail by other investigators (Swanson and Lienkaemper 1978; Keller and Tally 1979). Organic debris and specifically log jams alter the hydraulics of a reach by impeding flow. Characteristically, this reduces the available stream power and results in deposition of sediment behind the jam. The changes in channel morphology commonly involve:

(1) An abrupt step in the longitudinal profile at the jam with an associated decrease in gradient upstream of the jam;

(2) An increase in channel width upstream of the jam, and;

(3) A decrease in particle size (roughness) behind the jam.

Log jams can be important sites of sediment storage in low order streams. They often serve to attenuate the effects of a relatively instantaneous input of sediment to the channel from adjacent hillslopes by providing a storage compartment that may remain stable for many decades. Debris jams may also induce small to large scale failures from adjacent hillslopes by diverting flow into the banks and undercutting the toe of the slope. Finally, they present barriers to anadromous fish and in many cases prevent their upstream migration. Thus, log jams are an important determinant of the interaction between hillslope, channel and biological processes. As such, they merit careful study in any comprehensive program of watershed management.

The identification of severe and complex erosion processes and their potential threat to the resources of the Redwood Creek basin led to the expansion of Redwood National Park in 1978. Previous studies (Janda, et al., 1975, Coleman 1973) have focused on channel and hillslope processes centered around the main stem of Redwood Creek. The expansion legislation (Public Law 95-250) clearly states the need for a basin-wide study of sediment source areas and sediment transport. This paper reports the initial results of a study on sediment routing in the tributaries of Redwood Creek. Specifically, I would like to: 1) describe the present understanding of sediment routing in tributary streams with the Redwood Creek basin, 2) describe the role of organic debris in storing sediment and initiating landslides, and 3) to present a conceptual approach to determining when it is appropriate to remove large organic debris as part of stream channel restoration.

STUDY AREA

Sediment storage and sediment transport in tributaries of Redwood Creek are strongly influenced by three basin characteristics. First, the main stem channel of Redwood Creek is structurally controlled by the Grogan Fault and the unusually elongate geometry of the basin is a strong reflection of this (Figure 1). As

Figure 1: Location map of the Redwood Creek Basin

a result, there are no major tributary forks[1] to Redwood Creek and only a few tributaries are larger than the majority (Figure 2). Therefore, most tributaries are characteristically low order, high gradient streams draining small watersheds (Figure 3). Their channels are in general deeply incised and have narrow, discontinuous floodplains. In all, there are 74 tributary basins drained by second order or higher streams.

Secondly, the weakly indurated and pervasively sheared rocks underlying the Northern California Coast Ranges are highly susceptible to erosion and mass wasting. The Redwood Creek basin is underlain by rocks of the Franciscan assemblage (Bailey, et al., 1964, Harden, et al., 1981). The Grogan Fault roughly bisects the basin and juxtaposes unmetamorphosed and slightly metamorphosed clastic sedimentary rocks on the east against quartzofeldspathic-mica schist to the west. Tributary streams are nearly equally divided between those draining sedimentary rock and those draining metamorphic rocks.

Finally, tributary watersheds are distinguished by predominant forest type and degree of timber harvesting. Eighty-five percent of the Redwood Creek basin was forested prior to the initiation of logging (Janda, et al., 1975). Under natural conditions, the northern third of the basin supported mixed stands of mature old-growth redwood and Douglas-fir (here called "redwood dominated" forests) while the southern two-thirds supported primarily mixed Douglas-fir and hardwood forests (here called "Douglas-fir dominated" forests). Logging was initiated in the basin as early as 1936. Today, over 65 percent of the basin has been logged with the majority of this occurring the last 25 years. Most units have been clear-cut and tractor yarded. Twenty percent of the basin, virtually all within the Redwood Creek unit of Redwood National Park, remains as uncut virgin forest and the remaining 15 percent is comprised of prairie and oak woodland (Janda, et al., 1975).

STUDY OBJECTIVES AND METHODS

The data presented in this paper are part of a more general study on sediment source areas and sediment transport in the Redwood Creek basin (Kelsey, et al., 1981b). As a first step in determining the magnitude and timing of sediment contribution from tributaries, streamside landslides and channel-stored sediment were measured conjunctively in 14 basins. These tributaries represent a wide variety of physiographic settings, forest types and drainage areas. Basic data for these basins are given in Table 1.

SEDIMENT SOURCE AREAS AND SEDIMENT TRANSPORT IN TRIBUTARY STREAMS

Sediment routing in tributary watersheds involves a complex set of interactive hillslope and channel processes. Source areas adjacent or proximal to perennial streams mobilize sediment most effectively. The most common

[1] Prairie Creek is the largest tributary to Redwood Creek. It drains approximately 104 km^2 and enters the main stem of Redwood Creek just upstream of Orick. However; due to the marked differences between the physiography and geology of this tributary and the majority, we have not included it in our study to date.

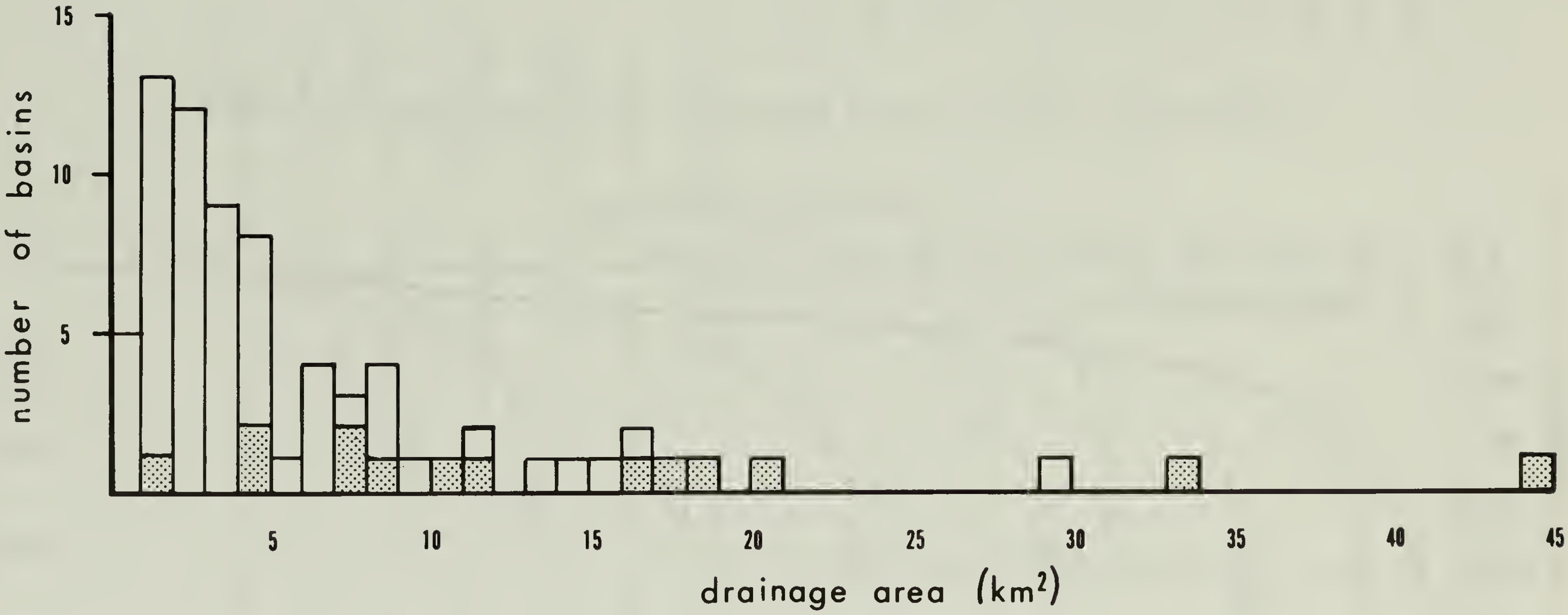

Figure 2: Distribution of tributaries by drainage area. Shaded areas indicate basins sampled for stored sediment and stream-side landslides.

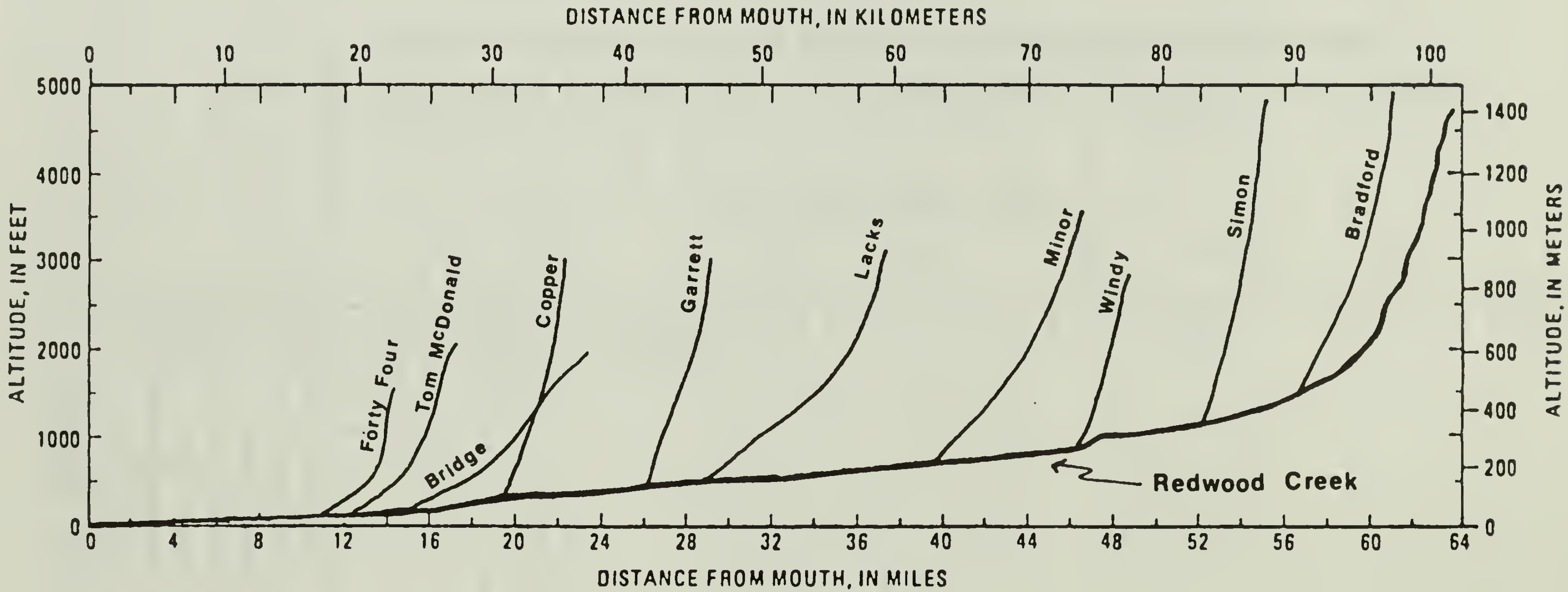

Figure 3: Longitudinal profile of Redwood Creek and selected tributaries

TABLE 1

GENERAL INFORMATION FOR STUDY BASINS

TRIBUTARY	DRAINAGE AREA (km^2)	PREDOMINANT ROCK TYPE (1)	PREDOMINANT FOREST TYPE (2)
Lacks Creek	44.03	SS	DF
Minor Creek	33.57	SS	DF
Coyote Creek	20.41	SS	DF/RW
Devils Creek	18.03	SH	RW
Tom McDonald Creek	17.95	SH	RW
Bradford Creek	16.50	SS	DF-O-P
Upper Redwood Creek	11.14	SS	DF-O-P
Garrett Creek	10.75	SS	DF
Forty Four Creek	8.08	SH	RW
Harry Weir Creek	7.80	SS/SH	RW
Copper Creek	7.43	SS	RW/DF
Windy Creek	4.50	SS	DF-O-P
Simon Creek	4.50	SS	DF-O-P
N. Fork Slide Creek	1.55	SS	RW

(1) SS: Unmetamorphosed and slightly metamorphosed sedimentary rocks of the Franciscan Formation.

SH: Quartz-mica schist of the Franciscan Formation.

(2) RW: Predominately redwood forest with minor amounts of hardwood and Douglas-fir.

RW/DF: Predominately redwood forests with significant amounts of Douglas-fir.

DF/RW: Predominately Douglas-fir forests with significant amounts of redwood.

DF: Predominately Douglas-fir with associated hardwoods.

DF-O-P: Nearly equal amounts of Douglas-fir forests, oak woodland, and prairie.

mass movement mechanisms in these basins are complex earthflows, slumps, debris slides and debris avalanches. Large gullies and rills resulting from fluvial transport of soil and regolith are the most obvious surface erosion features. Sediment storage in stream channels occurs behind accumulations of large organic debris, in fill terraces nested against adjacent hillslopes, in point bars or as aggraded bed material.

Streamside landslides in tributary watersheds are as large and as complex as similar landslides along the main channel of Redwood Creek. The 20 largest streamside slides in the tributary basins of this study total 1,591,000 tons. By comparison of the 634 landslides measured along the main stem of Redwood Creek upstream of State Highway 299, the largest 20 slides have delivered 1,624,000 tons to the channel.

Massive aggradation in the lower reaches of Redwood Creek illustrates the inability of a stream to transport the available load. Sediment transport in tributary channels, however, differs markedly from the main stem of Redwood Creek. A comparison between the amount of landslide material delivered to the channels of the tributary study basins and the amount of sediment remaining in storage serves as a partial gauge of the transport efficiency of these streams (Table 2). A majority of the study streams store a relatively small (less than 20 percent) proportion of the material supplied to them by streamside landslides. Those tributaries which store proportionally more than 20 percent either drain old-growth redwood forest or are small basins which were severely effected by landsliding. The fact that tributaries transport a high proportion of the sediment delivered to them is largely a reflection of their steep gradients (Figure 3). Average gradients in the reaches of Redwood Creek downstream of Snowcamp Creek (Figure 1) range from .04 to .001. Average gradients for reaches in tributaries are seldom less than .01 and often exceed .20.

Stored sediment provides only an incomplete measure or record of sediment transport through a watershed. Continuous and periodic sampling of water, suspended sediment and bedload discharge, however, generate data on sediment yield more directly. The U. S. Geological Survey has, in cooperation with the National Park Service, operated gaging stations on selected tributaries since the 1974 water year (Iwatsubo, and others, 1975, 1976; Water Resources Data for California, Pacific Slope Basins, published annually). Nolan and Janda (1981) used water and suspended sediment discharge records to assess the impacts of timber harvesting on sediment transport in Redwood Creek tributaries characterized by diverse terrain and land use history. They found that suspended sediment concentrations for tributaries exceeded those for Redwood Creek at discharges with a recurrance interval of approximately five years or greater. In other words, at higher discharges, tributaries become major sediment source areas and are more efficient agents of sediment transport than the main stem of Redwood Creek.

The final gauge on the relative importance of sediment storage in tributary basins is provided by comparison with field measurements of stored sediment in the main stem of Redwood Creek. Data from the study basins may be used in conjunction with the distribution of basins by size (Figure 1) and thus to arrive at an estimate of the total amount of sediment stored in all tributaries. Such extrapolation indicates that the tributary streams store approximately 15 percent as much total sediment as Redwood Creek (Kelsey, *et al.*, 1981a)

LARGE ORGANIC DEBRIS: ITS EFFECT ON SEDIMENT TRANSPORT AND MASS MOVEMENT

Under most conditions, these low order streams lack sufficient discharge to purge their channel of large organic debris. Thus, channel process and channel morphology in Redwood Creek tributaries are strongly influenced by organic debris. This point is highlighted in the work of Keller and Tally (1979). In their studies of old-growth redwood streams, they found that variables such as pool and riffle spacing, elevation drop and channel area were, in large measure controlled by the presence of LOD. The relative size of organic debris determines the degree to which debris influences channel form and process. Old-growth redwood trees are renowned for their girth and resistance to decay. Even the largest streams do not carry sufficient runoff under any conditions to move massive redwood logs. Consequently, debris jams tend to be stable and may remain in place for hundreds of years and they influence channel morphology for periods of time on the order of 1,000 years (Kelly and Tally 1979).

Accumulations of LOD serve to attenuate the effects of a relatively instantaneous input of sediment to the channel from adjacent hillslopes by providing a storage compartment that may remain stable for long periods of time. LOD, and particularly log jams, are the most important sites of sediment storage in old-growth tributaries (Table 2). The mean percentage of total sediment which is stored by LOD in the six streams draining redwood forests is 74.5 percent. Of the basins dominated by Douglas-fir and prairie-woodland vegetation, the mean percentage of sediment stored by LOD is 37.5. Organic debris accumulation in the latter types of basins tends to be less because Douglas-fir deteriorates more rapidly than redwood and because the relatively smaller sized debris can be moved more readily by high streamflows. Commonly, the majority of sediment in the Douglas-fir and prairie-woodland tributaries is stored in the lower gradient reaches near their mouths as backwater terraces deposited concurrently with high stages in Redwood Creek.

Organic debris in channels can have marked effect on hillslope processes as well. Debris may induce small to large scale failures by diverting flow into streambanks and undercutting the toe of the slope. The importance of organic debris in contributing to slope failure is illustrated in Table 2. The percentage of sediment supplied from landslides induced by flow diversion around large organic debris is higher on the average for tributaries draining old-growth redwood forests than for those draining Douglas-fir forests. This is again a reflection of the larger size and greater resistance to decay of redwood debris compared to Douglas-fir.

REMOVAL OF ORGANIC DEBRIS FROM CHANNELS

As a rehabilitative measure, the merit of removing organic debris from stream channels must be approached on a site-specific basis. Previous reports (Kelsey, et al., 1981a, 1981b), as well as this report, stress the fact that the amount of sediment in storage in tributary streams is substantially less than that in the main channel of Redwood Creek. Therefore, removing a jam for the sole purpose of removing the sediment behind the jam will have a minimal effect on basin-wide sediment yield. In the Redwood Creek watershed, the reasons for removing a jam are to reduce stream bank instability caused by flow diversion around the jam and/or to remove a barrier to anadromous fish.

TABLE 2

DATA ON SEDIMENT SOURCE AREAS AND CHANNEL-STORED SEDIMENT FOR TWO GROUPS OF STUDY BASINS: REDWOOD DOMINATED (TOP), AND DOUGLAS-FIR DOMINATED (BOTTOM)

TRIBUTARY	TOTAL LANDSLIDE MASS DELIVERED TO TRIBUTARY CHANNELS (TONNES) [1]	TOTAL STORED SEDIMENT (TONNES) [2]	PERCENTAGE OF STORED SEDIMENT TO LANDSLIDE MASS	PERCENTAGE OF TOTAL SEDIMENT STORED BY LARGE ORGANIC DEBRIS	PERCENTAGE OF TOTAL LANDSLIDE VOLUME CONTRIBUTED FROM ORGANIC DEBRIS RELATED SLIDES
Devils Creek	156,000	50,400	32.6	91.3	19.7
Tom McDonald Creek	84,200	80,000	95.0	55.7	56.3
Forty Four Creek	42,300	81,800	193.4	82.8	18.4
Harry Wier Creek	57,500	29,200	50.8	75.5	34.2
Copper Creek	109,200	18,700	17.1	82.0	N/A [3]
North Fork Slide	38,700	24,300	62.8	56.9	11.5
	MEAN		75.2	74.0	28.0
	STANDARD DEVIATION		63.5	14.6	17.8
Lacks Creek	988,100	120,000	12.1	48.9	1.2
Minor Creek [4]	564,400	219,300	39.0	13.4	0.9
Coyote Creek	238,200	22,000	9.2	52.1	7.4
Bradford Creek	225,800	27,000	12.0	16.2	19.4
Upper Redwood Creek	172,100	32,700	19.0	27.0	29.7
Garrett Creek	144,900	18,800	13.0	69.5	1.6
Windy Creek	241,600	116,200	48.0	18.5	2.6
Simon Creek	347,800	74,700	21.5	29.3	4.4
	MEAN		21.7	37.4	9.5
	STANDARD DEVIATION		14.2	19.8	10.9

[1] Landslide mass computed by taking the product of the measured volume and an assumed soil density of 1.6 $grams/cm^3$ (100 lb/ft^3)(Jim Popenoe, Personal Communication).

[2] Stored sediment mass computed by taking the product of the measured volume and an assumed density of 1.9 $grams/cm^3$ (120 lb/ft^3)(Jim Popenoe, Personal Communication).

[3] Causes of slides not noted during collection of data.

[4] Data on sediment delivery from Minor Creek earthflow provided by Mike Nolan, U.S. Geological Survey, Water Resources Division, Menlo Park. An additional 169,000 tonnes of sediment were delivered to Minor Creek by large gullies.

The approach to determining the feasibility of removing a log jam for the purpose of reducing stream bank instability centers around producing a quantitative statement of the erosion potential of the site. The procedures for evaluating a site involve simple field measurements and are outlined below:

(1) Assess the stability and composition of the jam keeping in mind that jams comprised of redwood logs are, in general, more stable and decay-resistant than Douglas-fir jams.

(2) Survey a longitudinal profile of the channel, extending downstream and upstream of the site using a tape, rod, and hand level. The survey provides an estimate of the depth and channel length of stored sediment associated with a jam.

(3) Establish monumented cross sections across the channel and onto the adjacent hillslopes beyond the possible limits of excavation or failure.

(4) Construct a morphologic map of the area showing channel perimeter, distribution of organic debris and other pertinent hillslope and channel features.

(5) Estimate the depth and length of channel fill from the longitudinal profile. In cases where excavation of material off hillslopes is necessary to insure stability, the amount of material to be removed from the hillslopes can be estimated from the cross sections and from field observations.

(6) Measure planimetric areas of channel and hillslope features from the morphologic map. The total volume of sediment in storage within the channel and on the slope can be computed by taking the product of the surface area of the feature and the estimated depth of sediment as determined by the profile or cross-section.

(7) The amount of work necessary to remove the jam is evaluated at this point. The costs of excavating material off hillslopes and from the channel can be determined knowing the volumes of sediment. The feasibility of treating this site over others is then weighed in terms of the projected amount of sediment saved from introduction into the channel. The potential impact on aquatic habitat is an additional factor that although not as easily assessed should be taken into account.

In the event that the jam is pulled, it is useful to make some simple measurements while work is in progress to determine if the excavation is adequate or beyond what was prescribed.

The longitudinal profile and cross-sections are resurveyed following the rehabilitation work and again after subsequent winter seasons. The net gain or loss of sediment from the site is again computed as per (5) and (6) above. With this information, the rehabilitator can accurately say what amount of sediment has been removed from the site both through and after treatment and judge the effectiveness of the work in reducing the amount of sediment available for downstream transport.

A case example will serve to illustrate both the conceptual and methodological approach to evaluating the removal of organic debris from a perennial stream channel. A series of moderate-sized jams were removed from the main stem of Copper Creek during site-specific rehabilitation work in late summer, 1979. A "Humboldt crossing" constructed in 1969 had deteriorated over the last decade and the logs had moved downstream to form three debris jams. The jams and the ponded sediment associated with them were diverting flow into the streambanks and were inducing several stream-side failures in the road fill prism adjacent to the channel. At this site, Copper Creek is a second-order stream and drains 1.4 km^2.

The longitudinal profile of the stream and six channel cross-sections were surveyed on four separate occasions: prior to rehabilitation, immediately after heavy equipment work, and after the subsequent two winter seasons. A tape and compass map of the area was also made prior to rehabilitation. These data were then used to compute the volume of material removed during heavy equipment work and during subsequent winter seasons. A total of 1,100 m^3 of sediment was excavated by heavy equipment; 450 m^3 of alluvium was removed from the channel and 650 m^3 was removed from the oversteepened hillslopes adjacent to the channel. As a result of 1980 winter storms, 430 m^3 of sediment left the site with all of this loss being associated with channel scour. An additional 50 m^3 was lost during the 1981 winter. The hillslopes have remained stable through both winter seasons. The minimal amount of sediment lost since the first winter season suggests the site is rapidly approaching stability and that the primary objective of stabilizing the hillslopes, has to this point in time, been reached.

During heavy equipment work, it became exceedingly difficult for the equipment to operate in the channel and the projected "stable" channel bed was never reached. Subsequent winter storms downcut through the remaining sediment only to expose more large organic debris. Although the existing channel is more stable, the possibility exists for new jam formation at the same site. This problem was also noted in the evaluation of stream clearance at the Airstrip Creek rehabilitation unit (Kelsey and Stroud, 1981). It appears that partial removal of organic debris has limited effects as in many cases, additional debris soon becomes exposed or lodged and thus forms a new jam. A full evaluation of these efforts will be possible only with the passage of time and collection of additional data. Nonetheless, it appears reasonable to consider removing large debris jams when they contribute to massive slope failure.

CONCLUSIONS

The tributary drainage basins within the Redwood Creek watershed are major sediment source areas. Sediment routing in these basins involves a complex set of interactive hillslope and channel processes. Data from 14 study basins draining diverse terrain suggests that the majority of these streams are capable of transporting a high percentage of the sediment supplied to them. This conclusion is supported by earlier studies (Nolan and Janda, 1981; Kelsey *et al*., 1981b) which contrast the sediment transport characteristics of Redwood Creek and its tributaries. In addition, the amount of sediment stored in tributaries is estimated to be only 15 percent of the amount stored in the main stem of Redwood Creek.

Large organic debris plays an important role, particularly in the old-growth redwood forests in determining channel form and process. On the average, tributaries draining redwood forests store a higher proportion of sediment than tributaries draining Douglas-fir forests or prairie-woodland terrain. In addition, the amount of sediment delivered by landslides whose cause is related to flow diversion around large organic debris is higher for old-growth streams than for Douglas-fir or prairie-woodland streams. Organic debris accumulation in the redwood forests tends to be greater because redwood is more resistant to decay and because of its size, mobilized less frequently, if at all. Thus, debris tends to be stable and may remain in place for hundreds of years.

The above conclusions form an important conceptual base from which to view the removal of large organic debris as a rehabilitative measure. Organic debris accumulation in the tributary stream channels within the Redwood Creek basin is important primarily in its effect on slope stability and on the migration of anadromous fish. A preliminary evaluation of debris jam removal at Copper Creek suggest that in the case of the former, the erosion potential of a site can be reduced substantially by such a treatment.

ACKNOWLEDGMENTS

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STRATEGY FOR RESTORATION OF CHANNEL STABILITY, CARMEL RIVER, MONTEREY COUNTY, CALIFORNIA

Robert R. Curry[1] and G. Mathias Kondolf[2]

ABSTRACT

The Carmel River Basin of 670 km^2 was dammed in the 1920's. Prior to that, the lower 24 km alluvial reach had been a high-gradient braided largely-ephemeral arroyo typical of chaparral-dominated central coastal watersheds. Fire suppression, reservoir sedimentation, and a sequence of low-flood magnitude years led to channel incision, narrowing, and growth of a major riparian vegetation community. Loss of riparian vegetation in some sites, coupled with moderate magnitude flood flows caused destabilization of the channel locally and a return to conditions more typical of those prior to 1920. A management plan has been developed to attempt to achieve the conditions of quasi-stability to which the residents had become accustomed by the mid-1960's when riparian vegetation began to die back.

INTRODUCTION

The Carmel River drains a 670 km^2 (255 mi^2) basin. Rising in the rugged Santa Lucia Mountains and passing through the 24 km (15 mi) long, alluviated Carmel Valley, it ultimately discharges into the Pacific near Carmel, Calif. (fig. 1). This alluvial reach is sub-divided by a bedrock constriction and narrowing of the valley (the "Narrows") into a lower 16 km (10 mi) reach (the "Lower Carmel") and a middle 8 km (5 mi) reach (the "Middle Carmel"). The "Upper Carmel" refers to the segment above San Clemente Dam (fig. 2). Average annual rainfall in the mountainous headwaters with elevations to 2133 m (7000 ft) is 1040 mm (41 in) but decreases to 430 mm (17 in) in the lower valley. While the upper river is perennial, the lower river is intermittent, with surface flow typically from December through June. Near the river's mouth, average discharge is 2.7 cms (97 cfs), and the bankfull discharge (here, the 2.4 yr flow) is 79.2 cms (2800 cfs).

Two water supply dams, the Los Padres and San Clemente Dams, together impound about 3000 ac-ft (fig. 1). The Carmel basin supplies most of the water for the Monterey Peninsula cities of Monterey, Pacific Grove, Seaside, and Carmel. As these areas have grown, demand for water has risen substantially. To meet demand, California-American Water Company (Cal-Am), a private utility, has drawn increasingly upon water supply wells in the alluvium along the lower and middle Carmel valley over the past two decades. Of the 13,000 ac-

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Figure 1a) Vicinity map of the Carmel River Basin. 1b) General map of the Carmel River Basin. (U.S. Army Corps of Engineers, 1967)

ft total exported from the basin in 1980, 9,000 ac-ft was diverted from reservoirs, and 4,100 ac-ft was extracted from streamside wells.

By the late 1960s, residents were complaining that vegetation was dying off near the wells in the "mid-valley" region, in the vicinity of Robinson Canyon Road (fig. 2, also see Lee, 1974). The Carmel Valley Property Owners Association hired a forestry consultant to study the vegetation problem; he concluded that lowered water tables near the wells killed the vegetation (Zinke, 1971). Cal-Am hired another consultant, who acknowledged that lowered water tables near the wells affected vegetation, but observed that the effect was simply an acceleration the "natural succession" of vegetation (Stone, 1971).

The drought of 1976-1977 imposed additional demand on streamside wells. The die-off of phreatophytes was significant in the mid-valley region and above the Narrows - two areas of substantial groundwater withdrawal. The high flows of 1978 and 1980 resulted in severe bank erosion, primarily in areas where bank-stabilizing vegetation had been affected.

HISTORY

River course and pattern changes were documented by comparing maps of the Carmel River from 1858 to 1945 and aerial photos of the river from 1939 to 1980. Extensive channel surveys were conducted in 1965 by the Corps of Engineers and again in 1980-81 by the Monterey Peninsula Water Management District.

CHANGES IN COURSE

Historical changes of the Carmel River from Garland Ranch to the mouth were assessed. The 1858 and 1882 channels were determined from boundary surveys. The 1911 course appears on the USGS Monterey 15′ topographic map of 1913 (based on surveys in 1911-12), and the 1945 course is taken from the USGS Monterey and Seaside 7.5′ quads of 1947 (based on aerial photography in 1945). The 1947 maps were photorevised in 1968, but the only mapped revision in the river′s course was downstream of Garland Ranch, where a northward bend of the river was eliminated by highway construction.

Comparison of these channels reveals nine localities where lateral channel migrations of 250-500 m (820-1640 ft) occurred during the 87 years between 1858 and 1945. Except for the changes in course near Garland Ranch Park, no major shifts of course have occurred since the survey of 1911-12, which was completed after the flood of 1911. While more gradual migration and changes in channel geometry have occurred since, dramatic changes in channel course that would be evident at mapped scales are absent from 1911 to 1945. This is consistent with the observation that most major shifts take place during large floods. No floods comparable to the 1911 event occurred between that year and 1945, nor have they since.

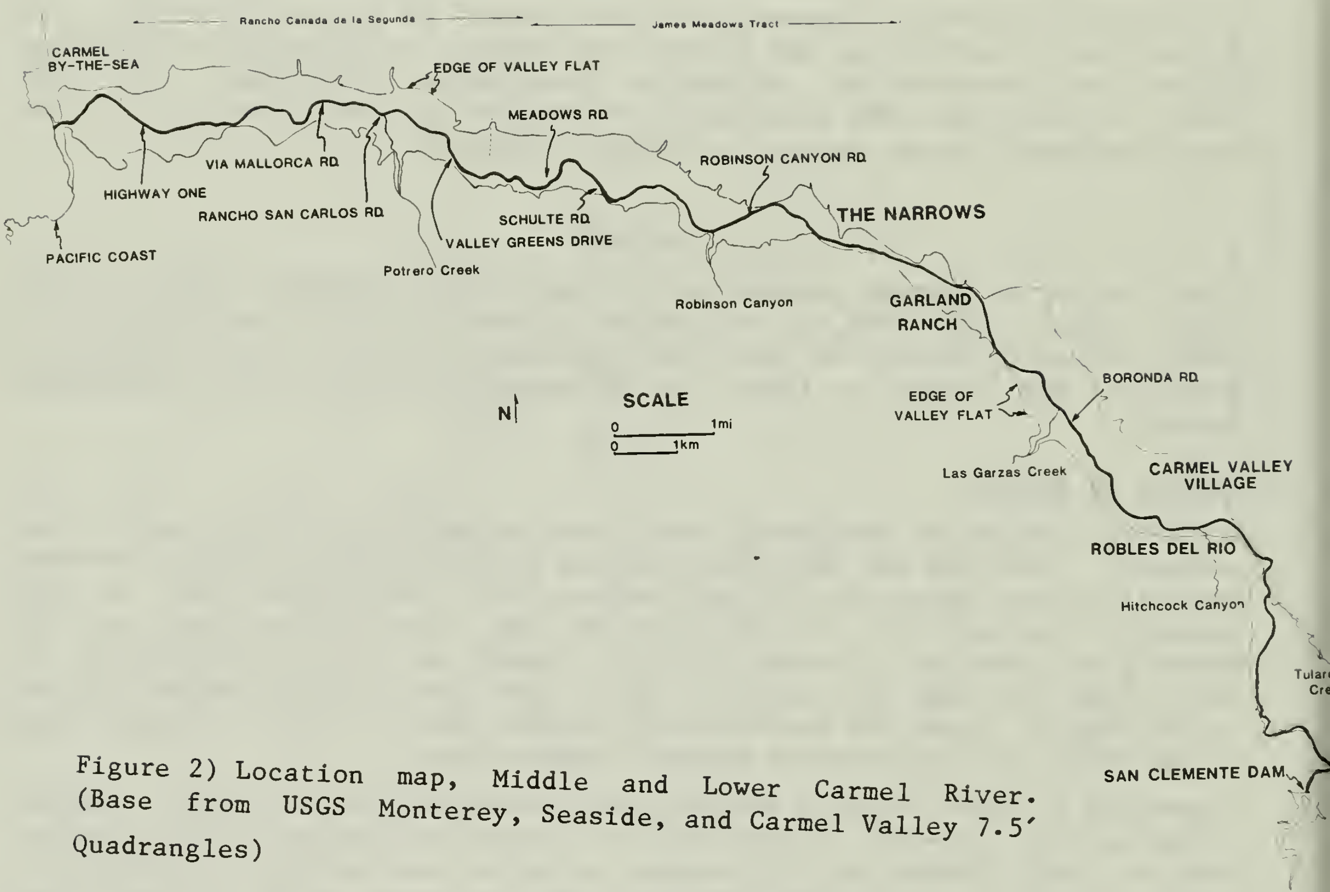


Figure 2) Location map, Middle and Lower Carmel River. (Base from USGS Monterey, Seaside, and Carmel Valley 7.5′ Quadrangles)

FLOOD HISTORY

The earliest flood of record along the Carmel was the great statewide deluge of 1862. While no records exist to document the exact magnitude of this flood, it was severe enough to induce the few valley residents to move to higher ground (Roy Meadows, pers. comm. of family history). Most of the great changes in channel course visible between the 1858 and 1882 channels in Rancho Canada de la Segunda probably occurred during this flood.

The next great flood occurred in 1911. An account in the Monterey Cypress of March 11, 1911, reports that Fannie Meadows and Roy Martin lost ten acres and a pear orchard due to lateral migration of the river. Their adjacent properties extended downstream from the present Schulte to Meadows roads. The flood of 1911 was a large magnitude event. Before it was swept away, a staff gauge at the present site of the San Clemente Dam indicated a discharge of 480 cms(17,000 cfs). In 1914 another major flood occurred, but this one was far less destructive. It is not known whether this flood was significantly lower in magnitude than the 1911 event, or if it simply caused less disruption because it flowed through a channel preadjusted to the large 1911 flow.

No comparable floods occurred in the following decades. The absence of floods, together with the drop in sediment load resulting from construction of the San Clemente Dam on the main channel in 1921, served to permit channel incision, narrowing, and increased sinuosity.

CHANGES IN SINUOSITY AND GRADIENT

Sinuosity, defined as the ratio of stream channel length to valley length, was computed for several sequential channels. From 1911 to 1945, the reach of river from Garland Ranch to the mouth increased in sinuosity from 1.11 to 1.18. The reach from Sleepy Hollow to Las Garzas Creek experienced an overall increase in sinuosity of 1.05 to 1.09 from 1917 to 1954. Slopes computed from the 1911 and 1945 mapped channels from Garland Ranch to the mouth show a decrease from .0034 in 1911 to .0029 in 1945. At sites of local disturbance with increased bank erosion and resulting imposed sediment load, very considerable increases in gradient are noted today. For example, the reach from the Manor Well to Schulte Road increased from a gradient of .0017 in 1965 based upon Corps of Engineers surveys to a gradient of .0059 in 1981 based upon current surveys. The overall increase in sinuosity and decrease in gradient from 1911 to 1965 suggests that the Carmel River stabilized in the aftermath of the 1911 flood.

CHANGES IN CHANNEL PATTERN AND FORM

Channel pattern (pattern in plan view, e.g. meandering, braided) and form (cross sectional shape, e.g. narrow, wide) of the Lower and Middle Carmel River have changed dramatically since the last major flood and dam construction. No doubt, the entire Lower and Middle Carmel was strongly modified by the 1911 and 1914 floods. The resulting channel is probably well represented by the historical photos (ca. 1918) from the Slevin Collection (U.C. Berkeley). These photos (plate 1) of the river, at and downstream of the Narrows, near Robinson Canyon Road, show a wide, sandy channel, reflecting the recent passage of a major flood.

By 1939, the Lower Carmel had developed a narrower, more sinuous channel while the Middle Carmel retained much of its braided character, as

Plate 1) Carmel River channel, 1918, viewed from right bank upstream from location of present Robinson Canyon Road bridge. (Slevin Collection, Bancroft Library, U.C. Berkeley)

demonstrated by aerial photography of 1939.

This change in channel pattern occurred concurrently with the increase in sinuosity and decrease in gradient apparent by 1945. Together, they indicate that the Lower Carmel had adjusted to the absence of major floods and to the cut-off of 60% of its previous sediment load (based on drainage area upstream of San Clemente Dam). These adjustments included channel narrowing with encroaching vegetation, an increase in sinuosity, and reduction of gradient through incision. Similar adjustments have been documented in other rivers in response to the absence of floods or to construction of upstream dams (Leopold, et al., 1964, p.453-458).

Above the Narrows along the Middle Carmel, similar adjustments took place, but they occurred later. The 1939 aerial photos show the scars of numerous anastamosing channels in the Middle Carmel. By 1971, most of these scars no longer appeared on the photos. Accompanying this change in pattern was degradation of the bed. Sequential cross sections show 1.5 m (5 ft) of degradation under the Boronda Rd. bridge from 1946 to 1980.

By the 1960s, most of the Lower and Middle Carmel had developed a narrow, sinuous, well-vegetated course. It bears repeating that these conditions developed only in the absence of major floods and depended upon a cut-off of upstream sediment by the dams. Additionally, before their suppression by European settlers, fires occurred regularly in the upper Carmel watershed. U.S. Forest Service studies in the Santa Lucia mountain headwaters demonstrate an approximate 21-year fire frequency from the record preserved in the oldest fire-scared trees from 1640 to 1907. From 1907 to 1977 there was no fire, and then the Marble Cone Fire burned a major portion of the northern mountain range. The accumulation of sediment in the Los Padres reservoir after the Marble Cone fire of 1977 was dramatic. The capacity of this reservoir decreased from 3200 ac-ft upon closure in 1947 to 2600 ac-ft in 1977, a loss of storage of 600 ac-ft in 20 years. Following the Marble Cone fire and the high flows in the ensuing winter, the reservoir's capacity decreased to 2040 ac-ft by the end of 1978. Thus, in one year the reservoir lost 560 ac-ft of storage (B. Buel, Monterey Penin. Water Mangmt. Dist., pers. comm., 1981). This post fire sedimentation rate was nearly twenty times greater than the pre-fire rate. Prior to dam construction, all this sediment passed through to the Middle and Lower Carmel. It is probable that a wide, steep channel would have developed to transport these high sediment loads. However, it is notable that the sediment contributed by the recent bank erosion has passed through lowermost reaches of the Carmel (Valley Greens Drive downstream) without destabilizing that narrow channel. The stability of this lowermost reach may be due to the stability of vegetation in that unpumped area of consistently high groundwater. Alternatively, it may be in part due to the automobile bodies and rip-rap emplaced within the banks or to the extensive irrigating of stream side golf courses. Without these stabilizing influences, the channel might have widened in response to the higher load. Alternatively, such a narrow channel in its natural state, protected only by bank vegetation, may be able to pass these high loads without disruption of its existing geometry. In this latter case, the observed changes in channel pattern, form, gradient, and sinuosity must be ascribed to recovery from the major floods of 1911 and 1914.

RECENT BANK EROSION

Peak discharges over the winters of 1978 and 1980 were 168 cms (5920 cfs) and 208 cms (7360 cfs) respectively. These flows resulted in massive bank erosion along parts of the Middle and Lower Carmel. Most severly affected was the region upstream of Schulte Road Bridge. Here the channel at bankfull discharge (defined as the flow with a recurrence interval of 2.4 years on an annual maximum series) increased in width from 13 m (43 ft) to 35m (115 ft) in two years. This increased the width/depth ratio from 15 to 113. Aerial photographs show the changing aspect of this reach from 1939 to 1980. In 1939 and 1965, a narrow channel fringed by dense riparian vegetation is visible (plate 2a and 2b). The 1977 photo indicates no obvious change in the channel, but does show a marked thinning of streamside trees (plate 2c). The 1980 photo exhibits a major widening of the channel, most of which occurred during one storm in the winter of 1980 (plate 2d).

Throughout the Middle and Lower Carmel, the river banks are composed of unconsolidated sands and gravels, which lack cohesive strength in the absence of binding vegetation. These banks apparently offered no resistance to lateral erosion. A comparison of surveys and air photos of 1965 and 1980 from Schulte Bridge upstream .6 km (.4 mi) indicates that 100,000 m^3 of bank material was contributed to the river locally, mostly during the winter of 1980. The resulting channel is wide and floored by sand and gravel (plate 2d).

Similar, but less destructive lateral erosion occurred near Robinson Canyon Road. The well vegetated narrow channel of 1939 and 1965 had suffered a loss of riparian trees by 1977 and substantial bank erosion by 1980.

The die-off of bank vegetation and consequent lateral erosion appear to be coincident with lowering of water tables below the root zone of trees in the vicinity of water supply wells. Downstream of Valley Greens Drive, where no producing wells were located, the riparian community remained largely unaffected during the drought. The channel there remained stable during both the 1978 and 1980 winters. A plot of water table elevations for the drought, i.e. drawdown (October 1977), and post-drought, fully-recharged conditions (May 1978) shows far less drawdown in this lowermost reach of the Carmel (fig. 3). This figure shows that along much of the Middle and Lower Carmel the water table was drawn down about 10 meters. This is generally considered to be below the root zone of riparian willows (Zinke, 1971). Most points of figure 3 were chosen to be distant from major producing wells so that regional water table elevations would be shown, but one point (at 8.5 km upstream) fell within the cone of depression of a producing well. The depression of the water table here reflects the widespread drawdown created by wells in the highly permeable alluvium of the Carmel Valley. While the drought of 1976-1977 certainly exacerbated the drawdown problem, the drought alone cannot explain the fact that the vegetation die-off and subsequent bank erosion affected certain areas only.

MANAGEMENT RECOMMENDATIONS

The primary goal of local landowners has been the restoration of the main river channel to the conditions of the early 1960's. These conditions are

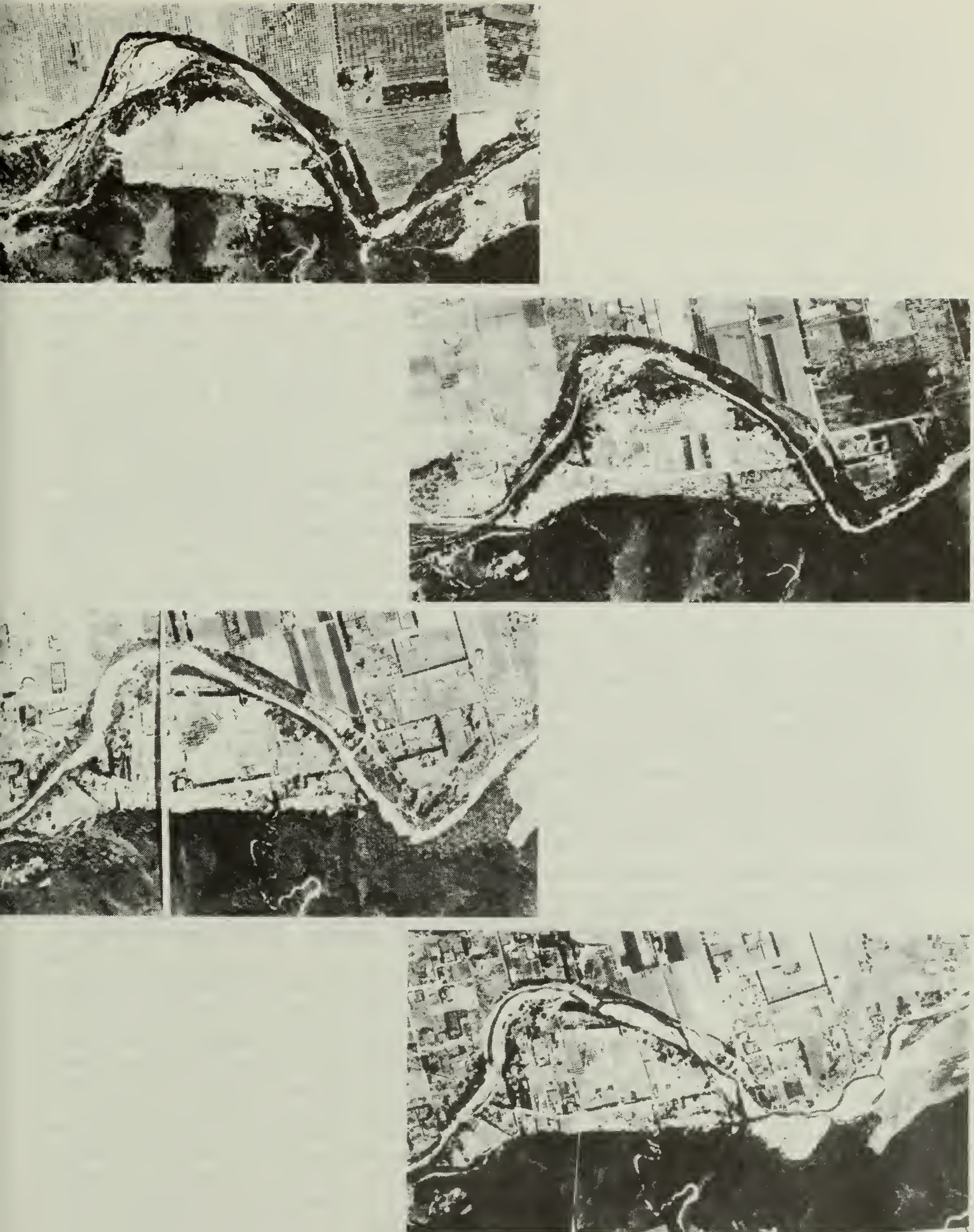
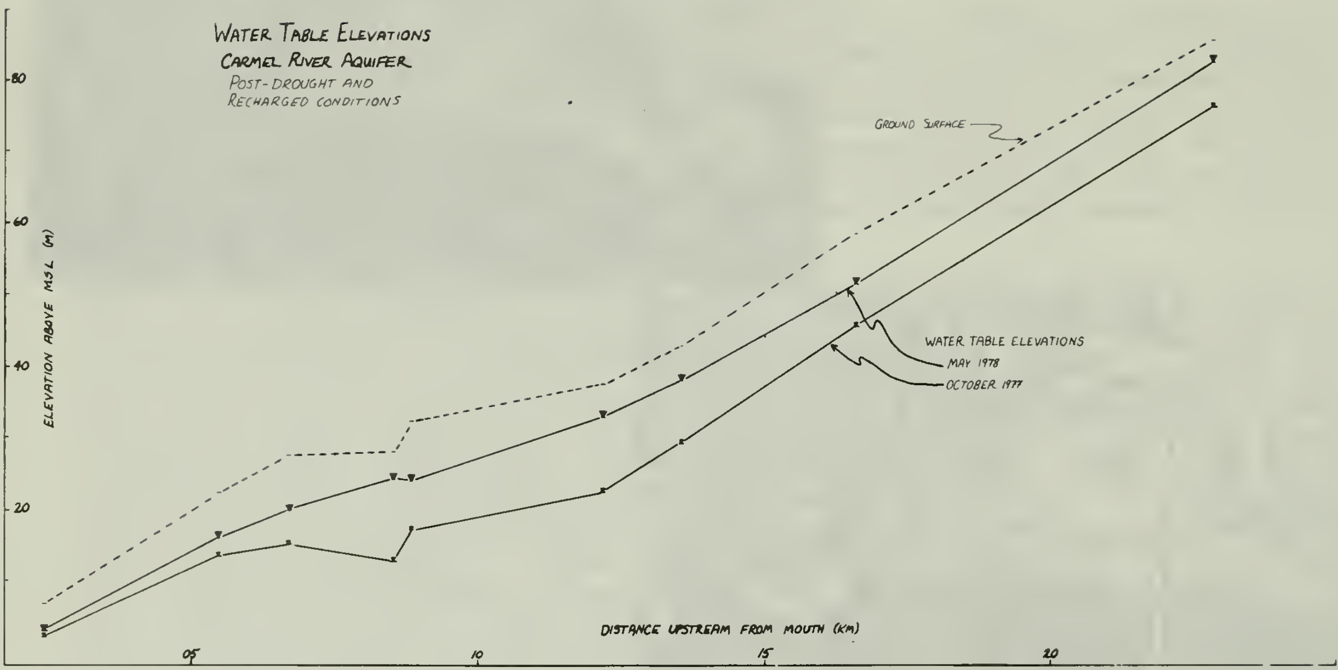


Plate 2) Aerial photographs of the Carmel River near Schulte Road bridge. a) 1939, b) 1965, c) 1977, d)1980. (Air photo collection, Monterey County Flood Control, Salinas)



• Figure 3) Water table elevations, drought and recharged conditions. (Data from Monterey County Flood Control well level records) not "natural" in that, although they developed without significant direct human intervention or planning, they did so in response to significantly altered sediment loads. The sediment discharge alterations were not natural in that they resulted from fire suppression, dam construction, and, possibly, from an unusually long period without significant flooding. Thus, management recommendations must be those that reestablish and maintain a quasi-stability. Any such effort must be taken with full knowledge that no such "stabilization" can be permanent.

EROSION MITIGATION

Efforts by individuals to control bank erosion along the Carmel include those with a wide range of cost and effectiveness. Rip-rap has been used with mixed results. Among the materials used for rip-rap on the Carmel are ornamental dolomite, concrete blocks, and rubble from Cannery Row. Gabions and pervious fences with rock fill have been used successfully. Some landowners are attempting to establish willows on their eroding banks, but many of these seedlings are not adequately irrigated and die. One of the most popular revetment strategies is emplacement of automobile bodies in the eroding banks. The individual bank protection efforts thus far are uncoordinated and may have deleterious downstream effects. The government agency charged with managing the area's water resources, the Monterey Peninsula Water Management District, is now considering an integrated management plan for the Carmel River. As part of this effort, experimental work is ongoing in 1982 with various vegetated revetments such as "willow rolls". Some of these will be irrigated and others will be established without irrigation if possible.

Since the primary source of in-channel sediment today is bank erosion, and since severe channel destabilization occurs wherever banks are eroding rapidly, the primary initial goal of erosion mitigation is bank stabilization through revegetation. Where bank recharge or regional groundwater levels remain high enough throughout the year to support stabilizing vegetation, a simple goal of replanting damaged sites is sufficient. Since most such sites are presently well vegetated, no immediate remedial work need be done. Where seasonal groundwater "overdraft" has contributed to loss of bank vegetation and where active ongoing erosion and bed aggradation make revegetation problematic, more effort is needed. Here three basic plans are being considered.

To provide sufficient moisture to maintain bank-stabilizing vegetation through periods of moisture stress, the Monterey Peninsula Water Management District has undertaken research on the physiological ecology of site-adapted suitable vegetation. Studies are now underway to determine the maximum depths from which water may be extracted by plants that help retain channel banks at higher flows, without leading to seasonal die-back or reestablishment of unsuitable rooting patterns.

After this is known for the local species (primarily willows and alder), plans will be made to supplement water needed to maintain bank vegetation. Phreatophytes will be watered, when needed, to maintain a vigorous community for erosion control, maintenance of engineered bank stabilizing structures, and development of suitable riparian wildlife and fisheries habitat. To accomplish this, the Water Management District is investigating 1). direct surface irrigation (now done by drip and sprinkler in one reach), 2). injection irrigation (to depths that maximize bank-stabilizing root development), and 3). flow regulation through controlled releases from the reservoirs to recharge bank storage directly.

Structures designed for channel bank stabilization will be primarily those that utilize vegetation as an integral part of the structures. Such "biotechnical" approaches are desirable primarily because of need to restore fishery habitat as well as bank stability. An excellent review of such vegetative bank stabilization work is presented by Siebert (1968). The papers presented elsewhere in this volume by Gray and by Seidelman provide examples of use of this technology for slope stabilization as well.

RE-DESIGNING AND RE-TRAINING THE OPTIMUM CHANNEL

The "river training" experience of New Zealand engineers provides a possible model for restoring unstable reaches of the Carmel (Nevins, 1967). Their procedure is to determine "design geometries" from stable reaches and to re-engineer unstable reaches to the design geometries. Cross sectional geometry, sinuosity, and gradient of the stable reaches are duplicated as closely as possible in the unstable reaches. Initially, bank protection works are used to stablize the banks and willows are planted. Once fully established, the willows are expected to become the principal bank stabilizing agent. The re-engineered channels in New Zealand have remained stable at all but very high flows. If large discharges disrupt the design channels, these reaches can be re-engineered to design specifications at a lower cost than the initial work (Nevins, 1967).

For the Carmel River, the stable reaches downstream of the disturbed reaches can serve as models for design geometries. In figure 4, cross sections are plotted for an eroded reach upstream of Schulte Road (section 37) and for a stable reach about 1.5 km (1 mile) downstream (section 45). No tributaries enter between these sections, so discharge remains essentially constant. Yet the present-day geometries are vastly different. Surveys by the U.S. Army Corps of Engineers in 1965 indicate that the reach encompassing section 37 was characterized by a geometry closely resembling that of the present-day section 45. Thus, a design stable geometry for section 37 could be drawn largely from the existing geometry at section 45. Certain corrections would have to be made for differences in gradient, sinuosity, and bed material size between these reaches. Fortunately, many of these parameters are well documented for the stable, pre-disturbance Carmel River.

Width-to-depth ratios for vegetated channels that had stabilized following dam construction were, in 1965, on the order of 15-25:1 for a 2.4-year recurrence interval bankfull flow. Design of restabilized channels will emulate these ratios. Vegetated permeable jacks will be used to constrain the channel to these widths. Since aggradation has gone on locally during the recent destabilization, depth and gradient manipulation will have to be accomplished to restore stability. Current plans are to investigate opportunities for "flushing flows" that can be augmented with reservoir releases during periods of seasonal high flow. Preliminary field evidence suggests that flows on the order of magnitude of the mean annual flood are effective for bedload transport and channel incision. Primary goals are to develop sediment transport and sediment routing models that will optimize transport while minimizing bank erosion and local overbank flooding caused by aggradation. Since sequential or long-duration low magnitude flows lead to bed armoring and cessation of further downcutting, management models must accommodate natural or induced flows that will effectively mobilize armor layers.

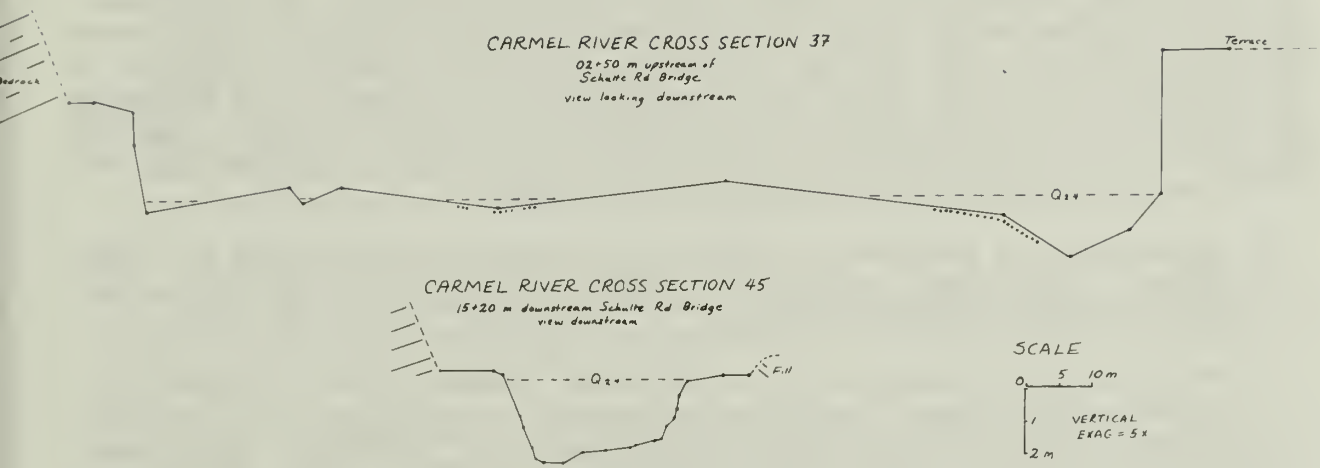


Figure 4) Channel cross sections of the Carmel River near Schulte Road Bridge. Section 37: 250 m (820 ft) upstream of bridge, Section 45: 1520 m (5000 ft) downstream of bridge. Discharge remains essentially unchanged between reaches. (From field surveys by the authors)

This modeling is being done using Modified Einstein and Meyer-Peter and Muller bedload transport functions calibrated with bedload transport measurements and scour observations made during a 200 cms (7000 cfs) discharge event in January, 1982.

The success of a river training program depends, in part, on a favorable flow regime in the years following channel redesign. A major flood (e.g. a 20-30 year event) in the first few years following the redesign may take out the new banks before they have been stabilized by vegetation. A catastrophic flood (e.g. a 75-100 year event) will probably carve a new channel for itself regardless of how well-vegetated the existing banks might be (Nevins, 1967). Applying these concepts to the Carmel, we might expect that a flow comparable to the 1980 event within the first five-to-ten years following channel re-design could damage the design banks. An event comparable to the 1911 flow might take out the design banks whether vegetated or not.

CARMEL RIVER MANAGEMENT PROGRAM

To develop and implement a channel-stabilization program, the Monterey Peninsula Water Management District, in November, 1980, formed the Carmel River Advisory Committee. The express purpose of this body was to "Propose a comprehensive program of activities, institutional arrangements and financing mechanisms to manage and maintain the health of the Carmel River riparian corridor". After 15 meetings and considerable staff work, a program plan has been developed. This plan proposes the following:

1. Formation of a management "Zone" for a 10-year minimum period in which actions take place and through which authority for restorative and preventive work is implemented.

2. Formulation of standards and a structural master plan to guide all streambank and channel modification projects. Guidelines are to set, at minimum, optimum channel width, depth, and bank steepness conditions; establish coordination requirements among adjacent landowners; evaluate cost and effectiveness of alternative bank stabilization approaches; establish preferred approaches; define acceptable circumstances and processes for sediment removal; set general engineering requirements for materials and design; and establish requirements for covering, replanting and maintaining works once completed. This work is to be done by a fluvial geomorphologist/engineer, and standards are to reviewed and revised annually as experience is gained.

3. Annual review is to be made of the full channel by a fluvial geomorphologist and a full flight-line of aerial photos are to be taken each spring to document changes and determine areas that may need protective work before the next season.

4. Snag and tree removal shall be conducted by the management zone annually in summer or fall to remove in-channel debris that can accelerate local erosion or deposition.

5. Technical assistance to landowners shall be provided by the water management district to facilitate state, county, and federal permits needed by landowners for river protection. Additionally, coordination

of efforts among landowners, assistance in design of works, coordination with local government, and assistance with funding shall be provided by the zone.

6. Sponsorship of river protection projects shall be done by the management zone for administration of outside funds where multiple owners are working on a single reach of riverbank. The zone further assumes responsibility for oversight of construction and maintenance efforts.

7. The pre-1967 longitudinal stream profile (post- dam construction) shall be set as a goal for restoration. Erosion of existing bed sediment to that profile shall be facilitated through either natural or controlled-release flows.

8. Maintenance of riparian vegetation shall be a primary goal of a river management program. This is to be accomplished through: a) monitoring the entire riparian corridor annually and sampling for physiological stress at permanent sampling transects, b) planting and revegetation is to be conducted by the zone according to priorities established annually using species that are site-adapted and with costs to be borne partly or fully by the zone, c) providing technical assistance for landowners, d) constructing irrigation systems to be operated and maintained by the zone where necessary, and e) regulating flows to enhance bank storage and groundwater recharge for maintenance of riparian vegetation.

9. Enforcement of standards established by the zone shall be its responsibility, including inspection of flood control works, prevention of removal of desirable vegetation, and prevention of unauthorized grading or bank modification along the channel.

10. Ordinances regulating activities potentially deleterious to riparian systems will require new legislation sponsored by the water management district covering groundwater withdrawal, access, rationing, and river dewatering. These legislative controls will be implemented to regulate the location, timing and amount of groundwater withdrawn for export from the watershed so as to maximize streamflows and minimize drawdowns to maintain and improve the health of riparian vegetation. Groundwater pumping will be regulated to maintain a groundwater table within an effective root zone and to provide instream flows uninterrupted by channel dewatering through overpumping. When water tables are pumped close to the limits of the riparian root zone, rationing may be phased in to minimize negative impacts.

11. Education and research on erosion prevention, vegetation, and grading will be a goal of the management zone.

12. Liability insurance, financial and legal administration, and land trust acquisition of riparian lands and rights-of-way are additionally being considered as responsibilities for the management zone.

Financial implications of such a management plan have yet to be clearly addressed by the water management district. Since taxing powers are vested in the agency and since many costs may be able to be included in the rate base of water users, it is not at all unreasonable to assume that the proposed program can be readily implemented. The proposed riparian management zone authority is to automatically expire after 10 years unless reenacted by the electorate. This 10-year period may well not be sufficiently long to insure retraining and stabilization of the channel, particularly if annual flood events during that time are not optimum for sediment transport without destruction of bank works.

WATERSHED MANAGEMENT

Not yet addressed yet clearly of import for the goals of the water management district is a comprehensive watershed management plan. Sources of sediment can exist in tributaries not protected by dams. Part of the watershed not impeded by dams is underlain by decomposed granitic soils that are subject to massive debris slides when altered through grading or other site changes. Monterey County only recently passed a grading ordinance and it has not yet been tested for adequacy. Large scale development projects involving simultaneous construction of golf courses and multi-unit housing are not uncommon and can contribute to sediment influx and stream-bank alteration.

Natural fire frequencies in the Santa Lucia Range headwaters between 1640 and 1907 averaged one fire every 21 years for any given site (Griffen and Talley, 1981). No fires occurred between 1907 and 1977. Fire suppression in the watershed has set up conditions that led to the disastrous Marble Cone fire of 1977, burning a major portion of the watershed above the dams. If such a fire occurs in the lower watershed, no amount of channel restoration will be effective.

Establishment of a comprehensive watershed management plan, regulating development rates, preventing impairment of permeable areas, protecting critical groundwater recharge zones, reestablishing fire frequencies through controlled burns, and planning experimental reforestation with genetically selected drought-tolerant site-adapted plants are all to be recommended for further consideration.

SUMMARY

The lower 24 km (15 mi) reach of the Carmel River is alluviated, and is divided by a bedrock constriction into a lower 16 km (10 mi) reach and a middle 8 km (5 mi) reach. This alluvial reach of the river has experienced major changes in channel course, pattern, and form over the past 130 years. Major floods in 1862 and 1911 changed the river's course by up to 500 m (1640 ft). After 1914, the absence of severe floods, coupled with dam construction upstream, led to a change from a wide, braided channel to a narrow, more sinuous channel. Accompanying this change was a decrease in overall gradient in the lower reach from .0034 to .0029 between 1911 and 1945.

By 1939, the date of the first coverage by aerial photography, the lower reach had developed a narrow, sinuous channel with well-vegetated banks. The middle reach of the river, however, displayed a predominantly wide, braided pattern. Between 1939 and 1971, this middle reach developed a single thread channel and downcut up to 1.5 m (5 ft).

As groundwater withdrawal from streamside wells increased in the 1960s, residents began complaining that riparian vegetation was dying near the wells. During the 1976-1977 drought, lowered water tables were associated with substantial die-off of riparian vegetation. The death of this bank-stabilizing community is associated with significant lateral erosion that occurred during the winters of 1978 and 1980. Upstream of the Schulte Road bridge, the river's bankfull channel increased in width from 13 m to 35 m, increasing the width/depth ratio from 15 to 113. Downstream, the channel remained stable despite passage of some of the sediment derived from the eroding reaches.

Individual efforts to control bank erosion have included planting of willows and and emplacement of various forms of rip-rap. The mixed success of these efforts demonstrates that a co-ordinated program is needed to manage the river. Most promising as a model for the Carmel is the experience of New Zealand engineers in "river training". Their procedure is to determine design geometries from stable reaches and then re-design disturbed reaches to the design geometry. After initial stabilization using engineering works, riparian vegetation is expected to serve as the primary stabilizing agent.

A river management program, focusing on the riparian zone, has been drafted and is being approved. This effort will emphasize restoration of a design channel, maintenance of riparian vegetation, and restoration of a fishery resource.

ACKNOWLEDGEMENTS

This study was supported by a contract with the Monterey Peninsula Water Management District. Our thanks to the District staff for generous assistance in every phase of the study. We are also grateful for the invaluable cooperation of Monterey County Flood Control, the California Fish and Game office in Monterey, and the Army Corps of Engineers San Francisco District. To the friends who helped with the field work, our thanks. Parts of this paper have been submitted for publication to the University of California, Davis, Riparian Systems Conference proceedings of 1981.

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SPAWNING GRAVEL ENHANCEMENT STUDIES ON
SIX NORTHERN CALIFORNIA RIVERS

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ABSTRACT

As part of the Resources Agency's Resource Investment Fund and the Wild and Scenic Rivers Program, the Department of Water Resources (DWR) is studying spawning gravel enhancement techniques and locating potential new spawning areas in six California rivers (Fig. 1). Three studies have been completed. These are the Sacramento River between Keswick Dam and Red Bluff (Parfitt and Buer 1980), the Klamath River between Iron Gate Dam and Humbug Creek, and the Shasta River between Lake Shastina and the mouth (Buer 1981). Construction of these proposed spawning areas would provide for an additional 16,000 salmon pair. Similar studies are in progress for the Feather River and the Wild and Scenic portions of the South Fork Trinity and Middle Fork Eel.

INTRODUCTION

The anadromous fishery has made a substantial contribution to the Northern California economy for many years, augmenting both the sport and commercial fisheries. However, spawning escapement of salmon in many streams has declined dramatically over the last century. There are many reasons for this, including dams, diversions, overfishing, major floods and droughts, gravel extraction, timber harvesting and attendant watershed degradation. Each river system differs in watershed characteristics and the specific causes of its fishery problems.

The upper Klamath River, the upper Sacramento River, and the Shasta River were once primary chinook spawning rivers. Few salmon now spawn in the reach below Iron Gate Dam on the Klamath River, and Shasta and Keswick Dams on the Sacramento River because the riffles are now armored by cobbles too large for salmon to move. This is due to loss of gravel recruitment from areas above the dams, to channel degradation and to scour of spawning gravel below the dams during high flows. Gravel extraction for aggregate has reduced tributary input. There are similar gravel recruitment problems, high water temperatures, and siltation and irrigation diversions, on the Shasta River. The Feather River below Oroville Dam is now being studied to determine what problems exist there.

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Figure 1. Northern California with darkened circles showing the locations of spawning gravel enhancement and stream geomorphology studies by the Department of Water Resources, Northern District Geology Section.

The South Fork Trinity and the Middle Fork Eel are both wild rivers without dams. Both were among the better salmon and steelhead streams in California and among the few streams in Northern California that support spring-run steelhead.

Both rivers were severely damaged during the December 1964-January 1965 flood. The flood, estimated to be a 100 year event, caused extensive bank failures, landsliding, and stream aggradation. In some areas, severe watershed damage was linked to the cumulative effects of areas logged before the flood (Scott, Buer and James 1979). Twenty to thirty feet of channel aggradation was common after the flood. This reduced the number of summer holding pools, degraded summer steelhead habitat, and silted in spawning gravel.

The fish runs on the Middle Fork appear to be returning but runs on the South Fork have not recovered.

METHODOLOGY

Each river system has its unique problems of hydrology, stream geomorphology and fishery. However, these rivers are similar in that a reduction over historic levels of adequate fish habitat has occurred. As a result of these studies, DWR has developed an investigative methodology for evaluating spawning gravel and enhancement techniques. These techniques are applicable to other salmon spawning streams in California. They include:

1. making an aerial photo atlas of the study reach;
2. compiling historic spawning, channel morphology and watershed data;
3. sampling the spawning gravel using bulk and surface sampling techniques;
4. analyzing streamflow data to determine the hydrologic characteristics;
5. identifying and surveying potential enhancement areas;
6. calculating critical discharge for bedload movement and calculating the gravel bedload budget;
7. recommending suitable enhancement sites.

AERIAL PHOTOGRAPHY

Nine by nine inch aerial photo surveys with a scale of 1:24,000 or 1:12,000 are flown along the river. The photos are enlarged to 1:6,000 for the 11 x 17" atlas sheets. River miles, a scale and a north arrow are shown for convenience.

The aerial photo atlas is used in the field to plot stream survey data, stream meandering, suitable spawning areas, and landslides. In addition, bank protection, blockages, riprap and unstable banks are plotted. To evaluate geomorphic changes such as stream meandering and landslide densities, data obtained from historic aerial photos and survey maps are plotted on the atlas. Historic spawning areas are also plotted where these areas have been located.

ENHANCEMENT SITES

Potential enhancement sites are identified by comparing stream gradients, critical flows, stream morphology, and gravel stability characteristics. The recurrence interval of critical flows determines the advisability of placing imported spawning gravel in the stream channel. The ten-year flood is used as a design criterion. If critical flows occur at less than ten-year intervals, retention structures such as rock or gabion weirs, deflectors, groins or dikes are recommended; instream enhancement is generally not advisable in such a case, and side channel development is preferable.

Side channel enhancement site selection is based on stream morphology, access, available spawning gravel near the site, environmental impact, flood flow routing and excavation needs (Photo 1). Instream enhancement sites are selected according to gravel transport equations and accessibility.

Enhancement sites were surveyed using transit, chain and rod. The cross-sections are plotted and a contour map and longitudinal profile of the channel thalweg for each site is drawn.

Design and construction methods differ between instream and side channel enhancement sites. Instream sites may degrade during flood flows, are generally more difficult to get to, and present problems with using equipment in deep or swift water. Construction requires placement of gravel and retention structures (Photo 2). Side channel sites require excavating portions of the channel and importation and placement of graded gravel. For side channel work, a weir may be placed across the upstream portal to control flows during and after construction. Downstream from the weir, gabions or rock weirs may be placed in a series of steps to create a pool-riffle sequence and control the gradient.

During the fall of 1980, DWR, in conjunction with DFG and CCC, constructed three enhancement structures on the Shasta River. These included a rock-filled gabion weir, a buttressed rock weir and a low rock weir. The purpose was to evaluate the effectiveness of different spawning gravel retention structures during high winter flows. Gravel trapped behind the weirs would also be a measure of gravel movement in the Shasta River. Gravel was also placed behind the weirs to see if spawning would occur. Finally, spawning activity on the emplaced gravel was evaluated. Approximately 3 000 ft^2 of new spawning area was created by this project. No salmon spawned at the site before the project, but an estimated 60 redds were counted in the new gravels in the fall of 1980.

HYDROLOGY AND STREAM CHANNEL GRAVEL CHARACTERISTICS

Stream hydrology is used to plan and design fishery enhancement structures and to determine the gravel bedload budget. Data developed from stream gage measurements include annual yields, mean and peak monthly flows, flood flow frequency analyses, and flow duration curves. Stream flow diagrams were developed for each stream and its tributaries, showing average yields for the four seasons.

The annual yields show the dry and wet years on record. The mean and peak monthly discharges are characteristic of a particular watershed. The hydrographs show large variations in flow, both during and between the years, reflecting the precipitation pattern, snowmelt and watershed characteristics. The peak monthly flow is the highest mean daily discharge for the month. This shows the flood events on record. Stream character and salmonid escapement are affected by these floods.

Flood frequency diagrams are used to predict the flood magnitude expected within a given number of years and to rate the floods that have occurred in the basin. The reliability of these predictions depends on the length of record.

Flow duration curves show the percent of time a specified discharge is equalled or exceeded.

The gravel budget is calculated by comparing hydrology to gravel characteristics, surveyed cross-sections, and other stream properties. These data are used in bedload transport formulas to determine the gravel budget. Using the formulas, critical velocities and the stability of emplaced gravel are also estimated.

Many methods have been used for sampling and evaluating spawning gravel. These include surface sampling, bulk sampling, and freeze cores. Bulk sampling and surface sampling were used for these studies, since freeze cores were too expensive and slow for large project areas.

Sieve analyses and the frequency distribution of the gravel sizes are used to determine the size suitability of the gravel for spawning. Statistical parameters useful for describing sediment samples are then calculated. These include the median, geometric mean, standard deviation, skewness and kurtosis.

The gravel budget is estimated using the Schoklitsch and Myer-Peter and Muller (MPM) equations (Vanoni 1975). Critical transport discharges (the flow where spawning-size gravel begins to move) are estimated by comparing flows with gravel movement and integrating to zero transport. Velocities were estimated using the Manning equation, gaging station data and direct measurements. These velocities are then compared to the Hjulstrom (1935) diagram as another estimate of initial movement (Fig. 2).

The Schoklitsch equation (Vanoni 1975) may be expressed as:

$$G_s = \Sigma i \; pi \; \frac{(25.3)\;(95.56)}{\sqrt{dsi}} \; S^{3/2} \left(\frac{Q}{W} - .638 \; \frac{dsi}{S^{4/3}}\right) IW$$

where G_s = bedload transport in yd^3/yr
pi = weight fraction of sediment samples of a particular size range
dsi = mean diameter of pi in feet
S = energy slope
Q = discharge in ft^3/sec
W = width in feet
I = interval that a particular Q occurred during a 100 day period

The calculation is repeated for the different combinations of pi and Q.

The MPM equation in the foot-pound-second units is:

$$G_s = 9.67 \left[3.306 \left(\frac{Qs}{Q}\right)\left(\frac{D90}{ns}\right)^{3/2} rS - .627\ D_g\right]^{3/2} IW$$

where n_s = roughness coefficient
r = hydraulic radius
D_{90} = gravel diameter at 90th percentile
D_g = mean gravel diameter
$\frac{Qs}{Q}$ = ratio of critical discharge to discharge

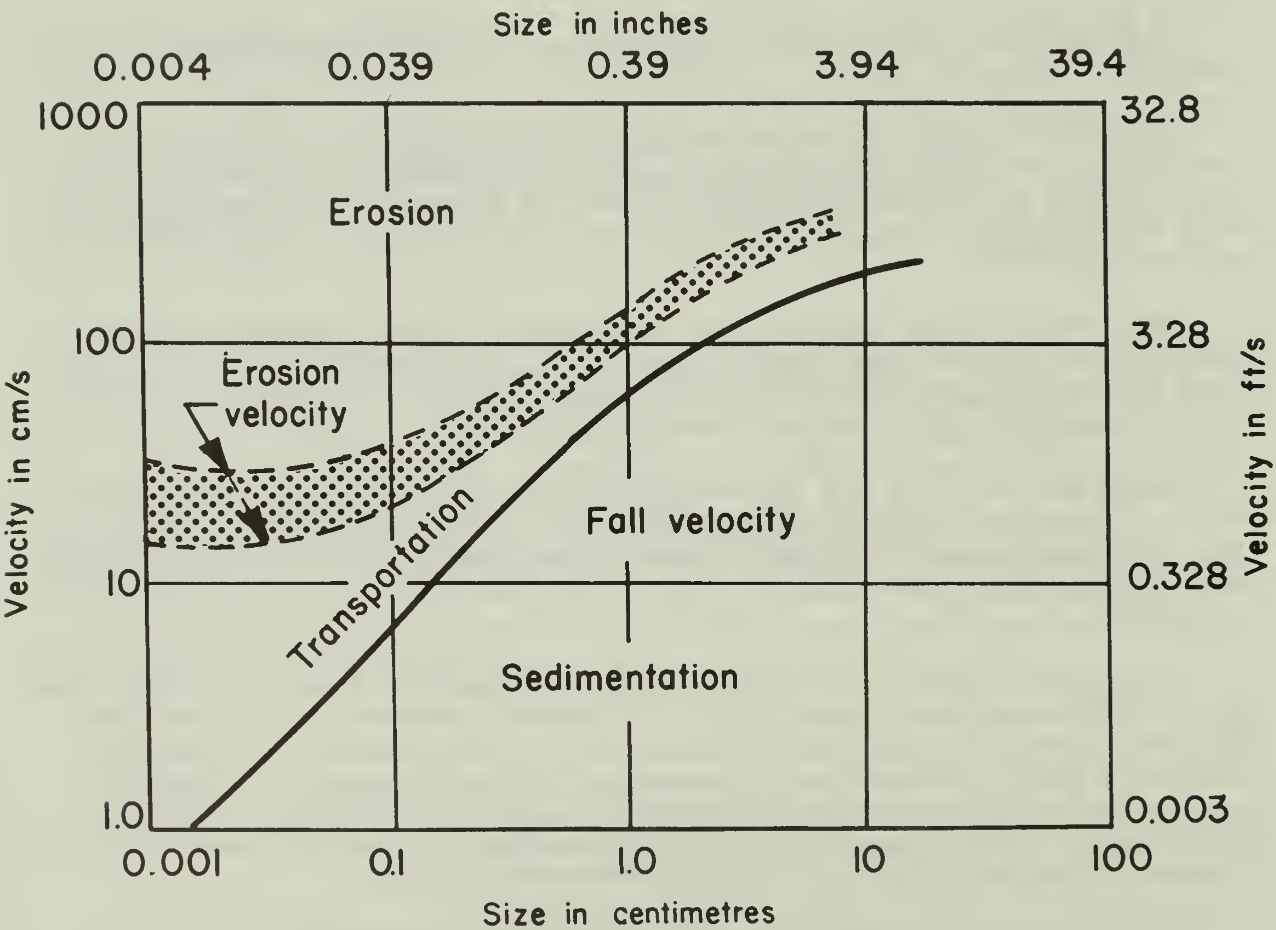

Figure 2. Curves of erosion and deposition for uniform material. Erosion velocity shown as a band. (Redrawn from Hjulstrom 1935)

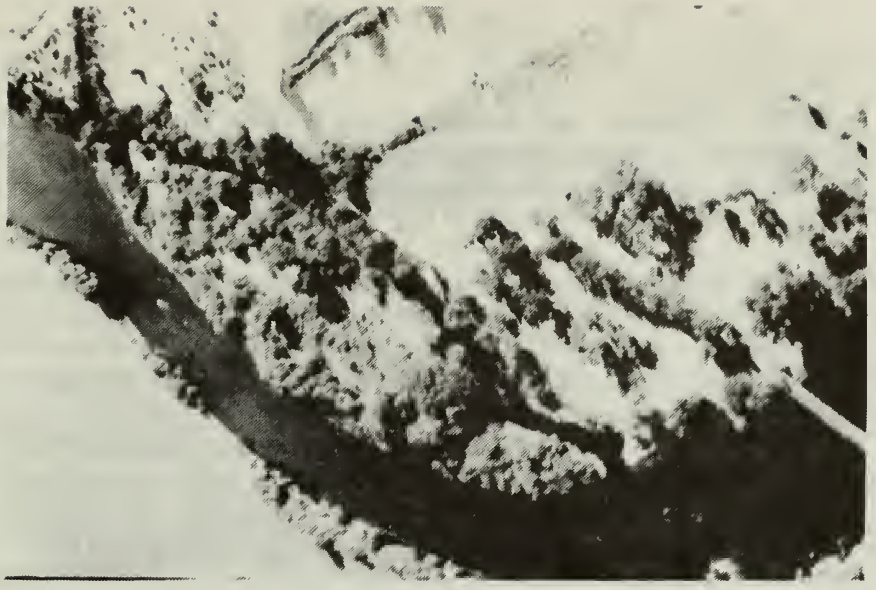

Photo 1 - Potential side channel enhancement site on the Klamath River. The site is protected from high flows that scour gravel in the main channel.

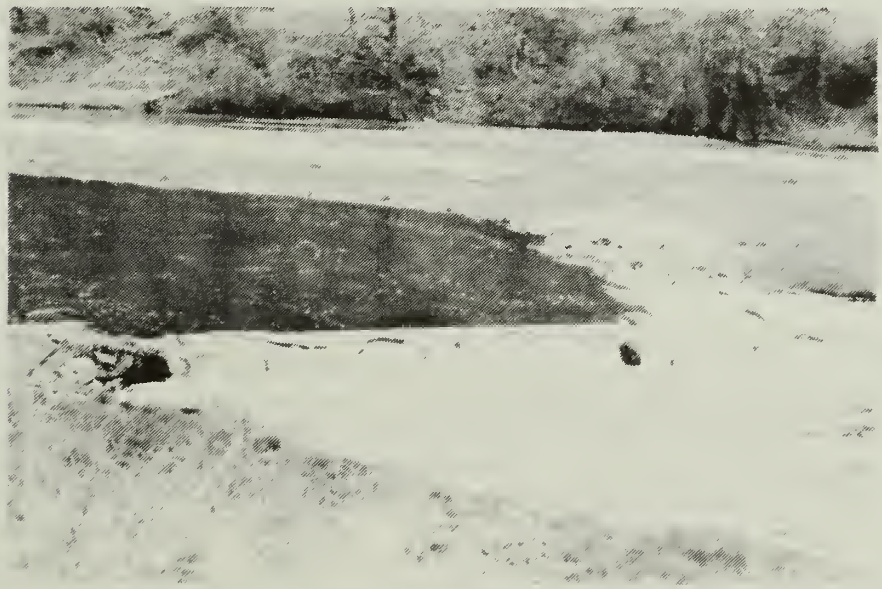

Photo 2 - Salmon Heaven instream enhancement site on the Shasta River. Low gradient and wide channel reduce flow velocities. Gabion was installed to trap gravel and provide additional spawning habitat.

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SIX RIVERS NATIONAL FOREST ANADROMOUS FISH HABITAT RESTORATION AND ENHANCEMENT PROGRAM

KERRY OVERTON, WILLIAM BROCK, JOSEPH MOREAU, JERRY BOBERG [1/]

In 1978, Six Rivers National Forest developed a fisheries and watershed management program aimed at restoring and enhancing anadromous fish populations and habitat. The two objectives for the program are: 1) identify habitat factors that are limiting fish production, and 2) develop and evaluate procedures to restore or enhance chinook salmon (Oncorhynchus tshawytscha) and steelhead trout (Salmo gairdneri) habitat in north coastal California streams. Projects included the placement of gabion weirs, boulders, and egg incubation boxes to create spawning sites, rearing habitat, and fry production, respectively. Biological and hydrological monitoring is being conducted to evaluate the procedures, develop guidelines and determine project cost effectiveness. Direct increases in fish utilization through improved chinook salmon and steelhead spawning and rearing habitat has resulted from the projects.

INTRODUCTION

The anadromous fishery resource in California has experienced a two-thirds decline over the last 35 years (Citizens Advisory Committee on Salmon and Steelhead Trout 1975). The decline has been attributed to degradation of habitat due to watershed disturbances (logging, roads, mining, grazing), floods, drought, impoundments, and increased demand on the fishery. The resource decline is creating severe socio-economic hardships to the north coast with resultant controversy over river, watershed and salmon management. The annual loss of revenue to Northern California has been considerable. In response to the declining fishery and increasing demand for the resource, management agencies have implemented policies and programs to protect existing habitat, restore lost or degraded habitat, and increase artificial propagation.

Six Rivers National Forest has 350 miles of anadromous salmonid habitat with an estimated annual value of 11.2 million dollars (Smith 1978). The primary spawning habitat for chinook salmon (Oncorhynchus tshawytscha) and steelhead trout (Salmo gairdneri) is found within the tributary streams to the main rivers. Inventories have identified a variety of habitat conditions within the Forest, ranging from poor to high quality, and a wide range of use patterns by the different fish species.

The Forest fishery restoration program started in 1978 with two objectives: 1) To identify and correct habitat factors that are limiting fish production; and 2) to develop and evaluate habitat restoration/enhancement procedures suitable for Northern California streams. This paper will describe the results and procedures involved in planning, implementing, and monitoring the projects.

PLANNING. Data on Forest watersheds were compiled from stream surveys to identify possible habitat limiting factors (i.e. sediment problems, lack of

1/ Six Rivers National Forest, Eureka, Calif.

spawning gravels, migration barriers). Based on this information, watersheds were prioritized and monitoring was initiated. Monitoring consisted of establishing "index streams" to identify fish utilization (adult spawners, redd counts, juvenile production) and the quality and quantity of habitat being utilized (i.e. spawning gravel quality, area of nursery habitat). Watershed inventories were initiated to identify continuous and potential sediment sources. Restoration/enhancement plans were then developed from the inventory data.

HABITAT LIMITING FACTORS. Habitat factors necessary for successful salmon and steelhead production have been well documented in the literature (Edmundson et al. 1968; Chapman and Bjornn 1969; McFadden 1969; Everest and Chapman 1972). Four major factors were identified which limit anadromous fish production on Six Rivers National Forest: 1) The lack of both quantity and suitability of gravels for spawning; 2) the absence of instream shelter for juvenile steelhead production; 3) the presence of fish migration barriers; and 4) the lack of adult spawners. The 1964 flood, combined with sediment-producing watershed disturbances are the primary agents responsible for the first three limiting factors.

FISH HABITAT RESTORATION / ENHANCEMENT

SPAWNING HABITAT. Spawning surveys by U.S. Forest Service biologists in Six Rivers National Forest in 1978-1979 identified specific streams where the lack of gravel accumulations were limiting chinook salmon production. The feasibility of creating gravel spawning areas by manipulating the stream channel was explored. This problem had been the subject of several investigations in Pacific Northwest streams. The Washington Department of Fisheries began experiments in 1969 to improve salmon spawning habitat through the use of gabion weirs, rock-filled wire mesh baskets (Gerke 1973). The gabion weirs were placed perpendicular to the flow across the channel. The weirs created gravel beds that were used by several salmon species (Wilson 1976). In some weirs placed perpendicularly to the flow, stress associated with peak storm flows have broken wire mesh, rolled gabions, and routed water around the bank ends of the weirs (Jackson 1974; Engels 1975).

The utility of rock-filled gabion weirs to hold gravel in place or to trap bedload gravel was demonstrated. However, the potential failure of such structures during peak flows prompted further experimentation in design. The "V" shaped weir design, similar to the structures developed in Oregon by Anderson and Cameron (1980), has been shown to reduce the impact of stream energy, lessening the stress on the weir and bank/structure interface.

Six Rivers National Forest began experiments with the "V" weir in 1979, placing 10 weirs in streams tributary to the Smith, Klamath, and Trinity Rivers of Northwestern California. In a detailed study of six of the weirs, single weirs placed at tails of pools were compared with pairs of weirs in series placed in riffles, for effectiveness in trapping bedload material suitable for spawning (Moreau 1981). The predicted weir effect in breaking up monotypic cobble reaches is shown in Figure 1. Weirs with splash aprons were compared to weirs without splash aprons for ability to withstand stresses from high flows in the same study. Monitoring methods included before and after topographic maps, longitudinal profiles, channel cross sections, and bed sampling by two methods:

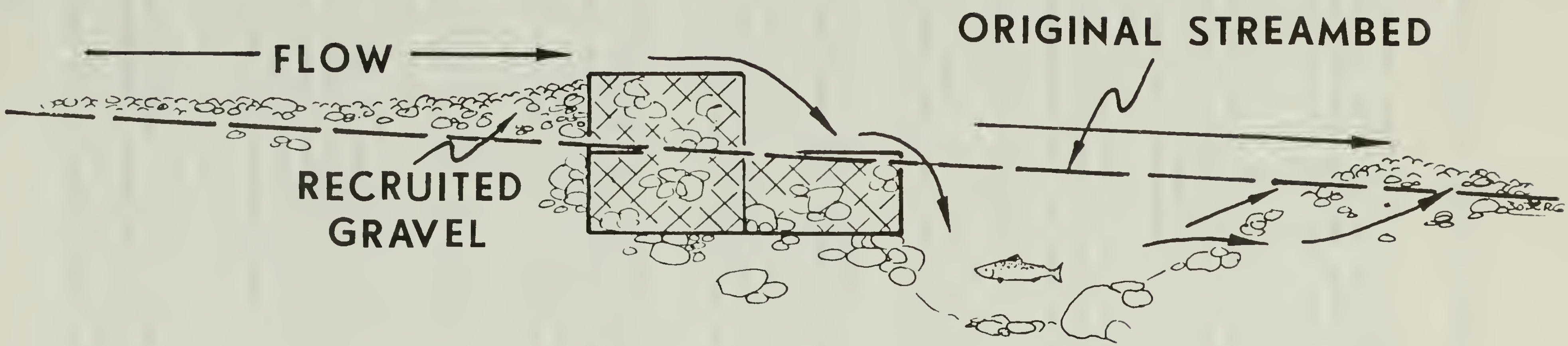

Figure 1. Cross - sectional view of gabion weir with splash apron and the observed streambed changes.

1) Use of a McNeil sampler (McNeil and Ahnell 1964); and 2) Pebble counts (Wolman 1954).

REARING HABITAT. Steelhead trout accounted for greater than six million dollars economic evaluation attributable to Six Rivers National Forest in 1977 (Smith 1978). This factor was the foremost incentive in exploring causes that may be limiting steelhead production on the Forest below optimum.

Many streams on Six Rivers were found to have a limited number of living and hiding places for age one and two year juvenile steelhead parr. This condition has lead directly to a deficient number of adult steelhead elsewhere (Narver 1976). Fry and parr stages are especially critical for steelhead because the operation of density dependent processes largely determines the strength of each year's age class and obviates the operation of other regulatory processes later in life (McFadden 1969). The purpose of this particular project was to rehabilitate rearing habitat of steelhead trout parr in Aikens Creek and Red Cap Creek, Klamath River tributaries, by the introduction of large boulders.

The limiting factor for the carrying capacity of juvenile steelhead is usually physical living space (Narver 1976). This component is modified by food availability which affects, at least indirectly, the population size. Competitive, territorial behavior for space leads directly to its division, and indirectly to division of the food resource among the individuals.

The demand for greater food consumption as a steelhead fry approaches seven months of age motivates the individual to leave shallow, calm side channel habitat and venture into the main flow of a riffle. The new territorial focus is preferably behind a stable object such as a boulder, where swimming metabolic energy is minimized (Chapman and Bjornn 1969). Requirements of depth, overhead cover, and intraspecific isolation can all be met at this type location (Edmundson et al. 1968; Parkinson and Slaney 1975).

In July, 1978, a 450 foot monotypic reach in lower Aikens Creek (summer flow 2 cfs) was divided into three sections: The upper section was left as the control reach; in the middle section large boulders (2-3 ft diameter) were winched into the stream; and in the lower section a combination of boulders and log deflectors were constructed. The work was completed by the U.S.F.S. Youth Conservation Corp.

Population estimates for each section were determined in September of 1979. Each section was blocked off by nets and an electrofishing succesive-removal technique was utilizied to determine fish numbers.

The Red Cap Creek experimental design was to compare fish populations and changes in channel morphology in a stream reach before and after boulder placement, with those of an adjacent control reach of identical length and similar morphological characteristics. The reach was accessible by a front-end loader to place the boulders. The need for rearing habitat improvement resulted from a channel diversion in 1975. Boulders totalling 80 in number were placed singly and in clusters in separate sections within the treatment reach.

Planimetric maps, channel cross-sections, and longitudinal profiles provided data concerning morphological characteristics. Fish population and biomass calculations were a result of intensive electro-shocking. The sampling occurred during the same time of year for two successive years. The time chosen was when stream discharge was least, thereby determining the period minimum carrying capacity.

FRY PRODUCTION. With the ever-increasing stress placed upon natural anadromous fish production, the use of artificial propagation or stream-seeding has become imperative in fisheries management. Recently, more emphasis has been placed on the use of streamside egg incubation boxes as a relatively inexpensive, low maintenance method of fry production. Incubation boxes such as those tested by Zimmer (1964), McNeil (1968), Bams (1970), Lannen (1975), Bams and Simpson (1977), and Allen et al. (1981), have been shown to produce fry which compare favorably in size and condition to wild fry (Bams 1970; Allen et al. 1981), and are generally of greater quality than hatchery fry (Parkinson and Slaney 1975). Incubation boxes have the capability of providing an egg-to-fry survival rate five to ten times greater than natural production.

In 1980, the Six Rivers National Forest anadromous fish program was expanded to include the development of a streamside egg incubation box system which could assist in the restoration or enhancement of chinook salmon and steelhead runs on the Forest. The objectives for this element of the program are:

1. To develop a streamside egg incubation box system compatable with small north coastal streams, which typically have a high silt load and are often unstable.

2. To elevate stream production to its potential in areas where instream improvement projects have increased the quality and/or quantity of available spawning habitat.

3. To restore or enhance stream production where spawning escapement of chinook salmon or steelhead has fallen below historical or potential levels.

The design of the Six Rivers incubation box system [1/] accomodates the following requirements: 1) A gravity flow water system capable of supplying six to eight gpm for each incubation box, with a stilling well filtration system; 2) A portable system of simple design in an easily constructed form with readily accessible materials; 3) A capacity to incubate 40,000 chinook salmon or steelhead eggs on a gravel substrate or on incubation trays; 4) A downwelling system, capable of dealing effectively with varying amounts of silt delivered to the box during the incubation and alevin development period; and 5) A capture or live well to preclude fry escapement for monitoring.

The incubation box is constructed of 3/4 inch exterior grade plywood, eight feet long, 16 inches wide, 21 inches deep, with 2X2 inch internal redwood reinforcing members (Figure 2). The box is tightly covered with a 3/4 inch hinged plywood top. The interior of the box is divided by baffles into three chambers: an incubation area; an outlet well; and a capture or live well. All seams and joints are glued and fastened with screws. The interior and exterior of the box are resin coated.

Water is diverted from an intake filter to a series of stilling wells by gravity (Figure 2). The water supplied from the end stilling well to the incubation box is controlled by a gate valve. The flow direction is downward through the incu-

1/ Initial Design by Dave Miller, Aquatic Biologist Simpson Timber Co.

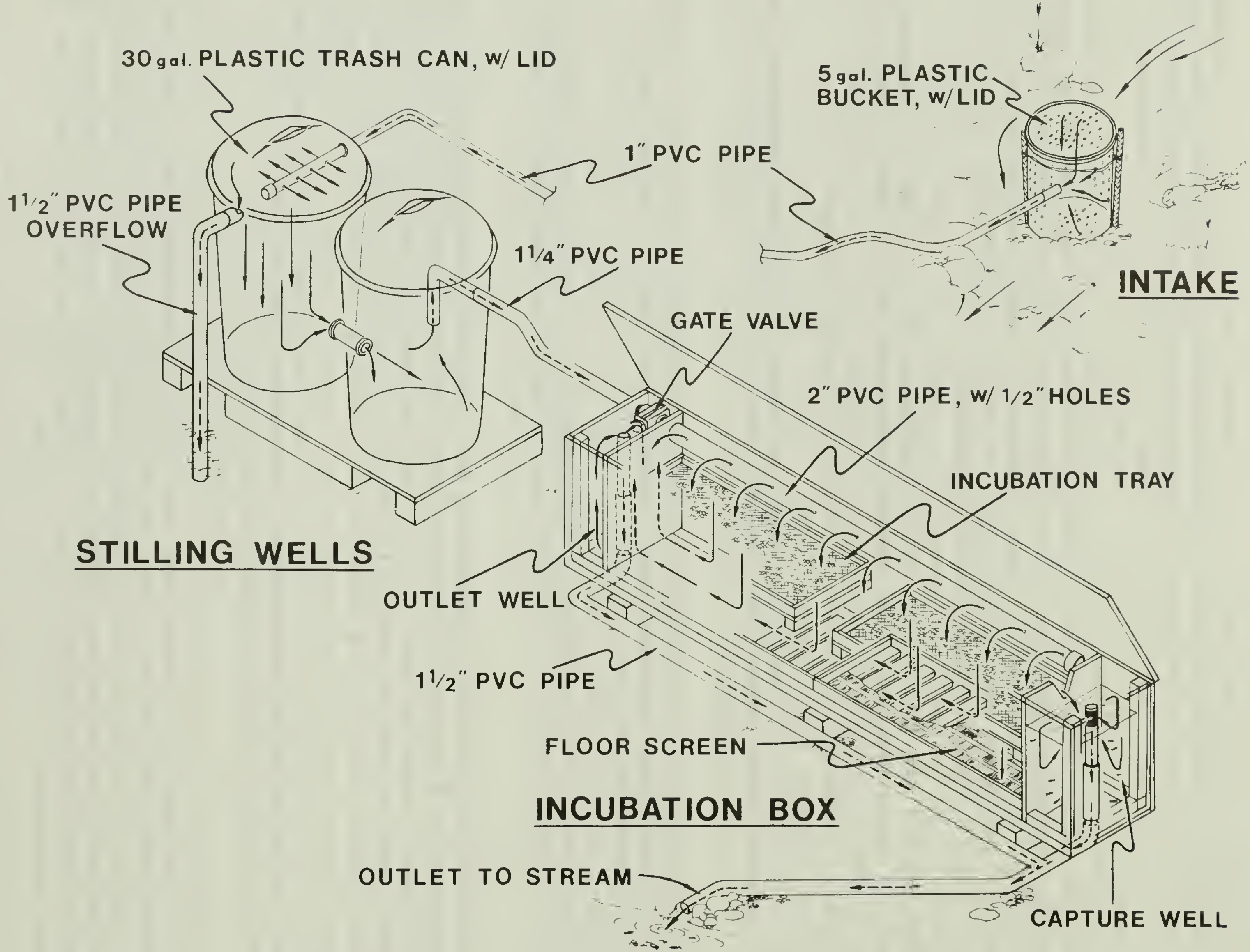

Figure 2. Diagrammatic view of the salmon and steelhead egg incubation box system.

abtion area, passing through a layer of eyed eggs resting on Vexar 1/ screen trays. The flow pattern continues through the floor screen and exits through the standpipe in the outlet well. Water may also exit the system through the screened standpipe in the capture well. The screened standpipe is removable for releasing fry.

Initially, three experimental sites were developed to assess methods, design,and fry survival rate of the proto-type downwelling incubation box. The sites included Quartz Creek, tributary to the South Fork Smith River; Red Cap Creek, tributary to the Klamath River; and the upper Mad River. Because site development was initiated in late fall of 1980, steelhead eggs were all that were available for the preliminary assessment.

FISH MIGRATION BARRIERS. Numerous miles of suitable habitat for anadromous spawning and rearing is not accessible because of log debris jams, boulder roughs and bedrock falls. Annually, existing and potential barriers are examined for removal or modification. Barrier assessment involves snorkel surveys, carcass counts, and habitat evaluation above and below the barrier. This information determines what will be gained in fish production by barrier removal.

Caution has to be exercised when dealing with woody debris jams. The instream bioenergy, instream shelter, and the physical make up of the channel is often governed by woody debris within the stream (Cummins 1974; Swanson 1978). Access is generally a problem as most barriers are remote. Helicopters, portable drills, explosives and man-power crews are the primary components for completing the work. Debris jams are modified to either ensure fish passage, eliminate bank erosion problems, or prevent future barriers. By cutting and/or cable anchoring of large key logs, and removing small debris, the debris jam can be stabilized and shaped to provide for fish passage, instream shelter and bank protection.

WATERSHED RESTORATION. Several drainages have sediment yields greater than the stream's transport capabilities. This is confirmed by measurements in embeddedness, pebble counts and substrate sediment composition. Watershed restoration designed to reduce sediment yields to near natural levels, will result in increases of fish habitat and augment inchannel habitat improvement projects. Inventories of entire watersheds are conducted to identify continous and potential sediment sources. An evaluation is conducted to determine if the source is treatable (i.e. determination of access, costeffectiveness of proposed treatments, and benefits accrued), and how it relates to other sediment sources. A restoration plan is developed, all sources are prioritized and the route of funding and implementing the projects are determined. The majority of the projects consist of structural and vegetal means of reducing sediment. Project monitoring is completed by photoregression and streambed sediment determinations above and below the sediment source.

RESULTS AND DISCUSSION

SPAWNING HABITAT. All gabion weirs trapped bedload, but the suitability of the trapped bedload for spawning, and the area of suitable bed material varied among the weirs. The quantity of bedload deposition appeared to be dependent on local

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hydrologic features (channel width and slope), rather than variation in weir design. Five of the six weirs trapped gravel after initial fall, 1979 storms, but a subsequent flood estimated at a five to seven year recurrence interval occurred in January, 1980. The flood apparently created beds of larger rock not optimally suited for spawning at two of the five weirs which had originally trapped suitable gravel. Chinook salmon spawning had occurred at five weirs prior to the January, 1980 flood. Weirs with splash aprons were apparently no more stable than weirs without splash aprons, but differences, if they exist, may become apparent after several years. Weirs settled in response to peak flows and leaned downstream, but no structures were destroyed. Scour channels occurred around the bank ends of two weirs which had not been adequately riprapped. After two winters, two of the weirs continue to provide significant areas of frequently utilized spawning gravel for chinook salmon and steelhead trout, while a third weir provides a small gravel area.

With knowledge gained from the first series of treatments, a spawning riffle utilizing a pair of "V" weirs with splash aprons was created in August and September, 1980. Approximately 220 cubic yards of graded gravel were placed at the site. After the gravel had rearranged from winter flows, the majority of it was between the two weirs. The total gravel area was then approximately 2,500 square feet. Chinook salmon and steelhead trout were observed using this area for spawning from November, 1980 to March, 1981. Table 1 describes the observed spawning benefits and project costs for Patricks Creek.

The projects of 1979 and 1980 have demonstrated that the "V" -shaped gabion weir is a useful management tool for providing spawning gravel. Monitoring of these completed projects will continue to determine the life span of the structures. Additional gabion and boulder weir projects are currently in the planning stage, and will be installed in selected streams on the National Forest.

Table 1. Project costs, observed spawning and monitary benefits are listed for the Patricks Creek spawning restoration projects.

YEAR	Structures Built	Cost	Observed Spawning	First Year Benefit*	Second Year Benefit
1979	Three Gabion Weirs	$5,000	7 Salmon Redds	$2,800	
			7 Steelhead Redds	$1,400	
			7 Salmon Redds		$2,800
			12 Steelhead Redds	$2,400	
1980	Two Gabion Weirs Graded Gravels	$18,000	8 Salmon Redds	$3,200	
			18 Steelhead Redds	$3,600	

Total Cost = $23,000
Total Benefit to Date = $16,200

* The above benefit figures are based on 1980 net economic values of approximately $200.00 for a chinook salmon spawner and $100.00 for a steelhead spawner (Smith 1978 values modified to reflect 1980 values).

REARING HABITAT. The Aikens Creek project resulted in a two-fold and a four-fold increase in juvenile steelhead numbers in the boulder-only section and the boulder-log section, respectively. There was a marked increase in age 1+ steelhead trout in the treated section.

Table 2 describes the results of the Red Cap Creek project. Stream surface area increased 7% and stream flow volume decreased 20% during the year in the control reach for a discharge of 26 cfs, as the channel became wider by 5% and shallower by 25%. The treatment reach uniformly increased 18% in surface area due to lateral erosion. Streamflow volume increased by 75% in the treated section where boulders were placed in clusters. The increase in pool stilling area averaged 1.10m^3 per boulder.

Table 2. Production of Steelhead Parr (age 1+ years), and stream morphology characteristics of Red Cap Creek. Data is per 100 feet (30.5 meters) section of respective reach. Data for boulder cluster section is used for treatment reach.

	Stream Morphology		Fish Production			
	Surface Area	Volume	Relative Biomass		Absolute Biomass	Population Estimate
Control Reach	m^2	m^3	g/m^2	g/m^2	grams	
Sept. 1979 (Q= 26 cfs)	284	85	2.18	7.26	610	20 (17-23)
Sept. 1980 (Q= 26 cfs)	297	65	1.28	5.69	381	13 (11-15)
Per-cent Change	5%	-24%	-41%	-22%	-38%	-35%
Treatment Reach						
Sept. 1979 (Q= 26 cfs)	326	65	0.77	3.80	254	9 (+0)
Sept. 1980 (Q= 26 cfs)	384	114	2.74	9.27	1,054	27 (25-29)
Per-cent Change	18%	75%	256%	143%	315%	300%

The control reach population of steelhead parr (age 1+) in 1980 was 35% less than in 1979. The section with boulder clusters in the treatment reach exhibited a 300% increase in number of parr comparing 1980 to 1979.

The control reach decrease in relative biomass of age 1+ parr of 41% per surface area and 22% per volume, are similar to the decrease of 38% in absolute biomass. The increase in absolute biomass of 315% in treatment reach parr, boulder cluster section, was greater than the 256% and 143% increase in relative biomass per surface area and volume, respectively.

Two sections where boulders were placed singly failed to produce desirable results the first year. Boulders were removed from one section and buried in channel aggradation in the other. The buried boulders were uncovered in the 1980-81 winter flows and are now providing rearing habitat.

Expenditures for the entire projects summed to $2,305. A benefit-cost analysis was calculated using a procedure developed by Ward and Slaney (1979). The analysis was calculated for the successful boulder cluster section. The initial cost must be included, and monetary values for returning adults and repeat spawners were derived by methods determined by Everest (1977). Beginning with four year old spawners, a benefit cost analysis (values discounted at 10%) after 10 and 20 years was 0.92 and 2.11, respectively.

FRY PRODUCTION. The egg incubation box systems at all three sites functioned favorably. Two of the systems experienced only minor problems, while the other suffered no difficulties. Approximately 1,800 mortalities were incurred at the Quartz Creek site due to a fungal infestation. From the 7,000 eggs placed in the Quartz Creek box, approximately 4,950 fry were produced and released, an egg-to-fry survival rate of 71%. The only difficulty at the Mad River site was the reduction of the outlet flow, due to a partially blocked pipe. The restriction of the outlet caused the box to over flow, losing approximately 900 fry. Approximately 8,850 fry were produced and released at the Mad River site from 10,051 eyed eggs stocked, yielding 88% survival. From 10,085 eyed steelhead eggs stocked in the Red Cap Creek box, 9,875 fry were produced and released -- a survival rate of 98%.

The preliminary assessment of the Six Rivers incubation box appears favorable with regard to cost, functional design and egg-to-fry survival. An initial investment of approximately $2,500 was incurred for each incubation box system, including site development, monitoring and maintenance. Each system has the capacity of producing 30,000+ fry annually. With the initial cost pro-rated over a probable life expectancy of five years, the cost per fry produced is approximately $0.02. The initial design of the downwelling system appears functional and easily maintained. The water supply system proved to be stable and handles fairly high silt loads adequately. Much of the research into fry production using incubation boxes maintains that a rugose substrate is a necessity for the development of high quality fry. However, most of these investigations have dealt with pink, chum or sockeye salmon fry production. McNeil and Bailey (1975) point out that there are indications that chinook salmon alevins may be better adapted to conditions in smooth substrate incubators. This may also be true with steelhead alevins. This preliminary study did not deal with size or quality of fry produced, only survival. A comparative study of the effects of a rugose versus smooth substrate on chinook salmon and steelhead fry quality will be initiated in the fall, 1981.

FISH BARRIERS. The removal of two fish barriers by the use of an Alaskan Steepass fish ladder and the blasting of a side channel around boulder roughs has resulted in an additional 60 miles of habitat made available for steelhead trout. Modification of 35 debris jams eliminated bank erosion problems and potential barriers; while creating rearing habitat by adjusting and stabilizing log debris to form instream shelter and pools. Thorough evaluation of each barrier or debris jam must be completed to ensure that long-term channel damage does not occur from jam removal.

WATERSHED RESTORATION. Watershed restoration projects to date have resulted in revegetating approximately 200 acres of bare erodible soils. The work has consisted of reducing sediment production from two major landslides and several road fill slopes. The Forest has currently inventoried 150,000 acres in search of problem sediment sources, with a continuing annual objective of 60,000 acres.

Benefits accrued from these projects have resulted not only in reduction of sediment delivered to the channel, but also include benefits to wildlife, timber, and soil productivity.

SUMMARY. The goal of Six Rivers National Forest is to increase anadromous fish habitat by 25% over the next five years, as well as improve the quality of water produced within Forest watersheds. The pilot projects discussed above have demonstrated that procedures do exist for restoring and enhancing habitat. These procedures are currently being utilized to develop total watershed plans to restore and enhance anadromous fish habitat and populations.

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AQUATIC RESOURCES REHABILITATION PROGRAM REDWOOD NATIONAL PARK[1]

Terry Hofstra

Abstract. Development of the aquatic resources program at Redwood National Park has departed from traditional fisheries enhancement programs. National Park Service policy provides for a balanced, self-propagating community that is representative of the undisturbed system. No one species or group of organisms is managed to maximize production. Therefore, the program seeks to determine existing conditions and to investigate linkages between biological and physical factors of stream systems.

INTRODUCTION

In 1978 Redwood National Park was expanded by approximately 48,000 acres. The expansion legislation, Public Law 95-250 also directed that a rehabilitation program be developed for these newly acquired lands which had suffered the adverse effects of timber harvesting and road construction (Agee, 1980).

The major thrust of the early rehabilitation program was to control erosion within these new areas (USDI, NPS, DSC, 1981). As such the rehabilitation staff was composed almost entirely of physical scientists. However; as the program developed, restoration of other ecosystem components were considered and therefore other specialists were added to the staff. The aquatic resources portion of the rehabilitation program began in mid-1980.

The purpose of this presentation is not to provide specific data on the early work of the aquatic program but rather to briefly outline the framework within which the aquatic resources program at Redwood National park (RNP) has developed. The program itself may be a departure from what might have been expected; that is, a fishery enhancement program aimed at maximizing production of anadromous salmonids. Certainly these resources have suffered from intensive land use. Techniques that have been developed to provide artificial spawning and rearing areas have contributed significantly to the maintenance and enhancement of salmonid populations in the Pacific northwest. Usually the lead in the development and implementation of these techniques has been taken by Federal land management agencies mandated to provide multiple uses of the resource under their jurisdiction. Each legitimate land use may affect another; for example, logging can directly impact the successful use of streams by fish that contribute

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to sport and commercial industries. To allow timber harvest and still provide for the maintenance of fish stocks often requires intensive management. Agencies like the U. S. Forest Service have had great success in developing programs that will enhance fish production in the shortest possible time.

In contrast, National Park Service (NPS) Policy (USDI, NPS, 1978) indicates that management will provide for a balanced, self-propagating community of organisms representative of the natural, undisturbed system. Multiple use is not a factor and no one species or group of organisms is managed to maximize production. Where other agencies may choose to populate a historically barren stream as mitigation for damage elsewhere, NPS policy would preclude such an action. Furthermore, management policy states that the need for regulating animal populations shall be documented and evaluated by research studies. The aquatic resources rehabilitation program has developed within this framework for management.

DETERMINATION OF EXISTING CONDITIONS

Rehabilitation implies resource damage and knowledge of existing conditions. Therefore, before alternatives for in-stream rehabilitation can be developed, existing conditions of the various environmental components must be determined. Aquatic invertebrate and fisheries studies have comprised the early program.

Invertebrate Studies

Aquatic invertebrate studies were the first investigations begun. The objectives of the studies are to determine the species that may be found in the park; to determine their availability as fish food organisms within various streams; to determine if certain community structures are representative of particular stages of watershed recovery; and to use invertebrates as indicators of the effects of watershed rehabilitation on aquatic resources. Artificial substrate samplers were selected after analyzing the advantages and disadvantages of other sampling techniques (Harrington, 1980). Our data indicate, as have previous studies, (Ferreira, 1976) that the composition of the sample more nearly represents the composition of the invertebrate community at the site. Further, the size, shape, and substrate used in the sampler can be modified dependent upon stream characteristics or experimental design (Harrington, 1981).

The first year's work involved general surveys. These involved placing samplers at several locations within tributaries in different stages of recovery and the mainstem of Redwood Creek allowing them to incubate for six weeks, collecting the sample and storing until analyzed. About half of our time was spent in surveying the Prairie Creek drainage. These data will provide background information that will be used in evaluating the impacts of a proposed U. S. Highway 101 Bypass around Prairie Creek State Park (USDI, NPS, DSC, 1981). Initial data indicate differences in community structure between and among the various streams but no definitive conclusions can be drawn until all of the samples can be analyzed.

This year's work has been more of an experimental nature. The objectives are to determine the effects to the invertebrate community of a specific rehabilitation project that involves removing fill from stream channel crossings. The acute impacts to community structures as well as patterns of recolonization in the new channel are being determined (Harrington, 1981).

Fisheries

To understand the rehabilitation potential of a watershed in terms of its fisheries resources it is necessary to understand how each life history stage of the species in question may be affected by that watershed. With anadromous fishes it is helpful to consider the watershed as a pair of "subsystems" representing requirements of 1) spawning; and 2) rearing habitat. Both of these subsystems acting on the different life history stages of fish determine the overall success of a watershed to produce anadromous salmonids.

The first step in evaluating potential rehabilitation of spawning habitat is to determine the tributaries that are accessible to adults and to evaluate whether barriers to migration are natural or man-caused. Within the context of NPS policy, streams with natural barriers would not be considered to have rehabilitation potential for anadromous salmonids; however, man-caused barriers may be removed. Once the streams that are available or that can be made available for spawning have been selected then a survey is conducted of the quality of the spawning habitat. This is usually a qualitative analysis of gravel composition but may be followed by more quantitative sampling. Finally, adult spawner surveys should be conducted on streams being considered for rehabilitation to determine actual use of the "assumed" spawning areas by adult fish.

The rearing habitat subsystem can further be divided into the upstream component and the estuary component. Where chinook salmon may be present an evaluation of estuarine conditions is considered essential (see Reimers, 1973). Upstream rearing areas are best evaluated during summer when factors such as temperature and flow may be most limiting. Estuarine conditions should be evaluated during the same period when maximum utilization of the area by juvenile chinook might be expected. The estuary should, however, also be evaluated in the fall and winter months when up-migrating adults may be utilizing the area.

Two studies have proven to be particularly important in providing insight into the existing quality and rehabilitation potential of spawning and rearing habitat within the Redwood Creek basin. These are a basin-wide nursery area study and the Redwood Creek estuary study. The nursery area study involved electrofishing the tributaries and mainstem of Redwood Creek during summer low flow conditions noting distribution and relative abundance of fish present. Dissolved oxygen, temperature, and conductivity were also measured in the tributaries in order to identify limiting conditions. Each tributary was surveyed in this manner in an upstream direction until a barrier to fish migration was encountered. The type of barrier, natural or man-caused, amount of cover, and substrate conditions were noted. This study (Anderson and Brown, 1980) while still incomplete provided information on streams available for spawning, whether barriers were natural or man-caused, a qualitative survey of the quality of available spawning habitat, and an analysis of the quality of upstream rearing areas. Another related survey to be conducted this summer, is a summer steelhead survey of Redwood Creek.

The estuary study was designed to gather information relating to existing and potential estuarine productivity. The study was composed of three general parts designed 1) to determine seasonal patterns in changes of water quality; 2) to determine and compare present patterns of inundation, seasonal morphological changes, and sediment sources with historic information; and 3) to determine abundance, distribution, and seasonal timing of use of the estuary by fish species. Preliminary data being obtained from this study indicate that the estuary is serving to limit production of chinook salmon in the watershed and that the development of rehabilitation alternatives is warranted. A more detailed discussion of this study is also being presented elsewhere at this symposium (Ricks, Larson, Salamunovich, 1981).

With initiation of spawning ground surveys to begin this fall in selected tributaries, studies will have begun on each of the watershed "subsystems" important to anadromous salmonids.

Other Studies

In forested streams with closed canopies, allocthonous material derived from the terrestrial environment is the major source of energy upon which stream biomass is dependent and limited (Fisher and Likens, 1973). The form in which this material is made available to aquatic organisms contributes to determining community structure. That is, food resources of differing sizes and ages contribute to variations in community structure (Reice, 1980) (Merritt and Cummins, 1978). Further, sediment transport, stream geomorphology, and other physical factors also affect aquatic community structure (Rabeni and Minshall, 1977). It is hypothesized that it is the interaction of a set of these factors with available energy resources which result in a given stream community structure (Vannote, et al., 1980).

Therefore, in order to fully understand stream community dynamics it is necessary to integrate biological and geomorphological studies. Because many of the events that bring about changes in aquatic systems in small coastal streams are episodic, such studies must necessarily be long term in nature. Such an investigation is beginning at the park (Hofstra, 1981). Permanent study reaches will be established in headwater streams within an old-growth redwood forest, a cutover area within which a stream buffer strip is retained and a cutover area in which no buffer strip is retained. The results of such a study should allow us to determine the "hows" and "whys" of biological changes by identifying and quantifying the linkages between biological and physical factors controlling stream structure within the redwood forest region.

CONCLUSION

Aquatic resource studies within Redwood National Park have concentrated on determining existing conditions. Data gathered from these studies should provide the basis for making decisions regarding the level of aquatic resources rehabilitati feasible within park streams. Other factors also need to be considered. For example, preliminary indications are that chinook and coho salmon populations are significantly depressed within the park. But, do we provide artificial spawning areas with the knowledge that the success of returning fish or out-migrating juveniles may be compromised by estuarine conditions? Or, are the numbers of fish present representative of what the watershed can support at this time and any fishery enhancement activities would necessarily require long-term maintenance or other commitments? Park Service management policies require careful consideration of such questions before implementing such major resource management activities.

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ALTERNATIVES FOR RESTORATION OF ESTUARINE HABITAT AT THE MOUTH OF REDWOOD CREEK, HUMBOLDT COUNTY, CALIFORNIA

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Abstract. Aggradation at the mouth of Redwood Creek has resulted in loss of productive estuarine and slough habitat throughout most of the year. At present, the timing of juvenile salmonid migration does not correspond with high invertebrate productivity which is dependent on estuarine conditions, substrate stability, and algae growth. During low flows, the sloughs are usually inaccessible to migrating salmonids. Aggradation of the sloughs has resulted from construction of flood control levees completed in 1968 and is compounded by the large upstream contribution of sediment. Rehabilitation alternatives include restoration of the natural circulation pattern, sediment removal, and control of water level.

INTRODUCTION

The mouth of Redwood Creek is located approximately 4.0 river km west of Orick, California. The relatively narrow floodplain is periodically inundated due to steep basin gradients, intense storms and rapid runoff characteristic of the region. The series of damaging floods in 1950, 1953, 1955, and 1964 prompted channelization of Redwood Creek in the vicinity of Orick. The downstream portion of the levee bypasses the last meander and diverts the flow directly to the ocean. Deleterious effects of restructuring the channel include loss of riparian vegetation, accumulation of sediment in areas which were previously viable fish-rearing habitat and isolation of productive slough areas.

The anadromous fishery of the Redwood Creek watershed has experienced a substantial reduction which is documented for the last 15 years by records available from Humboldt County Prairie Creek Fish Hatchery (Sanders, personal communication). Part of this decline is related to the degradation of salmon spawning and rearing habitat in the Redwood Creek basin. However, alteration of the estuarine environment has also adversely affected the fishery. The estuary serves as a transition zone between freshwater and saltwater environments and plays a crucial role in the lives of adult and juvenile salmonids.

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In order to gain a better understanding of existing estuarine productivity and governing physical processes, physical and biological studies were initiated at the mouth of Redwood Creek. These studies included water quality monitoring; determination of seasonal patterns of distribution and use by anadromous salmonids; determination of types and relative abundance of fish food organisms; and determination of historic and present patterns of inundation, sediment accumulation, flow, and general estuarine morphology. Such information is prerequisite to considering the feasibility of developing rehabilitation alternatives for the estuary. It also provides baseline data which will be used to evaluate the effectiveness of rehabilitation efforts.

HISTORIC CHANGES IN MORPHOLOGY

The original channel of Redwood Creek meandered to the south, turning to create an eddy against the north cliffs (Figure 1). Local residents indicate the water depth was at least 20 feet in this area before levee construction. Sediment was deposited extensively across the floodplain during overbank floods, but the channel areas were scoured. The infamous December, 1964 flood removed the entire beach from near the north cliffs to the Cal Pacific mill site. The abandoned channel on the north side of the floodplain (north slough) and the middle overflow channel were also flushed periodically.

Following the December, 1964 flood the Army Corps of Engineers finalized channelization plans for the lower 5.3 km reach of Redwood Creek. Construction of the levees was completed in September, 1968 (Figure 2). The direct and immediate effects included removal of riparian vegetation, destruction of pools and riffles, increased channel gradient, decreased substrate stability and alteration of the circulation pattern. Loss of circulation in the last meander created a south slough and the main flow was confined to a straight exit.

Other effects developed cumulatively, resulting from natural marine sedimentation interacting with the changed fluvial system. Tidal currents, overwash, and dispersal of river-borne sediment have filled (aggraded) the neck of the south slough by 3-4 m. Aggradation has resulted in isolation of the two sloughs and loss of access to the only undisturbed habitat remaining at the mouth.

The crest of the sand spit or berm has grown by 1.4 - 1.8 m since the 1964 Army Corps survey. This barrier prevents saltwater intrusion by overwash across most of the spit. Estuarine conditions develop only following periods of high ocean swells in late summer or early fall when saltwater enters through the mouth outlet or washes over the low berm on the north side. According to Pritchard (1967), an estuary is a semi-enclosed body of water which has a free connection with the open sea and within which sea water is measurably diluted with freshwater. Prior to channelization, more opportunity existed for a free connection between the ocean and embayment (Figure 1). The lower berm, lower channel gradient, and deep water area near the north cliffs suggest that historically there was considerable saltwater intrusion and estuarine conditions were prevalent. Thus, the levees have altered circulation such that presently no true estuary exists at the mouth of Redwood Creek.

Figure 1. Mouth of Redwood Creek in August, 1962, showing original channel with meander. Note outlet position on south side of the beach.

Figure 2. Mouth of Redwood Creek in May, 1978, showing flood control levees which were completed in October, 1968. Note sediment accumulation in the necks of the north and south sloughs.

SEASONAL CHANGES IN MORPHOLOGY

It is important to consider short-term or seasonal variations when comparing historic photographs and surveys with the present mouth configuration. Changing fluvial discharge and wave climate determine the seasonal progression of mouth morphology. High winter flows scour a channel which exits along the rocky north side of the beach. The north and south sloughs are connected to the main channel during high discharge.

In the spring, decreasing discharge allows waves at high tide to diffract around the south margin of the outlet. Waves deposit a lobe of sand on the back side of the berm which builds into the deep water embayment. Summer swell waves build up the beach face also. Under certain conditions this may be accompanied by migration of the creek outlet to the south. Longshore currents are produced by prevailing north-northwest winds. When high swells are actively transporting sand, these currents are effective in driving the longshore drift to the south. Migration progresses episodically and rapidly during conditions of north winds and swells. Waves deflect the channel against the southeast bank of the outlet, eroding the bank while depositing a sill on the northwest side. Wave swash (overwash) also aggrades the channel bed, raising it above the previous level. This process restricts the rate of outflow and results in the formation of a large embayment when rates of outflow, seepage, and evaporation are less than inflow. Continued wave swash may close the outlet and extend the berm further into the embayment. With expansion of the embayment, the south slough becomes connected when water levels exceed 1.1 m. The north slough remains inaccessible until water reaches the 1.2 m level.

Frequent slough flooding is a relatively recent problem as evidenced by the encroachment of rushes (*Juncus*) onto pasture lands. The highest backup of water ever observed by local residents occurred in January, 1981, just before the berm was eroded naturally. This problem may be due to aggradation in the slough areas and a higher berm. Also, the rate of seepage through the berm may be less than in the past. This could result from a shift to smaller sizes of sediment being transported from the Redwood Creek basin later in the year. High water levels induce local ranchers to breach the sand berm prematurely, sending fish and invertebrate fauna out to sea.

INVERTEBRATE PRODUCTIVITY

Redwood Creek, from the Highway 101 bridge to the mouth, can be characterized as "macrobenthically" poor. Low productivity from November through July, 1980, overlapped periods of peak downstream migration of juvenile chinook salmon (*Oncorhynchus tshawytscha*) and steelhead trout (*Salmo gairdneri*). The sloughs appear to support greater invertebrate production throughout the year. Although not showing any significantly greater diversity than the creek, the sloughs (especially the south slough) seem to provide for large biomass. This secondary production is limited to the margins and shallow portions of the sloughs. Hester-Dendy multiple plate sampling results indicated that organisms are not found in or on the substrate of the deep waters of the sloughs at least during late summer through early fall. It is not known whether this is a reponse to some limiting factor, though oxygen tensions are minimal to nonexistant in these "amacrobenthic" areas.

During the benthos sampling periods, there was an exeception to the poor secondary production of the lower creek. This was the appearance of extensive populations of the amphipod Corophium. These tube-building detritivores attained biomass levels that may be as high as any in the Redwood Creek watershed (13.4 g dry wt/m^2). The factors responsible for this crustacean bloom seemed to be linked with benthos stabilization and primary production of the filamentous algae, Cladocera. High winter and spring flows keep the substrate in constant motion. Once high creek flows have subsided, the capacity to transport material is diminished, and a stable substrate is created. In late June, 1980, an enclosed embayment became contiguous with both sloughs. This coincided with the reproductive cycle of the two species of Corophium. Corophium salmonis, which prefers a finer silty-mud substrate, and C. spinicorne, which tolerates a coarser sand substrate, established mixed populations within the new habitat (McCarthy, 1972). Unfortunately, the embayment was drained July 2, 1980 before any extensive sampling could be performed. However, within a month of the breaching, the embayment was reestablished and the macrobenthos was monitored. C. spinicorne dominated the populations upstream from the end of the levees, achieving a maximal biomass of 11.35 g dry wt/m^2. Mixed Corophium populations in the embayment reached biomass levels ranging from 1.4 - 13.4 g dry wt/m^2, 1.4 - 12.7 g dry wt/m^2, and 0.8 - 4.8 g dry wt/m^2 for the dates August 22, September 22, and November 1, respectively. The decreasing biomass is more a result of the dominance of smaller immature amphipods than decreases in individuals within the populations.

It is not known where the individuals responsible for this population overwinter. Although both species are present in the sloughs throughout the year, some evidence indicates that individuals may overwinter within the creek by virtue of the stable substrate provided within the interstices of the rip rap levee.

Stomach analysis was performed to evaluate fish feeding habits. Of the stomach studied to date, 71% contained insect material, with dipterans being the primary food items (67% of all stomachs). The steelhead trout, which tended to be larger and older, fed heavily on both species of Corophium (found in 71% of trout stomachs vs. 0% in the stomachs of the smaller chinook). The prickly sculpin, Cottus asper, and starry flounder, Platichthys stellatus, two non-estuarine species commonly found in Redwood Creek, consumed only Corophium, suggesting a bottom feeding behavior.

Consistent production within the creek, beneficial for the growth and production of migrating juvenile salmonids, is lacking. This may be due to the absence of suitable habitat and nutrient sources for the invertebrate populations. The barren habitat of coarse sand and gravel between the levees contributes to low invertebrate diversity. Any attempt to introduce new and different habitats for the invertebrate forage species would be advantageous to an increased production that would be stable throughout the year. Unlike the sloughs which gain much of their nutrients from autochthonous as well as allochthonous sources, the creek invertebrates rely much of the year on debris transported from upstream. Management actions to renew riparian habitat along the sandbars within the levees might stimulate increased secondary production.

FISH HABITAT

Historically, salmon and steelhead runs were much greater than at present. Part of this decline can be attributed to alteration of the estuarine habitat.

The obvious role of the estuary for anadromous salmonids is as the passageway to the sea for downstream migrant juveniles and to the stream for upstream migrant adults. In addition to serving as an access point, the estuary is an area for acclimation from freshwater to saltwater or vice versa; and as an area generally rich in food, where substantial feeding and growth of juveniles may occur.

Reimers (1973) documented the role that estuaries play in fall chinook salmon production. From scale analysis of spawning fall chinook, Reimers determined that the majority of returning adults spend June, July, and August as juveniles within the estuary before completing their seaward migration. His investigation determined that juvenile chinook spending less than three months in the estuary seldom returned to spawn in the natal stream. Reimers concluded that these fish did not survive as well as the fish that had spent three months in the estuary. Although not as well documented, it has been shown that juvenile steelhead will spend rearing time in the estuary (Amend _et al._, 1980) while coho salmon (_Oncorhynchus kisutch_) appear to move into the sea almost immediately.

If an embayment forms during the peak migration of juvenile chinook salmon and steelhead, the juvenile salmonids will reside in this area for an extended period before entering the ocean, as was the case during the 1980 migration. The embayment formed in early June and the salmonid population began to increase, indicating extended utilization of the area. The population was estimated at 20,000 salmonids on June 24, and the catch per unit effort (CPUE) was 200 fish per seine haul. These fish were free to migrate into the ocean, further indicating an affinity for the embayment. However, on July 2, the berm was breached by local ranchers because the embayment water threatened to flood their fields. The breaching released 75% of the water in embayment and caused juvenile salmonids to involuntarily enter the ocean. Sampling efforts following breaching showed a CPUE near zero, indicating a radically reduced population. The only fish caught were located near the outlet in one of the few remaining deep pockets of water. The juvenile salmonids appeared to be smolting (indicated by their silver appearance), before being flushed into the ocean, but to what degree the smoltification process had reached is not known. Wagner (1974) documented reduced survival and growth to salmonids involuntarily inducted into seawater before the fish smolted. Had the berm not been breached, the juvenile chinook and steelhead would have been afforded a period of improved growth before entering the ocean and, therefore, an increased chance of survival.

Man-induced breaching of the berm and the lack of adequate water depth within Redwood Creek also affects returning adult salmon and steelhead. Breaching the berm before the fall rains may induce adult salmonids to enter the shallow estuarine area and remain there because of insufficient flow for them to continue upstream migration. In this shallow area, the salmon and steelhead are very vulnerable to illegal fishing practices, which have been substantial in some years according to local accounts. Prior to levee construction, the deep water area adjacent to the rocky headland provided a protected holding area for adults, thus premature breaching of the berm was not as devastating to the salmonid population.

When the channel was redirected, much riparian and submerged habitat was lost. In the area of the south slough, a diverse habitat exists, i. e., trees overhanging the water, submerged logs, and a deep water area along the south bank. The south slough is generally isolated from the main creek and therefore usually unavailable to migrating salmonids except under high water conditions. During the main May and June, 1980 migration of juvenile chinook and steelhead, the south slough was accessible from the main creek only in late June. The migrating juveniles utilized the expanded habitat when it was accessible. Water quality parameters remained at acceptable levels throughout the year and were not a deterrent to usage by juvenile salmonids.

Habitat in the north slough is even less accessible for fish than in the south slough. Water quality is also a problem in the north slough. Anoxic conditions exist on the bottom because of poor circulation and accumulation of floating and submerged woody debris. This condition limits the growth of plants which could provide a substrate for invertebrate growth and cover for fish.

Conditions in the creek are substantially different from those in the north and south sloughs. The creek margins and banks are devoid of any vegetative cover. A filamentous algae bloom in the spring provides suitable habitat for invertebrates but is too dense to provide cover for migrating salmonids. Cover exists only when water levels are high, providing access to voids along the rock levee and protection afforded by increased water depth. During low water essentially no cover is available, subjecting the migrant fish to increased avian predation. Juvenile steelhead and chinook tend to congregate in the deeper water areas, generally adjacent to the south levee. Other areas within the lower creek between the levees are not utilized at low water levels except when an embayment forms.

REHABILITATION ALTERNATIVES

From an ecological perspective, the objective of rehabilitation at the mouth of Redwood Creek is to improve the quality of aquatic habitat. Alternatives range from relatively inexpensive, temporary measures to costly permanent projects which would be complicated by political and legal concerns. The options are listed in order of increasing effectiveness in the restoration of fish habitat. Although it would be desirable to restore the estuary to its pristine state, the effects of increased sediment input from upstream sources must be considered. Redwood National Park is monitoring the rate of recovery from damaging floods and poor land use practices that have occurred in the basin over the last 30 years. Until streamside landslides heal and stored sediment moves out of the system, the levees may function to direct sediment through the mouth area. However, restoration of the natural circulation pattern and removal of large sediment accumulations at the mouth are necessary to increase the productivity of the estuary. Reestablishment of estuarine conditions with intrusion of nutrient-rich saltwater is also desirable.

Dredging

Dredging the embayment to historical depth would increase the amount of habitat available to juvenile and adult salmonids; allowing access to both the north and south sloughs and creating a deep pool near the neck of the north slough. The deep pool near the north slough might become a bi-layered estuarine system providing an area for acclimation to seawater by juvenile salmonids which they lack at present.

Dredging would only be a temporary solution depending on the rate of resedimentation. Ideally, dredging should be used in conjunction with restoration of historical circulation patterns to speed a return to pristine conditions.

Controlling the Embayment Water Level

Controlling the water level in the embayment would prevent the summer flooding of local pastures and would also help maintain some of the limited habitat. If the water level was maintained at a high enough level, the south slough would remain connected to the main channel, significantly increasing the habitat available to migrating fish.

By manipulating the length of the outlet, the embayment water level could be controlled. As the mouth migrates further south and the length of the outlet increases, the berms gets higher and the water level in the embayment increases. This migration reduces the flow gradient, decreases the water velocity and the amount of downcutting, and allows the berm to build higher. By reducing the length of the outlet, the channel gradient and water velocity would increase, resulting in downcutting through the berm and reduction of the water level in the embayment. Downcutting would be controlled by shortening the outlet gradually. This would allow time to evaluate the effect of each shortening and maintain an optimum embayment water level.

Circulation Through the Sloughs

Sediment in the necks of the north and south sloughs could be eroded naturally by diversion of sufficient flow through the sloughs. Pumping water from the main channel into the sloughs would not involve alterations of the levees, but would be costly in the long run. The natural force of high flows in Redwood Creek could be harnessed by constructing a spillway through the levee to the south slough (Figure 3). Another advantage to this alternative is that the amount of sediment delivered to the south slough could be regulated by the height of the spillway. Circulation could be enhanced by installing a culvert(s) in the north levee to deliver water into the drainage ditch that enters the south finger of the north slough. Properly designed, improvements would not result in loss of flood control as the levees would continue to contain high flows within the channel.

Partial Levee Removal

One alternative in the attempt to return the creek to its natural state would be the removal of the lower 1 km of the south levee (Figure 3). This rehabilitation alternative would allow the south slough to return to its status as a meander of the main creek. The result would be scouring of sand at the entrance, and an increase in the habitat accessible to migrating salmonids. Also, removal of that portion of the levee would allow dissipation of discharge over a widening area and thus create more stable substrates and areas for riparian habitats to develop, resulting in the enhancement of secondary production. Annual flooding of pasture lands resulting from levee removal could prove beneficial to soil fertility.

Removal of the lower 1 km of both levees would be similar in expected benefits to the previous option, and carry potential rehabilitation effects into the north slough. This alternative provides for both flood control for the town of Orick and the restoration of historical estuarine circulation patterns.

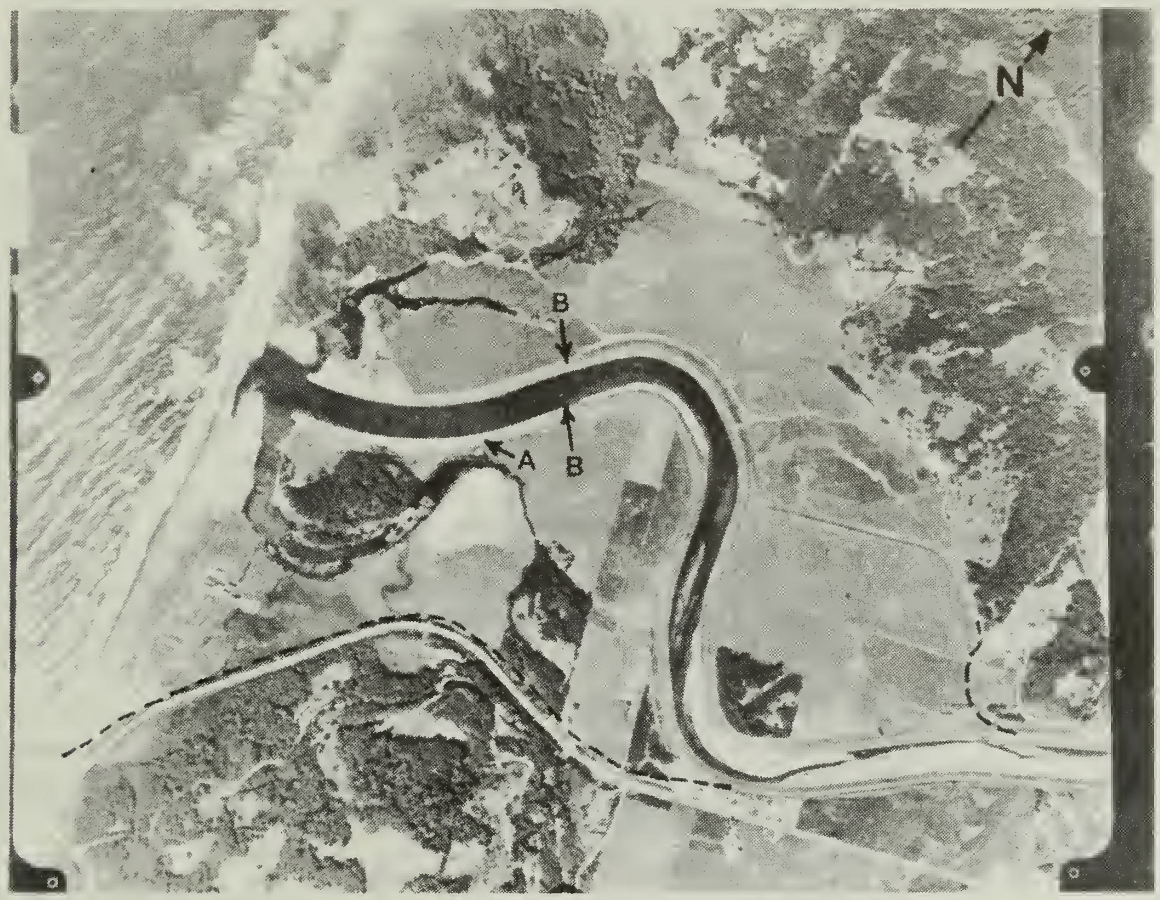

Figure 3. Redwood Creek showing the points of proposed options for restoration: levee spillway, (A); partial levee removal, (B); levee relocation, (Dashed line).

Relocation of the Levees

This alternative would be similar to partial removal of the levees except more of the lower creek would be returned to a natural condition. The levees would be rerouted at the first large meander west of Orick along Highway 101 (Figure 3). The county dump and pasture land might be subject to flooding on the south side. The levee could be rerouted on the north side to follow Hufford Road until it reached the hillslide near the mouth. Hufford Road could be relocated along the top of the levee to reduce the amount of land consumed by levee construction. Only pasture land on the north side of the creek would be exposed to flooding. Flood waters would flush away wastes and deposit nutrient-rich silt on the pasture lands. The benefits to terrestrial and aquatic wildlife would be similar to partial removal of the levees except more riparian habitat would be available.

CONCLUSION

The success of rehabilitation efforts depends on the cooperation of many agencies and individuals having regulatory or ownership interests at or near the mouth of Redwood Creek. Redwood National Park manages a quarter-mile strip of the coast. Humboldt County controls the levee and intertidal zone while private inholders own grazing land and forest near the mouth. The California Department of Fish and Game, Coastal Commission and U. S. Army Corps of Engineers will also be involved in management decisions. Flood control will continue to be a major concern. High flows which, in the past, flushed the north and south sloughs also affected some residents. Many would prefer not to repeat the experience. Thus, alternatives for restoration of estuarine habitat will be discussed by many people, hopefully with the unifying goal of fisheries enhancement.

ACKNOWLEDGMENTS

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HISTORIC SEDIMENTATION IN AN ESTUARY: SALT MARSH SUCCESSION AND CHANGE BIG RIVER ESTUARY, MENDOCINO COUNTY, CALIFORNIA

Laurie Marcus and Steve Reneau[1/]

ABSTRACT

The salt marshes bordering Big River Estuary have exhibited rapid vegetative succession in response to an accelerated build-up of levees along the estuary banks. Since the advent of logging in the watershed in 1852, the estuary has experienced major geomorphic changes. The natural progression of river deposits down the estuary has been greatly accelerated in the past 130 years.

Silt-laden flood water, slowed by tidewater flowing into the estuary, deposits sediment to form levees along the channel. These levees act to isolate salt marshes from tidal inflows. As tidal sloughs fill in and saline influence into the marsh diminishes, an unusual vegetative succession begins. Halophytic salt marsh plant species are replaced by riparian and coastal scrub plants. Salt marsh habitat is lost as a direct result of accelerated erosion in the watershed.

Detailed vegetation maps and comparative diagrams illustrate the significant changes these tidal flats have undergone. Comparison of recent infra-red imagery, field surveys, aerial photographs and historic photographs dating from 1860, reveal the time sequence of these vegetative changes.

INTRODUCTION

The estuaries of north coastal California are limited in distribution and, excepting the San Francisco Bay system, generally small in size. They experience a broad range of conditions governed by both the tide and flood cycles of their distinctive components: ocean and river. As the confluence of these two components, the estuary receives both river-carried sediment and tide-borne sand (Steers 1967). Estuaries are sites of active sedimentation. During flood stages, high tide waters mix with and slow, silt laden river water resulting in the deposition of sediment in the estuary. If river sediment loads are large, deposition in the estuary will also be great. San Francisco Bay provides one example; the large amounts of sediment produced by hydraulic mining in the Sierras were deposited in the Bay, significantly reducing its depth (Gilbert 1917). Consequently an examination of the geomorphic patterns found in an estuary can reflect erosional processes occuring in the watershed.

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Big River is amongst the largest watersheds along the Mendocino coastline, draining an area of approximately 165 square miles. As with other north coast rivers, discharge is concentrated during the winter and early spring, and summer outflows are quite low. Tidewater extends up the lower 8 miles and a series of eight salt marsh flats border the lower three miles. Unlike many estuaries, Big River estuary is not lagoonal but instead has a long linear channel. Crescent-shaped tidal flats alternate on either side of the channel corresponding with the alluvial deposits of the river. Redwood and mixed coniferous forest cover the steep slopes which border the channel (Figure 1).

Big River estuary has experienced rapid sedimentation of its channel and salt marshes since the advent of logging in the watershed. Timber harvesting which began in 1852 has been and continues to be the primary land use. These lands have been continuously harvested for 120 years using a variety of methods. The resulting erosion and transport of sediment down the river is evidenced by the historic changes in the estuary. The changes are cumulative and represent the long-term effects of timber harvest operations in the watershed. This paper seeks to document the depositional process occuring in the estuary, describe a relative time scale for these events and present the effects of this process upon the biotic components of the estuary.

METHODS

In order to assess historic changes in the estuary, a survey comparing the estuary's present condition with that in the early logging days was necessary. Therefore we not only documented present conditions through vegetation maps and topographic studies but also researched past information. We were able to contact a local expert on the early logging of Big River (Francis Jackson) and obtain historic photographs of the estuary. Many of the old logging structures remain and their former position in relation to the shoreline (as evidenced in the photographs) could be compared with their present position.

The vegetation maps were produced from a variety of sources. Initially in-depth field checks of each flat were completed producing rough maps outlining slough locations and vegetation distributions. A series of 144 aerial photographs were taken of the flats using both color and infra-red modes. The photographic series was designed for a 60% overlap between slides to assure complete coverage. The slides were photographed from a pre-determined altitude (8,000 ft.) to provide the desired projected scale (1 inch:200 ft.). Another set of color slides of the flats taken from a lower altitude (1,000 ft.) also were made during this flight. The final set of slides was created by photographing 1978 U-2 Nasa infra-red aerial photographs of the Big River Watershed. The slides were projected and an outline of each flat traced. Physiographic characters, slough systems, pans and vegetation forms, (trees, grasses, etc.) were mapped. The low altitude slide series was used to check vegetation lines and identifications. The field sketches were compared with the new maps to retain accuracy. Comparative diagrams of vegetation types were produced from black and white aerial photographs taken in 1952 and 1963. Vegetation types were defined by dominant species and all plant species encountered were collected and identified.

GEOMORPHOLOGY

The deposition of sediment is a natural geologic process in estuaries. However Big River estuary exhibits greatly accelerated sedimentation and an unusual

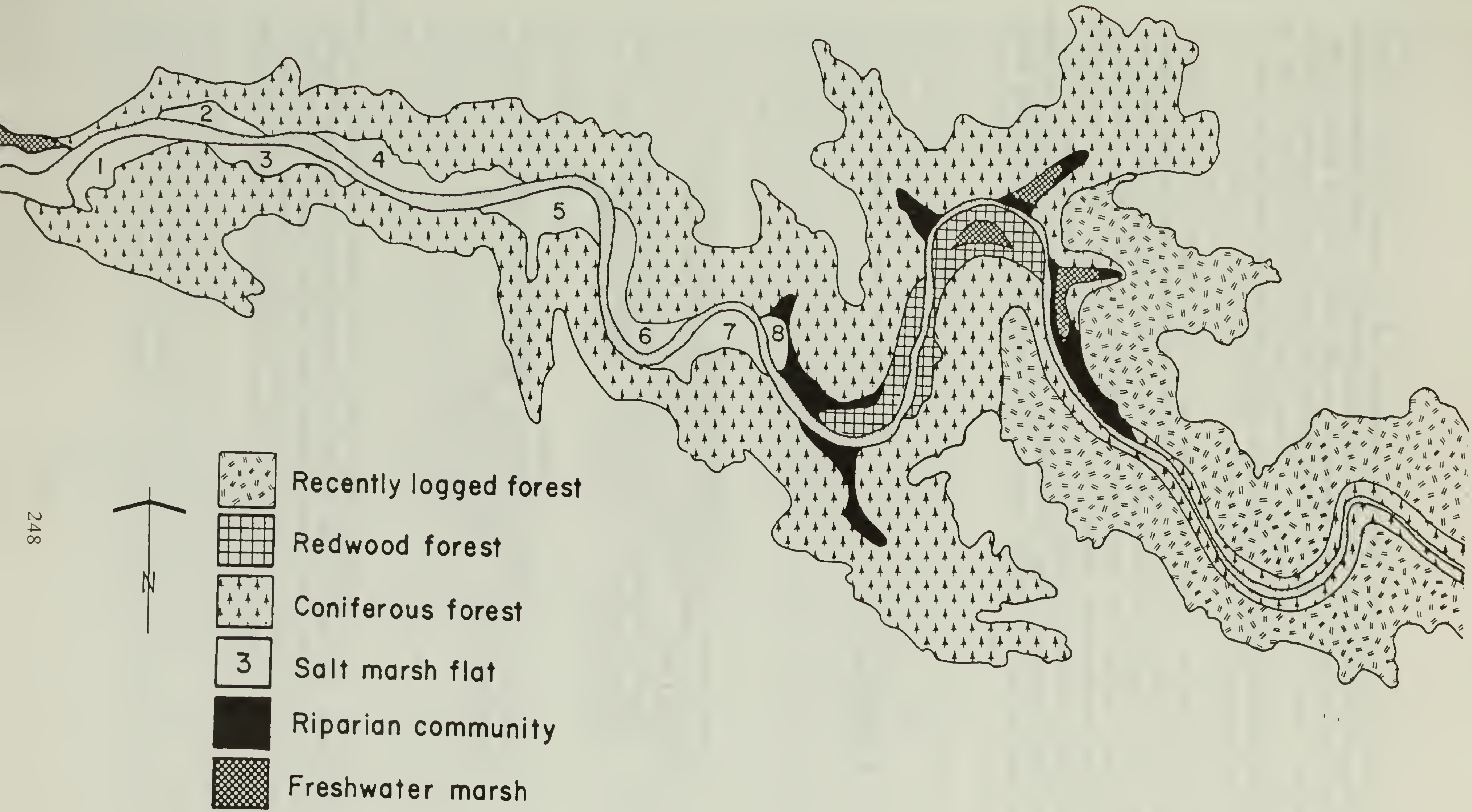

Figure 1. Big River Estuary, reference map of salt marsh flats.

pattern of deposition. The most obvious indicator of this accelerated process is the occurance of levees bordering the estuary channel. These levees extend along the channel down to 1.7 miles above the mouth and display a regular decrease in height. Their size varies from 40 ft. in width in the upper estuary to 10 ft. and less in the lower region. These levees record the transition in the estuary from primarily tidal influences (salt marsh and mudflat) to primarily river influences (floodplains).

These levees are formed as silt laden flood waters are slowed along the edges of the channel (Figure 2). The coarser, heavier sediments settle out forming an embankment along tidal flats and estuary channels. Driftwood and eelgrass beds located along the edges of the channel as well as tidal inflows act to slow down the flood waters and permit the sediment to settle out. Floculation of clay particles in the estuary may also contribute to this process. The increased sediment load resulting from erosion in the watershed cannot be transported out of the system by winter floods. The result is storage of the sediment in levees and on tidal flats.

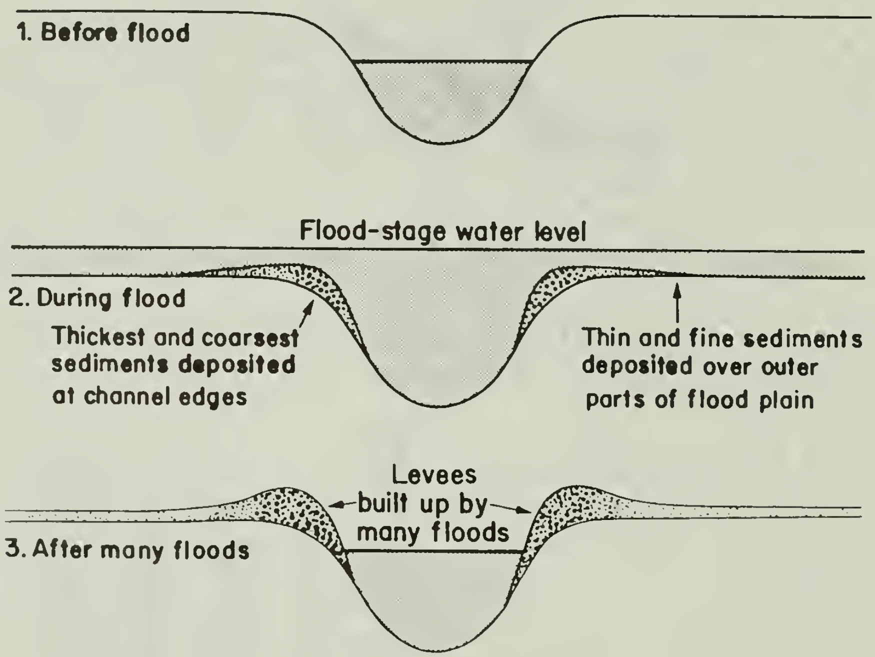

Figure 2. Formation of levees by river floods. As a river in flood stage overflows its banks, it rapidly decreases in velocity away from the channel and so drops most of its sediment, the coarser parts near the channel and the finer parts as a thinner layer of silt and clay over most of the floodplain. Successive floods build up the levees to ridges many meters high.

This sedimentation and levee build-up have taken several forms. The estuary banks have prograded resulting in a narrowing of the channel and an increase in floodplain size at the expense of mudflat and subtidal areas. Blockage or reduction in tidal influence has occured in the upper flats while a filling of sloughs and increase in mudflat height is found in the lower flats.

A few comparisons serve to illustrate these processes and estimate a time scale for their occurance. A railroad system was used to transport logs to the estuary during the early logging. A log dump located 3.8 miles upriver served as a spur of the railroad where logs could be dumped directly into the water. This log dump is shown in a historic photograph taken in the 1920s as standing in open water (Jackson 1975). The border of Flat 8 sloped gently away from the water. Today the pilings of this log dump stand adjacent to Flat 8, bordered by a levee 4 ft. in height. The historic development of this levee records a major change in the hydraulic conditions of the estuary. Winter floods were not able to deposit enough sediment to build levees at the site of the log dump prior to 1900. Since the photograph was taken, levees have developed 2 miles further down the estuary.

Once the logs were dumped into the estuary, they were rafted down to the sawmill at the mouth. To avoid stranding the logs on the tidal flats, rows of pilings were placed at the lower low tide line (Jackson 1975). Chains were stretched between these pilings and acted as a barrier to the floating logs. Presently in Flat 4, two sets of pilings occur, the outer one at approximately low tide line and the inner one trending back into the salt marsh. Two sets of pilings were installed during the logging operations before 1938 indicating that heavy sedimentation had extended the low tide line out into the channel, thus rendering the original set obsolete.

The filling of these tidal sloughs by sediment is demonstrated by the presence of several barges, buried in Flat 4. These barges were used for transport in the estuary. The barges are 42 ft. in width and were moored in the tidal slough, indicating the original slough was at least this wide. Presently the same slough is 7 ft. in width and the barge is buried adjacent to the bank.

SALT MARSH SUCCESSION

Accompanying levee build-up and siltation of slough systems are significant changes in the vegetative composition of the flats. As tidewater inflow to the flats is blocked rapid vegetative succession from salt tolerant or halophytic plant species to non salt-tolerant plants occurs. This successional scheme is unusual for salt marshes and represents a significant loss of wetland habitat in the estuary.

The circulation of salt water throughout the marsh is most important in determining the species distribution of marsh plants. Studies from England, North Carolina, San Francisco Bay and Oregon (Adams 1962; Hinde 1954; Miller 1950; Eilers 1979; Chapman 1938; Atwater 1979) have found tidal inundation to be the strongest determining factor in plant species distribution.

The channel systems found on Big River's flats are dendritic drainage sloughs formed through erosion by ebbing tides (Pestrong 1972). These flats are not completely inundated by tidewater and the slough channels are the only agent for tidewater inflows. Therefore, the distribution of these channel systems and their proportionate area within each flat is a direct measurement of saline influence to each marsh. The channel systems are extensive in the lower three flats becoming reduced to non-functional in the upper flats. Vegetation patterns coincide with the placement and extension of these slough systems.

Salt marsh plants, such as the succulent pickleweed, are specifically adapted for saline soils. They are able to store water in their tissues and thus avoid dessication. When saline inflows are reduced to marsh soils, as in the upper flats at Big River, the halophytes loose their adaptive advantage and are replaced by other species.

TABLE 1

FRESHWATER AND SALT MARSH PLANT ASSOCIATIONS

*--indicates dominant species

Vegetation Type	Species Composition	
pickleweed	Salicornia virginica	PICKLEWEED*
	Triglochin striata	ARROW GRASS*
	Jaumea carnosa	
	Cuscuta salina	PARASITIC DODDER
rushes	Juncus lesueurii	RUSH*
	Distichlis spicata	SALT GRASS
	Gramineae spp.	GRASSES
	Holcus lanatus	VELVET GRASS
	Hierochloe occidentalis	VANILLA GRASS
alders	Alnus rubra	RED ALDER
	Salix lasiolepis	WILLOW
coastal scrub	Baccharis pilularis	COYOTE BRUSH*
	Lupinus rivularis	LUPINE*
	Rubus ursinus	CALIFORNIA BLACKBERRY*
	Anaphalis margaritacea	PEARLY EVERLASTING*
	Senecio jacobaea	RAGWORT
	Foeniculum vulgare	SWEET FENNEL
	Erechtites arguta	FIRE WEED
	Rumex crassus	DOCK
	Carex salinaeformis	SEDGE
	Orthocarpus castillejoides	OWL'S CLOVER
	Pteridium aquilinum	BRACKEN FERN
	Rhus diversiloba	POISON OAK
	Convolvulus occidentalis	MORNING GLORY
	Geranium molle	CRANESBILL
	Gentiana amarella	FELWORT
freshwater or brackish-water marsh species	Typha latifolia	CATTAILS*
	Scirpus robustus	BULRUSH*
	Cicuta douglasii	WATER HEMLOCK
	Torilis arvensis	HEDGE PARSLEY
	Juncus effusus	RUSH
	Scirpus arnuus	BULRUSH
	Carex obnupta	SLOUGH SEDGE
	Plantago hirtella	PLANTAIN
	Potentilla egedei	PACIFIC SILVERWEED

The plant associations in the salt marsh flats are listed in Table 1. Vegetation types are defined by the dominant plant species (e.g. pickleweed, rushes). The coastal scrub assication while being dominated by coyote brush and lupine, contains many plant species from the disturbed ground community.

The various flats along the estuary have distinctly different vegetation. The lower three flats exhibit extensive slough systems and are covered with halophytic plants, pickleweed and rushes. The rushes, being less salt tolerant, occupy the more elevated areas of marsh where soils are less saline (see Figure 3).

Figure 3. Vegetation map of Flat 3. An extens ve slough system and predominance of halophytic vegetation characterize the lower flats.

The upper flats, however, exhibit a very different plant distribution pattern. Beginning in Flat 4, a levee occurs along the estuary bank blocking tidal inflows to the interior of the flat. The levee is higher than the surrounding marsh and is colonized by non-halophytic plant species of the coastal scrub and alder communities. Several of these plant species are nitrogen-fixing, containing nitrate producing bacteria in their root nodules. Consequently they have an advantage on the newly deposited,non-saline soils of the levees. Inside this levee in the marsh interior are low, depressed areas filled with pickleweed.

In Flats 5-8 a levee encloses the perimeter of much of the marsh, restricting tidewater inflows. Slough systems are greatly reduced or non-existent. Dead pickleweed patches which occur within Flat 7 are enclosed by a thick corridor of alder and scrub plants (see Figure 5). In this flat tidal inflows have been

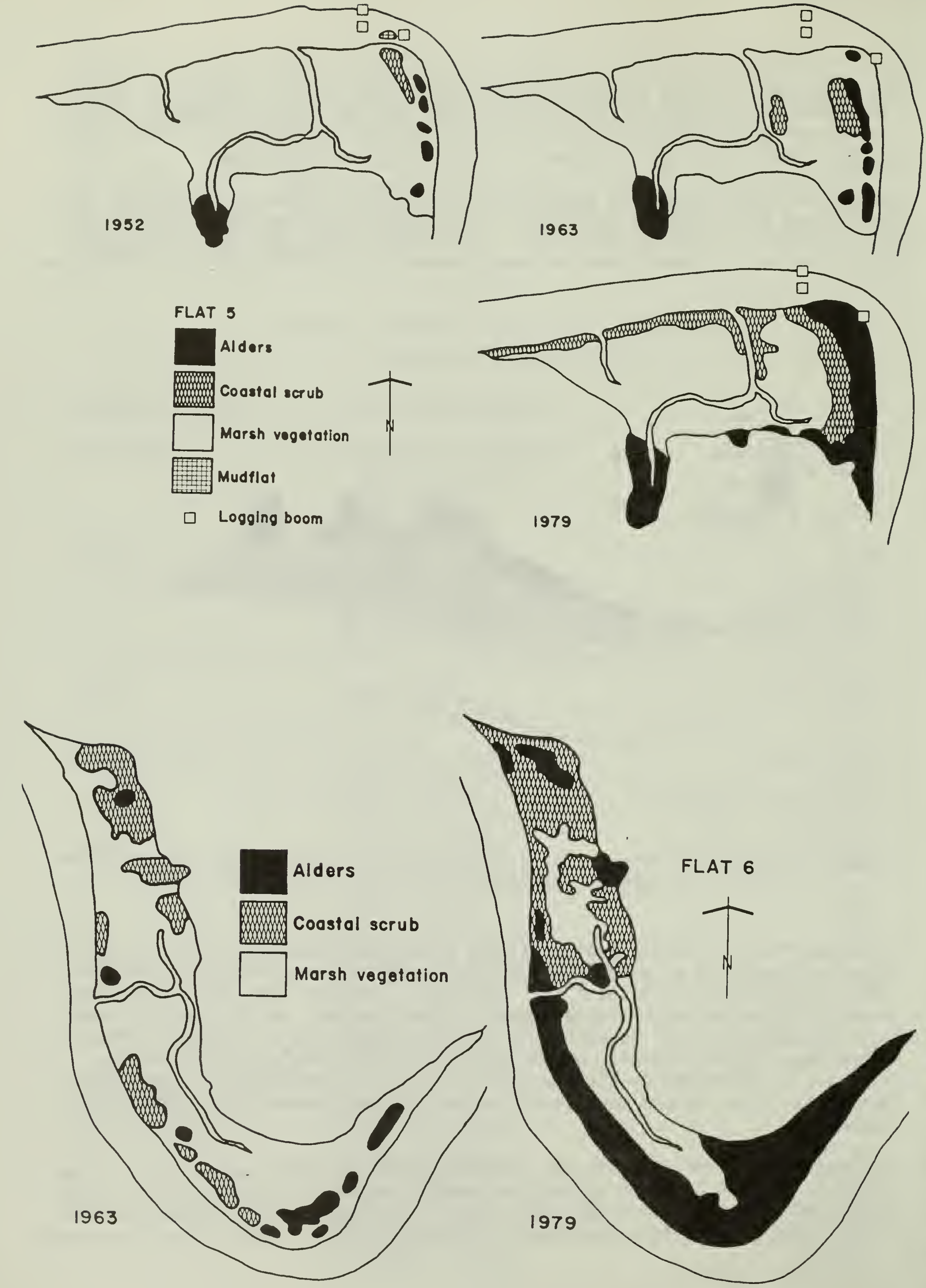

Figure 4. Comparison of vegetation in Flats 5 and 6.

completely blocked; a lower salinity level in the soils allows for the replacement of salt marsh plants.

In Flats 4 and 5 salt pans are found, just inside the levee and indicate the rapid deposition of sediment. These pans form as the marsh changes (Yapp 1917). During rapid sedimentation and halophytic plant colonization of muds, some regions become isolated. Normal submergence is restricted and with no drainage slough connections, the tidewater is trapped in these isolated regions. After this tidewater is caught within these pans, vegetative colonization is restricted. Even after evaporation has occured, the salinity level of the soil is prohibitive to plant growth.

Figures 4 and 5 illustrate the vegetative changes which have occured in the upper flats over the past 30 years. The replacement of marsh vegetation by coastal scrub and eventually alder, indicate a significant loss of salt marsh in the estuary. The enlargement of the levee is also illustrated in Flats 5 and 7.

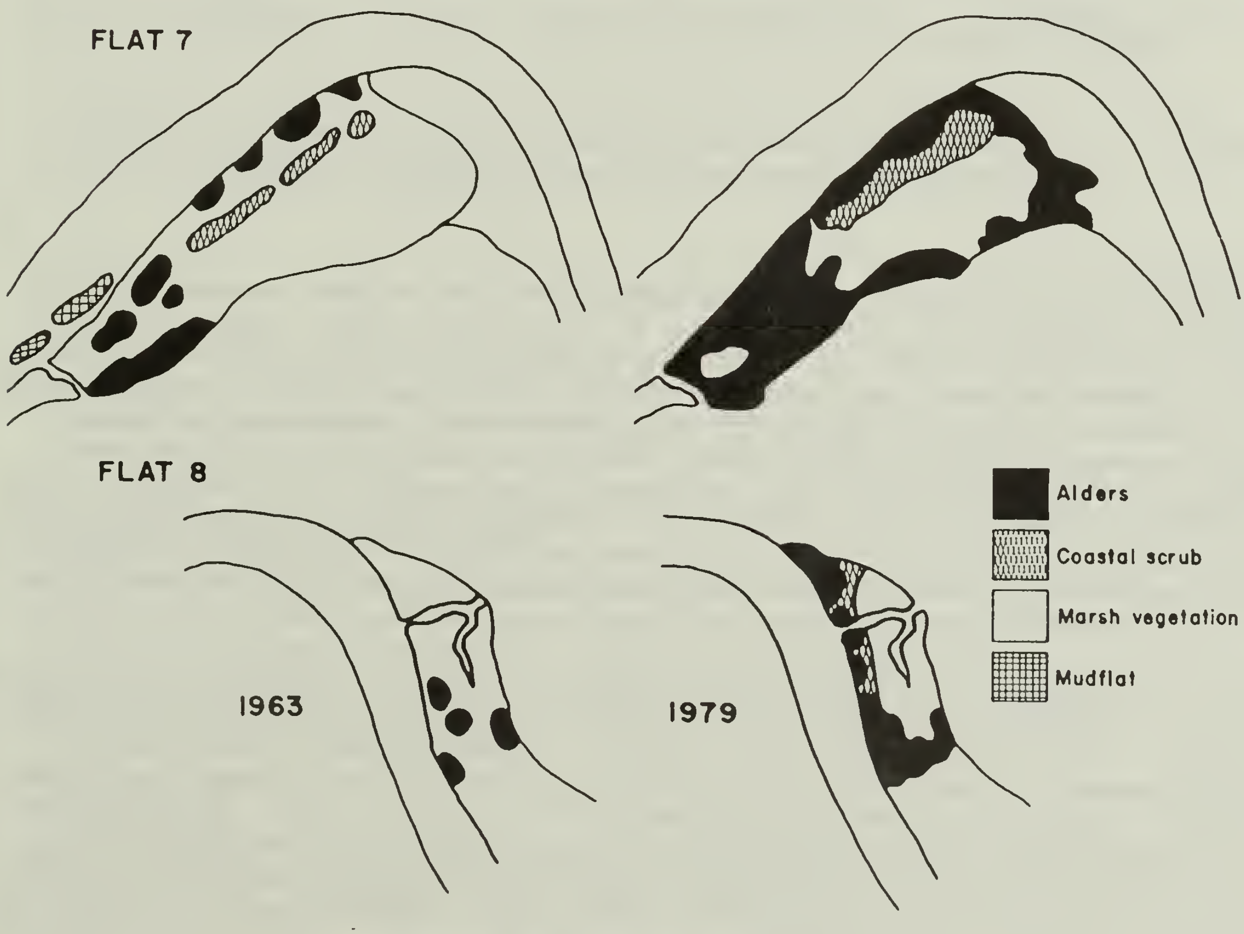

Figure 5. Comparision of vegetation in Flats 7 and 8.

Historic photographs (circa 1900) of Flat 1 reveal a mudflat with no vegetation of any type. Presently about half of this flat is covered with halophytic plants indicating a substantial rise in height of the flat. In addition this flat was across the channel from the logging mill pond. A row of old pilings still crosses its reaches diagonally. These pilings are the remnants of a wingdam, built in 1884 and used to direct the river's current toward the mill to flush sawdust and other debris (Jackson 1975). If the placement of these pilings in 1884 was such as to direct current movements then it may be assumed that they were placed in areas covered by water most of the time. At present, these pilings can have no effect on channel water currents, for they are located in a slough surrounded by islands of vegetation.

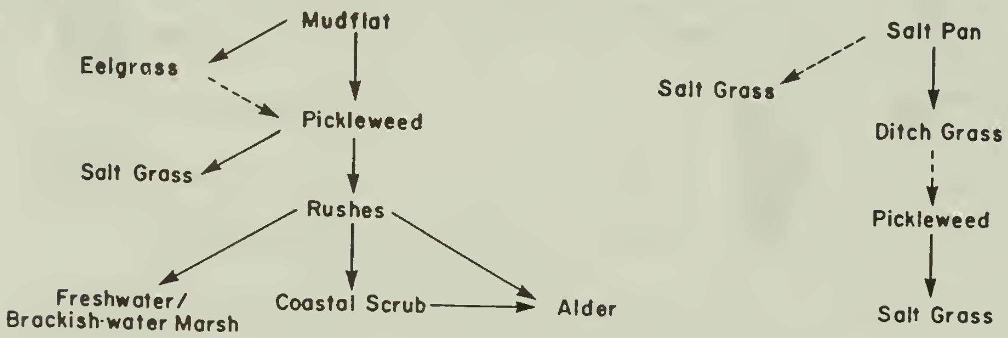

Figure 6. Salt marsh vegetation succession at Big River Estuary. Dotted arrow indicates hypothesized future vegetation succession.

By comparing the changes in the flats over time and between marshes, we have devised a successional scheme (Figure 6). The most unusual change in this salt marsh succession is the direct replacement of rushes by alder and coastal scrub. Other successional patterns (Chapman 1976) for European marshes result in freshwater marsh ultimately replacing salt marsh. While coastal scrub species are occasionally distributed around the periphery of salt marshes (Wherry 1920) wetland areas are not normally replaced by this community. The direct colonization of newly deposited levees by alder and coastal scrub acts to produce riparian woodlands over former wetlands. In addition sediment accretion in other salt marshes is commonly a gradual process with sediment distributed approximately evenly over the flooded area (Steers 1948).

Once these marshes are isolated from tidal infl ences, their productive capacity is lost. Juvenile estuarine fish, benthic invertebrates and algal blooms are common in the backwaters of tidal sloughs. Recent research indicates that tidal sloughs in Pacific salt marshes may be the location of the primary productive food base for the estuary (Zedler 1978; Eilers 1979). The reduction of slough systems reduces estuarine habitat available and consequently the productivity of the entire system. The long-term effects upon Big River estuary of this sedimentation and loss of salt marsh is undocumented. Further research is needed to determine the exact consequences.

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THE EVOLUTION OF APPROACHES AND TECHNIQUES TO CONTROL EROSION ON LOGGED LANDS IN REDWOOD NATIONAL PARK, 1977 - 1981

Ronald A. Sonnevil and William E. Weaver[1]

Abstract. The erosion control program at Redwood National Park began in 1977 with several small pilot projects intended to test a limited number of techniques and to evaluate overall program feasibility. In 1978 and 1979, work focused on the treatment of a wide variety of erosional problems through extensive experimental application of heavy-equipment and labor-intensive treatments. By 1981, the best, previously tested techniques were being systematically implemented with the goal of maximizing the effectiveness, or cost-effectiveness, of erosion prevention and control. Over this five year period, rehabilitation has shifted from a methodology dominated by labor-intensive treatments to one which emphasizes the use of heavy, earth-moving equipment. The once subjective approach developing work prescriptions solely through professional judgement has largely been replaced by the application of more standardized objective criteria for decision-making. Future changes in the erosion control program are expected to be less substantial than those which have already occurred.

INTRODUCTION

Redwood National Park is located in the downstream portion of the Redwood Creek basin, an elongate, 55-mile long, structurally controlled drainage in north coastal California. According to Janda (1978), sediment yields in Redwood Creek are unmatched for comparably sized, nonglaciated drainage basins in North America. In 1978, the U.S. Congress expanded Redwood National Park to include an additional 48,000 acres of land in the lower end of the Redwood Creek basin to preserve and protect a remnant of the once extensive coastal redwood ecosystem. About 36,000 acres of this area, which had been previously modified by road building and timber harvest, is now the focus of a large-scale rehabilitation program to reduce accelerated erosion rates and to speed the vegetative recovery of cutover lands.

The rehabilitation program is a multifacted effort designed to meet the following objectives: 1) to minimize the amount of sediment delivered to stream channels from areas disturbed by logging, including removal of approximately 250 miles of logging roads; 2) to restore and protect aquatic and riparian resources within tributaries and along the main channel of Redwood Creek; 3) to encourage the return of a natural pattern of vegetation on prairies

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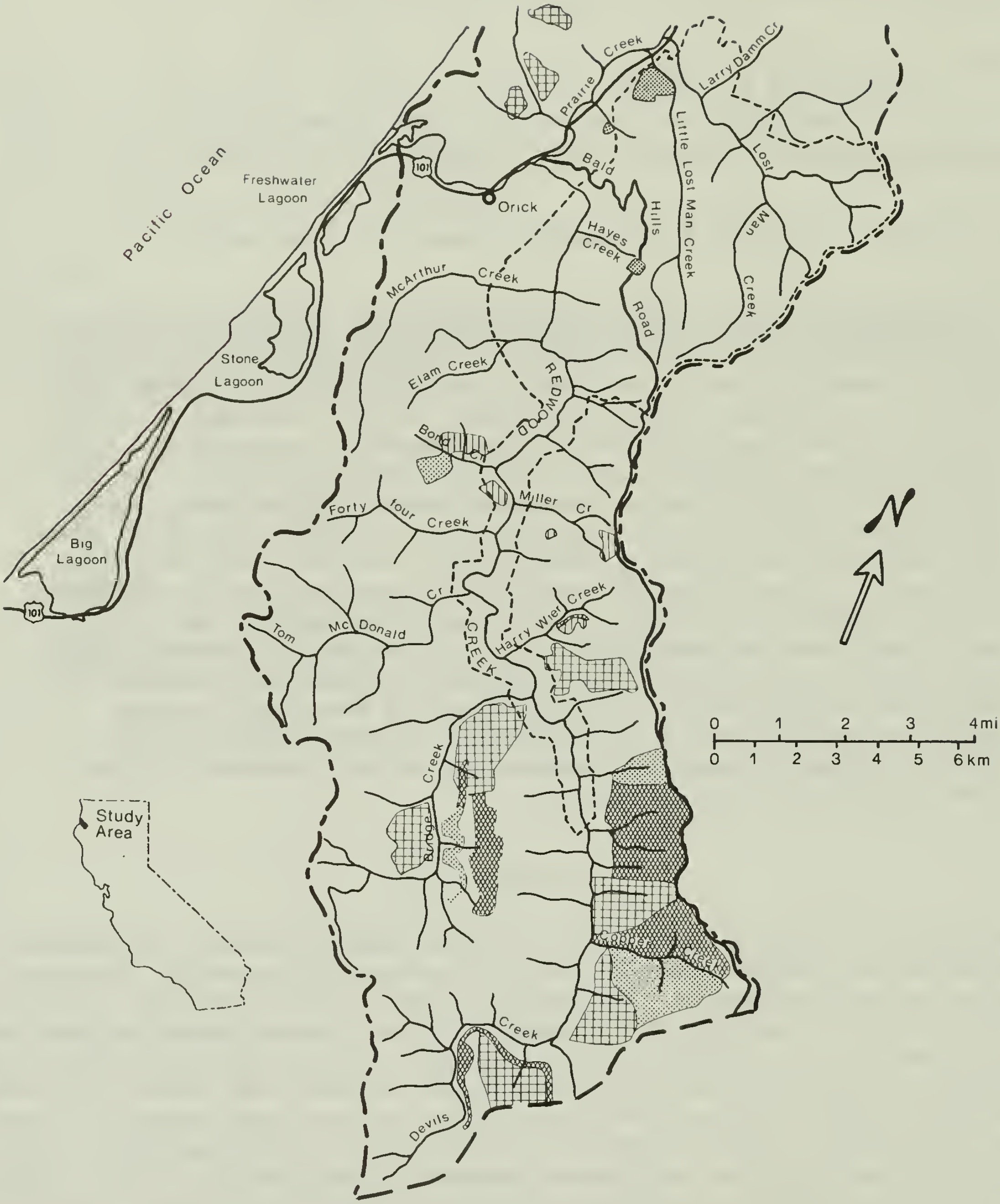

Figure 1. WATERSHED REHABILITATION PROJECTS IN REDWOOD NATIONAL PARK

- Pilot erosion control sites: 1977
- Areas treated in 1978
- Areas treated in 1979
- Areas treated in 1980
- Areas treated in 1981
- Park boundary
- Park boundary before expansion

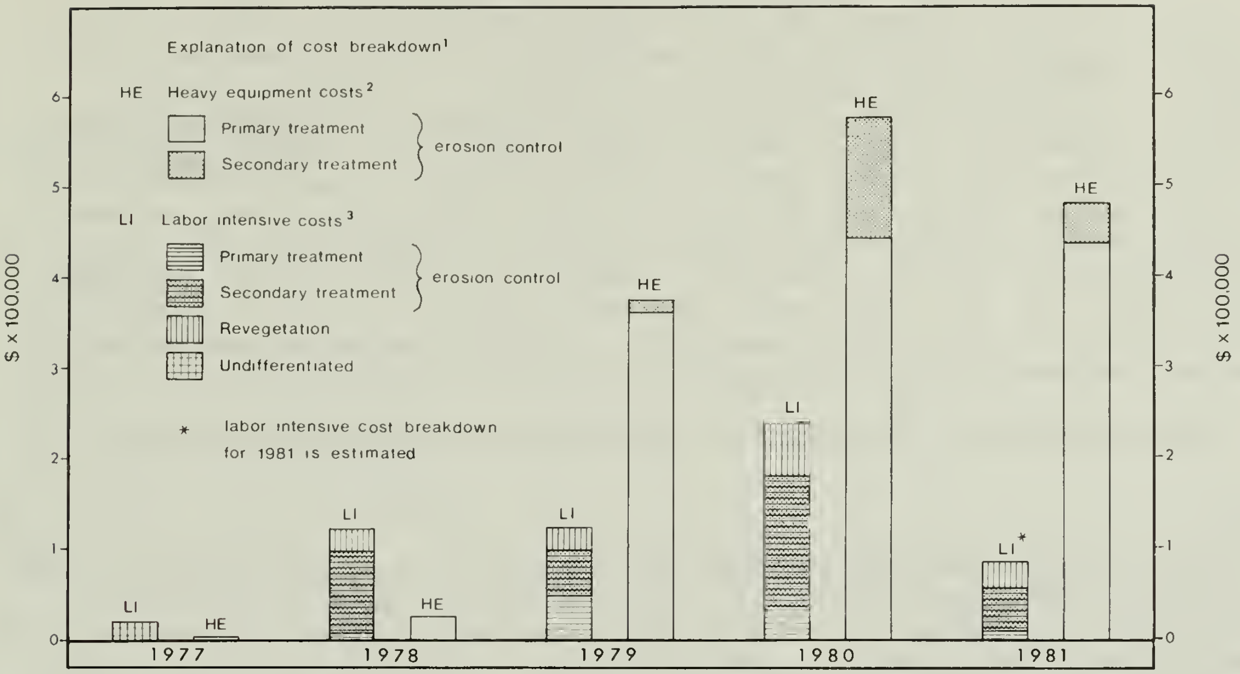

Figure 2. Comparison of erosion control costs at Redwood National Park: 1977-1981

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[1] National Park Service salaries associated with planning, supervising and administrating rehabilitation activities are not shown.

[2] Includes costs of heavy equipment rentals, with operators and fuel included.

[3] Includes costs of labor contracts, salaries of in-house laborers used to perform miscellaneous rehabilitation work and materials used for erosion control and revegetation. Salvaged wood (no cost to government) and milling expenses for boards used to construct erosion control devices are not included. Costs for wattles included in erosion control, not in revegetation.

and logged timberlands and; 4) to encourage the prevention and control of management-related erosion on private lands where timber is harvested upstream from the park. Fulfilling the first objective has been the primary emphasis of rehabilitation on Redwood National Park lands from 1977 to 1981. This is being accomplished through the use of primary and secondary erosion control treatments[1] which incorporate heavy equipment and/or labor-intensive techniques. In addition to erosion control activities, a companion program addresses revegetation of bare soil areas, including those disturbed during erosion control work. Other programs which address the remaining objectives are also in progress. This paper will review changes in approaches and techniques for erosion control during the first five years of the watershed rehabilitation program at Redwood National Park. Other reports within this volume (Bundros, et. al., 1982; Teti, 1982) and elsewhere (Kelsey and Weaver, 1979; Madej, et. al., 1980; Weaver and Madej, 1981) discuss site-specific erosion control costs and methodologies. Revegetation techniques used at Redwood National Park are reviewed in this volume by Hektner, et. al. (1982).

ANNUAL OVERVIEW OF THE REHABILITATION PROGRAM AT REDWOOD NATIONAL PARK

1977

In anticipation of Redwood National Park expansion, three pilot projects were initiated in the summer of 1977 to study individual erosion control and revegetation techniques, and to investigate the feasibility of implementing a large-scale rehabilitation program (Figure 1). Prospective test sites were chosen by park staff. Local contractors were requested to submit proposals for erosion control. Under this Request for Proposal (RFP) procedure, bidding parties were responsible for proposing specific rehabilitation treatments to be used at the various sites. Following negotiations, contracts were awarded on the basis of prescribed treatments and bid prices.

The main emphasis of the 1977 program was to test labor-intensive techniques judged, at that time, critical to control accelerated erosion from logged lands. Most erosion control techniques consisted of labor-intensive primary treatments intended to control surface erosion on bare hillslopes and to minimize erosion along stream channels or in active gullies. A lesser emphasis was to examine the feasibility of using heavy equipment for logging road obliteration. Table 1 generalizes work performed during 1977 rehabilitation, while overall costs are shown in Figure 2.

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1. Primary erosion-control treatments are those designed to provide for the immediate reduction in the potential for, or rate of, management-related sediment production or yield. They generally consist of heavy equipment treatments such as outsloping, ripping, construction of cross-road drains and waterbars, removal of soil and debris from stream channels, landslide stabilization and stream channel rediversions. However, labor-intensive techniques, when applied under these conditions, also represent primary erosion-control treatments (e.g., debris clearance from stream channels, gully stabilization techniques, waterbar construction, etc.). Secondary erosion control treatments consist of labor-intensive or heavy equipment practices designed to minimize erosion from areas disturbed during primary treatment. Secondary treatments commonly include such procedures as check dam construction and channel armoring applied to excavated stream crossings. Mulching, wattling, planting and seeding bare soil areas created during road outsloping, landslide stabilization and stream channel excavations also represent secondary erosion-control techniques.

Table 1. Summary of erosion control activities and techniques[1] used in Redwood National Park 1977-1981.

	1977	1978	1979	1980	1981
Miles of road treated	0.6	1.6	10.4	16.2	19.1
Haul road stream crossings excavated	0	7	64	93	90
Skid trail stream crossings excavated	0	16	57	75	34
Excavated stream crossings protected with check dams	0	10	7	24	0
Excavated stream crossings protected with rock armor	0	3	48	104	30
Mass movement features treated	0	0	1	2	1
Heavy equipment used	BD	B,BD,C	B,BD,C,D, E,G,L	B,BD,C, D,E,L	B,BD,D, E,L
Heavy equipment techniques	CR,OS, RD,WB	CR,OS, RD,WB DC	CA,CR,FD, LJ,OS,RD, DC,WB	CA,CR,FD, OS,PR,RD, DC,WB	CA,CR,GS, OS,PR,RD, DC,WB
Misc. labor intensive techniques to control surface erosion	DC,S, W,WB	J,M,RC, W,WB	CT,J,M,RC MS,S,W,WB, WT	HM,EB,J, MS,RC,S, WB	EB,MS,S, WB
Misc. labor intensive techniques to control erosion in stream channels or gullies.	CA,CD, WL	CD,GP, WL,CA	CA,CD,DC, F,WL	CA,CD, F,DC	CA,CD

ABBREVIATIONS

Erosion Control Techniques:

CA channel armoring
CD check dam
CR cross road drains
CT contour trenches
DC debris clearance
EB excelsior blanket
F flume
FD french drain
GP gully plug
GS gully shaping
HM hydromulch
J jute netting
LJ log jam removal
M mulch
MS straw mulch
OS road outsloping
PR prairie restoration
RC ravel catchers
RD road decompaction (ripping)
S seeding (grass, etc.)
W wattles
WB waterbars
WL water ladder
WT wooded terrace

Heavy Equipment:

B backhoe
BD bulldozer
C crane
D dump truck
E hydraulic excavator
G grader
L loader

[1] For definitions see Madej *et al.*, 1980; and Weaver and Seltenrich, 1981.

The scope and usefulness of rehabilitation work conducted in 1977 was limited by three principal factors. First, the National Park Service did not have access to cutover lands which were similar in harvest age, steepness of slopes, and erosional conditions to the proposed Redwood National Park expansion area (Figure 1). Second, funding for the experimental projects was not available until mid-summer 1977, allowing little time for planning and program design before the onset of winter rains. Thirdly, National Park Service personnel and local contractors were relatively inexperienced in erosion control techniques which could be successfully applied to steep, unstable lands found in the Redwood Creek basin. In a cooperative effort, the National Park Service drew heavily upon the experience and imagination of local contractors to design, test, and document various rehabilitation techniques.

Despite its limitations, the 1977 program was important because it revealed specific heavy equipment and labor-intensive techniques which would be useful and necessary for future rehabilitation work (Table 1). In addition, the 1977 program demonstrated some of the advantages of heavy equipment; revealed limitations of performing certain tasks with manual labor; educated park staff in certain contracting procedures; revealed the need for documentation of work accomplishments, unit costs, and task effectiveness; and pointed to the importance of the proper design, construction and maintenance of erosion control works.

1978

The expansion of Redwood National Park in March, 1978 (PL95-250) provided for the creation of a permanent staff to coordinate and direct rehabilitation activities in the newly acquired lands. During the following two years of experimental rehabilitation (1978 and 1979), emphasis was placed on the design, testing and refinement of various erosion control and revegetation techniques on areas displaying a wide variety of erosion problems. Incorporated into the program was a comparatively rigorous effort to document (by photographs and surveying) site conditions before, during, and after treatment together with detailed cost accounting of individual work items. Thus, a data base was established for a critical analysis of the cost and effectiveness of various rehabilitation treatments.

The five sites treated in 1978 (Figure 1) incorporated a wide variety of rehabilitation techniques (Table 1). Heavy equipment was used to "remove" roads (primarily by outsloping), reshape landings, and excavate fill material from road and skid-trail stream crossings constructed during previous logging operations. However, the majority of time, effort and money spent during 1978 involved the application of secondary labor-intensive treatments (Table 1, Figure 2) to protect areas from surface erosion, to prevent downcutting or widening of excavated stream crossings,and or promote revegetation on lands disturbed by heavy equipment during primary rehabilitation treatment. Labor-intensive contracts differed from the previous year in that individual work items were now defined by the Park Service and included as bid items. Under this Invitation for Bid (IFB) contracting procedure, contractors in 1978 were not responsible for prescribing the types of treatment to be performed on rehabilitation sites.

In 1978, National Park Service personnel were responsible for assessing and documenting erosion conditions on their sites, prescribing erosion control and revegetation treatments, supervising heavy equipment operations (via equipment rental agreements with local contractors), and preparing contracts and technical specifications for labor-intensive work. One major hindrance to effective experimental rehabilitation that year was an outcome of the late Spring, 1978, legislative expansion of the park. National Park Service scientists were unfamiliar with most of the newly added park lands and were rushed to locate suitable sites to test rehabilitation techniques. The delayed schedule severely restricted the time available for tasks such as erosion inventories, work-site prescription development, and contract preparation and advertising. In addition, since a plant ecologist had not been hired for the 1978 season, many revegetation techniques were modeled after 1977 methods. As a result, some of these techniques, especially the use of willow on dry sites, were inappropriate for the locations where they were applied (Madej et. al., 1981, Reed and Hektner, 1981).

The fundamental goal of the rehabilitation program has always been erosion control and the reduction of elevated sediment yields. Yet, not until the end of 1978 did it become apparent that extensive use of heavy equipment was necessary to fulfill this goal (Madej, et. al., 1980). Perhaps the most important contributions of the 1978 program were not those specifically associated with controlling increased erosion. For example, major benefits which have proven invaluable in subsequent years include: the experience gained in labor contracting; the development of more accurate prescriptions for the use of specific heavy equipment and labor-intensive procedures; the formulation of unit-costs for erosion control practices; and the development of a routine methodology for approaching watershed rehabilitation. In fact, this formulated approach (Department of Interior, 1981) continues to be applied to restoration work in Redwood National Park to the present time.

1979

In contrast with previous years, work in 1979 included ample lead time for planning and logistical arrangements. Early in 1979 critical sites had been identified, allowing park staff to inventory erosion features and finalize work prescriptions on three sites during the winter and spring months. This resulted in much larger (Figure 1) and more complex rehabilitation sites. One of these incorporated an area of over 600 acres, contained in excess of 100 major work locations, and required approximately $250,000 to treat. In addition, rehabilitation work on a fourth site was completed by means of a Request for Proposal (RFP) contract (Kelsey and Stroud, 1981).

The most significant erosional problems addressed in 1979 had resulted from stream diversions at poorly designed or unmaintained skid-trail and haul-road stream crossings. Many of these diversions resulted in the development of large gully systems on adjacent hillslopes or caused bank failures in nearby stream channels subjected to increased flows (Weaver, et. al., 1981a). Two sites involved recently constructed roads and cutover areas located on steep slopes adjacent to Bond Creek and Bridge Creek (Figure 1). These areas contained isolated, active erosional features and other very large potential sources for future sediment production and delivery. Erosional problems similar to those addressed in 1979 (particularly active or potential drainage diversions) have continued to receive high priority consideration in subsequent years.

The most extensive experimentation with heavy equipment and labor-intensive techniques in the five-year history of the rehabilitation program occurred in 1979. A large variety of equipment was used (Table 1) including: machinery to excavate and shape soil and debris removed from stream channels and road benches (backhoes, bulldozers, cranes, and a hydraulic excavator), equipment to load and haul materials to and from work sites (dump trucks and loaders), and equipment to prepare and maintain smooth road systems for efficient end-hauling (grader and water truck). In addition to testing new techniques, different types of equipment were used for similar work tasks, and individual work tasks were performed to varying degrees. For example, landing treatments ranged from a minimum of decompaction and draining with ditches, through mild outsloping, to almost complete removal of the landing fill material.

In 1977 and 1978, heavy equipment use had been restricted to primary erosion control treatments. In 1979, secondary treatments accounted for three percent of the total heavy equipment expense. Extensive experimentation with heavy equipment in 1979 resulted in a comparatively high cost for total work accomplished. However, these tests also provided an invaluable data base which has been used for subsequent cost analyses of heavy equipment operations, and resulted in significant improvements in the cost-effectiveness of rehabilitation work during 1980 and 1981.

Labor-intensive treatments in 1979 involved a wide variety of techniques used to protect stream channels from downcutting and bank erosion, and to minimize surface erosion on bare slopes disturbed by heavy equipment (Table 1). Approximately 50 percent of 1979 labor-intensive expenditures were for primary erosion control treatments on the RFP contract site, especially the manual removal of organic debris from stream channels. Total costs for labor-intensive erosion control in 1979 were, therefore, somewhat "inflated" because 70 percent of this expense was for the one RFP contract site. The high project expenditure resulted primarily from the park's trial use of a previously untested contracting method (cost-reimbursable, fixed price contract) that, in this instance, proved highly inefficient for watershed erosion control work (Kelsey and Stroud, 1981).

While most of the labor-intensive work during 1979 was performed by contract labor (RFP contract on one site, IFB contract for parts of two other sites), a minor portion was accomplished by a newly established park labor force. Delays and time allowances required by formal government contracting made this labor group an appealing and potentially valuable addition to the rehabilitation effort. The use of in-house labor crews permits the rapid application of mulches and installation of erosion control devices immediately following heavy equipment operations, and well in advance of the onset of winter rains. This had not always been possible during previous years.

In addition to personnel who directed and coordinated rehabilitation activities, another group was formed in 1979 to monitor and evaluate erosion control efforts at Redwood National Park. Since 1977 this task had been performed by the core rehabilitation staff. However, as sites became larger, more numerous, and more complex, a separate staff was needed to install monitoring stations, to evaluate new techniques used in a variety of settings, and to conduct studies aimed at improving the cost-effectiveness of ongoing operations. Additionally, a plant ecologist assumed full-time responsibility for prescribing revegetation treatments on project sites supervised by park staff and evaluating all revegetation treatments applied within the park.

By Spring of 1980, preliminary results from monitoring studies indicated that erosion from bare soil areas on 1978 - 1979 work sites represented only a minor component of the total post-rehabilitation soil loss occurring on these units.

Most of the erosion was found to be emanating from channel downcutting and widening. These findings supported the general trend of gradually reducing the relative emphasis placed on controlling surface erosion. Approximately 75 percent and 50 percent of the total cost for secondary erosion control treatments in 1978 and 1979, respectively, were designed to address this source of sediment. Significant reductions (to a low of 17 percent) continued in 1981. of the previously used labor-intensive techniques were also found to be excessively costly and/or ineffective, and some were discovered to create erosional problems greater than those they were designed to control (Weaver and Seltenrich, 1981). As a result, a number of techniques were discontinued or modified, and the thrust of future labor-intensive effort and experimentation was focused on stabilizing excavated stream channel reaches and promoting revegetation. Surface erosion was still to be treated on future rehabilitation sites, but in a more cost-effective manner.

1980

In 1980, twenty full-time personnel (geologists, hydrologists, plant ecologists, and technicians) were responsible for coordinating and supervising erosion control and revegetation activities on six rehabilitation sites (compared to six positions in 1979 and five positions in 1978). Five of these sites were supervised by park staff, the sixth site was treated by a contractor under a negotiated, firm, fixed-price RFP contract. A noncritical seventh site, located west of Prairie Creek (Figure 1), was treated as part of a training program conducted by a nonprofit, community service organization. This training site, discussed by Parsons and Rhode (1981), is not a source for data used in this report.

Heavy equipment treatments in 1980 continued to be partially experimental, but many techniques reflected standardized approaches developed over the previous three years (Table 1). Experimental use of heavy earth-moving equipment consisted of prairie restoration (gully and road obliteration), treatment of large scale mass movement features, the creation of new, artificial stream channel reaches, and extensive rock armoring of excavated stream channels. Secondary treatments (predominately rock armoring) accounted for 26 percent of the total heavy equipment cost in 1980 as opposed to only three percent of the year before.

Labor-intensive treatments in 1980 focused on the prevention of stream channel erosion in areas disturbed during the heavy equipment phase of rehabilitation. Most of the labor-intensive effort was spent on the construction of checkdams. Previously, in Redwood National Park, checkdams had only been constructed on stream channels draining between 10 and 40 acres. In 1980, checkdams were installed on larger stream channels draining up to 70 acres. This permitted cost and effectiveness comparisons of checkdams with machine-placed rock armor for similar sized streams. Labor-intensive techniques used to control surface erosion were simplified and involved only minor experimentation. The most expensive techniques (jute netting and excelsior blankets) were generally reserved for steep, freshly disturbed slopes judged capable of contributing significant quantities of sediment into adjacent stream channels. By far the most common treatment to control surface erosion on 1980 sites was the widespread application of straw mulch.

Most labor-intensive work on 1980 sites was accomplished by the recently enlarged park labor force. While two projects were completed by IFB and RFP contracts, a significant portion of the remaining labor-intensive work was provided by a nonprofit community organization for the handicapped (Redwoods United, Inc.), through a cooperative agreement with the National Park Service. The major advantage of having most of the labor-intensive work performed by park and Redwoods United labor forces was that nearly all erosion control treatments could be applied before the first, significant winter storms. In previous years, delays and legal time constraints associated with formal government contracting did not allow labor-intensive work to begin until well into the rainy season. However, in the absence of close supervision of in-house labor crews, some erosion control devices proved to be of lesser quality and/or more costly than similar devices constructed by contract labor.

Overall erosion control costs in 1980 were the highest to date for the rehabilitation program (Figure 2). This is primarily attributable to the amount spent for labor-intensive and heavy equipment secondary erosion control treatments. Weaver, et. al., (1982b) discuss the relative cost-effectiveness of primary and secondary treatments used at Redwood National Park and conclude that, in many cases, secondary treatments can be minimized or forfeited if a high-quality primary treatment is applied. This concept was used as a design criterion for much of the 1981 rehabilitation work and resulted in substantial savings with little noticeable decrease in the effectiveness of most rehabilitation work.

1981

In 1981, seventeen personnel were responsible for erosion control activities on six sites. Five sites were supervised by park staff and the sixth was treated under an IFB contract. Work in 1981 was designed to standardize, as much as possible, the approaches and techniques used for watershed rehabilitation. Prior to 1981, work prescriptions received varied amounts of review and were commonly based on subjective evaluations of the severity of existing or potential sediment sources to be treated. In some cases, this resulted in a very high unit cost for the amount of erosion prevented (i.e., dollars spent per cubic yard of soil "saved"). In 1981, prescriptions were determined by quantifying the potential for future erosion from each prospective work site and subjecting work plans to a detailed professional, peer reveiw. Decisions to perform individual work items were then based upon the size (volume) of the potential sediment source, the amount of damage which heavy equipment would do to the existing vegetation and the estimated unit cost for the amount of erosion prevented ($/yd^3). Additionally, individual treatments in stream channels were designed by quantifying the expected 20-year return-period discharge at each work site. As a result the decision to treat a work site within any one of the rehabilitation units became more defensible and less dependent on subjective judgment.

A primary emphasis of 1981 rehabilitation work was to minimize the application of costly and/or ineffective secondary erosion control treatments. At the same time, more emphasis was placed on thoroughly completing the more cost-effective primary treatments. This resulted in a measurable reduction (compared to the previous year) of heavy equipment expenditures (Figure 2). Additionally, the types of equipment used for rehabilitation tasks were standardized and much of the work was accomplished by the most efficient earth moving machinery: bulldozers and hydraulic excavators.

Unique to 1981, one rehabilitation project was totally devoted to the stabilization of a large, active landslide (near Emerald Creek at the site of a unit treated in 1978 (Figure 1)). Smaller and/or less active landslides in the park had been treated in previous years, but such work represented only single elements of larger rehabilitation units. The cost for the Emerald Creek landslide treatment represented approximately 18 percent of the total heavy equipment expenditure for primary erosion control treatments in 1981. However, this landslide had the potential for contributing at least as much sediment to Redwood Creek as the combined total of all other sediment sources identified and treated within Redwood National Park in 1981. While landslide stabilization is an extremely difficult and frequently unsuccessful undertaking, the potential benefits can be enormous.

Labor-intensive costs in 1981 were the lowest in four years and resulted from a concerted effort to minimize the application of less cost-effective secondary erosion-control treatments (especially checkdams) on rehabilitation sites. Most of the labor-intensive erosion control work was performed by the National Park Service and Redwoods United labor forces. One site had minimal treatment under an IFB contract. Revegetation work on two other sites was accomplished by IFB contract, and the remaining four sites were planted and seeded by park laborers.

SUMMARY AND CONCLUSION

Watershed rehabilitation at Redwood National Park has grown from small pilot projects all directed by one person, through an extensive experimental phase with five to six personnel responsible for four to five sites, to a multifaceted organization of twenty to twenty-five people directing and evaluating erosion control and revegetation activities on six to seven sites. Expenditures expanded with an increase in personnel, experimentation, and size of rehabilitation sites but leveled off with refinement of the program. Evaluation of data from previous years directly influenced expenditures in 1980 and 1981 by emphasizing the most cost-effective treatments and minimizing less cost-effective work items.

Given the large number of changes in procedures and techniques which have occurred in the rehabilitation program, it is difficult to demonstrate improvements in the cost-effectiveness of work items and techniques with the generalized data in this report. The varied nature of complex physical conditions encountered on rehabilitation sites also makes it impossible to compare annual expenditures with the accomplishments listed in Table 1. However, the data presented does summarize annual trends in overall expenditures and demonstrates an evolution in the number and variety of erosion control practices used at the park.

The approach to erosion control shifted from an experimental phase, where judgements to treat an erosional problem were often subjectively formulated by individual project leaders, to a more systematic process implementing an objective approach, with considerable peer review, which attempts to quantify potential sediment sources and the benefits to be obtained by treatment. Additionally, various design criteria have been incorporated into the program to standardize and improve specific treatments.

Many significant erosional problems within the park are caused by debris in or near stream channels and result from the construction of roads or tractor skid trails during previous timber harvest activites. The methodology for treatment of these erosional problems has evolved from a program dominated by labor-intensive techniques to one emphasizing the use of more cost-effective heavy equipment treatments. In general, the most effective and efficient erosion-control practices have been those primary treatments which reduced existing and potential sediment sources through the use of heavy earth moving equipment.

Early in the program, secondary erosion control treatments were exclusively accomplished by manual labor. However, as the rehabilitation program evolved, the role of heavy equipment for secondary treatments in stream channels increased. This resulted because channel armoring with coarse rock fragments is more permanent and maintenance-free than wooden structures (i.e., checkdams, flumes, and water ladders). Additionally, the size and amount of rock needed for adequate channel protection commonly requires heavy equipment for cost-effective application. The amount of secondary, in-channel treatment has fluctuated considerably; a result of logistical access, cost-effectiveness analyses of previous years' treatments, and budgetary restrictions. For example, the percentage of excavated stream crossings which received secondary channel protection treatments (i.e. rock armor or checkdams) ranged from 57 percent in 1978, 46 percent in 1979, a high of 76 percent in 1980, to a distinct low of 21 percent in 1981. The treatment of surface erosion has remained labor intensive. Expensive treatments such as wattling, wooden terraces, and ravel catchers, however, have been replaced by a more cost-effective application of straw mulch.

The rate and degree of evolution of erosion control work at Redwood National Park has been substantial over the last five years. The majority of changes in the next few years will probably be variations of those practices which have already been tested. Two major factors which may affect the direction of future program changes include: 1) budget restrictions, which underscore the continuing need for increased cost-effectiveness, and 2) the continued evaluation of treatable sediment sources and causes of management-related erosion. Increased cost-effectiveness is likely to be accomplished through new procedures resulting from re-evaluation of in-house versus outside contracting methods to perform various labor-intensive work tasks, the examination of contracting methods for "routine" road removal projects, and by evaluation of the results of minimal in-channel secondary erosion control treatments emphasized on 1981 rehabilitation sites.

The continued evaluation of those sediment sources remaining in the park which are significant, accessible, and treatable will directly affect the level of future treatments applied and will also influence the role assigned to the prevention and stabilization of mass movement features. For example, much of the rehabilitation work completed between 1978 and 1981 has addressed recently cutover areas which contained skid trail stream crossings needing treatment. On many older cutover areas which have been subjected to major storms in the past two decades, skid trail crossings are commonly washed out and their treatment is no longer necessary. Extensive natural revegetation also makes reopening these areas less desirable. In the future, as the proportion of older cutover area to be treated increases, the number of skid trail crossings excavated each year will decrease. Consequently, assuming a stable budget, the length of road annually treated and the size of individual rehabilitation sites is likely to increase. In addition, while the rehabilitation program emphasized the control and prevention of road and logging-related fluvial erosional problems, there has been a continual increase in the effort expended to control mass-movement features. Attempts to stabilize mass-movement features in the future will largely depend upon the potential for damage to downstream resources, the feasibility and cost of treatment, and the probability of success.

ACKNOWLEDGMENTS

The erosion control program at Redwood National Park has involved literally hundreds of people over its five year history. All of these individuals, through their ideas and their work, have influenced the content and evolution of this unique program. Legislation expanding Redwood National Park provided an initial direction to the restoration efforts. However, most of the change in succeeding years has come about through the efforts of labor and equipment contractors, through external scientific and professional peer reviews, and through an introspective analysis of the costs and effectiveness of procedural and technical elements of the program. The National Park Service is indebted to those individuals who have contributed to the evolution and success of the watershed rehabilitation program. We would like to thank Elizabeth Babcock, Danny Hagans, Mary Hektner, Lee Purkerson, Terry Spreiter, Pat Teti, and Ken Utley for their review of this manuscript.

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EROSION CONTROL IN REDWOOD NATIONAL PARK, NORTHERN CALIFORNIA, 1980

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Abstract. In Redwood National Park, erosion control treatments are aimed at reducing accelerated sediment yield from lands disturbed by timber harvest and road construction. Such practices address both active and potential sediment sources to streams. In 1980, detailed mapping of five rehabilitation units identified active gully systems, stream courses diverted from their natural channels, unstable road and skid trail stream crossings, and mass movement features. Approximately 1276 ha were examined in detail. Of this land, erosion control work was performed on 32 ha. Primary erosion control treatments utilize heavy equipment to perform earth moving tasks. These treatments, which result in the redirection of altered drainage networks and the removal of unnatural sediment sources, accounted for 58 percent of the total cost. Secondary erosion control treatments provide protection to areas freshly disturbed by primary treatments. These measures include bed and bank protection for excavated stream channels, and surface protection for bare soil areas. Secondary treatments, which utilize heavy equipment and manual labor crews, accounted for 34 percent of the total cost. The proper design of stream channel excavations can minimize secondary treatment costs. The proper application of heavy equipment can lower unit costs and increase the cost-effectiveness of erosion control treatments.

INTRODUCTION

In 1978 Redwood National Park was expanded by 19,400 ha in the lower Redwood Creek basin. Of this land, 13,400 ha had been severely disturbed by timber harvest and road construction. Concurrent with park expansion, a multi-faceted, large scale rehabilitation program began. Rehabilitation efforts focused on reducing the amount of sediment delivered to tributary streams of Redwood Creek from disturbed areas, and restoring a natural ecosystem. This paper summarizes the erosion control work supervised by Redwood National Park staff in 1980. The erosion control treatments used and their costs are discussed. Finally, examples of unique erosion problems and treatments found on four rehabilitation units are described. The reader is referred to the paper written by Sonnevil, et. al. (1982) describing the evolution of erosion control in Redwood National Park, and by Teti (1982) which offers a detailed look at one of the rehabilitation units completed in 1980.

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Erosion control work proceeds in three phases. First, rehabilitation units are mapped in detail during the rainy season. Active and potential sediment sources are identified and an erosion control plan is developed. During the second phase, heavy equipment performs earth moving tasks. Equipment work is performed during the dry season, and is generally supervised by Redwood National Park staff. The third phase involves labor intensive work and is performed by park labor crews, labor contract, or voluntary youth organizations.

As identified by field mapping, timber harvest activities had caused severe and widespread disturbance to natural drainage networks and hillslope areas. Roughly 60 percent of the 1980 rehabilitation units had been logged since 1970, of which 80 percent had been tractor yarded. Tractors had commonly entered and crossed stream channels to obtain access to felled timber. In doing so, tractors would sidecast earth and woody debris into natural stream channels creating new sediment sources and potential stream diversions. Skid trail crossings each contained an estimated 70-230 m^3 of fill material. While these commonly eroded during large storm events, some remained intact and diverted streamflow down skid trails or across hillslopes causing severe gully erosion. Skid trail surfaces also concentrated storm runoff and their cutbanks often intercepted winter groundwater levels. Where waterbars had not been constructed, or were improperly placed, skid trails developed gullies and, in several instances, directed storm runoff onto unstable log landings.

Stream diversions, gully erosion, and mass wasting of fill material were also common along haul roads where culverts had been infrequently spaced, improperly sized, and/or poorly maintained. Some ephemeral and intermittent streams had been diverted by road construction because culverts had not been installed. During storm events, culvert capacities were often exceeded and culvert inlets frequently plugged with debris. As a result, streamflow either: 1) breached the road surface eroding massive volumes of fill from road crossings, 2) discharged onto broad hillslope areas causing gully erosion, or 3) was diverted into an adjacent stream channel causing accelerated bank and channel erosion as a result of increased streamflow.

The erosional processes described above were common to all 1980 rehabilitation units. However, the combination of underlying geology, hydrologic events, severity of ground disturbance, and natural erosional processes caused the development of unique or complex erosion problems. Newly created surficial processes and the redistribution of mass on unstable hillslopes, re-activated pre-logging mass movement features, and, in some cases, initiated new ones. It should also be noted that most of the erosion observed on the cutover units appeared to stem from the major storm events in 1972, and 1975.

EROSION CONTROL TREATMENTS

Erosion control treatments consisted of primary and secondary treatments. Primary treatments are earth moving functions performed by heavy equipment to: 1) redirect drainage networks altered by haul road and skid trail construction, and 2) remove both active and potential sediment sources to streams. Secondary treatments encouraged the stabilization of areas freshly disturbed by primary treatments. These treatments included the placement of check dams and rock armor in excavated stream channels, and the application of straw mulch and revegetation treatments to bare soil areas. Both heavy equipment and manual labor crews performed secondary treatments. In 1980, five rehabilitation units were completed under the supervision of Redwood National Park staff. Approximately 1276 ha were mapped in detail. Of this land, erosion control work was performed on 32 ha which includes 23.5 km of haul roads. The total cost of erosion control work was $587,320, of which, primary and secondary treatments accounted for 58 percent and 34 percent respectively. Figure 1 provides a breakdown of all costs.

Drainage networks were redirected by removing haul roads, excavating road and skid trail crossings, treating log landings, and constructing waterbars. The degree of road removal considered road bench stability, proximity to stream channels, and road location (prairie or forest). Road removal utilized combinations of dragline cranes, hydraulic excavators, crawler tractors, backhoes and/or dump trucks. Typically, road surfaces were decompacted (ripped) to a depth of 50 cm using chisel teeth mounted to a D-8 (or equivalent) crawler tractor at an average cost of $427/km. Road benches were then either: 1) cross-road drained (closely spaced, deep troughs cut across the road bench to decrease concentrated inboard ditch runoff), 2) partially outsloped, or 3) completely outsloped. In 1980, 23.5 km of haul roads were removed. Of this total, backhoe-tractor teams cross-road drained 14.6 km of forest roads at an average cost of $1515/km. Partial outsloping was performed on 5.8 km of forest roads by hydraulic excavator-backhoe-tractor teams at an average cost of $1750/km. In the prairies, where aesthetics were also considered, excavator-tractor teams completely outsloped 3.1 km of roads at a cost of $4297/km (fig. 2).

Like haul roads, log landing surfaces are compacted and concentrate storm runoff. To improve infiltration rates and disperse surface runoff, tractors ripped and partially outsloped landing surfaces. A total of 26 landings (.2 - .3 ha each) were treated at an average cost of $1200/landing.

Waterbars direct concentrated runoff from compacted, bare soil areas onto more stable, vegetated ground. Properly constructed and placed, waterbars can de-water active gully systems and prevent further gullying. Tractors and/or backhoes constructed waterbars on skid trails ($9 - $30 each) at an average cost of $19 each. Labor crews also constructed waterbars, but only in areas where equipment access was impractical ($19 - $48 each).

Primary erosion control treatments also included the removal of active and potential sediment sources to stream channels. Such sediment sources included haul road and skid trail crossings, unstable or oversteepened fillslopes along roads, and unstable log landings. In 1980, an estimated

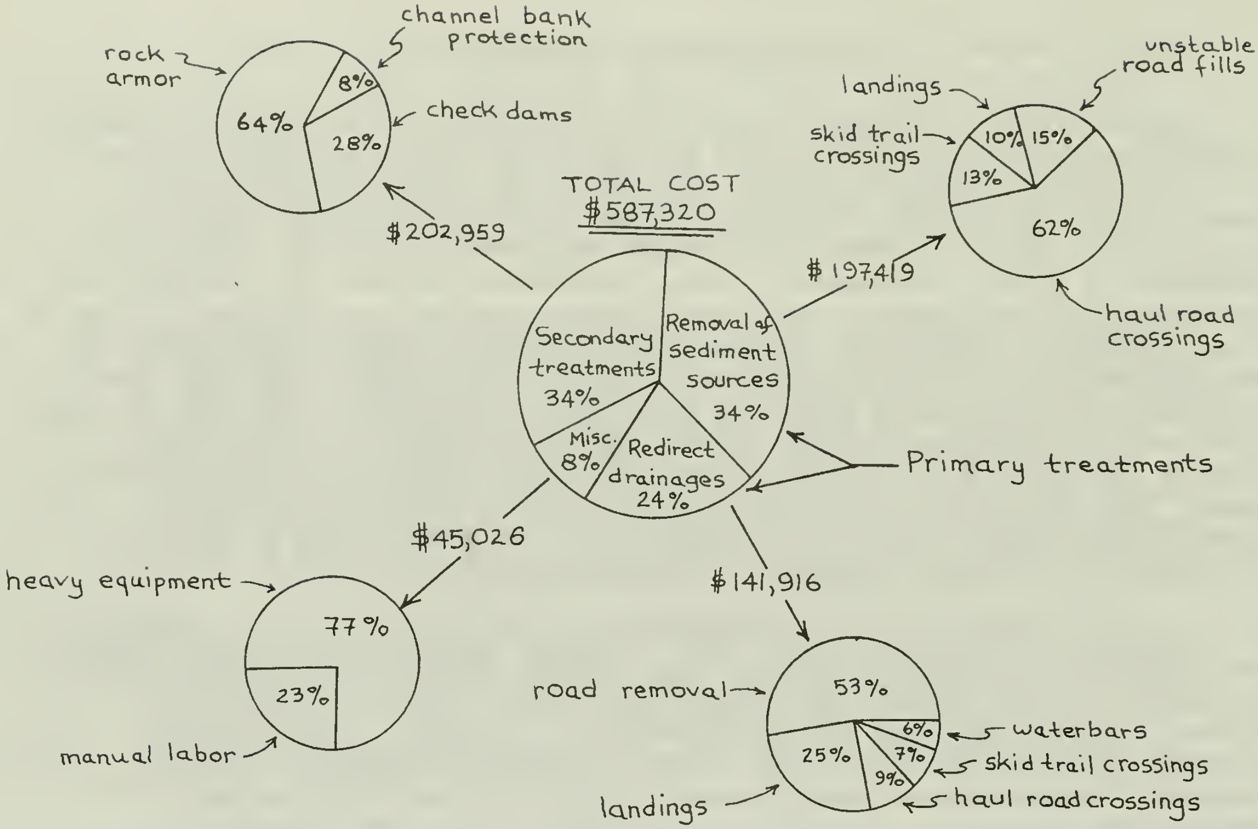
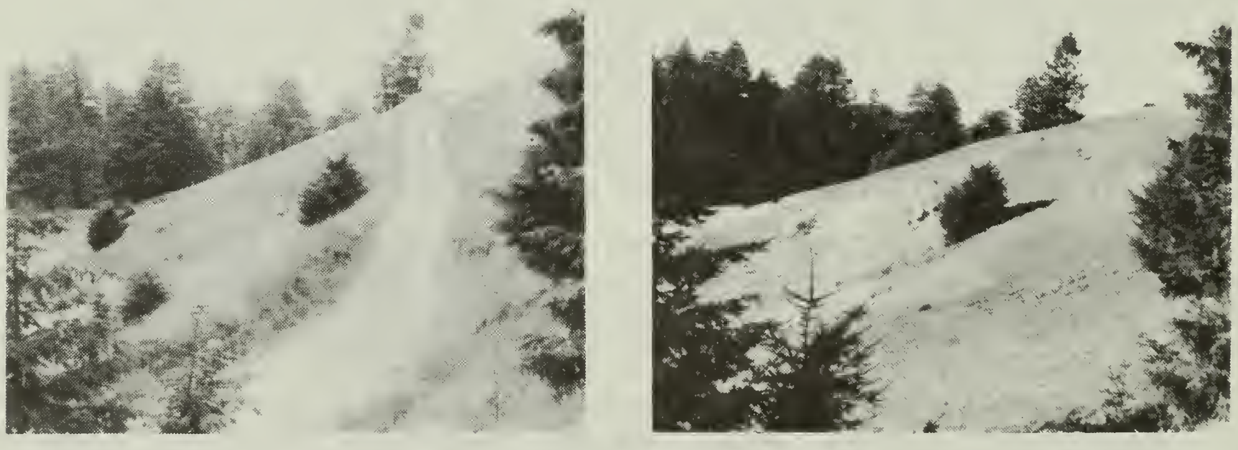


FIGURE 1. Cost breakdown to perform 1980 erosion control work.



(a) (b)

FIGURE 2. Before (2-a) and after (2-b) sequence of prairie road removal (complete outsloping). A hydraulic excavator and crawler tractor retrieved sidecast material from below the outer edge of the road and piled the material against the road cutbank. The crawler tractor then spread the piled material to blend with the surrounding slope morphologies.

35,400 m^3 of fill was excavated from stream channel crossings at an average cost of $4.90/$m^3$. Stream channels were excavated to approximate pre-logging sideslope geometries and channel gradients (fig. 3). Skid trail crossings accounted for 8700 m^3 ($2 - $9/$m^3$), and haul road crossings accounted for 26,700 m^3 ($2 - $15/$m^3$). Typically hydraulic excavators, dragline cranes, or backhoes, and crawler tractors or loaders removed fill from road crossings and stored the removed fill within 60 m from the excavation site. At some stream channels, the adjacent road cutbanks intercepted groundwater and this prevented the immediate area from being used as storage. Excavated fill from such road crossings was loaded into dump trucks to be transported (endhauled) and stored at a dry, stable location ($6.50 - $11/$m^3$). A similar approach was prescribed to treat unstable road segments located above stream channels where suitable storage space was not available. Approximately 1500 m^3 of unstable road fill was retrieved and endhauled ($5 - $9/$m^3$).

Secondary treatments were designed to minimize channel erosion in newly excavated stream channels, and to eliminate rill and gully erosion on freshly disturbed ground. Channel protection consisted of rock armor and check dams while adjacent banks were protected by combinations of straw, seed mixes, jute netting (loosely woven hemp), Curlex (shredded aspen in a monofilament netting), and seedlings.

Crawler tractors, dump trucks, and track-mounted loaders were used to quarry and transport rock to excavated stream channels. A total of 6300 m^3 of rock was delivered to rehabilitation units at an average cost of $12/$m^3$ ($9 - $22/$m^3$). Stream channels required 26-325 m^3 of rock ranging from 15-90 cm in diameter. Any combination of crane, excavator, or backhoe, and tractor or loader placed rock in stream channels at costs ranging from $1.50 - $21/$m^3$. Using heavy equipment, the average cost for rock placement was $7.25/$m^3$. Labor crews performed the final adjustment of rock placed by heavy equipment, and placed rock in smaller channels where large boulders were not essential. In these smaller channels, labor costs for rock placement ranged from $19 - $57/$m^3$ and averaged $42/$m^3$. Rock armor adjusts slightly in response to the first runoff events, and requires little or no maintenance.

Like rock armor, check dams can minimize channel erosion in newly excavated stream channels. Check dams are constructed from milled redwood boards and have an estimated useful life of 10 years. Prior to 1980, check dams were commonly constructed in small streams, and were capable of containing an estimated peak discharge of less than .2 cms. In 1980, experimental check dams were constructed with the largest group capable of containing an estimated 1.4 cms peak discharge. A total of 424 check dams were constructed at an average cost of $109/dam ($25 - $1400/dam). Single board check dams, averaging 1 m high and 2 m long, cost from $25 - $84/dam and averaged $37/dam. The average cost to construct multiple board check dams (1.3 m high, 4.6 m long) was $156/dam and ranged from $117 - $1400/dam. Check dams must be periodically inspected and maintained to prevent plugging and washing-out of the entire structure.

(a)

(b)

FIGURE 3. Before (3-a) and after (3-b) sequence of a haul road crossing excavation from an intermittent stream channel. As a primary treatment, a crawler tractor and track mounted backhoe-loader excavated approximately 769 m^3 of fill from the stream channel. Rock armor was prescribed as a secondary treatment and was placed by the same equipment. The excavation required a combined total of 18 equipment hours, and rock placement required 5 hours. The total treatment cost $1530.

Secondary treatments were also designed to prevent sheet, rill and gully erosion from bare soil areas, to preserve open soil structure and high infiltration rates, and to aid in subsequent revegetation. Straw mulch was applied to bare soil areas at rates of 4500 - 6700 kg/ha; average cost of application was $1800/ha. On steep channel banks (>25°) jute netting was applied over a straw layer and anchored to the ground with redwood stakes. This technique prevented the straw from being blown off the channel banks and added further protection against surface erosion and soil compaction. The average cost to apply straw and jute netting was $1.55/m^2 ($15,000/ha).

SITE SPECIFIC EROSION CONTROL TREATMENTS

The erosion control treatments described in the preceding section were typical of most work performed in 1980. However, unique erosion control treatments were prescribed to treat unusual or complex erosional processes identified on each of the rehabilitation units.

Bridge Creek, M-6-2 Road and Slope Unit

An erosion control treatment unique to the Bridge Creek, M-6-2 rehabilitation unit was the attempted stabilization of a .80 ha landslide. Constructed in the early 1970's, the M-6-2 road crossed 20°-27° hillslopes approximately 100 m above the main channel of Bridge Creek. Underlain by highly sheared schist, areas on the hillslope had an accelerated soil creep/landslide history. On one such area, an estimated 4200 m^3 of fill had been sidecast onto the crown of an old landslide during road construction. A small log landing had also been constructed there. Three tractor skid trails, constructed immediately above and leading down to this landing, created further ground disturbance in this naturally unstable area. The disturbance caused by road and skid trail construction altered surface and groundwater drainage characteristics and loaded the crown of the slide. In all probability, groundwater levels were also increased by the clearcutting of upslope areas. As a result, an 80 m wide, approximately 100 m long hillslope region, including the road prism, failed in response to 1972 storm events. Portions of the slide mass continued to show recent, intermittent movement and a significant volume of material remained perched above Bridge Creek. Fresh, vertical displacements up to 1 m were observed along the crown and margin scarps, and discontinuous drainages maintained saturated soil conditions throughout several locations on the upper slide mass.

Stabilization efforts were directed towards unloading weight from the slide, and improving surface and subsurface drainage. During the wet season, springs and groundwater discharge areas created by skid trail cuts were located and mapped. During the dry season, a dragline crane and crawler tractor excavated an estimated 3076 m^3 of fill from the upper .30 ha of the slide, and dump trucks endhauled the material to a dry, stable storage location. The combined costs to excavate and endhaul the fill material averaged $6.91/m^3. Upon completion of the fill removal, groundwater discharge areas were relocated and combined with surface drainages to form an artificially constructed drainage network. A backhoe then excavated drainage channels throughout the treated portion of the slide to collect water and speed drainage across this sensitive area. To prevent bank and channel erosion, labor crews constructed 115 check dams in the drainage channels at a unit cost of $25.00 per check dam. Check dams averaged 1 m high and 1.3 m long. As a final treatment labor crews spread grass and red alder (Alnus oregona) seed and straw mulch, and planted red alder seedlings.

1920 Road and Slope Unit

Erosion control work unique to the 1920 rehabilitation unit included the extensive excavation of skid trail crossings and drainage ditches to improve drainage above a large, incipient hillslope instability. Located on the east side of Redwood Creek, the lower portion of this unit is underlain by highly sheared Franciscan sandstones and siltstones associated with the Grogan Fault. Active earthflows occur throughout this lower hillslope region and evidence of previous mass movement exists across the entire unit as "tread and riser" topography, old scarp traces, and a topographically inverted stream reach (i.e., flows along a ridge crest). The logging history of this unit dates back to the 1950's, but accelerated timber harvest did not occur until 1973-1975. Approximately 75 percent of this unit was tractor yarded, and in portions of this unit, disturbance to natural drainage networks was extensive.

Winter field mapping identified a large, incipient hillslope instability near the southern unit boundary which appeared to be reactivated by altered, post-logging soil and groundwater conditions. Evidence of this slope instability was a small (3000 m^2) earthflow surrounded by discontinuous scarps and tension cracks which extended approximately 100 m to either side and 200 m above. Farther above the slope instability, the headwater regions of intermittent streams were extensively damaged by tractor activity. Stream channels were filled with sidecast material and crossed by numerous skid trails. In concert with several large perenneial springs which drained onto this area, surface drainage networks were discontinuous, poorly defined, and encouraged saturated conditions in the structurally sensitive hillslope area. These factors, when combined with the existence of inherently weak bedrock lithology, decreased evapotranspiration, and increased ground saturation, were accelerating slope instability.

Large, active earthflows occur along this hillslope and contribute large volumes of sediment to Redwood Creek. Erosion control prescriptions focused on reducing the earthflow potential of this hillslope instability. These measures were an attempt to prevent saturated soil conditions by collecting, directing, and speeding surface drainage. Two backhoes and a crawler tractor excavated skid trail crossings from stream channels, and constructed drainage ditches to direct spring flow into more stable watercourses. A total of 2200 m^3 was excavated from 21 skid trail crossings at an average cost of $625/crossing ($6.00/m^3). Three drainage ditches and 53 waterbars were constructed at average unit costs of $660 and $9.30 respectively. Finally, labor crews spread straw and grass seed on 1.7 ha of newly disturbed ground, and constructed 49 check dams to control surface erosion.

Maneze Creek Unit

On the Maneze Creek Unit, gully erosion was treated on hillslopes that had been extensively disturbed by skid trail construction during tractor logging in the early 1970's. Skid trails were not waterbarred following timber harvest, and storm runoff and intercepted groundwater concentrated on skid trails causing severe gully erosion. A particularly active gully system averaging 6.2 m wide and 2.5 m deep, had downcut through highly erosive Atwell soils and was delivering sediment directly to Maneze Creek, a perennial tributary to Redwood Creek. Furthermore, the gully system appeared to be accelerating the development of a large hillslope failure (estimated 20,000 m^3) by feeding a portion of its flow into the headscarp region of the hillslope failure. Below the headscarp, the gully was continuing to downcut and enlarge for the remaining 250 m of its length to Maneze Creek.

A diversion channel was prescribed to de-water the gully system. The diversion was designed to intercept hillslope runoff and gully flow from the stable headwaters of the gully and deliver the runoff directly to Maneze Creek. Heavy equipment excavated a low gradient, 200 m long diversion channel nearly along contour. Approximately 3800 m^3 of material was excavated at an average cost of $\$3.50/m^3$. Following the excavation, equipment placed 285 m^3 of rock averaging 60 cm in diameter to prevent channel enlargement and downcutting. Equipment cost to armor the channel averaged $\$12/m^3$.

W-Line Road and Slope Unit

Prairie restoration was the theme on the W-Line rehabilitation unit. This unit encompassed 81 ha of natural grasslands of Dolason Prairie across which 3.1 km of logging haul road had been constructed in the late 1950's. The lower 1 km was later upgraded to gain access to two timber units completed in 1977. The earlier haul road crossed emphemeral streams in 16 locations, and the crossings were either log/fill ("Humboldt") or fill constructions. Twelve crossings had either washed out or plugged and diverted flow down the inboard ditch of the road. Extensive gully erosion and channel erosion had occurred. Prairie soils are highly erodible, lack deep root structures which can inhibit the rate of downcutting, and have low infiltration rates and shallow groundwater levels. These factors make them especially sensitive to altered hydrologic conditions.

The high visibility and easy access to prairie land implies a greater potential for future visitor use and places a higher value on the aesthetic appearance of prairies than on logged forest lands. Therefore, erosion control prescriptions considered the aesthetic value of the prairies as well as the erosional processes. The haul road was completely outsloped allowing runoff to remain dispersed. Slope morphologies above and below the road were blended together so virtually no trace of the road was visible (fig. 2). Sixteen road crossings were removed by a hydraulic excavator and crawler tractor at a cost of \$4731 (\$295/each). The prairie road was completely outsloped by a hydraulic excavator and crawler tractor with a 6-way blade. Total cost to outslope 3.1 km of road was \$13,321 (\$4297/km). Secondary treatments included seed and straw application on recontoured slopes, and rock or small check dam placement in stream channels.

As for the success of erosion control treatments, we must assume a "wait and see" or "time will tell" position. All rehabilitation units are being closely monitored to evaluate the effectiveness of erosion control treatments.

DISCUSSION

Erosion control treatments are divisible into primary and secondary treatments. Primary treatments result in the physical removal of potentially erodible fill and woody debris, and the alignment and/or improvement of drainage networks. Secondary treatments provide protection to areas freshly disturbed by primary treatments, and can also be performed in areas inaccessible to heavy equipment.

Unit costs to perform primary treatments with heavy equipment vary between work sites and rehabilitation units. The reasons for such variations include: 1) location and accessibility of work sites, 2) size of road or stream excavation, 3) the amount of debris encountered during fill excavations, and 4) types of equipment used. Perhaps the most important factor is the latter. Unit costs are affected by equipment application simply by having the right equipment for the job. Based on the past three years of experience, hydraulic excavators and crawler tractors appear to be the most cost-effective equipment combinations for most earth moving tasks.

In 1980, secondary treatment costs accounted for 34 percent of the total cost for erosion control. Of this cost, check dams and rock armor account for 92 percent. Check dams and rock armor minimize bank and channel erosion in excavated streams. However, the amount of sediment saved by check dams and rock armor can be one to two orders of magnitude less than the amount of sediment removed by primary treatments. Notwithstanding the effectiveness of check dams and rock armor, most stream channel excavations can be designed to accommodate runoff events having 20-year return intervals, thereby minimizing bank and channel erosion and reducing the need for costly secondary treatments.

In contrast to 1980, "erosion potentials" are now being performed to predict the cost-effectiveness of treatments proposed at all work sites. The sediment to be saved by performing a treatment is weighed against the cost to perform that treatment. Secondary treatment costs may be reduced by perhaps 80 percent by eliminating excessive rock and check dam treatments. Supervisory geologists and hydrologists are more experienced with heavy equipment and are utilizing equipment more cost-effectively. Finally through extensive peer review, prescriptions are being closely scrutinized to insure a more uniform, cost-effective statement of purpose, and application of techniques.

ACKNOWLEDGEMENTS

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REHABILITATION OF A 290 HECTARE SITE IN REDWOOD NATIONAL PARK

Patrick Teti[1]

Abstract. A 290 hectare (710 acre) site that had been tractor logged between 1969 and 1975 was mapped and treated for erosion control in 1980. Gullies up to 4.3 meters (14 feet) deep were the dominant erosion feature and were caused by the diversion of run-off by roads. A gully inventory in a 40 hectare (100 acre) sub-unit revealed management related erosion of 1.3 centimeters (one-half inch) in seven years although all mapped erosion occurred in gullies that occupied only a half a percent of the land area. The most cost-effective erosion control treatments were the de-watering of active gullies and the excavation of road fill from stream crossings.

INTRODUCTION

In this paper the logging related erosion processes and major erosion control treatments on a 290 hectare (710 acre) unit within the Bridge Creek drainage of Redwood National Park are described. This site was one of six sites which were mapped and rehabilitated in 1980 under the direct or indirect supervision of Redwood National Park geologists. The focus of this paper is on the major logging related sediment sources to the fluvial systems from this unit and on the treatments performed to reduce future sediment yields from those sources. The observations and conclusions are those of a single author and are based on experience within an area in which the surficial geology is not representative of the whole park.

This unit is located on the east valley side of Bridge Creek, a major left bank tributary to Redwood Creek. Total relief from the creek to the ridge top is 510 meters (1680 feet). Approximately 90 percent of the area mapped and treated has slopes of 35 to 45 percent but slopes of 100 percent or more are common next to channels draining 20 hectares (50 acres) or more.

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Figure 1 shows the location of the hillslope that was mapped in the spring of 1980 and treated beginning in the summer of 1980. Treatments of logging haul roads continued in 1981 but only 1980 treatments are discussed here.

About 90 percent of the old growth redwood and fir forest on the site was clearcut by tractor logging between 1969 and 1975. Skid trail density was measured from aerial photos to be 474 meters per hectare (635 feet per acre) and a total of 12.1 km. (7.25 miles) of haul roads had been constructed, all of which were still in place in 1980 except for where a stream had washed out the road fill of two crossings. The timing of logging with respect to the spring storms of 1972 and 1975 is shown in figure 2. Fifty percent of the unit was logged before the 1972 storm (1969 to 1971), forty-six percent was logged between the 1972 and 1975 storms (1972 to 1974), and four percent was logged after the 1975 storm (1975).

Soils and parent material are of critical importance to the potential erosion of a disturbed hillslope. In particular, the depth from the soil surface to competent bedrock or boulders determines the maximum possible depth of gullying by water that is diverted onto a hillslope. It also provides some insight to the stability of a channel after its bed and banks are disturbed by logging equipment, particularly if the channel substrate consists of strong tree roots overlying soils or weathered bedrock that are composed of small particles, easily entrained by flowing water.

Most soil in this unit was colluvial and had a brown, clay loam B-horizon of about 40 cm. (16 in.) thickness. A plus B-horizon thickness was 50 to 100 cm. (20 to 40 in.) (Jim Popenoe, Redwood National Park, oral communication, 1982). Schistose boulders were typically found in the cut banks of roads and in the bottoms of gullies at a depth of about 3 meters (10 feet). Boulders were also common in the beds of streams draining about 20 hectares (50 acres) or more. However, boulders or bedrock were seldom observed in the beds or banks of smaller streams, except where disturbance related erosion had enlarged a flowcourse. The roots of trees and understory vegetation were interwoven into a strong mat in the banks of all of the most stable channels, and appear to have been the major source of strength in the smaller channels prior to logging. The full extent of logging related disturbance in headwater tributaries was, however, not always obvious due to the high degree of disruption of channel beds and banks by logging equipment, disturbance of drainage networks by roads, and higher than normal sediment storage in channels during this period of post-logging slope readjustment.

GEOMORPHIC MAPPING AND INTERPRETATION OF EROSION PROCESSES

A total of about 50 person days were spent mapping the hydrologic and geomorphic features of this unit at a scale of 1:1800. The purposes of mapping were: 1) to provide the basic information necessary to plan and implement erosion control treatments; and 2) to document the erosion features associated with road construction, logging, and natural processes.

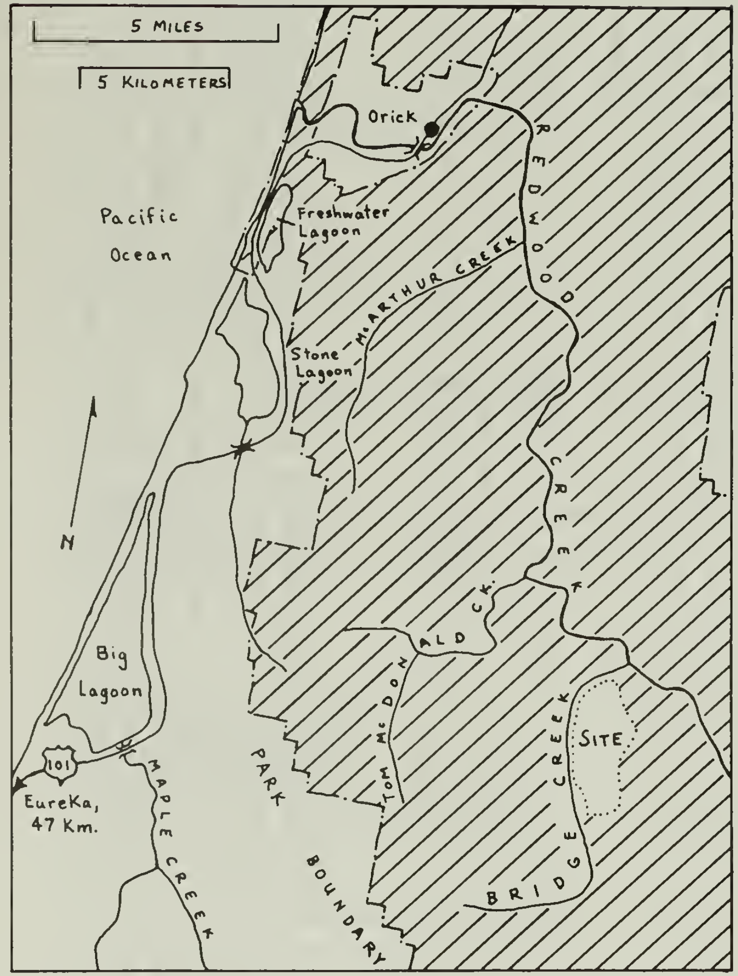


Figure 1. Location Map

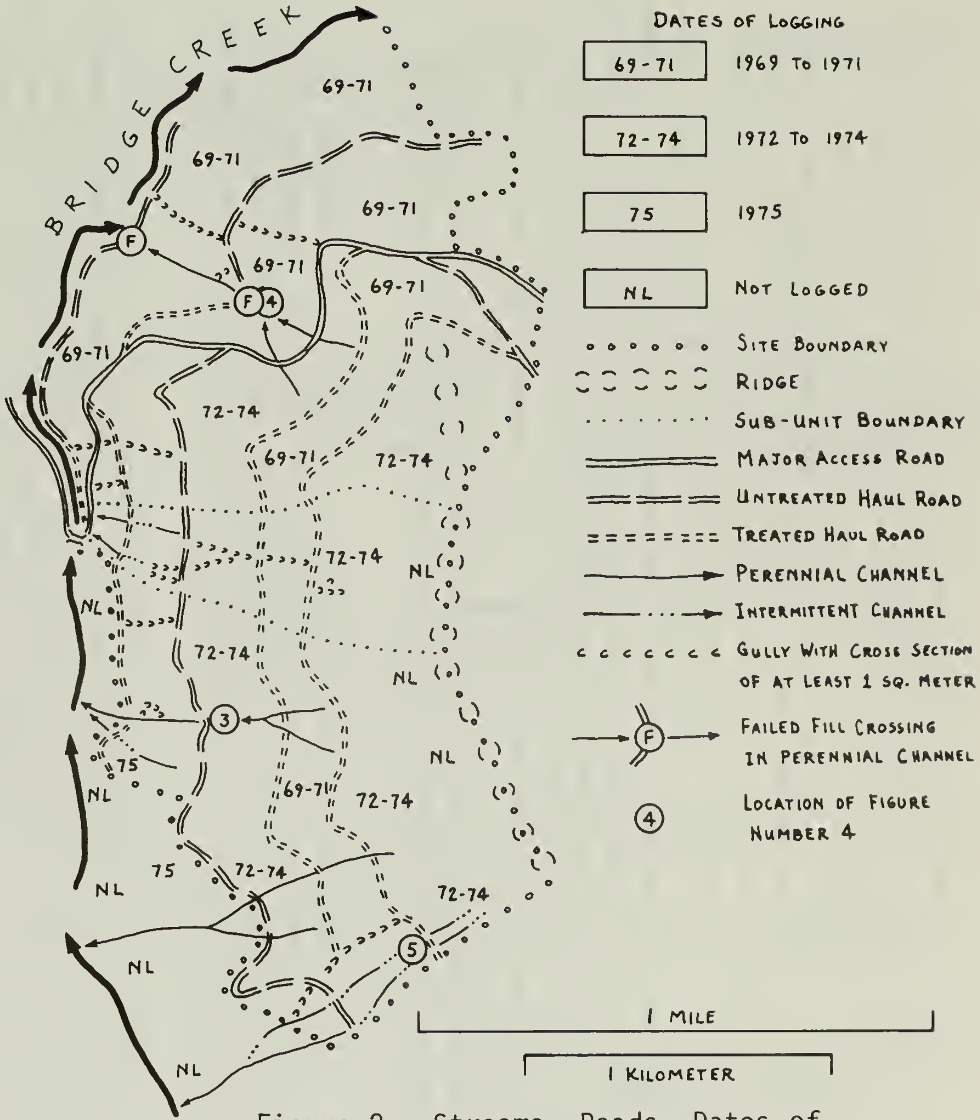


Figure 2. Streams, Roads, Dates of Logging, and Other Features on the Site

Field work revealed an assortment of gullies up to 23 square meters (250 square feet) in cross sectional area, up to 4.3 meters (14 feet) in depth, and ranging in activity from very inactive to very active. The most active gullies had vertical or overhanging banks, were deeper than they were wide, were totally unvegetated, and were observed to be contributing sediment at the time of mapping with water discharge during rainy periods in order of 10 liters per second (.36 cfs). The presence of all of these gullies can be explained by the diversion of water by skid trails, haul roads, and misplaced culverts. All of the most active gullies were found on slopes which had been logged since 1972. The most inactive gullies had beds and banks that were fully vegetated with alders. Their sideslopes had gradients of around 100 percent but were stable. In many cases their beds were composed of schistose boulders or bedrock. Some gullies had become inactive due to the water supply being shut off, for example by water from a culvert outfall finding a new course on a slope and cutting a new gully. Other gullies continued to convey the diverted runoff and eroded their beds and banks until a condition of relative stability was reached.

An important observation in terms of sediment yield was that the gully and stream channel network was very efficient at transporting fluvially eroded sediment. From observations of stored sediment it was estimated that 90 to 99 percent of the net gully volume eroded from this hillslope was delivered to Bridge Creek.

Figures 3, 4, and 5 show examples of three of the major sediment sources on this unit and also provide a sample of the geomorphic mapping. Figure 3 shows a skid trail crossing of a stream draining 28 hectares (68 acres). The crossing had been constructed by filling the channel with logs and earth fill to a depth of about 3 meters (10 feet). The major impact of this crossing as of the time of mapping was the diversion of flow out of the natural channel resulting in a gully from which 380 cubic meters (500 cubic yards) of soil had been removed in a distance of 46 meters (150 feet). The gully had become nearly inactive due to exposures of boulders in its bed and natural revegetation on its sideslopes, but the fill in the skid trail crossing constituted a future source of sediment.

Figure 4 shows a road failure at the intersection of a haul road and a stream draining 28 hectares (a different stream than the one mentioned in the preceding paragraph). At this location, about 23 cubic meters (30 cubic yards) had already been eroded and the potential for future erosion (without treatment) was estimated to be 100 cubic meters (130 cubic yards).

Figure 5 shows an example of one of the most important problems with haul roads on this unit, gullying due to a misplaced culvert. This problem was considered important for four reasons: 1) the volume of gullying was large; 2) such gullies on this site were still very active; 3) the problem was preventable at the time of road construction; and 4) the problem was easily treatable by rehabilitation techniques. In this example, a stream draining only 5.7 hectares (14 acres) was diverted out of its natural channel by the inboard ditch and through a culvert onto a slope about

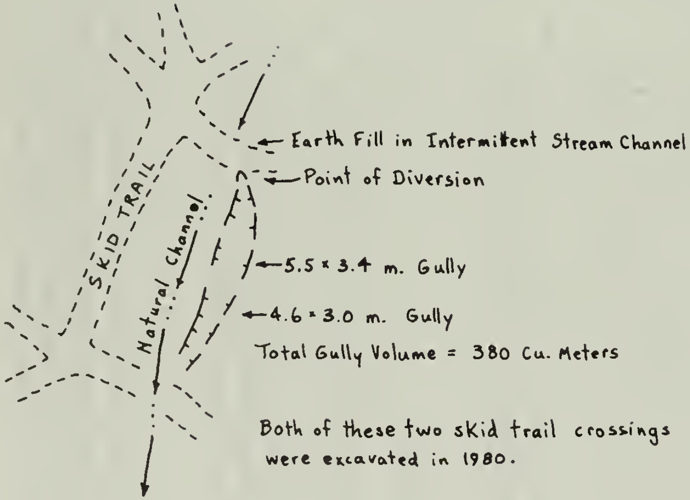


Figure 3. Gully Caused by Diversion of Stream at Skid Trail Crossing

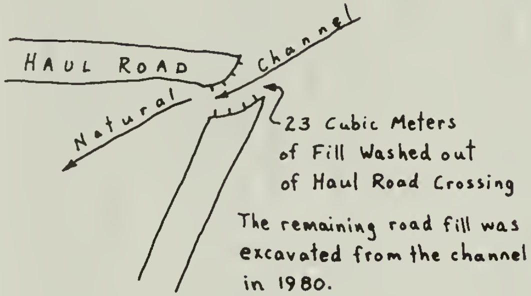
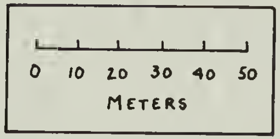


Figure 4. Failure of Earth Fill at Haul Road Crossing of Stream



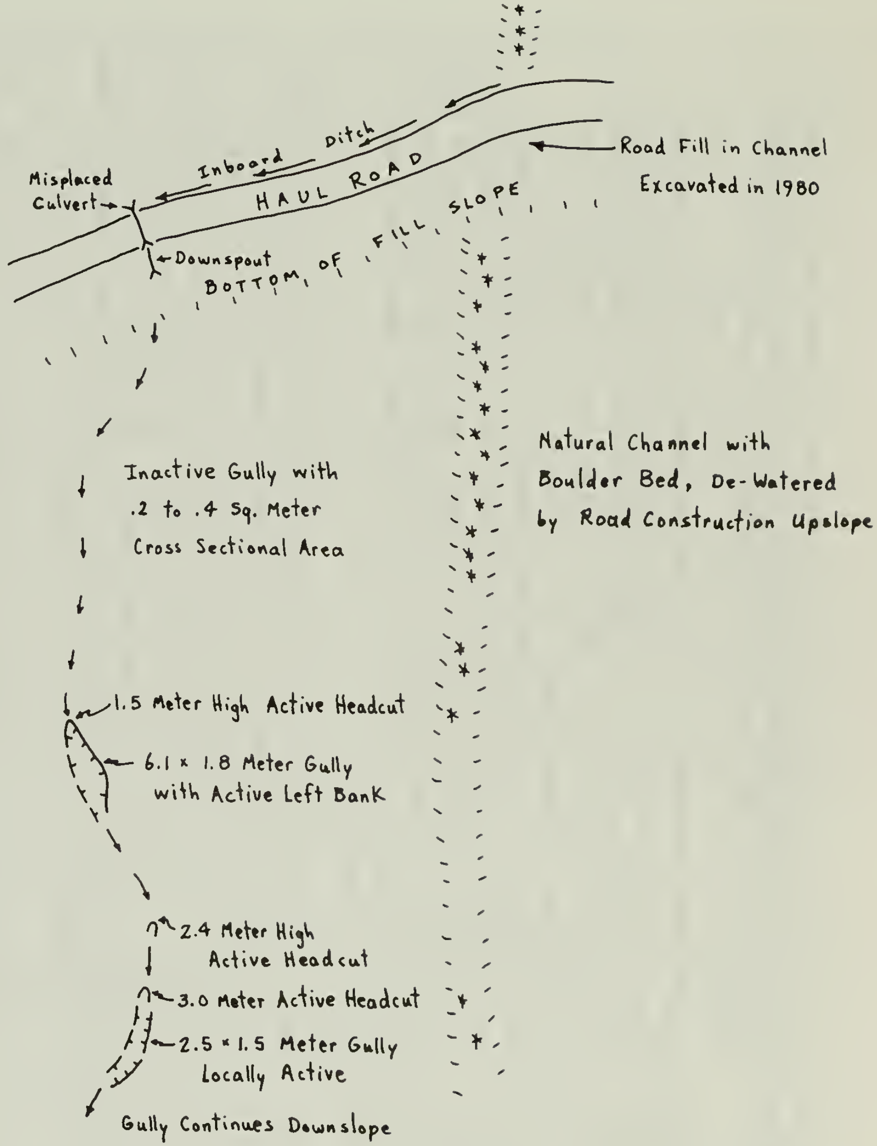


Figure 5. Gully Caused by Misplaced Culvert

Returning once again to the subject of erosion features on the whole 290 hectare site, the following generalizations and conclusions are made: 1) Gully erosion was relatively insignificant within an elevation of 100 meters (330 feet) of the ridge due to small drainage areas. 2) The most important sediment sources, in terms of volumetric yield of sediment to Bridge Creek, were gullies that resulted directly from skid trail and haul road construction procedures. 3) Some gullies had become virtually inactive as sediment sources by 1980 but other gullies clearly had the potential for continued sediment yield. 4) Failures of road fill at stream crossings were not as large a sediment source as gullies between the time of road construction and 1980. However, the relative importance of road fills at stream crossings would have been expected to increase with time as gully systems eventually stabilized and culverts at stream crossings occasionally became plugged or eventually disintegrated, thus exposing overlying road fill to erosion.

Only 2 haul road crossings, out of a total of 26 crossings of streams draining between 4 and 40 hectares (10 to 100 acres) on this site had washed out to the point of the road being impassable by truck, by 1980. However, there were 6 other crossings that were either partially washed out or which showed evidence of failure and repair prior to park acquisition of the land in 1978. Partially failed and intact crossings therefore represented a major potential sediment source because of their large volume (150 to 1150 cubic meters each) and their proximity to stream channels.

The relatively dry winters along the north coast between the time of park expansion and the winter of 1979-80 made it difficult to anticipate the full importance of a sediment source that has recently been observed to be a major one associated with roads in the park. This is the rapid mass movement of saturated haul road and skil trail fill into stream channels. Such failures occurred within this site and in other parts of the park in response to the storm of late December 1981 which brought 22 to 34 cm. (8.5 to 13.4 in.) of rain to the higher elevations in the park between 14 and 21 December. The record from the O'Kane recording rain gauge maintained by the National Weather Service near Highway 299 along Redwood Creek indicates that virtually all of this rainfall occurred in the three days of 18 to 20 December. Because these sediment sources were not anticipated, their treatment is not discussed in the next section.

TREATMENT METHODOLOGY

Erosion treatments were planned only after mapping of complete hydrologic units. This was considered important because of the extent to which natural drainage networks were disrupted by roads and trails. The main considerations in planning treatments were the potential for future erosion, cost of treatment, and the amount of ground disturbance that would result from treatment.

Future sediment sources (potential erosion) were categorized according to two main types: 1) hillslope gullying by diverted surface runoff; and 2) failure of road fill into stream channels. In simpler terms, these sediment sources are due to either water having been diverted where it

80 meters (260 feet) away. This diverted stream gullied its way downslope for a distance of 490 meters (1600 feet) and removed a volume of 1620 cubic meters (2120 cubic yards) before rejoining its natural channel.

The mapping of gullies on this site includes width and depth measurements in sufficient detail to quantify all gullies larger than .09 square meters (1 square foot) in cross sectional area. However, at this time only those gullies in a 40 hectare (100 acre) sub-unit shown in figure 2, have been tallied for this site. This sub-unit spans the full 510 meter (1680 feet) elevation range of the hillslope and is crossed by four logging haul roads. It is not necessarily quantitatively representative of erosion on the rest of the unit but the character of management related sediment sources and erosional processes is representative. Total mapped gully volume in this 40 hectares was 5200 cubic meters (6800 cubic yards), most of which was derived from gullies with cross sections of at least 5 square meters (54 square feet). The largest gully cross sections were 11.6 square meters (125 square feet) and the deepest gullies were 4.3 meters (14 feet) in depth. The pattern of gullies on this unit reveals discontinuities in plan view and in long profile that are a direct result of interception of water by skid trails; diversions by inboard ditches, culverts, and landings; and an increase in the volume of diverted runoff downslope. Tractor logging between the ridge and the highest haul road left a network of skid trails (almost completely without waterbars) which converged downslope. This network of skid trails intercepted storm runoff into the inboard ditch of the first (highest) haul road. This runoff, which under natural conditions would probabaly have been spatially dispersed and not even emergent as surface runoff, formed a gully with a cross sectional area averaging .91 square meters (9.7 square feet) between the first and second roads. At the second road the flow spilled out onto a landing which diverted the runoff in three different directions. The resulting gullies, each with a volume of at least a few hundred cubic meters, formed in response to different runoff events and probably in different years, as indicated by their different ages of natural revegetation. The flowcourses which caused these three gullies converged at the third road and below this point there was no more major gullying.

Erosion in the gully system described above could have been reduced by some simple procedures. Waterbars on the skid trail network between the ridge and the first road, along with more culverts on the two upper roads, would have kept runoff more dispersed on the hillslope. Also, some maintenance of the landing on the second road could have confined runoff into a single gully, the oldest of which was 2 to 3 meters (6.5 to 10 feet) deep and had begun to stabilize by the time the second gully formed.

Most of the erosion problems in the 40 hectare sub-unit originated on slopes which were logged between 1972 and 1974. Between the summer of 1972 and spring of 1980 there were seven rainy seasons. Erosion is therefore assumed to have occurred in seven years. Total volume of soil loss, which was mapped entirely as gullying by diverted surface runoff, was measured as 5200 cubic meters (6800 cubic yards). This is equal in volume to a loss of 13 mm. (.5 inch) averaged over the whole sub-unit although virtually all of the mapped erosion occurred on only about a half a percent of the area.

does not belong or dirt being placed where it does not belong. As trivial as it may sound, the preceding sentence leads directly to the main part of the treatment methodology: 1) put water back where it belongs on a slope (e.g. with waterbars and diversion trenches); and 2) remove earth fill from stream channels. These two types of treatments were the highest priority treatments and were accomplished almost entirely by heavy equipment (dragling crane, hydraulic excavator, tractors, and a backhoe). Decisions to treat or not to treat potential sediment sources were based on considerations of the volume of sediment that could be "saved", the degree of revegetation, the magnitude of storms to which the region had already been subjected, the amount of disturbance necessary for heavy equipment to reach the site, and site specific considerations of slope stability and possible erosion control techniques.

Figure 3 and 5 show examples of both types of sediment sources, as defined in the preceding paragraph. Both crossings in these two figures had sources associated with diversions (already eroded) and sources associated with fill in stream channels (potential erosion). Both crossings were excavated down to an approximate reconstruction of the corresponding channel long profiles and cross sections, thereby accomplishing both main types of treatments at the same time, that is, de-watering of active gullies and removal of fill from stream channels. Excavation of fill from the crossing in figure 4 and from most other crossings on this site falls under the second main category of treatment, or removal of earth fill from channels. The construction of waterbars and diversion trenches are examples which fall into the category of putting water back where it belongs on the slope, or the repair of micro-drainage networks.

The partially failed road crossing shown in figure 4 was also excavated down to a close reconstruction of the original long profile and cross section. Approximately 23 cubic meters (30 cubic yards) of this road fill had failed prior to excavation but it was estimated that additional 100 cubic meters (130 cubic yards) could be eroded in the future. This potential erosion was considered sufficient to justify heavy equipment access and complete removal of the road fill from the stream channel.

Sediment sources in the 40 hectare watershed discussed earlier were related to disturbances of types 1 and 2, therefore treatments consisted of both the reconstruction of drainage networks and the excavation of road fill from stream channels. Between the ridge and the highest road, 29 waterbars were constructed to disperse surface runoff. The highest haul road was cross-road drained (in addition to being ripped) in order to keep surface runoff from becoming concentrated in the inboard ditch. At the second haul road the flow was considered sufficiently channelized, and draining a sufficient area (5.2 hectares, 13 acres) to justify the full excavation of road fill from the channel. Between the second and third roads, a trench diverted the flow out of a very active gully and into an older, well-vegetated, gully. This part of the hillslope was so disturbed that no stable, natural channel was apparent. The third haul road was left intact in 1980 and at this point, the flow passed through a culvert and into well-defined, incised channel. At the fourth road the fill was fully excavated from the channel and at the fifth road, immediately above the right bank of Bridge Creek, the road was left intact and flow is accommodated by a properly placed culvert. Excavation of the untreated crossing was planned for a later date.

Task	Erosion Control Category	National Park Geologists	Heavy Equipment	Manual Labor
Geomorphic mapping and planning of treatments	C[1]	$5,690	--	--
Restoring small drainage networks (e.g. waterbars)	A		$28,207	$1,660
Removal of fill from close proximity to channels	A		36,447	833
Protection of excavated stream beds and banks by check dams, rocks, mulch and alder plantings	B		2,770	23,401
Seeding, fertilizing, mulching and planting roads	D		--	7,071
Salvage 60,000 board feet of timber	D		3,935	400
Miscellaneous costs	C	16,140[2]	1,351	2,967
	Sub-Totals	$21,830	$72,710	$36,332

Grand Total = $130,872

[1]A - decreasing fluvial shear stress on erosive materials.
B - increasing shear strength at points of high shear stress.
C - erosion control overhead costs.
D - non-erosion control costs.

[2]$14,000 of this was the cost of supervision.

Table 1. Cost Breakdown for Rehabilitation on this Site.

The next largest major category of work was the restoration of small drainage networks by heavy equipment. This included ripping and cross road draining 8.2 km. of the 12.1 km. of haul roads on the site (4.9 of the 7.3 miles), the construction of 48 waterbars on skid trails, the construction of 4 backhoe trenches, and the installation of 2 culverts on haul roads that were to remain on the site for one year or more. Thus 50 percent of the total cost, or $64,654 was spent on restoring small drainage networks and removing earth fill from stream channels with heavy equipment alone.

The third largest major expense from table 1 was the protection of the beds and banks (including sideslopes) of excavated stream channels in road fill crossings by manual labor, at $23,401 or 18 percent of the total cost. Most of this amount (68 percent) was spent on the seven largest crossings, the largest single cost being the construction of check dams. At the three most expensive installations, 32 check dams each with a capacity of .7 to 1 cubic meters per second (25 to 35 cfs) were installed at a cost of $7520. Compare this with the cost of excavating 1945 cubic meters (2548 cubic yards) of fill from the same three crossings at a cost of $11,780. There is a question concerning the cost effectiveness of check dams and the other treatments relative to each other in absolute terms. This is addressed in the next section.

COST EFFECTIVENESS

In this section, estimates are made of the costs per unit volume of erosion prevention by five different types of treatments. The costs of these treatments are known but the amount of erosion that would have occurred without treatments must be estimated. Although subjective, these estimates are based on many observations on this site of erosional features which are analogous to those that would probably have formed under non-treatment scenarios.

Two worksites provide examples of the de-watering of active gullies and were the most cost-effective treatments on this unit. One of the two sites consisted of excavating the road fill from the crossing shown in figure 5, thereby also de-watering the gully associated with the misplaced culvert. The other gully, not shown in a figure, was de-watered by the installation of an additional culvert and flow dissipation structures in a haul road that was to remain within the unit after 1980. The added culvert intercepted inboard ditch runoff and diverted it into a low gradient (25 percent), slope with very good vegetative ground cover and dense fir seedlings. The gully that was de-watered formed on a slope of 45 percent. Estimates of potential erosion without de-watering of these two gully systems are based on bank sloughing back to 100 percent side-slopes, upstream migration of headcuts for a distance of between 15 and 30 meters (50 to 100 feet), and gully bed width enlargement to 1.5 meters (5 feet).

De-watering the first gully by the excavation of a small (92 cubic meter) road fill cost $399 and it was estimated that the erosion of 1600 cubic meters (2100 cubic yards) was prevented, for a cost-effectiveness of 25 cents per cubic meter (19 cents per cubic yard). De-watering the second gully by installing the culvert and some additional flow control structures cost $1475 and prevented an estimated 3590 cubic meters (4700 cubic yards) of soil erosion for a cost-effectiveness of 41 cents per cubic meter (31 cents per cubic yard). The average cost-effectiveness of these two gully de-watering treatments was 36 cents per cubic meter (28 cents per cubic yard).

All earth fill in haul road crossings of stream channels was assumed to be a potential sediment source, even if there was a properly placed culvert in the fill, due to plugging or culvert intakes by debris, insufficient culvert capacity during a large storm, or culvert disintegration. The volume of fill that would have failed had the excavations not been done was estimated by assuming that streams would have eventually eroded the fill down to a straight long profile with a bed of 1 to 2 meters wide and with sideslopes of 70 to 100 percent. On the average, this represents about 70 percent of the volume that was actually excavated from the channels since sideslopes were excavated with gradients of about 55 percent. Therefore, about 70 percent of 4800 cubic meters or 3360 cubic meters (4400 cubic yards) of erosion was prevented at a cost of $36,447 (from table 1) for a cost-effectiveness of $10.85 per cubic meter ($8.28 per cubic yard). This does not include the added cost-effectiveness that would result if some road fills would have caused diversions and gullies had the excavations not been done.

The two preceding estimates of cost-effectiveness are for heavy equipment treatments directed at reducing fluvial shear stress on erosive materials. The first, de-watering of active gullies at 36 cents per cubic meter of erosion prevention, is probably very near the practical limit of maximum cost-effectiveness, and does not represent typical values for the repair of drainage networks in general. The cost per unit erosion prevention of the more common work in this category, such as the construction of waterbars and cross road drains, was probably lower although it would be difficult to quantify. This is because they do not serve to alleviate any easily identifiable point or linear sediment source as do stream crossing excavations and the de-watering of gullies. Thus, there is no overall estimate for the cost-effectiveness of restoring small drainage networks.

The next most cost-effective erosion control treatment was calculated to be the addition of quarried rock to the beds and banks of freshly excavated stream channels. A total of $3428 was spent in the quarrying, delivery, and application of 76 cubic meters (100 cubic yards) of rock for 7 channel reaches averaging 10 meters long and 2 meters wide (33 feet long and 6.6 feet wide). The costs of rock application ($1210 on heavy equipment and $778 for labor) also include the salvaging and placement of about 15 cubic meters (11 cubic yards) of rock encountered while excavating road fill. About half of the mass of rock applied to channels was composed of clasts larger than 35 cm. (1.1 feet).

Skid trail and haul road crossings were excavated down to a close mimic of the original stream long profile and channel bed widths. It was estimated that the difference in channel erosion with rocking and that without rocking would have averaged .75 square meters (8.1 square feet) in cross section. This yields a cost-effectiveness for channel rocking of $59 per cubic meter ($45 per cubic yard) of erosion prevention.

Subsequent to the construction of diversion trenches and excavation of fill from crossings, one or more follow-up treatments were prescribed at almost all work locations. The purpose of these treatments was to increase the resistance of stream beds, banks, and sideslopes to fluvial erosion. Freshly excavated sideslopes adjacent to stream channels were treated with straw mulch at a rate of 4.5 tonnes per hectare (2 tons per acre) and those sideslopes with a gradient of 55 percent or more were additionally treated with a layer of Curlex (a brand name for shredded aspen wood from American Excelsior Company). Nine of the sixteen excavated haul road and skid trail crossings were protected with quarried rock with a maximum dimension of 1 meter (3.3 feet) and/or check dams made of redwood boards. Factors considered for the prescription of these in-channel structures were channel gradient, expected peak flow, the probability of encountering buried channel boulders, logistics, and cost.

Most active gullies on the site were treated by parital or virtually complete de-watering, but not all gullies could be de-watered. One gully that could not be de-watered was instead stabilized by the installation of check dams, submerged spillways combined with energy dissipators or flumes at knick points, and flow deflector boards at undercut banks.

In the most fundamental context of erosional processes, the goal of keeping soil on the slope and out of the fluvial system must necessarily be achieved by a combination of: 1) reducing shear stress on materials of low shear strength; and 2) increasing shear strength at points of relatively high shear stress. De-watering active gullies, excavating earth fill away from close proximity to channels, and constructing waterbars served to reduce the actual and potential fluvial shear stress on easily eroded materials. Treatments that served to increase shear strength at critical points were the construction of check dams, submerged spillways, flumes, energy dissipators, and the application of rock in channels. Heavy equipment expenditures were strongly weighted in the direction of the former (25 to 1) while labor intensive expenditures were equally strongly weighted in the direction of the latter (also 25 to 1).

A total of $130,872 was spent on this 210 hectare site through the payment of wages, salaries, a labor contract, and for heavy equipment rental. Table 1 lists the major tasks that were accomplished and the costs per task. Two items are included that do not contribute directly to erosion control. These are seeding, fertilizing, mulching and planting roads; and salvaging downed timber that was either already sawn or was blocking access to work sites. The other costs were related to erosion control treatments and accounted for 91 percent of the total cost.

The largest single cost in table 1 was for the removal of 4800 cubic meters (6300 cubic yards) of fill from 18 skid trail and haul road crossings at a cost of $36,447 or 28 percent of the total cost. The ten largest excavations of road fill from stream channels had a volume of 4720 cubic meters (6180 cubic yards) and cost $30,800 to excavate.

The cost-effectiveness of check dams was estimated by assuming the same difference in erosion for treatment and non-treatment of an excavated stream crossing as for the application of rock. At a cost of $7520, 32 check dams with 150 cm. by 30 cm. (5 ft. by 1 ft.) spillways were installed along 37 meters (120 feet) of channel in 3 road crossing excavations. This yields a cost-effectiveness of $91 per cubic meter ($70 per cubic yard) of erosion prevention for check dams. This does not include the cost of 80 check dam boards consisting of about 2400 board feet of old growth redwood lumber milled on site from salvaged logs.

A total of $5556 was spent for the control of surface erosion on 3700 square meters (.91 acres) of freshly excavated sideslopes at 13 haul road crossings. This included the spreading of straw mulch on all side-slopes, the application of Curlex on slopes greater than 55 percent, and the planting of alder transplants on 30 to 61 cm. (1 to 2 ft.) centers. By assuming a non-treatment effect of 1 cm. of additional soil loss, the cost-effectiveness of mulching and planting excavated sideslopes is $150 per cubic meter ($115 per cubic yard) of erosion prevention.

The cost-effectiveness estimates described above span two and one-half orders of magnitude from $.25 to $150 per cubic meter ($.19 to $115 per cubic yard) of erosion prevention. Based on these estimates, the different categories of treatment can be arranged according to different costs per unit volume of erosion prevention. That is, in order of decreasing cost-effectiveness: 1) de-watering of large active gully networks; 2) excavation of stream channel fills down to a close mimic of original channel geometry; 3) addition of rock to excavated channel beds and banks; 4) check dam construction in excavated channels; and 5) application of mulch and planting of trees on freshly excavated sideslopes of channels.

In December 1981, there were two apparently rapid mass movement failures of perched fill which traveled a distance of about 100 meters down slopes of 45 to 60 percent into stream channels on this site. If they had been accurately anticipated, they could have been prevented with about the same cost-effectiveness as the excavation of road fill from stream crossings. However, it would have been much less cost-effective to "pull" an entire road reach in order to prevent a single such failure. The careful mapping of headscarps, breaks in slope, leaning trees, and anomalous soils and groundwater discharge zones can help identify potential failures of this type.

A point of agreement among geologists is the relatively greater cost-effectiveness of heavy equipment over manual labor for any job that is feasible for equipment. For example, on this site the installation cost for single board check dams with a backhoe assisting laborers was 70 percent of that for installation by laborers alone ($47 versus $67 each). The efficiency of equipment is also seen in waterbar construction costs which were 65 percent of the cost for manually constructed waterbars ($30 versus $49 each). The most dramatic comparison is, however, the cost of excavation by heavy equipment versus that by manual labor. Heavy equipment moved earth fill an average of about 15 times further than that moved by labor contract at only one-fifth the cost per unit volume ($6.70 versus $32 per cubic meter). These comparisons do not take into consideration the additional benefits of heavy equipment relating to the speed with which it can accomplish a given task and improved safety through the reduction of total person hours at a work site.

The preceding paragraphs contain cost-effectiveness information that can be generalized in terms of conceptual and logistical approaches to reducing erosion on this site. The conceptual approach involved: 1) reducing fluvial shear stress on erosive soils by returning the micro-drainage network to a more normal state and by removing erosive materials from channels; and 2) increasing shear strength at points of high stress by armoring unnatural and disturbed flowcourses with rock, check dams, submerged spillways, flumes, and alder plantings. In simple terms, the logistical approach involved specific choices of using heavy equipment or labor in applying treatments that fall under 1) and 2) above. The estimates indicated that the most cost-effective techniques were in the category of 1) above and that heavy equipment use should be maximized in order to minimize the need for labor intensive work.

Comparisons of cost-effectiveness should not be taken as criteria for eliminating less cost-effective techniques. For example, mulching and planting channel sideslopes have purposes other than just erosion control, namely revegetation, aesthetics, and perhaps aquatic habitat improvement. Also, management policies in the national park are different than those on other lands. While the reduction of short term and long term sediment sources was the major goal of rehabilitation on this unit, the identification of goals and management criteria are organizational and personal decisions that differ with land ownership and with land managers.

CONCLUSION

Although some post-logging erosion features had apparently become inactive by the spring of 1980, there were many sites with obviously high potential for continued sediment yield. Active gullying associated with misplaced culverts was originally identified as the major sediment source for the next decade. However, debris flows from saturated haul road and skid trail fill during the winter of 1981-82 indicate that this source might have been at least as important as gullying would have been in the next decade. Failures of road fill from intact stream crossings would have been another major sediment source, as culverts intermittently failed at different stream crossings, probably over a period of decades.

The reduction of sediment sources on this sites was estimated to cost between less than a dollar and about ten dollars per cubic meter of sediment for the most cost-effective erosion control technqies. The least cost-effective treatments for which estimates were made, were mulching and planting excavated channel sideslopes, at a cost of around $100 per cubic meter of sediment reduction. The accuracy of cost-effectiveness estimates is expected to improve with time as the sample size of treated sites increases and as the sample becomes more representative with occasional large rain events. Improving these estimates is considered useful for application outside the park and for better identifying treatment priorities on future sites within the park.

ACKNOWLEDGEMENTS

This was not a one person project. I would like to thank the other park geologists, the heavy equipment operators, park laborers, NRG, Inc., park administrators, and taxpayers for their interest and support. Special thanks go to Matt Horns and Greg Bundros for their help in mapping, treatment decisions, and supervision of heavy equipment.

THE EFFECTS OF INTENSIVE FOREST LAND-USE AND SUBSEQUENT LANDSCAPE REHABILITATION ON EROSION RATES AND SEDIMENT YIELD IN THE COPPER CREEK DRAINAGE BASIN, REDWOOD NATIONAL PARK

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Abstract. The detailed erosional inventory of a 246 hectare tractor yarded clear-cut area in the Copper Creek drainage basin, a tributary to Redwood Creek, indicates widespread management-related sediment production and yield. The most important sources were gullies and enlarged channels caused by stream diversions. These accounted for 83 percent of the total measured erosion of 124,435 cubic meters. Ninety-two percent was attributed to four management-related causes while over 80 percent could have been entirely avoided by better land-use practices. Most of the increased erosion occurred during three major storm periods in 1972 and 1975. The delivery ratio for 91 percent of this erosion is conservatively estimated at 0.85. By 1979, 47 percent of the gully systems were inactive. Erosion control eliminated roughly 80 percent of the continuing and expected future management-related erosion.

INTRODUCTION

A significant problem associated with timber harvesting in mountainous terrain is the degradation of watershed resources resulting from increased rates of soil erosion and sediment yield. Few places in North America display this more graphically than the Redwood Creek basin where physiographic, geologic and climatic factors and complex land-use patterns have contributed to exceptionally high rates of erosion. For example, during six years of record beginning in 1971, Redwood Creek at Orick, California, transported a mean annual suspended sediment load of 2,619 metric tons per square kilometer (7,480 t/mi^2), 32 percent higher than the Eel River at Scotia, California (Janda, 1977), which has previously been characterized as the most rapidly eroding, non-glaciated basin of comparable size in North Amercia (Brown and Ritter, 1969). While Redwood Creek's suspended sediment discharge has been estimated to be 8.6 times greater than the expected normal rate of delivery (Anderson, 1979), some tributary basins displaying severe ground disruption from recent timber harvesting have yielded 17 times as much suspended sediment, per unit area, as nearby unharvested basins (Janda, 1977). One such highly impacted area is the Copper Creek drainage basin, a 7.3 km^2 (2.8 mi^2) watershed

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recently incorporated within the expanded boundaries of Redwood National Park (figure 1).

Prior to timber harvesting, 59 percent (445 hectares) of the Copper Creek drainage was covered with conifer forests dominated by coastal redwood (Sequoia sempervirens) and Douglas-fir (Pseudotsuga menziesii). Vegetation on the remaining 41 percent (314 hectares) consists of Oregon white oaklands (Quercus garryana) on the middle and upper slopes and prairie grasslands along the ridgetop areas. The conifer forest lands were logged between 1955 and 1971 with three years of multiple re-entry selective logging from 1958 to 1961 followed by clear-cutting and tractor yarding of the remaining residual timber in 1970-1971. This final phase of logging was marked by extreme ground disturbance (approximately 80 percent bare soil) over virtually the entire forested portion of the basin. In conjunction with the rehabilitation of the 246 hectare (607 acre) cutover area south of the main channel of Copper Creek in 1979, a detailed inventory of erosion sources was conducted to determine the magnitude and causes of accelerated erosion rates and to identify the extent to which various types of erosion on tractor-logged slopes have contributed to increased sediment yields.

SITE DESCRIPTION

This report deals with data collected on the logged portion of the Copper Creek basin south of the main stream channel and upstream from the K & K bridge crossing (figures 1 and 2). The site, which excludes the oak woodlands and prairie grasslands extending upslope from the boundary of the logged area to the divide, represents approximately 32 percent of the watershed and 55 percent of the cutover area within the basin. Figure 3 depicts a portion of the study area immediately following logging in late winter, 1972. Elevations at the site range from 170 to 730 meters (560 to 2,400 feet) and the average hillslope gradient ranges from 30 to 50 percent.

The Copper Creek watershed is underlain by interbedded graywacke sandstones, mudstones and conglomerates of the Franciscan complex. Hugo soils overlay most of the fractured bedrock found within the basin and study site. The Hugo soil series is widespread in forested areas on Franciscan terrain and represents over half of the forest soils in Humboldt County (Cooper, 1975). It is a fine loam, which typically develops on colluvial material and exhibits a comparatively high infiltration capacity. Soils of the Atwell series also occur locally on the study site and are predominately exposed along the streamside slopes of Copper Creek and its tributary channels. The high clay content of this soil and the highly fractured siltstone and mudstone parent materials on which it forms explain its close association with areas of slope instability.

Annual precipitation near Copper Creek, between 1938 and 1980, averaged approximately 2,032 mm (80 inches). Four major storms (1964, 1972 (2), and 1975) have occurred in Copper Creek since logging activities began in 1959. While the magnitudes of the 1972 storms were probably less than either the 1964 or 1975 rainfall events (Harden et al., 1978), their erosive impact may have been greatest, since clearcutting and tractor yarding was completed the year before. Dendrochronological evidence not presented in this report suggests that timing of the four major storms correlates well with the most active periods of gully development on the study site.

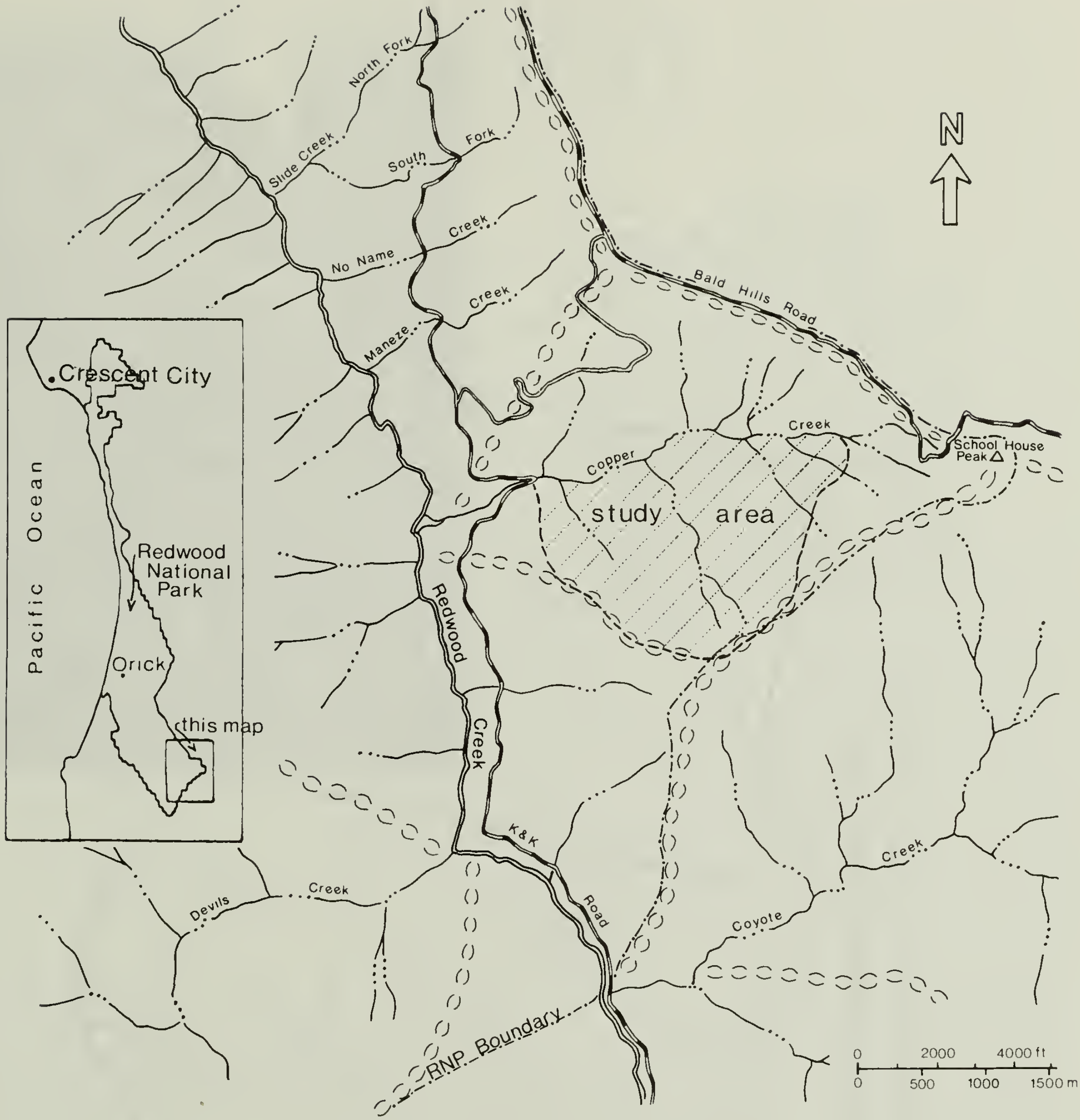
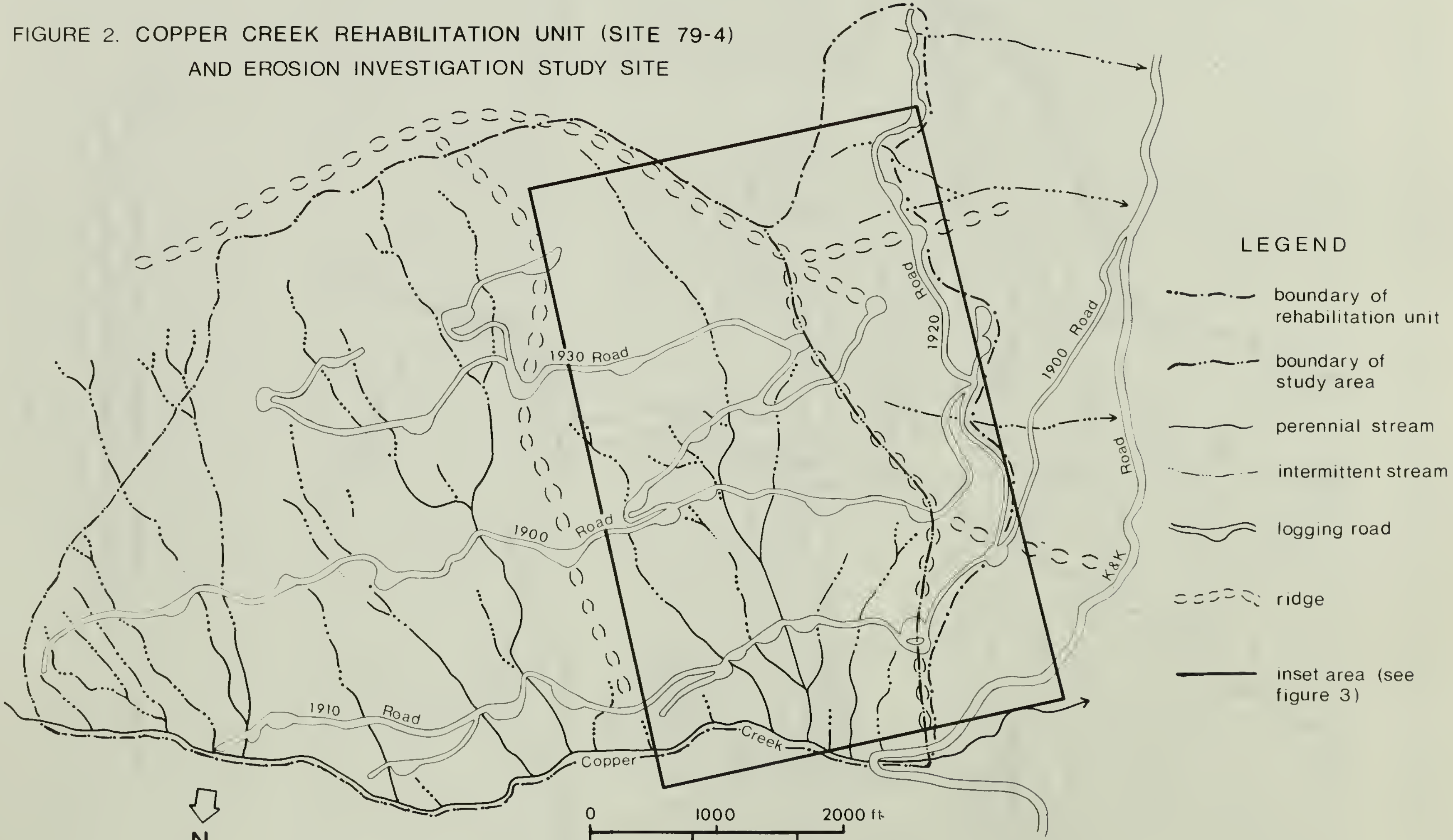


Figure 1. Location of Copper Creek Drainage Basin and Erosion Study Investigation Site

FIGURE 2. COPPER CREEK REHABILITATION UNIT (SITE 79-4) AND EROSION INVESTIGATION STUDY SITE



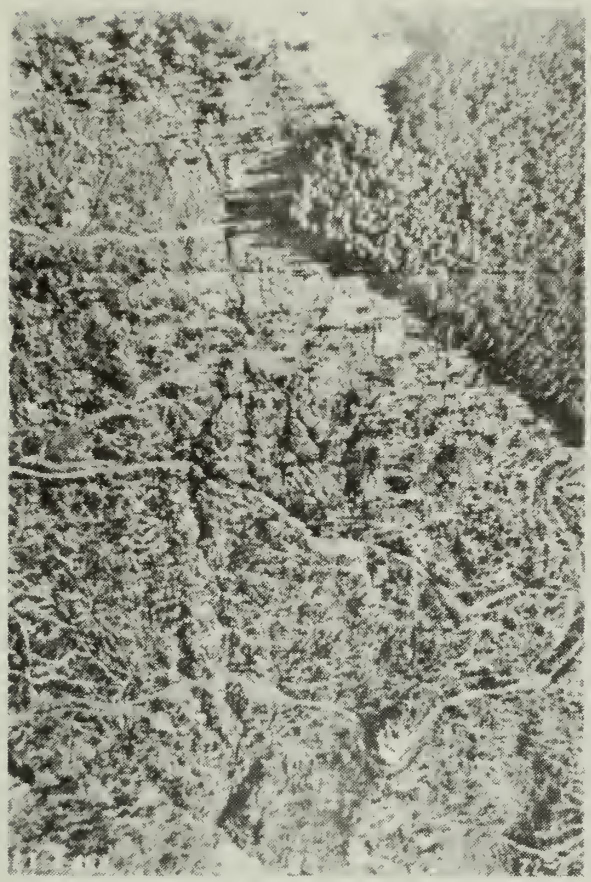


Figure 3. Aerial photograph (3/7/72) of west section of study site (see inset area, figure 2). Photo shows site conditions following 20 year return period runoff event. Note the degree of ground disturbance associated with the clear-cut tractor yarding completed in 1971. Old growth forest (upper right, outside of study area) was logged the following year.

METHODS

As a prerequisite to watershed rehabilitation activities, a detailed geomorphic map of the site was compiled during 2.5 months of intensive field work by several geologists. Active and inactive erosion sources, including all gullies with cross-sectional areas as small as 0.09 square meter (1 ft^2) were located and plotted on enlarged aerial photographs. With this geomorphic base map to guide future work, a two-phase, quantitative inventory of sediment sources was then initiated.

Exclusive of rilling, sheetwash, and small cutbank failures, erosional features on and adjacent to 9.3 kilometers (5.6 mi) of logging road and 27 log landings were numbered and indexed, according to grid coordinates, on the geomorphic base map. The field data sheets include sketches, volumetric measurements, detailed descriptions and causes of the erosional features. Feature lengths and cross-sections were measured with a tape and survey rod. Cross-sections were measured at 6.1 meter (20 ft) intervals or more frequently if a significant change in size or shape occurred. A total of approximately 160 erosional features were described and measured in the roads survey.

In its second phase, the survey focused on erosion features found on slopes adjacent to the major road systems and within the study area (figure 2). These included enlarged or gullied natural stream channels as well as all newly formed hillslope gullies greater than 0.27 square meters (3 ft^2) in cross-sectional area. Interfluve gullies smaller than this were often included in the measurements when they were elements of dicontinuous systems containing larger gullies. The only features excluded from the hillslope inventory were sheet and rill erosion, and isolated streambank failures along otherwise unimpacted watercourses (those not subjected to substantially increased discharges). The field methods defined in the road erosion survey were also used to measure and describe erosional features on the slope. However, the detailed sketches included in the road survey were usually replaced by verbal descriptions in order to facilitate measurements. A total of approximately 180 features representing 15.5 kilometers (9.3 mi) of gullies and gullied natural channels were included in the slope survey.

The analysis described below combines the information from the road erosion survey and the slope erosion survey. The data set consists of approximately 340 features or 3,500 cross-sectional measurements representing the total volume of erosion measured in the field. Locating and determining causes for erosion were often the more time-consuming and difficult aspects of the field study since causes were sometimes obscure and often, more than one cause could be attributed to a single erosional feature. Primary and secondary causes were located and recorded in the field for each erosional feature. This study presents only the primary causes. In a few cases, where two causes seemed to equally influence a feature, both causes were listed as primary and the volume was divided between them.

ACCELERATED EROSION

Gully systems on the site are widespread, complexly interconnected and represent the most dominant erosion process contributing to increased sediment yield (Table 1). The majority of gully-causing problems are associated with numerous

TABLE 1. SOURCES OF SEDIMENT PRODUCTION FROM THE COPPER CREEK STUDY AREA, 1971-1979

Sediment Source	Total Hillslope Erosion[a]					
	(% by length)	(% by volume)	(% stored locally)	(% transported downslope)	(m^3)	(yds^3)
New gully systems	90	70	0[b]	70	87,104	113,933
Gullied or enlarged stream channels	5	13	0[c]	13	16,177	21,159
Logging road fill failures	1	2	1	1	2,489	3,255
Slumps on logging roads	2	4	4	0	4,977	6,510
Landslides associated with logging roads	1	8	4	4	9,955	13,021
Combined gully/fill failure on logging road	1	3	0	3	3,733	4,883
Totals...............	100	100	9	91	124,435	162,761

a. does not include 12,030 m^3 of landslide erosion contributed from the sideslopes of the study area along the Copper Creek channel; excludes sheet and rill erosion and isolated tributary bank failures.

b. only the voids of gully channels were measured; no attempt was made to measure stored sediment on the gully bed, hence all eroded sediment, represented by void space, had been transported downslope.

c. on-site storage of sediment in the tributaries to Copper Creek is estimated at far less than 10 percent of total hillslope erosion; steep, supply-dependent streams moved virtually all erosional products supplied to them downslope and, eventually, off-site.

diversions of low-order stream channels on the clear-cut hillslopes. These problems reflect widespread tractor disturbance in and adjacent to the natural channel system, the lack of road maintenance between the initial selective harvest and subsequent re-harvesting, and the abandonment of the dead-end logging road system after clearcutting activities were completed in 1972. For example, by 1979, 18 of 23 culverts (78 percent) positioned along the 9.3 kilometer (5.6 mi) road network were totally ineffective and two of the five functioning culverts were partially plugged with sediment and debris. Such failures frequently led to road wash-outs or stream diversions and the creation of hillslope gullies. In addition, logging haul roads crossed 24 ephemeral and intermittent streams where no drainage structures were installed to transport streamflow through the road prism. These, together with numerous skid-trail stream crossings on hillslope areas, also served to divert previously channelized runoff across bare soil areas and resulted in the development of extensive gully networks.

In addition to gullying, accelerated erosion within natural, pre-existing stream channels contributed to sediment production from the tractor-yarded areas. Deterioration of skid-trail stream crossings and tractor disturbance adjacent to stream channels directly introduced soil and organic debris into the streams. Skid-trail crossings commonly diverted streamflow out of one stream, across hillslopes and into another stream system, resulting in the adjustment and enlargement of channel dimensions due to increased discharges. Soil and organic debris perched on steep channel-sideslopes caused slope failures into the adjacent stream channels. This debris, in conjunction with increased surface runoff and sediment delivery from cutover hillslopes, initiated additional channel enlargement and streamside landsliding. As a result of these disturbances, numerous stream channels on the site locally exhibited unstable, vertical sideslopes and enlarged channel dimensions.

Volumetrically, 70 percent of the accelerated erosion measured on the 246 hectare (607 acre) study area was derived from newly-formed gullies, while an additional 13 percent was derived from gullied natural stream channels which were adjusting to increased discharges and sediment loads (Table 1). The remaining 17 percent of measured erosion, by volume, was associated with landslides and slumps. These were almost exclusively derived from unstable logging-road fill slopes and cutbanks located on steep slopes near the bottom of the study site. Atwell soils, steep hillslope gradients and emerging groundwater, all common on the lower slopes, led to the increased susceptibility to mass soil movement in this region.

Of nearly 14.5 kilometers (9 mi) of gullies measured on the hillslopes (exclusive of both erosion on the road prisms and gullied natural stream channels), those with a cross-sectional area exceeding 1.1 square meter (12 ft^2) accounted for 95 percent (64,000 m^3) of the total gully erosion by volume, but only 50 percent by length. Those gullies over 0.5 square meters (5 ft^2) in cross-sectional area explained all but approximately one percent of the total measured volume. Initial results suggest future surveys of hillslope gully erosion on similar terrain may be simplified by inventorying erosional features, and then measuring only those channels in the larger size classes.

CAUSES OF ACCELERATED EROSION

Ninety-two percent of the measured post-harvest erosion, by volume, was

TABLE 2. Primary Causes of Management Related Sediment Production from the Copper Creek Study Area, 1971-1979

Primary Cause	Total Hillslope Erosion[a]			
	(% by length)	(% by volume)	(cubic meters)	(cubic yards)
1. lack of culvert maintenance	17	33	41,063	53,711
2. skid-trail stream crossing or other tractor disturbance in stream channel	36	31	38,575	50,456
3. lack of drainage structures at logging road stream crossings	16	15	18,665	24,414
4. mass-movement associated with logging roads and landings; due to unstable fill-slopes	3	13	16,177	21,159
5. misplaced culvert (placed down road from stream crossing)	4	4	4,977	6,510
6. increased surface runoff, due to harvesting, yarding and road building	18	3	3,733	4,883
7. lack of inboard ditch maintenance	6	1	1,245	1,628
Totals........................	100	100	124,435	162,761

a. does not include 12,030 m^3 of landslide erosion contributed from the sideslopes of Copper Creek.

attributable to four principal causes (see Table 2): 1) lack of road (especially culvert) maintenance (33 percent); 2) tractor disturbances in natural stream channels principally related to flow diversions originating at stream crossings (31 percent); 3) lack of culverts at logging-road stream crossings with consequent diversion of stream flows into road side ditches and/or across overland areas (15 percent); and 4) oversteepened road fills which subsequently failed (13 percent). Three other identified causes (see Table 2) cumulatively accounted for only eight percent of the total measured volume of increased sediment production.

During road construction, culverts were generally placed on the largest streams. Following abandonment of the road system in 1972, the subsequent plugging of these drainage structures caused the diversion of a number of second-order streams and the development of large hillslope gullies. While this "type" of gully accounted for the greatest volume of accelerated sediment production from a single cause (33 percent), they involved only a comparatively short total gully length (17 percent of total measured length). Thus, large stream discharges developed gully systems with the greatest cross-sectional dimensions (twice the average cross-sectional area compared to gullies from the next leading cause), but these same diverted waters quickly rejoined natural, pre-existing channel systems.

Skid trail stream crossings were frequently constructed on the small intermittent and ephemeral stream channels. Subsequent diversions of these waters caused the development of extensive gully systems on the dense network of skid trails found between the major drainage channels. While gully cross-sections were moderate in size ($\bar{x}$ = 4 m^2 (43 ft^2)), the gullies derived from skid-trail stream diversions accounted for over one-third (36 percent) of the total cumulative length of measured erosion features in the study area and 31 percent of the total volume. In contrast, it is noteworthy that gullies which developed on skid trails or other bare soil areas, and whose source of discharge could only be attributed to direct rainfall or intercepted subsurface flow, accounted for 18 percent of the total length of measured gullies but only three percent of the total volume. This type of erosion feature, although ubiquitous on the study site, produced comparatively little sediment.

SEDIMENT PRODUCTION AND SEDIMENT YIELD

The erosion study documented 124,435 cubic meters (162,761 yds^3) of management-related erosion, most of which occurred on the slopes and in the tributaries to Copper Creek predominately from water years 1972 to 1979. Assuming a bulk density of 1.76 grams per cubic centimeter (110 lbs/ft^3) (Popenoe, 1981, personal communication) this represents an accelerated erosion rate of 11,190 metric tons per square kilometer per year (31,970 $tons/mi^2/yr$). Primarily over the same time period, an additional 61,250 cubic meters (80,120 yds^3) of recent landslide erosion has occurred on the steep sideslopes to the main channel of Copper Creek (revised from Kelsey et al., 1981), 20 percent of which originated from within the study area (12,030 m^3). Thus, including streamside landslides, a maximum of 136,465 cubic meters (178,496 yds^3) of material could have entered Copper Creek from within the study area alone. A quantitative survey of sediment currently in storage along the entire length of the Copper Creek channel indicated 9,700 cubic meters (12,690 yds^3) of sediment is still in residence (Kelsey, et al., 1981, p. 100), most of which is found behind debris jams or in lower gradient reaches downstream of the K & K bridge.

While it is clear that virtually all the landslide debris from slopes adjacent to Copper Creek entered the main channel system, it is much more difficult to determine sediment delivery ratios for those processes acting on hillslope areas upslope from the main stem of Copper Creek. A survey of tributaries within the study area indicates a highly efficient transport system whose rate of sediment discharge is more dependent on supply than on stream power. Sediment storage in these steep channels is insignificant. Delivery ratios in excess of 0.90 are estimated for material which reaches or enters the active stream channels tributary to Copper Creek.

Landslides located adjacent to stream channels, gully systems and gullied natural channels are extremely efficient sediment delivery mechanisms. In the Copper Creek study area, these three erosion sources accounted for 91 percent of the measured volume of hillslope sediment production (Table 1). Including the 12,030 cubic meters (15,735 yds^3) of landslide debris contributed from basal hillslopes directly to the main channel (20 percent of 61,250 m^3), these three comparatively efficient mechanisms of sediment production and delivery generated over 125,265 cubic meters (163,850 yds^3) of sediment from the study areas. Assuming a conservative sediment delivery ratio of 0.85 (5 to 10 percent less than that estimated from field measurements), management related sediment yield from the study area averaged over 9,575 metric tons per square kilometer per year (27,350 $t/mi^2/yr$) roughly since completion of clear-cut tractor yarding and abandonment of the road system in 1971[1]. Given that some non-management related erosion also occurred during this period, total sediment yield may have been, perhaps, 10 percent greater (see Anderson, 1979, p. 3608). This is 3.4 to 3.9 times the total annual yield rate of Redwood Creek from 1971 to 1976 (estimated at 2,450 to 2,800 metric tons per square kilometer per year (7,000 - 8,000 $t/mi^2/yr$)) and 32 times the estimated "pre-disturbance" or prehistoric annual sediment yield from the Redwood Creek basin (Anderson, 1979, p. 3608).

EROSION CONTROL

Rehabilitation and erosion-control work on the Copper Creek study site was completed in 1979-1980. Work primarily consisted of excavating the remaining tractor-constructed stream crossings, re-diverting streams out of gully systems and back into their appropriate natural channels, removing culverts and fills at road crossings of ephemeral, intermittent and perennial water courses, excavating unstable, oversteepened fill slopes located near streams, decompacting previously impermeable road surfaces and outsloping roads or excavating cross-road drains and waterbars to provide for uninterrupted, dispersed hillslope runoff. In addition, a variety of labor-intensive erosion-control practices designed to

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1. It should be emphasized, again, that preliminary data suggests sediment production and yield from the study area was highly "event dependent" and that a significant proportion of the measured erosion occurred during the major runoff events of 1972 and 1975. "Average" sediment yield is thus highly dependent upon the time period selected for analysis. For this reason, the computed rates are for comparison purposes only and likely do not represent the actual sediment discharge rate for any given year.

reduce short-term soil erosion from areas disturbed during heavy equipment rehabilitation operations were also employed (e.g. see Kelsey and Weaver, 1979; Weaver and Madej, 1981).

When rehabilitation was initiated in 1979, eight years following clearcutting, 47 percent of the features measured during the erosion inventory were judged to be inactive and no longer contributing significant quantities of sediment to downstream areas. Erosion-control work corrected roughly 80 percent, by volumetric contribution, of the remaining, currently active sediment sources at a total cost of $250,000. Except for the removal of two main-channel log jams and the associated stored sediment, erosion-control work within the unit was primarily concentrated on hillslopes removed from the immediate vicinity of the Copper Creek channel. Such rehabilitation effectively eliminated a great deal of continuing gully erosion. However, we conservatively estimate that no more than 25 percent of the currently active mass-movement features along the main channel were stabilized by upslope gully dewatering or the removal of unstable or perched road-fill material[1]. In addition, while no estimate has been made of the effect of rehabilitation on reducing the potential sediment yield from currently inactive landslides or from mass-movement features along tributaries to Copper Creek, such reduction could also be substantial if major storms occur in the near future.

Immediately prior to rehabilitation activities, management induced mean annual sediment yield[2] from the 2.46 square kilometer (.95 mi^2) study area of Copper Creek was estimated at 4,690 metric tons per square kilometer per year (13,410 $t/mi^2/yr$), of which roughly two percent, or 100 metric tons per square kilometer per year, was derived from landsliding along the main channel. We estimate that erosion control work effectively reduced sediment yield from management caused hillslope erosion by 80 percent and landslide sediment production by 25 percent to a total of 995 metric tons per square kilometer per year (2,840 $t/mi^2/yr$), far less than the long-term mean sediment yield of Redwood Creek.

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1. The great majority of landslides along Copper Creek occurred during the storms of the early 1970's, while only a few were present (visible) on 1966 aerial photography. Conservative calculations, assuming all mass-movement occurred in 1964, yield a delivery rate of roughly 800 $m.tn/km^2/yr$ while a more realistic assumption, that most occurred in the period after 1971, results in a calculated yield of nearly 1,500 $m.tn/km^2/yr$. For the purpose of this paper, we have used a conservative estimate of 1,000 m.tn/km/yr. Based on field observations and aerial photo analysis, we have also judged that 10 percent of these features were still active at the time of the erosion inventory in 1979.

2. The method of computation assumes hillslope and landslide erosion sources in the study area generate sediment at the mean annual rate (total measured erosion transported downslope divided by the number of years since erosion first began) multiplied by the delivery ratio and percent of features still active in 1979. While this method is frequently used in the literature for general comparative purposes, erosion in the study area appears to have been much greater during the major storm events of the earlier 1970's. Additionally, sediment yield from evolving gully systems are not likely to remain constant through time, even in the absence of fluctuating hydrologic inputs. However, we would have expected _at least_ this yield during years which included storm events comparable to those already documented on the study site.

Over the life of the rehabilitation program, similar relative reductions from other rapidly eroding logged lands in the park will substantially reduce tributary contributions to the sediment supply of the lower Redwood Creek channel. Excessive accumulations of sediment that are stored along many reaches of Redwood Creek represent a secondary source of available debris which will be gradually removed by future winter flows. Successful erosion-control work can therefore reduce accelerated hillslope erosion rates, decrease tributary stream sediment yields, and minimize the potential for increased sediment yields resulting from continued gully diversions and stream captures. In much the same manner as main channel aggradation eventually became a substantial problem, conversely the cumulative effect of many small watershed projects in alleviating sediment delivery from logged hillslopes should result in the net long-term improvement of off-site physical and biological channel conditions.

CONCLUSION

Although current forest practice rules governing timber operations in California are much more comprehensive than they were in the early 1970's, much can still be learned from observing and documenting the long-term effects of past land-use activities.

Most of the identified causes of increased sediment production in Copper Creek (Table 2) could have been addressed through preventive erosion control and careful land management practices. For example, the construction of waterbars on skid trails, a common practice since the enactment of the Forest Practice Act in 1973, might have reduced soil loss by over 3,700 cubic meters (4,840 yds^3), or three percent of the total measured erosion. More significantly, such techniques as excavating or "dishing-out" skid trail stream crossings, installing properly sized culverts wherever logging roads crossed channels of perennial, intermittent or ephemeral streams, and maintaining roads and drainage structures (especially during and immediately following storms) could have prevented nearly 90 percent of the documented erosion on the Copper Creek study area. To minimize long-term post-harvest erosion from logged areas, roads can either be continually maintained or "put-to-bed" through the conscientious practices of waterbarring, culvert removal, and stream-crossing excavations.

As an example of the potential impact of tractor loggging and road construction on erosion rates, water quality degradation, and downstream sedimentation, Copper Creek may represent a worst-case situation. However, preliminary data from other basins tributary to Redwood Creek also indicate generally high delivery ratios and sediment yields (unpublished NPS mapping, 1979 - 1981; Kelsey, et al., 1981). In marked contrast, the high rates of erosion and sediment discharge measured in the Copper Creek basin far exceed the computed delivery ratio of .22, an accelerated sediment yield of 208 and a total yield of 533 metric tons per square kilometer per year (594 and 1,696 $t/mi^2/yr$, respectively) measured in the comparably sized Caspar Creek experimental watershed from 1967 to 1976 (Rice, et al., 1979). Rather than draw detailed comparisons and contrasts between these two examples, it is important to note the wide range of documented rates of accelerated erosion and sediment yield from steeplands within the same physiographic province.

While factors such as climate, topography, soil type, and geology can affect the erosional susceptibility of logged land, high rates of accelerated erosion are not necessarily inherent to logging activities. Information gathered for this report suggests that the amount of management related erosion often reflects the extent to which those conducting timber harvest accept certain responsibilities during and subsequent to logging activities. These responsibilities include sound road-building and design techniques, minimal tractor disturbance in natural stream channels, and stringent road maintenance standards during and following timber harvest activities. The majority of the erosional problems on the study site (over 80 percent, by volume; see Table 2) could have been prevented by the proper placement of road drainage structures and a regular road maintenance program. Thus, the severity of the erosional problems reflects not so much the harvest methods as the practices employed during and following the conduct of harvest operations. Post-harvest erosion control, while beneficial, is more costly and less effective than careful planning and prevention since many sources of accelerated sediment production become either inaccessible, uncontrollably large, or inactive with time.

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CASPAR CREEK

What have we learned, what can we learn from this project?

Forest B. Tilley[1/]

INTRODUCTION

For 18 years Jackson Demonstration State Forest, managed by the California Department of Forestry, has been the site of a comprehensive watershed experiment. This experiment, on Caspar Creek five miles south of Fort Bragg on the Mendocino coast (fig.1), is a cooperative project between the California Department of Forestry and the U. S. Forest Service, Pacific Southwest Forest and Range Experiment Station. The Department of Forestry provides the project area, conducts the treatment and collects much of the field data. The Station provides technical assistance, some funding and much of the data processing.

The California Department of Fish and Game, the California Department of Water Resources, the California Division of Mines and Geology and Humboldt State University were all cooperators during initial stages of the project but have since dropped out.

The study area is composed of two similar watersheds, the North Fork (1,228 acres) and the South Fork (1,047 acres) of Caspar Creek. The topography runs from broad rounded ridge tops to steep slopes near the stream. The underlying geology of the Caspar Creek drainage is described by Krammes and Burns (1973) as sedimentary rocks of Cretaceous age. Soils mapped in the area were formerly classed as the Hugo and Mendocino soil series. These soils are now being mapped by the Soil Conservation Service as Irmulco-Tramway and Van Damme series.

These soils are formed from hard to highly weathered sandstone. They are moderately deep to deep and usually well drained. They have a clay to clay loam subsoil ranging from 20 to 60 inches deep and they are classed as slowly permeable.

Forest cover on both watersheds consists of fairly dense stands (60,000 board feet per acre) of second growth redwood (*Sequoia sempervirens* (D. Don) Endl.). Douglas-fir (*Pseudotsuga menziesii* (Mirb.), hemlock (*Tsuga heterophylla* (Raf.) Sarg.), grand fir (*Abies grandis* (Dougl.) Lindl.) and some minor hardwoods. These stands are now 80 to 100 years old. Both drainages were clearcut and burned in the late 1800's, the North Fork about fifteen years after the South Fork. There were some selected pole and piling operations conducted along a few of the ridge tops during World War II.

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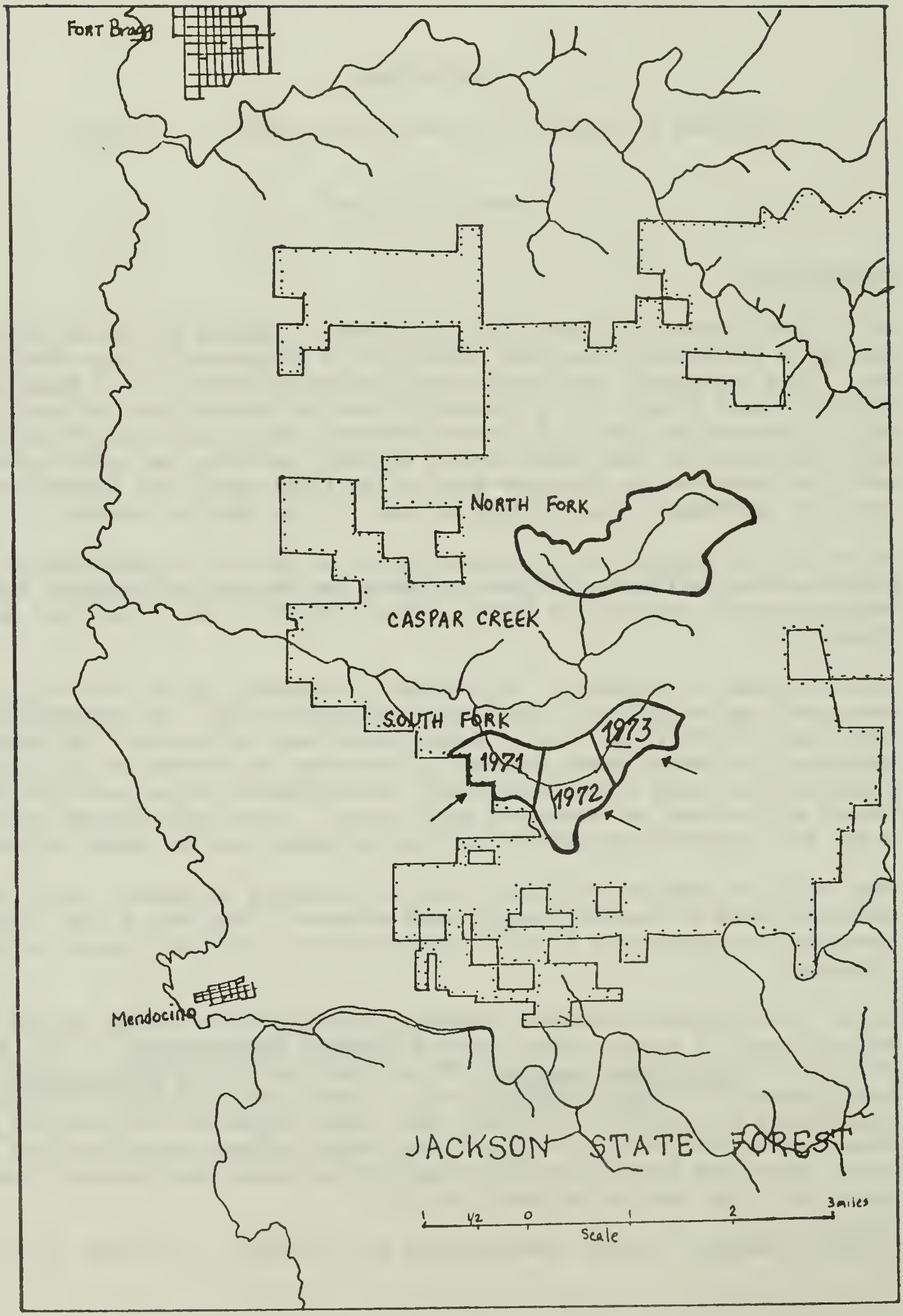
FIGURE 1.



Fort Bragg
NORTH FORK
CASPAR CREEK
SOUTH FORK
1971
1972
1973
Mendocino
JACKSON STATE FOREST
1
1/2
0
1
2
3 miles
Scale

Undergrowth consists of huckleberry (Vaccinium ovatum (Pursh.), tanoak (Lithocarpus densiflorus (Hook. & Arn.) Rehd.), sword fern (Polystichum munitum (Kaulf.) Presl.) and other species typically found in association with redwood/Douglas-fir type. The climate is common to north coastal California with foggy days during the summer and mild winters. Rainfall averages 40+" per year falling mostly during the period of October through May.

The State of California acquired the area from the Caspar Lumber Company through a purchase agreement reached in 1947. Acquisition was for the purpose of including a redwood forest in the State Forest system. Chapter 9 of the Public Resources Code relates to Purposes, Policies and Management of State Forests. Management is specifically defined in Section 4639 (PRC) as the handling of forest crops and forest soil so as to achieve maximum sustained production of high quality forest products while giving consideration to values relating to recreation, watershed, wildlife, range and forage, fisheries and aesthetic enjoyment. It was under this premise that the Caspar Watershed Study was initiated in 1960.

The primary objectives of the study are to measure the sediment yield of a north coastal watershed and to quantify the degree to which logging a relatively undisturbed second growth forest affects water quality, flood peaks, suspended sediment and bedload.

Measurements were carried out on both the South Fork or "treated" watershed and the North Fork or "control." The measuring process started in 1961 with the installation of rain gages in and around the selected watersheds. In November 1962 installation of "V"-notched weirs and attendant Stevens A-35 recording stream gages in both watersheds was completed. This was followed by a period of calibration. In the summer of 1967 a road system was built providing access to the South Fork watershed. From 1967 to 1971 measurements were taken to record the impact of this road construction. In addition, the aquatic habitat was studied to determine the changes caused by road construction. The results of this study were published by Krammes and Burns (1973).

Selective logging of the South Fork watershed began in 1971 and was completed in 1973. In total 38.3 million board feet were harvested from 1,000 acres. The amount of ground disturbance and effect on timberstand resulting from this selective harvest is summarized in table 1. The 15 percent total ground disturbance is about average as tractor logging normally takes up 10 percent to 25 percent of the surface area in roads, landings and skid trails.

The debris basins behind the weirs have each been cleaned out three times since 1962. Cross sections of the weir ponds are measured annually and before and after each cleanout to provide information on the amount of debris and bedload each stream produces.

Table 1. Harvest effects on South Fork watershed.

Timber volumes	Per acre	Total	Percent
Stand before harvest	61.3 MBF	184 MBF	100
Harvest volume	38.3 MBF	117 MBF	64
Leave stand	23.0 MBF	67 MBF	36

Ground disturbance in acres and by percent of total watershed.

Type of disturbance	Acres	Percent
Roads	55	5.2
Skid trails	87	8.3
Landings	21	2.0
Total	163	15.5

RESPONSE TO DISTURBANCE

The effects of logging were summarized by Tilley and Rice (1977) and were explored in more detail by Rice, et al. (1979). Ziemer analyzed the effect on storm flow response (in press) and Lisle discussed the project as part of a field trip to observe natural and management related erosion in Franciscan Terrane of northern California in April of 1979.

SEDIMENT LOADS

Rice, et al. concluded that road building and logging changed Caspar Creek from supply dependent to stream power dependent. That is, before disturbance sediment discharge in Caspar Creek was dependent on the availability of material. After road building and logging sediment discharge was more a function of the ability of the stream to transport material. This change resulted in substantial increases in suspended sediment discharge. The most significant effect was on water quality. The effect of timber harvest on site quality expressed through changes in nutrient regimes is not part of the current project. However, degradation of site quality as projected through soil losses, which can be estimated from erosion or sedimentation measured on Caspar Creek, would indicate that timber harvesting as conducted in the South Fork, given existing soil depths and estimated replenishment rates, would not be cause for concern.

In addition to the suspended sediment and bedload measurements at the weir, the erosional impact of logging was measured from seven plots throughout the South Fork. These plots were part of a larger study conducted by Datzman (1978) to assess soil movement associated with the various logging systems studied. This study included 102 plots stratified so as to sample important site variables, such as partial cutting, clear cutting, tractor yarding and cable yarding, in as many combinations as possible. Each plot was based on a 10-chain transect through a landing. Additional transects were run across the slope at 2-chain intervals bisecting the skid trail system leading into the landing. All major events (defined as one cubic yard or gully cross section in excess of one square foot) within the plot were surveyed. Nine of these 102 plots for a total of 94 acres were located in the South Fork watershed. A net soil loss of 151 cubic yards per acre was recorded in Caspar Creek as opposed to an average of 90 cubic yards from the partial cut analysis and 134 cubic yards from the total tractor yarded analysis for all 102 plots.

Most of the soil movement recorded in this survey came to rest downslope from its original position. Many of the measurements were of road bank failures which slumped on to the road bed.

One of these seven plots accounted for almost one-half of the erosion or displacement measured. This plot encompassed a landing located on the toe of an unstable rotational failure. When compared with other groups from Datzman's data and other studies, domination by a few large events appears to be common in analysis of erosional data. This landing location along with problems with waterbar placement makes Caspar Creek a good test of the logging practices common before the implementation of the present Forest Practice Rules. Therefore Caspar Creek appears to be an acceptable model for logging impacts resulting from selective tractor harvests of second growth stands during that period. This landing location also points out that the most important determinant of disturbance and erosion is not variation in site conditions but how those variations are treated.

An additional potential contributing factor to erosion and sediment production is public access and use of secondary roads and skid trails for "recreation" and salvage. Hunting, fuelwood gathering and harvest of minor forest products are allowed on State Forests. Recently-logged areas are prime targets for these activities, therefore, the effects of logging may have been compounded for a few years by this continued minor disturbance. Steps have been taken in recent years to minimize this impact.

STREAM FLOW

Peak flow analysis as reported by Ziemer showed no significant impact by logging except on those peaks generated by the first three or four storms of the year. Ziemer concluded that the higher peaks from the logged watershed during early storms are the result of higher soil moisture levels due to differences in total evapotranspiration rates between the treated and untreated watersheds. These storms and resultant peaks usually are small (less than 12 cubic feet per second) and have relatively low transport capabilities, therefore, they account for a very minor portion of the sediment production.

THE LAST FOUR YEARS

The seven plots surveyed as part of Datzman's study were resurveyed in July of this year. This survey shows the extent to which recovery has taken place. Most of the ground surface has been covered with vegetation. The exceptions are some roads and landings where compaction was too great for seed to take hold and germinate. Rills and gullies measured in the earlier survey have for the most part stabilized and become revegetated naturally. No effort was made to artificially revegetate slopes, skid trails, roads or landings.

In 1978 some hand work was done to improve or repair drainage of skid trails and roads most severely affected by vehicle use since logging. Barricades were also erected to control access. The sale of minor forest products from the South Fork area was curtailed. These efforts were successful to varying degrees.

A total of approximately $10,000 or $10 per acre was expended on this waterbar/barricade work. To put this effort in relative terms, 150 man days were expended plus supervision, 1,000 vehicle miles and the purchase of hand tools, such as shovels, mattocks, post hole diggers and chain saws comprised the total expenditure.

Table 2. Rehabilitation expenditures (1978).

Salaries and benefits - 150 man days @ $50/day	$ 7,500
Supervision and support (clerical and staff time)	1,500
Vehicle (rental and maintenance - 1,000 miles @ 50¢/mile)	500
Tools and materials	500
Total	$10,000
$10,000 ÷ 1,000 acres = $10 per acre	

Continued monitoring of Caspar Creek supports the belief that the South Fork is progressing toward a stabilized state. Although the period 1978-80 has not included any major hydrologic events as occurred in 1966 and 1974 there has been a continued decline in suspended sediment loading of the South Fork and an increase in vegetative cover indicating a return toward a supply dependent regime. Stream channel observations help support this theory.

INTERPRETATION

We have discussed how Caspar Creek responded to logging, some minimal rehabilitation measures and their effect. We recognized some significant deficiencies, by today's standards, in the design and conduct of the logging operation, i.e., the location of some landings and the inadequacy of waterbar installation and maintenance.

Had the error in landing location been realized immediately some work could have been done to mitigate the problem. An estimated three days cat time would have been necessary to restore the landing to a reasonably stable slope configuration. The planting of approximately 1,000 alder seedlings on the landing site and skid trail approaches and the installation of check dams on the drainages downstream from the landing would have helped control entry of sediment to the main channel and eventually helped stabilize the area. However, these would have been "band-aid" measures. The best and most cost effective method would be to have not located the landing there to begin with and to have kept equipment intrusion to a minimum on surrounding unstable areas.

Avoiding the placement of a landing on the toe of this unstable area would have been far more cost effective than rehabilitation procedures. Certainly if we could have prevented the movement caused by that one landing (i.e., almost 75 cubic yards per acre), the potential hazard would have been less.

Under the current Forest Practice Act[2/] the preparation of a timber harvest plan requires an on-site analysis of the silvicultural method, harvest system and road network as well as provisions for erosion control based on topography and soils. This on-site analysis would probably have identified unstable areas and plans would have been made to avoid crossing them or provide for remedial measures immediately stabilizing the area.

If this area were to be logged today, the steeper slopes next to the streams would probably be cable yarded. Roads and skid trails would be farther from streams and water courses. Landings would not have been constructed in draws as was common practice when the South Fork was logged and drainage facilities would receive much more attention.

Cable yarding would require 4.5 miles of road to be constructed at the break in topography where slopes steepen to 50 percent or more as they drop into the canyon. It would also be twice as expensive as tractor logging. This would amount to sixty percent increase in logging costs for the area, which would have to be offset against the benefits of lessening soil disturbance and keeping it farther from the stream.

FUTURE PLANS

I have discussed what did happen with an "average" logging operation of ten years ago and what might have happened had the South Fork been logged today. The future plans for the Caspar Creek Study area include a proposal to use the North Fork area to study the results of a harvest operation carried out under strict adherence to a timber harvest plan developed under rules current at the time and employing technology, equipment and methods foreseen as the State of the Art ten to fifteen years down the line when the results will be known.

This plan will not only measure gross amounts but will trace the movement of sediment from its source through the system to the outlet. While this project will still have limitations as to its applicability outside of the redwood or north coast region, it will provide information on many of the questions that are of major concern to the project area.

A major limiting factor but what may also be a significant contribution of the project is determination of a "steady state" for the South Fork so that calibration may be achieved and allow the South Fork to become the control area. It is this determination among other factors that has prohibited setting a definite starting date for the project.

2/ Public Resources Code, Div. 4, Chap. 8.

One of the strongest reasons Caspar Creek is proposed for this continued study is the fact that twenty years of data are on hand and the major expenses of weir construction and instrumentation have already been absorbed. There will be additional expense for erosion trough construction and the instrumentation of these troughs necessary for measurement and tracking of sediment passing through the system. As in any endeavor the second time through benefits from the experience of the first activity, therefore, the cooperators have a much more lengthy list of variables to measure and consider.

This list includes, in addition to the precipitation, gross sediment load and stream flow measurements of the South Fork, before and after slope stability surveys, detailed sampling of suspended sediment through the smaller catchments, and tracking of bedload down the stream channel.

A significant part of the study will be the development of a linear model relating measured total storm sediment at stations to various physiographic and meteorological variables.

This model may give land managers better information from which to make intelligent cost effective decisions giving appropriate weight to all the important variables of soil, water and harvestable present and future timber resources.

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TWENTY YEARS OF REHABILITATION WORK IN BULL CREEK,

HUMBOLDT REDWOODS STATE PARK

by

Douglas Jager and Richard LaVen[1]

Bull Creek Watershed is located in California's Humboldt Redwoods State Park. Lower Bull Creek meanders through 700 acres of superlative redwood groves. Land use and abuse in the upper watershed, as well as large floods in 1955 and 1964, have caused accelerated erosion in the basin and severe damage to the alluvial redwood groves. Public and private concern have led to an aggressive land acquisition and channel protection program. Today the basin is in public ownership and is being managed to protect park values. Revegetation has been successful and surface erosion problems appear to be minimal. Large slope failures in the upper basin continue to supply excessive sediments to the Bull Creek channel system. Much of the lower channel has been effectively armored with rock riprap to minimize channel erosion and loss of alluvial groves.

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The 27,000 acre Bull Creek Watershed is located in southern Humboldt County about three miles northwest of the town of Weott. Basin elevations range from around 150 feet above sea level at Bull Creek's confluence with the South Fork of the Eel to a 3,000 ft. rim of ridges surrounding the upper watershed. The upper ridges, with slopes of 50% to 75%-plus, drop rapidly to a gently sloping valley with an elevation of about 500 ft. near Cuneo Creek. Channels draining those upper slopes have gradients of about 1,000 ft/mile. Bull Creek, the main stream draining the crescent-shaped watershed, has a total length of about 14 miles. Channel gradients are very low in Bull Creek's lower six miles.

Precipitation on the watershed exhibits strong orographic control. It averages about 88 inches/year, ranging from 115 inches on the basin rim to about 60 inches in the lower valley flats. Considerable storm runoff is generated during major events.

The original forest cover was of three major types: tanoak-madrone-Douglas fir-redwood, 14,000 acres; redwood-Douglas fir, 8,000 acres; and pure redwood on alluvial flats, 900 acres. Grasslands, brush, and oaks made up the balance of 4,100 acres. The size and quality of the alluvial redwood stands on the lower Bull Creek flats is impressive. Proposals to include the flats in a state park originated in 1917. About 8,100 acres in the lower watershed became a part of Humboldt Redwoods State Park and are now known as the Rockefeller Forest. Enchanting though they might be, the redwood stands offered little to the pioneers. Instead, early settlers were attracted to the more open lands of the middle and upper basin. Most of the basin had been claimed by 1895. Subsistence ranching and small scale logging occupied the residents for the next 50 years. Livestock grazing was widespread and the use of fire as a forage improvement technique was commonplace.

Logging came to Bull Creek in earnest in 1946 and continued unabated until 1961. By 1954, 50% of the upper watershed had been cutover. By 1960, the cutover area had increased to 85%, or 60% of the entire watershed. Logging methods employed were normal for the period. Almost no erosion control work or reforestation was attempted.

Timberland was converted to grazing land as a part of many logging operations. By 1959, conversion affadavits were filed on nearly 4,000 acres in the upper basin. Fire was used in the conversion process. Between 1950 and 1959, eight major fires burned 8,700 acres in the upper basin. The same period saw 48 fires of less than 100 acres. The largest fire burned 5,600 acres in the southern portion of the basin during the summer of 1955.

Prior to the 1955 flood, Bull Creek's lower reaches could be characterized as a narrow (40 to 60 ft. wide), deep, meandering channel with dense stream-side vegetation. The 1955 flood entrained a sawmill cold deck, cull logs, charred stumps, slash, houses, car bodies, propane tanks, mattresses, tires and a few coffins, mixed them liberally with the products of erosion, and deposited them in the lower six miles of the Bull Creek channel. Scores of large redwoods were toppled by bank failure and the 16,000 CFS flood crest and added to the mix. The county highway bridge over Cuneo Creek was buried by gravel. A program of channel clearance and debris burning was begun as soon as the water receeded.

Massive gravel movements from the upper watershed were in evidence, particularly in the upper reaches of Bull Creek and in Cuneo Creek. The gravel continued to move during high water in the years following 1955. A number of studies led to a recommendation that the entire watershed be purchased for inclusion in the park, both to protect the park and to permit maximum opportunity for controlling gravel movement. The acrimonious accusations and counter charges we have come to expect as normal behavior where resource conservation measures are concerned were soon heard, but most of the basin had state park status by the late 1960's.

Drs. Walter Lowdermilk and Hans Einstein were employed as consultants and studied Bull Creek and its problems. Dr. Lowdermilk designed a basin-wide channel protection and watershed rehabilitation program while Dr. Einstein developed a program for managing the enormous deposits of gravel sized sediment, estimating the volume to be on the order of thousands of acre feet.

Channel improvement and gravel control projects were well underway when the 1964 flood, with a 6,000 CFS peak, deposited up to 30 feet of sand, silt, and gravel in the upper reaches of Bull and Cuneo Creeks and buried another Cuneo Creek Bridge. In places, the Bull Creek channel was 400 ft. wide. Aggradation raised the channel in the lower reaches by 4 to 6 ft., a large alluvial delta developed at the point where Bull Creek discharges into the South Fork of the Eel, and the total of large tree losses from bank failure passed 850. Channel improvement and gravel control projects were begun anew.

Since 1955, much sediment and debris have moved through the Bull Creek channel and into the Eel. Much more has moved downstream, but is still in temporary storage within the Bull Creek basin. The basin has many large, active, sediment producing sources capable of contributing enough sediment to replace the evacuated material many times over.

We must report that the problems associated with sediment deposition in the lower Bull Creek channel today are nearly as serious as they were 15 years ago. The natural tendency of aggraded streams is to widen themselves rather than to deepen as they strive to regain their former channel capacity. In the lower reaches, this action, if unchecked, will result in renewed bank erosion and the loss of many more large redwoods.

At present, large quantities of sediment are being removed from the upper reaches and are being carried downstream by moderate flows. Moving downstream, this sediment encounters decreasing channel gradients and reduced velocities. Larger sized particles drop out and a decreased channel capacity is perpetuated.

Our reconnaissance of the main Bull Creek channel, supplemented with old cross-sections and longitudinal profiles, suggests that four distinct reaches are operative:

1. The upper Bull Creek channel, including everything upstream from a point about one-half mile upstream from the confluence of Cuneo Creek. This reach is rapidly regaining its pre-1955 level, but still exports sediment.

2. The middle Bull Creek channel, which extends from a point a half-mile above the confluence of Cuneo Creek to the reef barrier, a rock filled permeable concrete cribbing serving as an artificial intermediate base level. This reach is slowly degrading, but enormous amounts of gravel are stored in the filled-in valley.

3. The upper portion of lower Bull Creek, from the reef barrier downstream to the cascade created by the cut through the meander neck known as the old horseshoe. This channel reach was shortened by 1,900 feet by accelerated meandering during the 1964 flood. It has been in a degrading mode since then.

4. The lower portion of lower Bull Creek channel, a 2 1/2 mile long reach extending from the old horseshoe cascade to the South Fork of the Eel. This reach is actively aggrading.

Most reviewers can easily drive to and see much of the upper two reaches, both of which have been actively degrading. After viewing these reaches, they may acquire a feeling of optimism. We did; and it was not until we studied the old longitudinal profiles and walked the lower reaches of the channel twice that we began to recognize the degree of aggradation presently taking place in the lowest reach.

The old profiles show that this reach aggraded by two to six feet between 1961 and 1974. We also know that the 1961 channel bottom was several feet above the pre-1955 level. And while we do not have data more recent than 1974, we believe the trends shown have continued through 1981.

With their key purpose being the protection of the alluvial redwood groves, the specific objectives of the park's management program can be stated as:

1. Reduce the amount and influence the rate of sediment being contributed from key areas.

2. When and where appropriate, maintain large volumes of sediment in storage within the channels. Work towards a controlled release of this sediment.

3. When and where appropriate, maintain flow velocities capable of evacuating large volumes of coarse sediments from selected reaches.

4. Minimize channel bank erosion.

Because of the need for immediate downstream work and the initial lack of legal access to the upper watershed, the 20-year program has been one of land acquisition, channel manipulation, and channel maintenance while relying on natural revegetation to restore the hydrologic integrity of the watershed. Natural revegetation was slow in developing, but now provides some ground cover in all but the most unstable areas. The decision to wait for natural regeneration probably increased downstream maintenance costs and contributed to the volume of material presently working its way through the system.

Park managers have utilized a variety of techniques to control the movement of gravel and minimize channel erosion in the two lower reaches of Bull Creek, including channel clearing and shaping, flow spreading, gabions, revetments, groins, rock riprap, sediment retention structures, and artificial cascades.

Some of these techniques have worked well. Others lasted only temporarily. Channel clearing, channel shaping, and flow spreading were effective means of providing for the transport of large volumes of sediment. The need for an active channel clearing and shaping program remains evident today. Flow spreading, if practiced today, would only aggravate problems in the lower channel.

Initially gravel was piled against raw banks to protect the remaining flats from channel erosion. Piled gravel offers marginal protection against the erosive effects of low and moderate flows. It offers no protection against, and in fact disappears with, the first high flows. It is, however, an excellent way to prepare gravel for transport.

Later, wire gabions, log revetments, and log groins were employed. The gabions were short lived. Rock sizes, wire gauges, and gabion size were too small. Log revetments and groins were undercut and lacked the flexibility to adjust to changing channel conditions. Eventually they were replaced or covered with rock riprap.

Today, much of the lower channel is lined with large (1/2 ton) rock. Where this riprap was properly placed, it withstood the impact of the 1964 flood and became the treatment of choice. Because of continuing aggradation problems, additional rock riprap is needed in the lower channel.

Sediment retention structures were also utilized. Shortly after the 1955 flood the Army Corps of Engineers built a sediment retention dam in lower Cuneo Creek. It was completely filled with sediment in one year. We have not seen any evidence of it during our reconnaissances. Evidently, it was either buried or destroyed during subsequent floods. Dr. Walter Lowdermilk suggested a reef barrier be installed just above the alluvial flats. First constructed in September 1963, it failed during the winter of 1963 and was rebuilt in the summer of 1964. The 1964 flood covered the barrier with gravel. The barrier is now visible and though slightly damaged is functioning as an intermediate base level and as a gravel retention structure. We are recommending that the reef barrier be raised.

Dr. Lowdermilk also recommended that an artificial cascade of large boulders be placed just downstream from the reef barrier. Installed in the summer of 1964, today only a few large boulders remain in the vicinity.

This program is now undergoing intensive review, and the need for continuing with this or a modified program is presently being evaluated. We are certain that whatever the Park's course of action might be, the program will need continuity of management, annual maintenance, and periodic evaluation if it is to remain effective.

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Eagles Point Site Restoration

and Revegetation Project

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ABSTRACT

The Golden Gate National Recreation Area began a large labor intensive erosion control project in the Lands End area near 32nd Avenue and El Camino Del Mar in San Francisco in late February 1980. The site known as Eagles Point extends out into the Golden Gate Channel, between China Beach to the east and Deadman's Point to the west. As geographically situated, Eagles Point provides a panoramic view of the Golden Gate and Marin Headlands from the Golden Gate Bridge to Point Reyes. Due to its spectacular vista, scores of sightseers came for reflective recreation. As a result, hillside vegetation was trampled eliminating ground cover, exposing highly erodable Colma formation soils, and exposing tree root systems for twenty-eight Monterey Pines located at the site which resulted in their death.

The Young Adult Conservation Corps and the Youth Conservation Corps installed a network of checkdams, retaining walls, formal trails, steps, waterbars, vista platforms, range fence and nearly 80 tons of sand for fill with 3 tons of woodshavings and horse manure as a mulch cover. The three phased construction work project was completed by the end of July, 1980, with approximately 16 weeks of hard physical labor invested. Project cost was $24,148.24, including salaries, with an additional $4,037.00 in donated materials. The final stage of site rehabilitation involving the actual revegetation of Eagles Point was launched in mid-October, 1980. Irrigation by a hose sprinkler system was implemented using reclaimed water from the City of San Francisco. A winter rye grass was sown over the entire site to establish a ground vegetation. Native coastal shrubs were transplanted from the park's native plants greenhouse to the project site. A weekly maintenance program monitors vegetation spread, erosion of trails and continues native shrub plantings.

Introduction: Statement of the Problem

The spectacular panoramic view of the Golden Gate Channel and Marin Headlands as seen from Eagles Point was the catalyst to the accelerated erosion problem at the vista site. Eagles Point became a victim of its own popularity. Park visitors emerging from under the tree canopy at El Camino Del Mar Drive walked out onto the point's ridge to feel the ocean breeze, smell the Pacific's waters, listen to the surf, and view the ocean environment as it meets the coast.

Through the subtle leisure activities of reflective recreation, thousands of park visitors eventually trampled all but the highest mounds of vegetation on the point. With ground vegetation removed, the weak soils of the Colma formation were now exposed to the severe marine environment of gale winds and driving rains. What had probably started out as a few beaten paths leading down the slope to the cliff edge, eventually branched out into a myriad of finger trails. This led to the formation of a large gully system in the western basin and also on the lower west slope of the point itself just east of the large western basin.

By 1976 ground cover in the west basin was trampled beyond naturally regenerative abilities and erosional processes dominated the landscape. Accelerated erosion removed over five feet of top soil at certain sites. This resulted in exposed root systems of all thirty-two Monterey Pines. Twenty-eight mature trees and ground vegetation were removed. With unrestricted pedestrian traffic increasing, the accelerated erosion transformed a vegetated vista point in the Golden Gate to a textbook example of badland topography with many examples of exposed tree root systems. Once the hard-pan soils became saturated, storm runoff fed into one of three tributary gullies in the western basin's large gully system. Runoff on the east side of the ridge drained down to the lower gully field on the west slope of the point. The lower gully field extended from the cliff edge for 200 feet up the steep slope.

Since these conditions were a direct result of the impact by park visitors, the South District Ranger staff sought means to arrest the erosion problem and revegetate the site. In accordance with the 1972 establishing act of the Golden Gate National Recreation Area, the park lands in San Francisco and Marin were founded "to preserve for public use and enjoyment." The Act continues "...Management...shall utilize the resources in a manner which will provide for recreation and education...consistent with sound principles of land use planning and management...and shall preserve...and protect it from...uses which would destroy the scenic beauty and natural character of the area."

Geographic Sketch of Eagles Point

Located on the north shore of San Francisco in the Golden Gate Channel, Eagles Point protrudes out between Deadman's Point to the west and China Beach to the east. From the Lands End trail head at 32nd Avenue and El Camino Del Mar the point extends out as a narrow ridge, at first sloping down at a 10^{o} gradient. However, 180 feet from the Lands End Trail, the gradient drops steeply to 30^{o} for 160 feet to the cliff edge. The beach is approximately 150 feet below.

The east slope of the Eagles Point Ridge drops off steeply, ranging from 40^{o} to 85^{o} slope closer to the channel. The west slope is an open basin sloping at a 15^{o} gradient with an area of 40,000 square feet. With the exception of a few isolated mounds, over 70% of this basin area was unvegetated. Accelerated erosion dominated the landscape. In the lower end, mass wasting had degraded over 5 feet of top soil, whereas in the upper reaches 1 to 3 feet had been degraded. Sediments were washing into a large gully system that extended 82 feet up from the cliff edge with 45 foot long tributaries. The gully was 6.5 feet deep at its lowest point. During the winter of 1979-80 which was a wet year, the gully advanced 8 feet uphill. Gully width ranged from 12 to 4 feet.

Following the ridge 140 feet north of the Lands End Trail, a separate gully system fed by a small drainage produced extensive examples of badland topography. This gully system was 200 feet long by 25 feet wide. Parallel gullies 6 inches to 2.5 feet deep ran nearly the entire length of the field. The lower gully field and additional area to the west covered over 7000 square feet of unvegetated hillside.

Geology

There are three geologic formations exposed at Eagles Point. All three are associated with the heterogenous group of marine sedimentary and volcanic rocks of eugeosynclinal origin known as the Franciscan formation. The main rock component of Eagles Point is graywacke which forms the ridge and point. A small exposure of radiolarian chert is found on the ridge near the Lands End Trail. The badland topography is attributed to surfical deposits of the Colma formation. The Colma formation is of medium-fine orange quartz-feldspar sand with minor amounts of clay. The sands enclose clay beds 6 inches to 5 feet thick. A deeply gullied badland topography commonly develops on the Colma formation as it is soft and easily eroded. One can easily scratch it with the fingernail, but is consolidated enough in outcrop to stand indefinitely in steep to vertical slopes 5 to 20 feet high. Present evidence indicated that the deposits assigned to the Colma formation are Pleistocene in age, laid down at least 30,000 years ago.

Nearly the entire project site with the exception of the exposed ridge is made of the surfical deposits of the Colma formation. Approximately 60 feet from the cliff edge on the lower gully field, there existed a 12 inch layer of clay sandwiched between the Colma formation and the Franciscan graywacke bedrock.

Vegetation

John McLaren planted thousands of Monterey Pines and Cypresses in the Lands End area around 1924. Only four out of thirty-two trees survive today at Eagles Point from his plantings. Prior to the introduction of McLaren's trees along the Lands End Trail, the area was characteristically known for the wind manicured coastal shrub (see map). *Baccharis*, *Ceanothus*, *Lupinus*, *Salix*, *Elymus mullis*, Pearly Everlasting, Paint brush, Plantain, Beach Strawberry, Live-forever, Seaside Daisy, Yarrow, Wild buckwheat and assorted varieties of annual and perennial grasses (Fescues, ryegrass, vetch and bionegrass) were common plants.

In 1979, due to severe trampling, vegetation was restricted to isolated mounds and cliff edges. Remnant outcrops of the Colma formation that were protected by a topcover of vegetation were being undermined by wind erosion. Accelerated erosion had degraded the soil horizon leaving an armored surface of fragmented chert and graywacke across the main drainage above the gully. Gale force winds, blowing sand and total exposure created unfavorable conditions for natural revegetation to occur.

Until December 1979, the park had allowed the visitor trampling and unrestricted access to continue without plans for restoration. Many park visitors enjoyed the wild setting of exposed roots and gullies. The site as it existed prior to restoration reflected a natural unmanaged landscape which was a dramatic contrast to the neighboring urban park environment.

On February 12, 1980 the park's compliance committee met and formally decided that restoration work should be done to control the erosion and define visitor access. The committee requested designs for the checkdams, gabions, retaining walls and steps. Emphasis was placed on maintaining a natural appearance for the site with a minimum number of structures.

Erosion Control Structures

The Eagles Point rehabilitation project utilized four types of erosion control structures to stabilize soil and divert and distribute water flow. Checkdams, retaining walls, gabions and waterbars. All materials used in the fabrication of the structures was from reverse construction projects from areas throughout the park.

Barrier Fencing

Since the erosion problems and climatic environment were severe, restoration and revegetation of Eagles Point required exclusion of park visitors from the two eroding basins. Eagles Point serves three uses for the park visitors; those that want a view of the Golden Gate Channel and bridge from the main vista area; those that want a cliff side view of Deadman's and Eagles Point Beach and surfing area; and surfers desiring access to the narrow Deadman's Point Trail to the west. It was realized that if any of these traditional uses were halted the barriers would be ignored or vandalized. The final solution was to lay a designated trail that brought visitors down to the cliff edge to see the beaches and have a commanding view of the Golden Gate. Surfers would still have access to the Deadman's Point Trail. A 330 foot fence made of 4x2 galvanized wire, 4 feet high, supported by 4x4 posts encircled the rim of the basin in a horseshoe pattern. The program will maintain the fence until 1984 to prevent public access to the western basin until a ground cover is well established. Once the substantial shrubs like *Baccharis*, *Lupines*, and sage have grown to a mature height and regeneration is occurring, the existing fence will be removed. At this time it is recommended that a subtle barrier still be used to discourage access to the basin. Either logs or a low, 3 foot wire strand fence could be installed. Meanwhile, maintenance of the fence and trail system is critical to the success of this project to encourage the visitors to use only the formal paths.

Revegetation

Loss of soil from the project site was reduced by the installation of checkdams at various locations within the gully field. However, establishing a ground cover was the only permanent natural means to arrest erosion and prevent further degredation of the site. This was done in three stages. First, by installing checkdams, jute-rope netting and a mulch cover in critical areas, the soil would be stabilized sufficiently to allow revegetation. Second, seeding a grass cover anywhere that vegetation was not established. This would be the critical factor in halting the wind from blowing sand and establishing a fine root structure that would minimize soil loss. Third, reintroduce native shrubs to enhance the habitat and develop a more protective vegetative cover (Fig 2).

Twenty-five yards of manure were spread over the area, and 1500 yards of jute-rope netting was laid in both drainages. The second phase began in the spring of 1980 and was reinstated in the fall of 1980. Between April through January 1981, 270 pounds of grass seed was sown over the 47,000 square feet of unvegetated hillside found at the point. Below is a list of grass species that were purchased for this project.

Dryland Mix . . . . 207 lbs.

13.50% Blando Bromegrass
44.88% Tetraploid Annual Rye
24.69% Lana Vetch
14.99% Rose Clover
.05% Crops .04 weed

Ryegrass, Linn Perrenial . . . . 56 lbs.

Fescue, chewing . . . . 7 lbs.

Starting in late September, the San Francisco Parks and Recreation Department gave the Ocean District permission to tap the Lincoln Park irrigation system. A 200 foot rubber hose was used 3-4 times a week until late December 1980. This particular winter was a drought year, and rain did not fall regularly until late January. Recycled waste water is pumped to Lincoln Park and used for the irrigation of the golf green. By December grass was covering 85% of the site that was planned for revegetation. The grass grew stronger with better coverage when the woodshavings and horse manure were supplied. The mulch cover retained moisture for the grass seedlings, reduced the impact of rain, and delivered nutrients.

Native Plants

The final phase of the project called for a revegetation program using native coastal shrubs (Fib. 2). By accelerating revegetation with a substantial ground cover two objectives were met. Extensive planting of coastal shrubs added a renewable erosion control resource to the site. This enriched soils with nutrients, delivered a constant supply of leaf litter, strengthened the weak soil structure, and discouraged public use of drainage areas.

Three species of shrubs are being planted in large numbers, along with additional coastal plants for diversity. Baccharis, Bush lupine, and Beach Sagewort are being transplanted from cuttings that have been rooted at the Ocean District Native Plant Nursery. Selected cuttings are clipped from native stock from Fort Funston, Lands End and Fort Scott areas, allowed to root, hardened up, and transplanted at the site about four months later. The nursery began in October 1980 with 318 transplants completed by March, 1981. Transplanting will continue in the fall of 1980. At present the nursery stock is being developed on a rotational basis. The major benefits of this are that selected cuttings of local native plants are used, thereby working with a gene-pool that has evolved especially adapted to this coastal environment. Another advantage is the reduced cost in raising our own stock and eliminating the necessity of purchasing the plants from a commercial nursery which does not have local plants. Below is a list of native plants used in the revegetation project.

1. Baccharis pilularis
2. Lupinus arboreus
3. Artemisia pycnacephala, Beach Sagewort
4. Fragaria chiloensis, Beach Strawberry
5. Erigeron glaucus, Seaside Daisy
6. Ceanothus (cuttings/seeds)
7. Yarrow (cuttings/seeds)
8. Buckwheat (cuttings)
9. Monterey Cypress and Pine (seeds)

Some cyclical seeding of grass seed will continue in the fall of 1981, however, the main emphasis from now on is transplanting shrubbery.

Construction Logistics

The work project was separated into three phases, listed below are the goals of each phase.

Phase One - February 24 through March 14

-Build ten checkdams in main western gully
-Flag trail course for phase two

Phase Two - March 17 through April 29

-Grade and fill lower gully field
-Construct six retaining walls
-Build designated trail and appropriate shoring
-Construct the east and west vista platforms
-Install safety railings
-Lay jute rope and manure and seed

Phase Three - June 23 through July 24

-Remove hazard snags, tree stumps and dead limbs
-Construct main vista platform for tree root protection, gabion structure and stair trail.
-Build designated trail from main vista to lower vista trail
-Construct gabion for stair trail shoring on east cliff edge
-Install checkdams in small cliff gullies on east slope
-Install waterbars in appropriate locations on trail and hillslope
-Fill main gully and gabions with imported soil
-Construct range fence around restricted area

Both phase one and phase two were assigned to the park's Young Adult Conservation Corps (YACC). The Crew Leader supervised four enrollees throughout both phases. Phase three, which was very labor intensive was assigned to the Youth Conservation Corps (YCC). The Crew Leader supervised eight to ten enrollees. Both work crews had unskilled enrollees. As a result, the progress was slow; however, the final product was professional and of sound construction.

Man Hours

Phase One 14 days	Hours	Pay	Total Cost
1 Crew Leader	112	8.20	918.40
4 Enrollees	448	3.10	1388.80
1 Park Technician	112	6.49	726.88
Phase Two 33 days			
1 Crew Leader	264	8.20	2197.60
4 Enrollees	1056	3.10	3273.60
1 Park Technician	264	6.49	1713.36
Phase Three 25 days			
1 Crew Leader	200	5.50	1100.00
8 Enrollees	1600	3.10	4960.00
1 Park Technician	200	6.49	1298.00
Maintenance Personnel			
2 WG-5	24	8.09	388.32
2 WG-3	24	7.33	351.88

Continuing Maintenance

1 Park Technician	160	6.49	1038.40

TOTAL SALARY COST 19,355.24

TOTAL MAN HOURS 4,464

Materials

All lumber used at Eagles Point was from reverse construction projects in the park or purchased as recycled material. Approximately 500 board feet of 2x12s were used to build checkdams and retaining walls. The planks all came from Ft. Cronkhite where the YCC had removed buildings in the summer of 1977 and 1978.

The 182 eight foot railroad ties were used to build the stair trail and gabions. Although the YACC had purchased about 50 of these, the remaining 132 ties were donated by the Santa Fe and Belt Railroad and were all recycled.

Rebar, nails, jute rope netting, range fence, and tools were paid for by both the YACC and YCC. Nearly 2950 lineal feet of rebar was used to anchor the railroad ties on the stair trails and gabions. 1500 hards of jute rope netting was staked at the site to stabilize soil and hold down manure and seed.

Approximately 25 yards of wood shavings and horse manure were brought to the site and spread by buckets and wheelbarrows. Material cost came to $8,830.75

Material Expenses

YACC Cost	$3966.00
YCC Cost	730.00
Ocean District Cost	97.75
Donated/Recycled	4037.00
Actual Federal Money Spent	4793.00

Sand Fill

19 dump-truck loads of clean sand were delivered from Ft. Mason to the site. The San Francisco Park and Recreation Department gave Ocean District staff permission to cross the golf course with the dump trucks to get closer to the site. From the Lands End Trail the sand was then wheelbarrowed by hand down the steep slope and dumped into the main gully. To fill all ten checkdams required 77 tons of sand. The wheelbarrows were then pushed back up a 12 inch wide ramp to the Lands End Trail to minimize the impact on the remaining sparse vegetation. The remaining 38 tons of sand was used to cover the exposed tree roots under the main vista platform. Transporting sand by wheelbarrow was

very laborious and exhausting work but because of the slope gradient of the gully and the 200 foot cliff beneath it, maintenance was reluctant to use heavy equipment in fear that it would go over the cliff edge.

Conclusion

The Ocean District of the Golden Gate National Recreation Area is the sole guardian of the remaining pristine coastal habitat in the San Francisco peninsula. Areas supporting native shrubs, grasses and plants should be protected and enhanced whenever possible. Eagles Point site restoration and revegetation project illustrates the National Park Service's commitment to protecting the natural resources from uses that would destroy the scenic and natural character of the area. Whenever site restoration is attempted in the park, Eagles Point Project should be used as an example in maintaining the appearance of a natural unmanaged landscape, even though structures have been built to control erosion. As the growing seasons pass, ground cover will eventually obscure the low retaining walls, checkdams, and waterbars.

At the same time, whenever the natural resources are being threatened, the park should not hesitate in taking bold measures, such as installing temporary barrier fencing to insure site restoration and protection. The management objectives of this project were to halt accelerated erosion, restore native habitat, and provide public access that was in harmony with the site enhancement. To fulfill these goals, 4,464 man hours were invested. Project expenditures and salaries cost $24,148, with an additional $4,030.00 worth of donated and scavenged materials. By utilizing youth work crews, instead of the park's maintenance division, the government saved $13,130 in salary cost (based on a WG3 salary, $7.33/hr.).

As annual visitor levels approach 12 million people, the impact on park lands in the Ocean District increases each year. There are many other sites in the park that require attention as did Eagles Point. Had this project not been implemented, accelerated erosion would have continued unchecked. The gully field would have degraded further and lengthened after every large storm. Trampling would have continued and the remaining vegetation would have died.

Fortunately, this scenario was discontinued. Eagles Point is slowly recovering. At present, the once barren slope is now a lush grass hillside with native shrubs being planted and others naturally recolonizing. The gullies are filled and the trampling has stopped. This project will not be completed or determined a success until the coastal shrubs are well established and regeneration is occurring. As for now, Eagles Point has been preserved as a land form, as habitat, and with a trail design that the public may use and enjoy with a minimum of impact. This was accomplished by implementing sound principles of land use planning, natural resource management techniques, and hard, physical intensive labor.

Fig. 1
Headwall to main gully in the upper basin. The gully was 81 feet in length and six feet deep.

Fig. 2
Exposed tree roots as a result of severe trampling

Fig. 3

View looking east across main gully and basin, note bare soil and exposed tree roots.

Fig. 4

Same view as Fig. 3 seven months later with a ground cover established and tree roots buried.

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THE USE OF COST-EFFECTIVENESS AS A TECHNIQUE TO EVALUATE AND IMPROVE WATERSHED REHABILITATION FOR EROSION CONTROL, REDWOOD NATIONAL PARK

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Abstract. Traditional cost-benefit analyses cannot be routinely applied to rehabilitation practices because soil and many other watershed amenities have little net economic value. Consequently, the success and effectiveness of restoration practices are best evaluated by the extent to which carefully formulated objectives are met. Controls on cost-effectiveness are, by definition, twofold. Cost is influenced by such factors as program goals, indirect expenses, professional judgment and treatment design standards. Erosion control effectiveness is influenced by temporal changes in vegetative and structural treatments, erosional mechanisms and the relative timing of erosion control work with respect to the original land use disturbance. Quantitatively predicting and evaluating cost-effectiveness are the two most valuable tools for best achieving erosion control objectives. In the park, over three orders of magnitude difference exists between the most cost-effective primary technique and the least cost-effective secondary procedure. Even treatments designed to control similar problems display cost-effectiveness differences of over one order of magnitude. Whether in conjunction with the original land use or as a part of subsequent rehabilitation activities, prevention is clearly the most cost-effective technique for minimizing sediment production and yield.

INTRODUCTION

The effectiveness of watershed rehabilitation, like any other work, is primarily dependent upon the degree to which stated goals have been obtained. Success can only be judged when clearly defined objectives have been established against which results can then be compared and evaluated.

In isolated situations where the end-product of such work has an immediate and directly quantifiable market value, a cost-benefit analysis will help determine the advisability of initiating, continuing and/or modifying restoration activities. For example, in-stream habitat improvement which results in increased salmonid fishery production may be economically justified on the basis of its positive net economic return (Everest, 1978; Ward and Stanley, 1979). Unlike an industrial setting, however, the chief economic benefactors of such improvement work are generally not those

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who expend the funds at the restoration site. Thus, while the sportsman and the fishing industry may gain from habitat improvement accomplished on private or public forest lands, the economic benefit does little to stimulate private incentive for such work.

Similarly, while nearing the end of an era marked by abundant (albeit diminishing) natural resources, justifications for watershed rehabilitation based on long-term economic returns have not yet been seriously considered in the market place. For example, there is a loss of growth sites on commercial forest lands resulting from inadvertant but avoidable soil loss (e.g. landsliding and gullying). However, this loss has not yet been determined serious enough to warrant substantial procedural changes, such as self-imposed, modified logging practices or post-harvest corrective work (erosion control), solely for the purpose of maximizing future timber yield (California Board of Forestry, 1980).

As a consequence of these limitations, rehabilitation effectiveness must be judged on the qualitative degree to which stated goals have been or are expected to be attained rather than on economic return. Since unitless cost-benefit ratios for such work would require the assignment of unique monetary values to project benefits, cost-effectiveness ratios may be used instead. In this manner, various techniques used to attain a given goal may be compared on the basis of the cost and the relative effectiveness of each method attaining all or some portion of the desired end result. Thus, while cost-benefit analyses may be used to justify the expenditures of funds in classical economic situations, an evaluation of the relative cost-effectiveness of watershed rehabilitation work will only describe which methods are best helping to achieve the goals with the least expenditure of funds. Depending on the stated goal(s), the land manager may wish to maximize effectiveness, minimize cost or maximize overall cost-effectiveness.

This paper will describe the use of cost-effectiveness as a tool to improve watershed rehabilitation practices. The examples used in the following pages are based on experiences and data accumulated over five years of rehabilitation for erosion control. The first section, describing controls on cost-effectiveness, and those on predicting and evaluating cost-effectiveness, are primarily taylored to the subject of erosion control. However, most of the discussions and techniques are broadly applicable to a wide range of management actions involving natural resources; especially where traditional cost-benefit analyses are not possible. The paper concludes with our current analysis of the cost-effectiveness of specific techniques and procedures used for controlling sediment production and sediment yield on logged lands in the park.

CONTROLS ON COST-EFFECTIVENESS

The controls on rehabilitation cost-effectiveness are derived from three principal sources. First, the goals of the program are of greatest overall importance in determining how cost-effectiveness will be measured and evaluated. The other two controls are, by definition, those factors which influence the effectiveness of treatments and work procedures, and those factors which determine project costs. The remainder of this section will describe the more important variables which influence each of the three controlling elements, especially as they relate to erosion control work at Redwood National Park.

Goals

The two fundamental goals of the park's watershed rehabilitation program are: 1) to restore the acquired area to a natural, self-functioning redwood forest ecosystem, and 2) to reduce accelerated erosion rates and sediment yields which continue to impact park resources (United States Department of Interior, 1981a). Although revegetation and restoration of the biological system are important elements of the program, primary emphasis has been placed on the reduction of accelerated sediment production and delivery. With this objective for the park's erosion control program, cost-effectiveness is measured, and techniques are evaluated, on the basis of treatment costs and the amount of sediment removed or prevented from entering active channels where it could be transported downstream. The measure of cost-effectiveness used in the park's program (and in this paper) is the unit cost-per-volume of sediment "saved" from sediment yield ($\$/yd^3$) over a specified period of time[1].

Although the primary goals of any rehabilitation program may not vary through time, other factors will frequently control short-term objectives and thereby influence levels of cost-effectiveness. For example, in the park's program initial emphasis was necessarily placed on experimentation and development of new erosion control techniques at the potential expense of effectiveness (Madej, et al., 1980). As methods were developed and refined, the focus shifted to those critical areas where sources of accelerated erosion could be easily and inexpensively treated. In this manner, major sources of sediment were rapidly controlled or eliminated at a comparatively small cost. Currently, as the most cost-effective work is completed, rehabilitation efforts are concentrated on those features which remain significant sediment producers, yet may require greater costs to effectively control. As a consequence, costs may rise and cost-effectiveness may decrease substantially. Treatments in the future will be directed toward areas of potential accelerated sediment production (e.g. intact logging roads), and the objective will become one of erosion prevention rather than erosion control. In practice, erosion control work on a single rehabilitation unit in the park typically involves two or more of these elements simultaneously.

The dynamic nature of immediate goals in a long-term rehabilitation program sometimes makes cost-effectiveness evaluations most applicable to limited, short-term objectives. For example, in the park's program, the immediate goal of erosion-control technique-development temporarily supplanted the long range goal of minimizing increased sediment yield (Sonnevil and Weaver, 1982). Thus, in 1978, rehabilitation sites were selected to provide numerous opportunities for controlling a wide variety of erosional problems. As previously defined, cost-effectiveness during this experimental phase was not of overriding importance in determining work site locations or technical prescriptions for erosion control. Where objectives and other conditions do not change through

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1. Other resource rehabilitation projects could measure cost-effectiveness in a number of ways. Depending upon the goal, these might include: $\$/ft^2$ increase in spawning area or $\$/ft^2$ increase in useable, summer fish-rearing habitat; $/planted shrub or tree surviving after some time interval; $/newly established and inhabited nesting site for some desirable bird species; among others.

time (as has been the case in the park program since 1979), technical improvements, increased efficiency and experience aid in improving effectiveness, decreasing costs and raising overall levels of cost-effectiveness.

Effectiveness

By definition, factors which influence the effectiveness of erosion control work also partially determine the cost-effectiveness of these techniques. Many treatments may show little or no change in their effectiveness through time (e.g. road outsloping, channel excavations, waterbars, rock armor). Other treatments, however, exhibit temporal variability that ultimately affects the effectiveness (and cost-effectiveness) of erosion control work. For example, successful revegetation will provide additional stability and protection to a disturbed site as the plants increase in size and number (Reed and Hektner, 1981). It thereby represents an erosion control treatment whose effectiveness increases through time. In areas where natural revegetation is hindered, planting a variety of native or stabilizing species may be ineffective for immediate or short-term erosion control, yet its effectiveness gradually increases through time, without the need for additional expenditure. This makes revegetation one of the most cost-effective long-term treatments. In direct contrast, some erosion control treatments tend to become less effective through time, especially mulches and structural devices such as wood check-dams, flumes, and water ladders. Even though these measures provide highly effective, immediate protection against accelerated erosion, their limited life-spans result in continuing maintenance costs and generally decreasing levels of effectiveness.

Rehabilitation treatments can be applied to account for these temporal changes. For example, at an excavated stream crossing, the sideslopes may be seeded or planted with coyote brush, alder, and conifer seedlings, and then covered with straw mulch. The bare, newly exposed channel can be check-dammed and inplanted with willow cuttings or alder seedlings along the bed and banks. In this fashion, straw and check dams should provide immediate protection against rilling and channel erosion. On the sideslopes, straw mulch will deteriorate over several years, but brush and/or willow and alder will grow to provide litter and direct groundcover. As they, in turn, reach the end of their life spans and begin to senesce, conifers will have reached a size where their foliage and root systems provide continually increasing protection. In the stream channel, properly designed and maintained check dams will continue to provide protection for years (Kelsey and Weaver, 1979). However, as they begin to deteriorate, the expanding root network of woody vegetation planted in and along the channel will have a compensating, stabilizing effect. Rapid or large adjustments of the restored stream channel can be avoided. These same techniques, applied individually, might provide negligible short-term protection (e.g., planting conifers) or provide little or no long-term benefits (e.g., straw mulch). The proper application of a combination of appropriate treatments can provide overall protection of essentially unchanging or increasing effectiveness.

In addition to changes in the effectiveness of erosion control work through time, the type and magnitude of erosion processes can also exert substantial control on the effectiveness (and cost-effectiveness) of watershed rehabilitation (e.g. see Kelsey, et al., 1981). Some erosional processes (e.g. raindrop and sheet erosion) are highly amenable to treatment and effective control, yet their relative contribution to sediment production and yield may be minimal. On the other hand, deep-seated mass movement features, while perhaps contributing a proportionately larger quantity of sediment directly to the stream system, could require huge expenditures to treat. In many cases, these sediment sources may not even be controllable. Because of this, cost-effectiveness should not be the only management tool used to influence the decision-making process. Either cost or effectiveness may be of overriding importance depending on the importance, relative size and complexity of the delivery mechanisms.

Perhaps the greatest single factor determining the ultimate effectiveness (and cost-effectiveness) of watershed rehabilitation relates to the relative timing of the original land use or ground disturbance and the onset of erosion control activities (Kelsey, et al., 1981). A simplified, schematic representation of this concept is shown in Figure 1. Some erosion features may be so far advanced by the time treatment is contemplated that they are either beyond one's ability to effectively treat or they are no longer generating significant quantities of sediment. For example, in the Copper Creek drainage basin, eight years after logging, nearly 50 percent of the gully systems were no longer active (Weaver, et al., 1982). Those gullies which still carried their channel-forming discharges were probably yielding sediment at only a fraction of the initial rate following management-related disturbance.

Depending on the timing of major storms, if roads are not maintained, and cutover hillslopes and erosional features in the park are allowed to remain untreated for long periods of time (approximately 10-20 years), the disturbance to soil and newly established vegetation caused by rehabilitation activities could potentially outweigh the benefits derived from these erosion control efforts (Figure 1). This results from rapid revegetation and a rapid rise, and then decline, in rates of elevated fluvial sediment production following timber harvest and road construction in the coastal region of northern California. Where logging roads could continue to cause stream diversions and consequent gullying in the park, treatment benefits may still outweigh impacts for several decades. For these reasons, it is critical either to plan and conduct land-use practices in a fashion to strictly minimize subsequent erosion, or to initiate rehabilitation and erosion control work immediately upon completion of operations. In this manner, treatment costs can be substantially reduced and the bulk of erosion may be altogether avoided (Figure 1).

Costs

Unlike factors which control the effectiveness of rehabilitation work, those elements which influence costs are more amenable to quantification and manipulation. In practice, realistic project objectives are frequently developed only after available financial resources have been determined. The stated program goal(s) indirectly assign a desired minimum level of erosion control protection the land manager is willing to accept. Specific objectives to work towards the goal(s), as well as the intensity of work activity, are then established in relationship to the funding available. Such goals could include the revegetation of all bare soil areas, a measurable increase in suitable fish spawning habitat, a reduction of accelerated erosion rates, decreased sediment yields, improved stream-bank and stream-bed stability, or a complete return to pre-disturbance conditions, among others. Successfully attaining these end results involves and requires the employment of a variety of different techniques, intensities of effort and monetary expenditures.

Several other considerations which directly affect the cost of rehabilitation work include: 1) the magnitude of indirect costs (access, administrative overhead, profit, supplies and materials, etc.) which do not specifically result in attainment of objectives but which represent unavoidable costs; 2) subjective professional judgment used to outline the problems and the desired methods of rehabilitation; and 3) in the case of erosion control work, the size or intensity of hydrologic event which treatments, structures and excavations are designed to successfully withstand.

Under some circumstances, indirect costs can become prohibitively large. Depending on the method of contracting, costs not directly involved with on-site labor and heavy-equipment erosion control work can exceed 50 percent of total rehabilitation expenditures for an area (Kelsey and Stroud, 1981). Similarly, but on a smaller scale, re-opening abandoned road systems to treat continuing erosion problems along or adjacent to the roads can also increase costs and have an adverse impact on the cost-effectiveness of the overall effort.

Errors or differences in professional judgment (generally the result of a lack of relevent experience) can also result in rapid cost escalations which thereby significantly reduce rehabilitation cost-effectiveness. For example, in 1977, and to a lesser extent in 1978, project supervisors in the park perceived surface erosion to be a critical problem on rehabilitation sites. Extensive treatments were applied to control this source of soil loss (Madej, et al., 1980). In actuality, after close measurement and subsequent field observations it was not found to be as significant a process as originally thought (Weaver and Seltenrich, 1981). While the treatments may have been effective, they were also of very low cost-effectiveness ($/yd^3 "saved").

Other professional judgments applied during field operations can also affect levels of cost-effectiveness. For example, the use of drag-line cranes or hydraulic excavators to perform stream-crossing excavations may be needlessly expensive if the same jobs could be done with equal effectiveness and at a lower cost by more efficient machinery (e.g. bulldozers). Similarly, most stream crossings in the park, if excavated with 30 percent channel sideslopes, show few, if any, post-rehabilitation slope-stability problems. However, if the sideslopes would have been equally as stable at 50 percent steepness, significantly less soil could have been excavated at no measurable loss of effectiveness. Reductions in cost-effectiveness attributable to errors in professional judgment can be largely eliminated through increased experience, and regular and repeated peer review conducted before, during and after field operations.

Due to the nature of physical and meterologic processes in north-coastal California, and high rates of sediment production and yield, the ultimate test of erosion control effectiveness is the large hydrologic event. To account for this, treatments must be designed to accommodate geomorphically relevant flows while still minimizing project expenditures. In the park, channel protection devices and stream channel excavations are currently constructed to withstand the calculated 20-year return period runoff event.

Significant increases in costs commonly associated with small increases in treatment design standards or minor improvements in effectiveness will lower rehabilitation cost-effectiveness. For example, 1500 cubic yards of fill might be excavated from a stream crossing at a total cost of $5,500. Assuming that all 1500 cubic yards would have been eroded if the crossing had not been treated, the cost-effectiveness of this excavation was $3.70 per cubic yard. To stabilize the new channel and prevent local downcutting and bank erosion, rock armor or check dams can then be placed in the stream bed. To prevent an estimated additional loss of 100 cubic yards, $2,500 might be spent on this protective treatment. The comparable unit cost (cost-effectiveness) is then $25 per cubic yard "saved" from erosion. Clearly, the added protection is accomplished at significantly reduced levels of cost-effectiveness. The decision to pursue such costly measures depends on a number of factors including, but not limited to, the nature of downstream or on-site resources being protected. In the park such decisions are not strictly based on quantitative determinations of cost-effectiveness ($\$/yd^3$). A number of factors are evaluated prior to intiating erosion control work. These are listed and discussed in the following section.

PREDICTING COST-EFFECTIVENESS

Areas which display advanced erosion problems may have evolved to the point where erosion control work is no longer justified (e.g. see Figure 1). It is important, therefore, to predict or estimate the cost-effectiveness of rehabilitation work before it is conducted. In this way, the greatest results can be achieved with the available funds. Areas which have progressed beyond cost-effective treatment can also be objectively recognized.

The prediction process involves five basic steps. They include: 1) delineating active versus inactive erosion features; 2) identifying potential sources of future erosion; 3) defining those problems which are technically treatable; 4) delineating those active or potential erosion sources which are accessible by heavy equipment, or whatever tools are needed to treat the problems; and 5) estimating the cost-effectiveness of the proposed treatments. The listed order of these steps is one which logically follows the intensive geomorphic mapping and erosion inventory which must precede rehabilitation. Of the currently active or potential erosion sources identified in a watershed, it is likely that only a fraction of these will be both accessible and controllable, and many may no longer be cost-effectively treated.

In erosion control work, prior determination of cost-effectiveness and the decision whether or not to treat an area hinges on an evaluation of: 1) the potential volume of sediment to be lost to erosion; 2) the probability of occurrence for this sediment release; 3) the expected rate of delivery or amortization period over which soil loss would occur; 4) the expected delivery ratio (the ratio of sediment yield to sediment production); and finally, 5) the cost associated with access and effective treatment. Although many of these factors can only be subjectively and qualitatively determined for many sites, recognition of their importance and usefulness in predicting the cost-effectiveness of proposed erosion control work is paramount to making educated decisions and defensible plans for watershed rehabilitation.

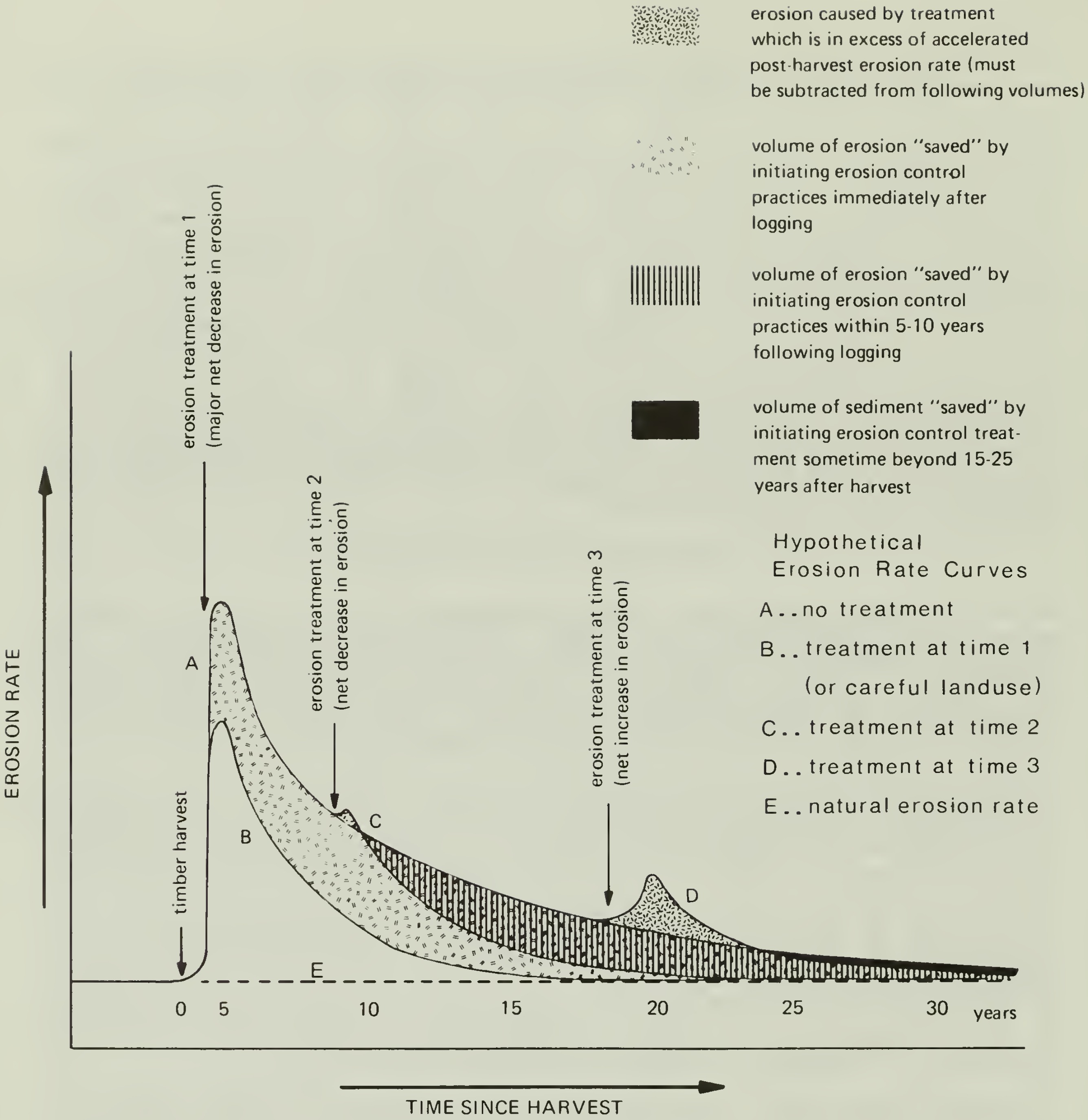

Figure 1. Schematic representation of fluvial erosion rates as affected by erosion control. Diagram is simplified for illustrative purposes. It excludes such factors as the effect of major storms and the delayed occurrence of mass movement processes following timber harvest. All else constant, the greatest rates of post-harvest erosion are expected in the first five years following land use. Time scale is included only for general reference. Depending upon erosional processes, climatic conditions and land use history, each area will display unique sediment yield curves.

On most erosion control work-sites in the park, "erosion potentials" are calculated and cost estimates are made to provide a pre-work estimate of cost-effectiveness. For example, at skid-trail and logging road stream crossings, the potential volume of sediment which could be eroded is determined by graphically reconstructing original channel sideslopes and the configuration of the pre-logging stream profile (depth to thalweg). The assumption is made that, eventually, all material contained in a fill crossing will be eroded and carried downstream. Subjective evaluations are also made to show which crossings have a distinct probability of causing future stream diversions (e.g., through culvert plugging) and developing hillslope gully systems. As a preventive measure, crossings which show a potential for diverting streamflow are routinely excavated.

While it is certian that material introduced into an active stream channel will eventually be eroded and moved downstream, the rate of material transport is highly variable. In the park, factors used to evaluate this rate include: 1) the amount (percentage) of the fill which has already been lost to erosion; 2) the magnitude of storms and runoff events (discharge) which have occurred on the site since the fill was emplaced; 3) the calculated, 20-year return- period discharge at the crossing site; 4) channel geometry and 5) the condition of other fill-crossings upstream and downstream within the same channel or in nearby streams. These "indicators" are used to estimate the residence time of the fill material. The same observations, with a close look at current and potential sediment storage sites in downstream reaches, allow a good estimation of the sediment delivery ratio to be expected over various time frames. On potential hillslope or logging-road work-sites located at some distance from active streams, estimated delivery ratios drop significantly and become an important consideration in cost-effectiveness predictions.

The final step, predicting cost-effectiveness, requires an accurate estimate of project costs, including the expenses of accessing the work site and effectively treating the erosion problems. Contractors can provide valuable assistance in determining proper types of earth-moving equipment, suggesting approaches to specific tasks and estimating job costs. Labor costs for various erosion control practices can be derived from literature reviews or estimated on the basis of sample applications on nearby areas. If carefully documented, previous work can be an invaluable tool for assessing future treatment costs (e.g. Bundros, et al., 1982; Teti, 1982). In the park, the ultimate decision to proceed on a project or a particular work site is generally based on an objective analysis of the expected costs, the potential for future erosion and sediment yield and the probability for successful control or prevention. Quantifying these factors for the purposes of predicting cost-effectiveness is an important part of assuring successful and efficient erosion control work.

EVALUATING COST-EFFECTIVENESS

Post-rehabilitation evaluation of completed work is the greatest available tool for improving the effectiveness and cost-effectiveness of general approaches and specific techniques for erosion control. For maximum benefit, it is thus critical to maintain detailed accounting of work performance and costs during every readily distinguishable phase or element of a project. During the heavy equipment phase of rehabilitation work in the park, project supervisors keep hourly and daily records of where work is being done, the pieces of equipment used, the job tasks (e.g., outsloping, waterbar construction, etc.), the rate work is completed (e.g., ft/day, yd^3/hr, etc.), the cost of each task (e.g., $\$/yd^3$), and overall task performance and quality (see Bundros, 1980; Hagans, 1980; Teti, 1981; Spreiter and Johnson, 1981; Wosika, 1981). These detailed records are used to determine the pieces or combinations of equipment which are most cost-effective for each task and the operators who are most adept at this work.

Similarly, work and cost documentation are integral parts of all labor-intensive rehabilitation work performed in the park (e.g. United States Department of Interior, 1981b). Each labor contract contains a bid item which requires the contractor to keep accurate work records on forms provided by the park. Each task is broken down into as many component parts as are needed to clearly delineate actual unit expenditures. Unit bid prices (e.g., $/check dam) are not always considered valid indicators of actual costs to complete the various tasks. They are estimates which typically involve a variety of other complicating factors.

The most useful tools for evaluating the effectiveness of work procedures and erosion control techniques are those derived from field data and experience. Repeated photo-documentation, written notes and sketches based on field observations collected during storms and periods of high runoff, and group discussions and recommendations generated during organized peer review sessions are methods of evaluation which commonly result in changes in operating procedures. Technical changes in erosion control work generally evolve in response to a quantitative evaluation of physical processes. Techniques which have been used to measure erosion and evaluate the physical effectiveness of erosion control work in the park are straight-forward and numerous. For example, surface erosion on treated and untreated sites has been documented through various techniques including detailed hillslope cross-sections, grids of erosion pins, and rainfall-runoff/erosion plots involving the use of sediment collection troughs. Pre- and post-rehabilitation channel erosion is measured with detailed cross-sections and longitudinal profiles, accurate morphologic maps and winter-storm sediment sampling. Additionally, detailed checklists have been used to document the effectiveness of measures used to prevent or control both hillslope and channel erosion. Accurate topographic surveys, stake lines, groundwater wells, piezometers and detailed mapping have been used to monitor the response of mass movement features to rehabilitation and other environmental controls.

A modest program designed to measure the absolute or relative effectiveness of various procedures and techniques can pay for itself many times over. In the Redwood National Park rehabilitation program, less than five percent of the total budget is allocated to an evaluation program, yet the results of monitoring costs and effectiveness have provided a substantive basis for making major changes in the direction, approach and details of on-the-ground restoration over the last three years (Sonnevil and Weaver, 1982; Hektner et al., 1982).

RELATIVE COST-EFFECTIVENESS OF REHABILITATION WORK AT REDWOOD NATIONAL PARK

Erosion control work in Redwood National Park is divided into primary and secondary treatments. Those elements designed to provide for the immediate reduction of management-caused sediment production or yield are considered primary treatments. They are most closely associated with the ultimate objectives of erosion control and landscape rehabilitation. Most primary erosion control practices used in the park from 1978 to 1980 were accomplished at a cost-effectiveness of from one to ten dollars per cubic yard ($/yd^3) of sediment removed or prevented from entering local channels and being transported downstream (Table 1).

Disregarding the fact that the sources of increased erosion are associated with a variety of failure probabilities and subsequent delivery ratios, the cost-effectiveness of treating these erosion problems can vary over a range of two orders of magnitude, or more. For example, by excavating fill-crossings on natural stream channels, each cubic yard physically removed represents an equal volume saved from future erosion and sediment yield. However, in diverting streams out of rapidly eroding gullies and back into their natural channels, each cubic yard excavated at the diversion point could ultimately result in 10, 100 or more times the savings in potential future erosion that might have been generated by the untreated, active gully system. Large, rapidly eroding gully systems can be totally dewatered through simple, comparatively inexpensive excavations at the source of the diversion (Teti, 1982). It may also be technically possible to treat some large landslides at cost-effectiveness levels better than $1 - $10 per cubic yard. However, stabilization is typically difficult and/or prohibitively expensive regardless of overall cost-effectiveness.

Secondary erosion control practices are those designed to minimize erosion from areas disturbed during primary treatment. They typically consist of a variety of labor-intensive erosion control and revegetation techniques, as well as heavy equipment work needed to transport and place channel armor. A listing of average costs and the range of relative cost-effectiveness of secondary erosion control techniques used in Redwood National Park is shown in Table 2 and Table 3. Perhaps the most important information to be gleaned from these tables, in comparison to each other and to Table 1, are the relative ranges of cost-effectiveness. Primary erosion control techniques used in the park are from one to three orders of magnitude more cost-effective than secondary treatments, except where the primary work done was of inherently lower cost-effectiveness. Similarly, on logged lands in Redwood National Park, secondary treatments used to control channel erosion (Table 2) are generally much more cost-effective than treatments to control surface erosion (Table 3). This difference reflects the greater importance and contribution of erosion from post-rehabilitation channel scour and adjustment as compared to surficial soil loss from bare areas.

It is significant to note that even among methods designed to treat similar erosion problems (e.g., sheet or rill erosion), there may be well over an order of magnitude difference in their relative cost-effectiveness (Table 3). This usually arises from large variations in the cost of application rather than major differences in effectiveness. For example, in the park, straw mulch and jute-secured straw mulch have provided comparable protection to bare slopes under 70 percent in steepness. However, the high cost of installing jute makes this a much less cost-effective treatment. By definition, maximizing cost-effectiveness entails a trade-off between maximum effectiveness and minimum cost. In addressing erosion control problems, it must be recognized that maximizing cost-effectiveness may result in unwarranted compromises.

Table 1. Cost-effectiveness of primary erosion control treatments used to prevent or minimize sediment production and yield in Redwood National Park, 1978-1980.

Treatment	Average Cost Paid in Park (\$)(1)*	Cost-Effectiveness Range (\$/yd^3 "saved")(2)
Road ripping (decompaction)	350-450/mi	unquantified(3)
Construction of cross-road drains (4)	1000-3000/mi	unquantified(5)
Waterbar construction on skid-trails		
machine constructed	5-50 ea (6)	unquantified(5)
hand-labor constructed	30-300 ea (7)	unquantified(5)
Forest road outsloping for erosion control (8)	2500-9500/mi(9)	1-10(10)
Prairie road outsloping	~7000/mi(11)	unquantified(12)
Excacavation of skid-trail stream crossings	125-1350 ea(13)	1-10(10)
Excavation of logging road stream crossings (14)		
under 750 cubic yards	~2000 ea	1-10(10)
750-1500 cubic yards	3000-3500 ea	1-10(10)
those requiring endhauling	~4000 ea	1-10(10)
Rediversion of stream flow from gullies back into natural stream channels	125-4000 ea(15)	0.1-0.5(16)
Gully stabilization(17)	variable	variable
Prairie gully obliteration	variable	unquantified(12)
Removal of perched debris from the perimeter of yarder pads and cable landings	1000-5000 ea(8)	1-10(10)
Large landslide excavations(18)	20000-30000 ea(19)	1-10(10)(20)

*see succeeding page for footnote explanations

Footnotes to Table 1:

1. Cost based on 1978, 1979 and 1980 unpublished data. "Average" depends on site conditions.

2. Primary goal of Redwood National Park program is to minimize management-related sediment production and yield (i.e., to "save" soil from moving into stream channel systems and, eventually, downstream); no time frame for the eventual occurrence of the erosion has been specified for these calculations although complete loss is anticipated over a period from one decade, or less, to one century. Cost-effectiveness calculation assumes total loss, without reference to time.

3. Treatment results in increased rate of revegetation and reduced surface runoff, and produces an unknown decrease in road surface, ditch, gully, and downslope stream channel erosion. Road fill failures are also reduced by an unknown quantity.

4. Assumes construction every 150 feet, on average; cost range dependent on type of equipment (tractor, backhoe and hydraulic excavator, in order of increasing unit costs)

5. Treatment results in reduced concentration of surface runoff and an unknown reduction in road surface, ditch and gully erosion from adjacent hillslopes.

6. Tractor-constructed waterbars, \$5 to \$20 each; backhoe-constructed waterbars, from \$5 each for areas with good access and requiring little travel time between work sites, to \$50 each where access is poor (e.g., on steep slopes) and results in high travel time.

7. Average cost was \$60 each; range dependent on length and substrate hardness at each waterbar location.

8. Costs depend upon the concentration of organic debris and the amount of endhauling required; generally, up to 75 percent of the cost may be in debris removal while the remaining 25 percent is taken up by actual outsloping of the landing.

9. Narrow roads using only tractor, \$2500/mi; narrow roads using tractor and backhoe, \$3000-\$4000/mi; roads across moderately steep terrain using tractor and hydraulic excavator, \$5000-\$7750/mi; roads built across steep, unstable ground using a dragline crane and tractor, with some endhauling required, up to \$9500/mi (all figures include ripping costs, but do not include the expense of stream crossing excavations).

10. Assumes sediment production would have occurred had the excavation not been performed, and that erosion would have been translated into sediment yield in adjacent stream channel systems. Does not include benefits realized from preventing future stream diversions, and associated gully erosion, which might have occurred without treatment.

11. Full outsloping utilized tractor and hydraulic excavator.

12. The dual goals of rehabilitation on prairie or grassland areas include: (1) erosion control and prevention, and (2) scenic or site restoration of a high visitor-use area; thus the measure of cost-effectiveness used in this table does not apply.

13. Costs dependent upon site accessibility; $\bar{x}$ = \$400 for tractor and backhoe combination; $\bar{x}$ = \$300 for tractor and excavator tandum.

14. Excavations primarily performed by tractor and hydraulic excavator; some completed with drag-line crane.

15. Cost of re-diversion is typically associated with stream crossing excavation at point of diversion.

16. Assumes diverted stream flow would continue to cause increased erosion and had not yet formed a stable, non-eroding channel. Results derived from Teti (1982), Weaver et al. (1982) and unpublished Redwood National Park data.

17. Treatments include armoring, check dams, bank protection and gully headcut stabilization. Costs and cost-effectiveness dependent on type and extent of treatments applied, their effectiveness, and the expected rate of erosion had the erosion control work not been accomplished (see also Table 3 for a more detailed discussion of the cost-effectiveness of these methods).

18. Streamside landslides in the size class of 60,000 to 100,000 cubic yards, of which approximately 4500 to 7000 cubic yards (7%) are excavated from the crown region. Other remedial measures may also be employed on a site-specific basis, but those figures are not included in this analysis.

19 Cost includes endhauling a short distance to a local storage area (0.25 mile).

20. Assumes a one-to-one soil loss potential; that is, each cubic yard of material excavated from the slide mass is considered one cubic yard "saved" from eventual delivery to an adjacent stream channel.

Table 2. Cost-effectiveness of secondary erosion control treatments used in Redwood National Park to minimize or eliminate short-term post-rehabilitation channel scour(1)

Channel Treatment(2)	Cost-Effectiveness Range(3) ($/$yd^3$ "saved")	Comments
Water ladders(4)	20-70(5)	for short reaches
Brush check-dams(6)	10-30(7)	short lived; for small gullies
Small board check-dams(4)	10-30(8)	highly effective; may require maintenance
Large board check-dams(9)	30-50(10)	very expensive; require maintenance
Hand-placed rock armor(6)	20-70(11)	limited to small channels; low flows
Machine-placed rock armor	10-50(12)	very effective; requires good access

1. In certain circumstances, these techniques may also be considered primary treatments. In the park, they are typically employed at excavated skid-trail and logging-road stream crossings.
2. The treatments listed here are not interchangeable; each technique is best suited to a particular situation. Thus, treatments are not directly comparable in terms of cost-effectiveness.
3. Assumes treatment is 100% effective; most methods provide 60% to 90% effectiveness in the first year of average rainfall, and a reduced effectiveness with time (with the possible exception of machine-placed rock armor). Cost-effectiveness would therefore be somewhat lower than that listed (i.e. higher $/$yd^3$ value). Figures refer to first year cost-effectiveness.
4. As used in the park, structures work best when confined to channels which carry a 20-year peak discharge of 6 cfs, or less.
5. Average cost=$700 (1978 data) for 30 ft. structure; erosion prevented = 10-40 yds^3. A more cost-effective treatment would be to excavate a small channel.
6. As used in the park, treatments work best with flows of 2 cfs, or less. Brush dams used mostly in narrow gullies, not in excavated stream crossings.
7. Treatment cost for 60 ft. channel (9 dams) = $135.(1981 wage rates); erosion prevented = 5-20 yds^3.
8. Average cost for a 60 ft. channel (9 dams) = $320.(1978-1979 data); erosion prevented = 10-40 yds^3.
9. As used in the park, large-board dams work best when used on channels which carry a 20-year peak discharge of 20-30 cfs, or less.
10. Average cost to treat a 200 ft. channel = $9450. (13 dams on a 1980 work site; includes first year maintenance costs); erosion prevented = 200-300 yds^3, based on nearby untreated crossings.
11. Average cost to armor a 60 ft. channel = $370. (1978-1979 data); erosion prevented = 5-20 yds^3. Cost assumes rock is available on-site.
12. 1980 cost to rock a large, 275 ft. channel = $4180.(includes blasting and rock delivery; size = 6-18 in.); erosion prevented = 200-300 yds^3. Mean cost to treat 12 crossings (avg.65 ft long) = $530.; erosion prevented = 10-40 yds^3.

Table 3. Cost-effectiveness of secondary treatments used to control surface erosion in Redwood National Park.

Slope Treatment	Mean Cost[1] ($/10,000ft^2)	Cost-Effectiveness[2][3] ($/yd^3 "saved")	Relative Effectiveness[4] (1 = most effective)
Contour trenches[5]	430	40-80	6
Wooded terraces[5]	590	60-120	9
Wattles[5]	2500	250-500	10
Ravel catchers	668	70-140	7
Grass seed with fertilizer	99	10-20	8
Hydroseed	600	60-120	4
Straw mulch[6]	180	20-40	3
Jute-secured straw mulch[7]	2360	240-480	1[8]
Excelsior blankets[7]	1970[9]	200-400	1[8]
Wood chips[5]	950	100-200	5

1. Based on 1978 and 1979 data.
2. Computations based on treating a 100-foot-long stream crossing excavation with bare, 50-foot-long side-slopes at a 50% gradient (total area = 10,000 ft^2). Volume of erosion from this area is assumed to be 5 to 10 yds^3 (all of which leaves the slopes and enters the adjacent stream channel system) until living ground cover is established. These figures are well in excess of erosion rates measured from plot and trough studies from similar settings within the park and produces conservative or "better-than-probable" values of cost-effectiveness.
3. Assumes treatment is 100% effective. Most methods have been shown by independent tests to be from 30% to 80% effective in the first year. Cost-effectiveness would not be expected to be as good as indicated.
4. As measured in plot studies or as inventoried on rehabilitation sites.
5. Use of this method was discontinued in 1979.
6. Dominant treatment used to control surface erosion, 1980 to present.
7. Dominant treatments used to control surface erosion on steep slopes (over 70%), 1980 to present.
8. Jute-secured straw and excelsior blankets are of roughly equal effectiveness.
9. Based on 1980 purchase data and 1979 installation costs.

Some techniques may be only marginally effective yet their cost-effectiveness is high. Grass seeding, an inexpensive erosion control treatment, is one such example (Weaver and Seltenrich, 1981). If the objective is controlling surface erosion, a slightly more effective, less cost-effective method could be chosen (e.g. straw mulch). Likewise, jute-secured straw mulch may be the most cost-effective technique in circumstances where other treatments provide an unacceptably low level of effectiveness (e.g. on slopes steeper than 70 percent; see Weaver and Seltenrich, 1981).

In general, secondary treatments are characterized by one or more factors which significantly limits their ultimate cost-effectiveness. They include: (1) the volume of potential erosion being prevented is usually small when compared to the volume treated during primary or heavy equipment rehabilitation work; (2) by nature, the total cost of a task performed by manual labor can be extremely high when compared to costs for performing the same types of work with machines; and (3) the products of labor techniques are commonly plagued by either limited life-spans, limited capacity or resiliency or, in the case of revegetation, delayed effectiveness. If program objectives demand short-, immediate-, and long-term protection, such practices can be justified. If short-term increases in sediment production would endanger downstream riparian or aquatic resources in need of protection, then labor-intensive treatments are essential (Teti, 1982). However, if ultimate concerns are only focused on the long-term reduction of accelerated sediment yields, many of the secondary treatments listed in Tables 2 and 3 would not be cost-effective.

Other factors have significantly affected the costs and, hence, cost-effectiveness of primary and secondary treatments used in the park. An unskilled or inefficient heavy equipment operater can more than double the price of stream channel excavations. Similarily, the selection of an improper piece of earth-moving machinery for any given job can result in cost increases of over 50 percent. An example is the utilization of a hydraulic excavator or backhoe in instances where a crawler tractor could perform the same task at a cheaper rate and in a shorter time period. Recognition and timely correction of inefficient procedures is dependent on the experience and ability of the project coordinator, and is enhanced by a system of technical peer review.

The cost-effectiveness of labor-intensive work is primarily controlled by: (1) the selection of proper techniques designed to treat the actual (as opposed to perceived) erosion problems; and (2) the method of accomplishing the work (contracts, in-house labor, etc.). Initially, surface erosion from park lands was perceived to represent a significant source of increased sediment yield and wattles were judged to be an appropriate treatment for bare soil areas (Madej, et al., 1980). However, quantitative studies and detailed field observations soon revealed surface erosion to be far less significant than channel or gully erosion, and wattling to be far more costly and less effective than a variety of other techniques available to treat sheet and rill erosion (Weaver and Seltenrich, 1981). Cost-effectiveness can be optimized by ensuring that: (1) each manageable erosion process is treated in relation to its actual importance in affecting sediment yield; and (2) both cost and effectiveness considerations are quantitatively evaluated in light of the variety of techniques available to treat each problem. Technique selection, which dictates both the overall level of cost and the effectiveness with which erosion is controlled, is based on professional judgement and experience. Utilization of the best available information on erosion processes and erosion control techniques, quantification of erosion potentials, and a critical field-review of proposed work elements by peers or experienced practitioners are the best methods to minimize the inclusion of unnecessary, ineffective and typically expensive procedures (Sonnevil and Weaver, 1982).

Labor costs, the second major factor affecting the cost-effectiveness of labor-intensive erosion control work, can represent a large percentage of watershed rehabilitation expenditures. On four 50-acre to 200-acre cutover areas treated in 1978 and 1979, labor costs alone ranged from $20,000 to over $80,000 each and comprised from 75 percent to 95 percent of the total project cost (Madej et al., 1980; Kelsey and Stroud, 1981). Four methods have been used to complete labor work in the park (Sonnevil and Weaver, 1982). In order of increasing cost-effectiveness, they are: (1) request for proposal (RFP),cost-reimbursement contract; (2) request for proposal (RFP),fixed price service contract; (3) direct labor hiring (if done on a temporary or part-time basis); and (4) invitation for bid (IFB),fixed price service contract. Although the incentive to do a rapid, inexpensive, and effective job is greatest with the competitively bid, IFB, fixed price service contract; administrative delays and legal requirements can sometimes make their use impractical when erosion control work must be completed prior to the commencement of winter rains. Hiring a part-time labor force allows the application of secondary treatments immediately following heavy equipment operations. However, the need for training and a comparatively lesser incentive to maximize work efficiency can increase the costs of this method. Thus, in-house labor must be temporary, well trained and well supervised or motivated to be cost-effective.

SUMMARY AND CONCLUSION

A number of factors have affected the cost-effectiveness of erosion control work conducted at Redwood National Park. Here, as elsewhere, cost-effectiveness can only be evaluated in terms of achieving clearly defined objectives within the framework of overall program goals and available funds. Controls on cost-effectiveness have been shown to depend upon the static or dynamic nature of short-term objectives and long-term goals, the mechanisms and "controlability" of sediment sources, and a variety of factors which show variation through time. These include the protection provided by revegetation and structural erosion control measures, and rates of post-disturbance sediment production and yield. Erosion control treatments can be selectively prescribed to provide short-, intermediate- and long-term protection to a site. Applications which ignore any of these time frames may fall short of meeting the primary objectives.

Prevention is clearly the least costly and most effective method for minimizing increased erosion and sediment yield. However, where corrective work is needed, quantitative predictions of erosion control cost-effectiveness can result in significant savings. Only those projects which can be completed within acceptable levels of cost and with beneficial results need be carried out. Cost-effectiveness calculations used in the park's program allow short-term comparisons between measures as widely divergent as the dewatering of gully systems, stream channel excavations, channel armoring, check damming, mulching and wattling.

Evaluations of the cost-effectiveness of specific primary and secondary treatments used in Redwood National Park show in excess of three orders of magnitude potential difference between the various techniques. Due to this large variation, extra efforts are now taken on park projects to complete the cost-effective primary treatments to the fullest extent possible. This reduces the amount of secondary protection needed to attain maximum overall cost-effectiveness. In many cases, adequate primary treatment may actually obviate the need for further protection at little or no loss of effectiveness.

Work at the park has shown that a successful erosion control program requires a rigorous evaluation and monitoring program which continually feeds information and findings back into ongoing rehabilitation work. Acceptable levels of cost-effectiveness can only be assured through the quantitative documentation of erosion processes and erosion control effectiveness. Accurate, detailed accounting of procedures, work elements and associated unit costs can then be used to establish the cost-effectiveness of watershed rehabilitation for erosion control.

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