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Patterns of Hillslope and Channel Recovery Following Disturbances in Steep, Forested Basins

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

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AN ABSTRACT OF THE DISSERTATION OF

Mary Ann Madej for the degree of Doctor of Philosophy in Geology presented November 22, 1999. Title: Patterns of Hillslope and Channel Recovery Following Disturbances in Steep, Forested Basins.

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Geomorphic response to watershed disturbances commonly results in alterations of landforms. Subsequent geomorphic recovery is dependent on the ability of flows to entrain, transport, and organize inorganic and organic material on hillslopes and in channels. This research analyzed changes in sediment production, channel structure, and channel organization following disturbances in steep, forested terrain. Examining a range of channel environments following sediment pulses permitted the development of a conceptual model predicting trajectories of channel change.

Extensive road construction and timber harvest on steep, forested hillslopes in the Redwood Creek basin, north coastal California, caused increased sediment yields to streams. This study examined the effectiveness of erosion control efforts on these disturbed hillslopes following a 12-year storm. The erosional response of treated logging roads was strongly related to their geomorphic setting: roads on gentle, convex, upper hillslopes contributed much less sediment than roads on steep, lower hillslopes (10 and 550 m^3 of sediment/kilometer of treated road, respectively). Since 1980, 300 km of

treated roads contributed about two percent of the total sediment load of Redwood Creek, north coastal California. Minimal treatment of roads in upper hillslope positions was effective in reducing sediment production, but more intensive treatments are needed for roads in middle and lower slope positions.

The response of channels to sediment pulses was also examined. Channels exhibited self-organizing behavior as they processed previously random hillslope inputs into regularly spaced bedforms at characteristic spatial scales. Variability and spatial patterns of channel bed elevations were related to the dominant bed material, presence of wood, channel gradient, and time since disturbance. Typical trajectories of change were increased magnitude and variability of water depths, and increased number, size, and regularity of bedforms. Concurrent with increasing development of bedforms was an increase in channel roughness.

The time scale of recovery varied with channel type. The frequency of flows capable of reorganizing bed material in steep, coarse-grained channels was low, and consequently the development of channel structure and organization was slow. In contrast, lower gradient rivers with easily mobilized gravel beds attained regular bar and pool spacing within two decades of a sediment pulse.

ACKNOWLEDGMENTS

This research depended heavily on measurements made over several years in many rivers and streams. Numerous people helped on survey crews over the years, and I especially wish to thank Vicki Ozaki, Carrie Jones, Brian Barr, Randy Klein, Deadra Knox, Greg Gibbs, Anna Bloom, Tera Curren, Dave Best, Julie Miller, Brian Adkins, and Natalie Cabrera for the long, wet hours of surveying, and the longer, drier hours of data analysis. Their astute field observations and stimulating discussions made this effort even more enjoyable. Brian Barr developed the database format used in the road restoration evaluation. Dwain Goforth developed the computer software to analyze longitudinal thalweg surveys. I wish to thank the many dedicated National Park Service geologists who designed, prescribed, and implemented the road treatments described in Chapter 2.

I am extremely grateful to the members of my graduate committee at Oregon State University. They were very supportive of my return to school after a hiatus in my academic training of many years. Gordon Grant, my major professor, was always ready to enthusiastically discuss geomorphology, and continually suggested more ideas to pursue than one could handle in a lifetime. Julia Jones opened my mind to the possibility of using landscape ecology concepts within a geomorphologic framework. Fred Swanson constantly motivated me to examine a problem from a broad perspective. Stan Gregory provided a much needed reality check when I became too speculative. Steven Esbensen served as another dedicated member of my graduate committee, and asked several thought-provoking questions.

I benefitted greatly from discussions with other colleagues, especially Tom Lisle, Leslie Reid, and Greg Bundros. I am grateful to the late Dick Janda, who long ago advised me that "many geomorphic concepts will be sacrificed upon the altar of the Franciscan Assemblage" and for his foresight in establishing a monitoring network in the Redwood Creek basin. I thank anonymous reviewers for their insight and helpful comments on various drafts of these chapters which were submitted to journals. Dr. Julia Jones and Jack Lewis provided statistical advice.

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Of course I wish to thank my family for their constant support and patience. I especially want to thank my mother and sisters for the gift of concentration this past summer, when they generously hosted my children so that I could write. And although my father, Dziadzie, and Bucia aren't here to see me graduate, I appreciate the love of the land that they each, in their own way, passed on to me. Al, Tami, and Angie have somehow survived my frustration and irritation in good humor, and are still willing to explore more rivers with me. Their constant encouragement and laughter kept me going these many years.

My wish for the Redwood Creek basin is that it someday will achieve its full potential of a healthy, vibrant coastal watershed. From its rain-shattered mountains to its redwood-shaded terraces and sun-baked gravel bars, Redwood Creek still holds many secrets of beauty, solitude, and primeval wonder. May the readers of this dissertation be inspired to come and visit this special place.

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Chapter 1

Introduction

Landforms evolve through an interaction of detachment, erosion, transport, and depositional processes. Two primary mechanisms of erosion and transport are mass wasting and fluvial erosion. Mass wasting processes involve the detachment and movement of organic and inorganic material as a mass, and include shallow debris slides, debris flows and torrents, slumps, and earthflows. Fluvial processes involve particle detachment and transport by flowing water, and include rilling, gullying, channel incision, and bank erosion. Fluvial and mass wasting processes interact to create landforms, to transport watershed products, such as water, sediment, wood, energy, and nutrients, from hillslopes to channels, and to route sediment through the channel network. Both fluvial and mass wasting processes are active across most steep landscapes, but the extent and rates of activity depend on the climate, bedrock, topography, vegetation and disturbance history of the watershed. Disturbances can alter magnitudes and rates of fluvial and mass wasting processes. The present research endeavors to quantify hillslope and channel response to several types of watershed disturbances.

Disturbances in drainage basins may be caused by natural events such as volcanic eruptions, fire, and floods. In addition, human activities, such as surface mining, timber harvest, dam construction, etc., can modify a natural disturbance regime through alterations of the type, frequency, magnitude, sequencing and spatial distribution of fluvial and mass wasting processes. Changes in hillslope and channel forms can be initiated by some disturbance of the system.

Many definitions of disturbance exist. Gerritsen and Patten (1985) defined disturbance as "any unusual change in the temporal sequence of values of either state variables or parameters that cause a resultant unusual deviation of state, transition function, response function or output from established norms." They list three criteria for a disturbance: the event must have a low frequency of recurrence, have low temporal predictability, and must be greater in positive or negative magnitude than nominal excursions of causal or affected variables. The key here is that the event is measured against some reference 'nominal' behavior, but the meaning of 'nominal' is left undefined. White and Pickett (1985) attempted to avoid defining 'nominal,' and define disturbance as "any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment." They focus on defining disturbance in terms of "disturbance regime descriptors" of a particular event, i.e., the spatial distribution, frequency, return interval, rotation periods, predictability, area, magnitude, intensity, and severity of that event. For a given disturbance descriptor, measures of central tendency and dispersion, as well as frequency distributions are of interest. Resh and others (1988) defined disturbance in stream ecosystems to be any relatively discrete event in time that is characterized by a frequency, intensity and severity outside a predictable range, and that disrupts ecosystem, community or population structure and changes resources of the physical environment. In their definition, "disruption" is not specifically quantified.

Consequently, whether or not a given geomorphic event is a 'disturbance' depends, at least in part, on the effects of that event on a feature of interest. Wolman and Miller (1960) proposed a measure of the importance of a particular geomorphic event, such as a flood. The effectiveness of an event of a given frequency can be measured by comparison of the relative amount of sediment transported or geomorphic work done. A later analysis (Wolman and Gerson, 1978) suggested that absolute values of magnitude and frequency of events do not necessarily provide satisfactory measures of geomorphic effectiveness. They defined the geomorphic effectiveness of an event in terms of the ability of an event to affect the shape or form of the landscape. Geomorphic work done by an individual extreme event can be scaled as a ratio to mean annual erosion, and the effectiveness of disturbance events in forming landscape features can be related to the rate of recovery of a pre-existing form following alteration by the extreme event (Wolman and Gerson, 1978).

Figure 1.1 displays a conceptual model of geomorphic response to a disturbance, which includes both the trajectories and rate of change. Geomorphic response to disturbance consists of four major parts:

1) A disturbance occurs in the system (Figure 1.1 A). Watershed perturbations can be instantaneous (landslides entering a channel) or chronic (increased fine sediment delivery from unpaved roads)

2) The lag time: the system may respond immediately (no lag time) or there may be a delay, or lag, before response occurs (Figure 1.1 B). For example, a channel immediately downstream of a large landslide will respond to the increase in sediment

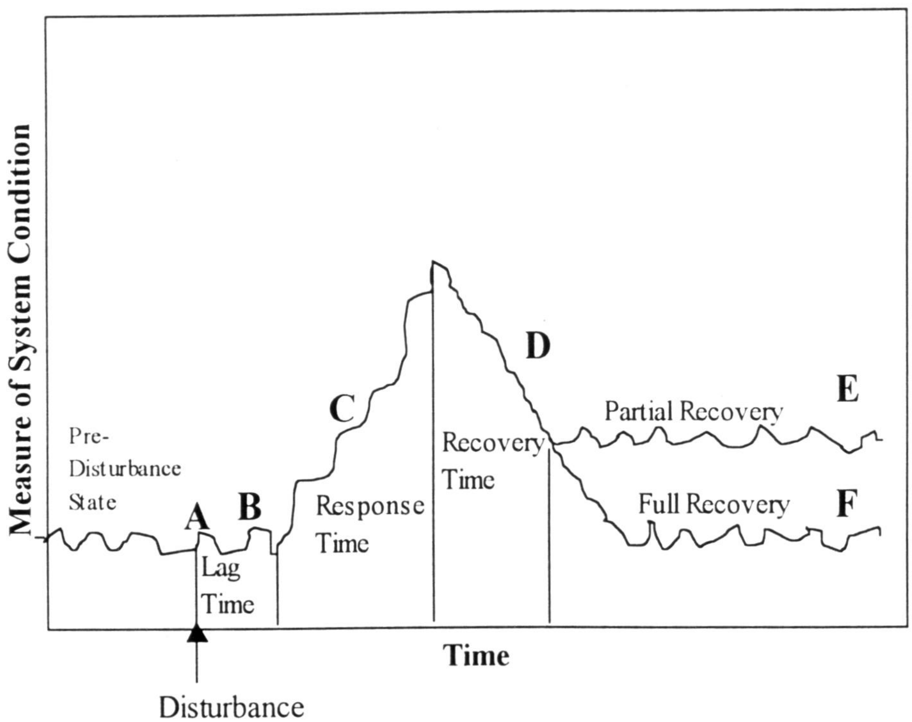

Figure 1.1: Schematic diagram of effects of watershed disturbance and recovery

immediately, whereas it may take several large flow events for reaches farther downstream to respond.

3) The persistence of system response. The time it takes for the change to occur (the response time) varies among systems (Figure 1.1 C). For example, Madej and Ozaki (1996) showed that following a large sediment input, aggradation occurred during a period of three years in a stream reach near the sediment input, but persisted over a period of more than ten years in downstream reaches.

4). The final phase of response to disturbance is system recovery (Figure 1.1 D). Systems vary in their recovery time (or relaxation time) in which the system returns to its pre-disturbance state (Figure 1.1 F). Alternatively, the system may not return to a previous state (Figure 1.1E). Several trajectories of recovery may be possible. Whether or not a hillslope or stream achieves full recovery depends on many factors, including whether it is physically possible for a change to be reversed. For example, if a threshold of competence is only attained during the disturbance event (such as a large flood mobilizing coarse channel bed particles), recovery of the pre-existing channel form following the flood will not occur.

The actual types of response following disturbances vary greatly from system to system. Many studies have examined geomorphic responses to changes in hydrologic regimes and sediment supply (Gilbert, 1917; Rhodes and Williams, 1979; Dietrich et al., 1989). Hillslopes and stream channels can respond over several spatial and temporal scales. For example, a localized event, such as a tree falling into a stream, may cause an immediate localized response, such as scour of a pool. In contrast, a dispersed disturbance such as a wildfire can lead to a more widespread change. Spatially, change may be localized to a single habitat unit (scour of a single pool), or can be evident within a stream reach (aggradation), or can be spread across a channel network (increased peak flows due to climatic change or land use).

This investigation focuses on the recovery phase following disturbances, as hillslopes and channels adjust to anthropogenic disturbances in steep, forested basins. Geomorphic response and possible recovery can be evaluated from several perspectives (Madej, 1996). Important characteristics of geomorphic change to consider are: a) the type of change (sediment texture, morphology, degree of wood loading, temperature, and hydrologic regime); b) magnitude and frequency of change; c) the spatial distribution of change (localized or widespread); d) the timing, duration and persistence of change;

e) the sources and range of variability and f) sequencing of events (what is the relationship of current change to the past history of changes in the stream channel?)

Not only are there several types of possible geomorphic responses, but even a single attribute of disturbance may be approached differently by investigators. For example, geomorphologists may focus on the magnitude of change (depth of scour in a gravel channel), whereas a biologist may be more interested in the timing of change (are there salmon eggs present when scour occurs?). A given channel response may be relevant during one phase of an organism's life history (spawning, for example), but irrelevant to other phases, such as rearing and migration. The sequencing of events may also be important, but few studies have addressed this variable directly (Benda et al., 1998). Finally, although one can define statistical significance of channel change, defining the biological significance of a given change is more problematic. In some cases, it may be questionable if geomorphologists can even detect the type of change that is biologically significant. Also, the mechanisms leading to biological recovery may be different than those governing physical recovery of the stream channel.

The present study focuses on changes in sediment production from hillslopes and resulting changes in channel structure, organization, and roughness. Some spatial and temporal scaling aspects of detecting geomorphic change are summarized in Figure 1.2. This schematic shows various components of natural and anthropogenic influences in a watershed that can result in geomorphic changes. Some, such as treefall or a small landslide, affect only a small area immediately adjacent to the event. The channel responds quickly, for example, by scouring its bed around a newly fallen tree. Other

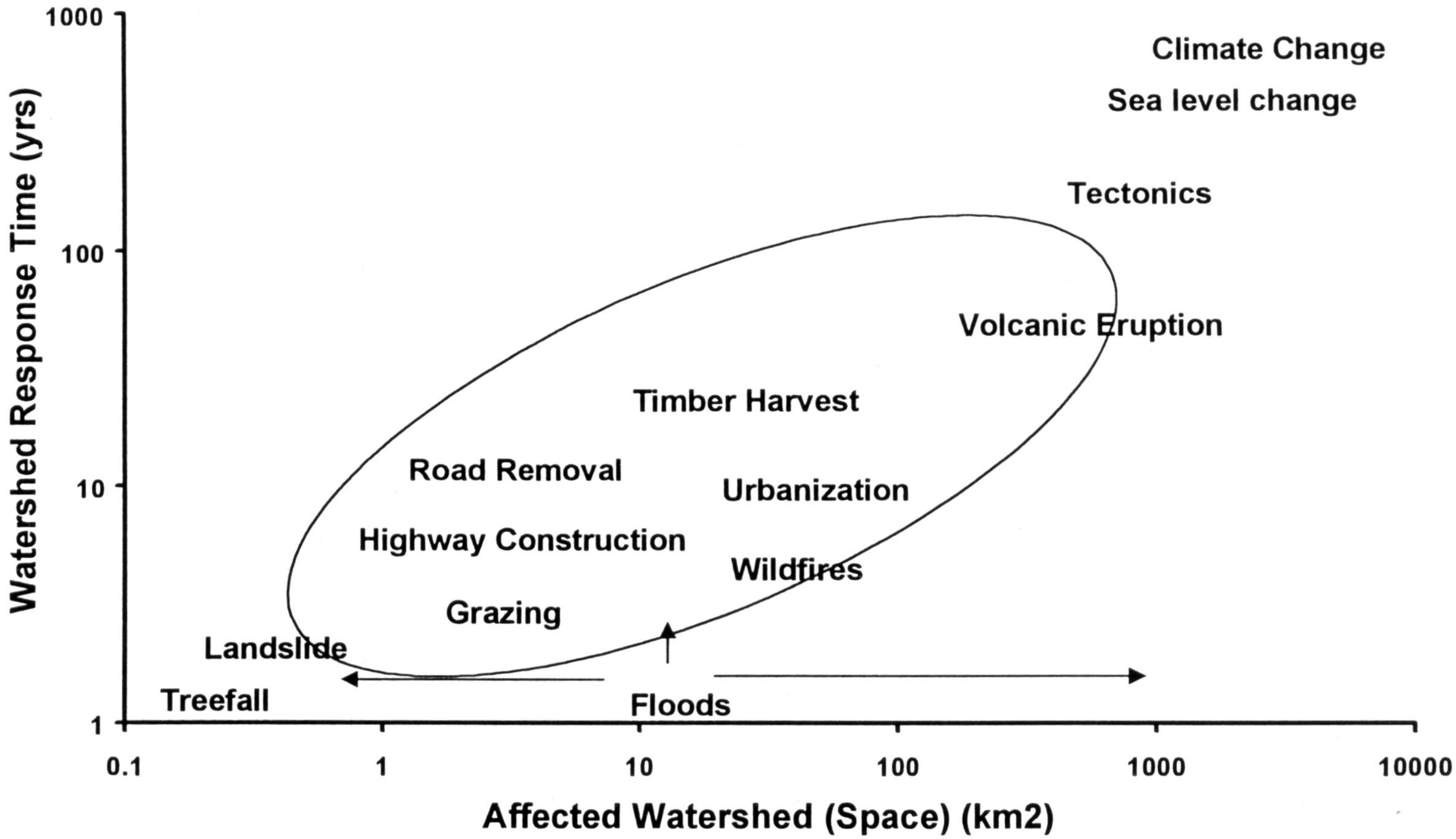

Figure 1.2: Space-time diagram of changes in watershed condition

activities, such as timber harvest and road removal, can influence sediment production over a larger area, and the time required for a channel to respond to these changes is longer. Some changes occur on such a long time frame and over such wide areas that it may be difficult to detect short-term responses. The research presented in this dissertation focuses on changes in sediment production and channel response over intermediate spatial and temporal scales (within the ellipse). Neither individual storm events (time scale of days) nor landscape evolution trends (time scale of thousands of years) are addressed by the data sets presented.

Chapter 2 considers disturbances in watersheds through the construction and subsequent removal of logging haul roads. In Redwood Creek in northern California, density of logging roads is high (5 to 7 km/km^2), and disruption of the ground surface and stream channels by haul and skid roads has been extensive (Figure1.3a and b). Effects of road construction in steep, forested basins have been well documented, and include soil compaction, increased erosion rates, and changes in runoff and hydrologic routing (Nolan et. al., 1995; Wemple et al., 1996).

Active restoration of this landscape through the removal and treatment of roads has been in process since 1978. One of the goals of the watershed restoration program is to accelerate hillslope and channel recovery following damage from past timber harvesting and road construction. The erosion control efforts, initiated by Redwood National Park in 1978, presently affect many subbasins of one to 30 km^2 within the larger 720 km^2 Redwood Creek watershed. To date, there have been few evaluations of

Figure 1.3a: Example of logging road and channel disturbance, Redwood Creek basin, California, circa 1975.

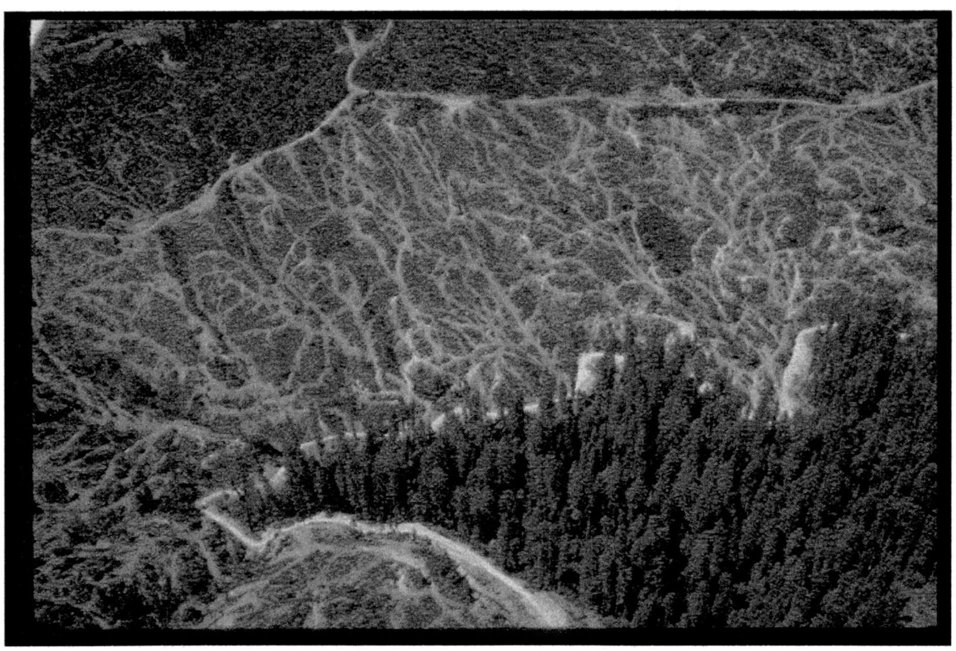

Figure 1.3b: Hillslopes in the Redwood Creek basin have a high density of skid roads and haul roads constructed during past timber harvest activities.

sediment production following restoration efforts. This chapter addresses sediment production and delivery following road removal. Channel surveys presented in Chapter 2 form the basis of further discussions of channel development in later chapters. In addition, the results of this evaluation of road removal and sediment production should be applicable to other forested regions with similar road-related erosion problems.

Chapters 3 and 4 focus on channel responses to changes in sediment production and delivery in drainage basins of < 1 to 700 km^2. Chapter 3 uses successive thalweg profiles in gravel-bed rivers to monitor changes in channel bed topography following large sediment inputs. Examples based on 20 years of monitoring data in north coastal California rivers are presented. Spatial and temporal trends in variations in channel bed elevation, distribution of water depths, percentage of channel length occupied by riffles, and strength of spatial autocorrelation are evaluated.

Chapter 4 builds upon the results of Chapters 2 and 3 by placing them in the context of trajectories of stream recovery. A conceptual model is presented that proposes a developmental sequence of channel structure, organization, and roughness following sediment pulses entering a stream. Recovery times and scales of channel structure and organization differ in different parts of the channel network. The model suggests how spatial structure and organizational changes are related to geomorphic processes and disturbance history, and this chapter examines channel development across a range of conditions. Underlying themes of the remainder of this dissertation include:

1) how basins respond following a change in sediment production, 2) what is meant by recovery in terms of channel structure and organization, and 3) the time required for channel structure and organization to be restored.

Changes in sediment inputs and resulting changes in channel morphology are important considerations in ecosystem studies. Ecological consequences of such channel changes are many, and include the availability, quality and connectivity of aquatic habitat and refugia, frequency of overbank flooding, and distributions of riparian and floodplain communities. These consequences are discussed more fully in Chapter 5, which presents a summary of findings, identifies future research needs, and discusses the implications of this research for land management decisions.

Chapter Two

Erosion and Sediment Delivery Following Removal of Forest Roads

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2.1 Introduction

Forest roads are significant sources of sediment in mountain watersheds (Megahan and Kidd, 1972; Janda and others, 1975; Kelsey and others, 1981; Best and others, 1995). Abandoned and unmaintained roads once used for timber harvest are common across the steep, forested landscape of southwest Canada and the Pacific Northwest of the United States. Haul roads constructed across steep slopes frequently result in massive landslides and extensive gullying that contribute sediment directly into stream channels. Sidecast material from road construction can fail when it becomes saturated, or gullies can form if road runoff is diverted onto previously unchanneled slopes (Weaver et al, 1995).

Road cuts and drainage structures, such as culverts, can disrupt natural drainage patterns. Stream crossings fail when culverts plug with sediment or wood, or are too small to convey storm discharge. In such cases the road fill at the stream crossing may be removed by erosion. Drainage structures can divert streams out of their natural course onto unchanneled hillslopes when the structures fail to function properly. For example, if a culvert plugs and the road grade slopes away from the culvert inlet, runoff may be diverted from the channel and may flow down the road onto an unprotected hillslope. These diversions frequently result in further gullying, road fill failures, or other landslides. Road cuts can intercept groundwater and increase the amount of surface runoff (Wemple, 1998). As a result of this hydrologic rerouting, some streams receive an increase in discharge, and the channels enlarge through downcutting and bank erosion.

In addition, widespread surface runoff from the road bench and cutbanks flows into inboard ditches, which commonly deliver fine sediment to channels.

In response to the erosional threat posed by unmaintained forest roads, the USDI National Park Service and USDA Forest Service fund programs to upgrade existing roads and to remove roads that are no longer needed for the transportation network. In 1978, the National Park Service initiated one of the earliest and most extensive watershed restoration programs focused on roads in Redwood National Park in north coastal California. At that time Redwood National Park was expanded to include 15,000 ha of recently logged lands. Most of the redwood forest on this land had been tractor logged, which resulted in an extensive network of unpaved haul roads and tractor trails (skid roads). The 15,000 ha park expansion included more than 650 km of abandoned haul roads and 4800 km of smaller skid roads. In response to concerns regarding downstream impacts of roads on streamside redwood forests and salmon-bearing rivers, the USDI National Park Service initiated a watershed rehabilitation program to reduce sediment production from these abandoned roads. The purpose of the program, as stated in Public Law 95-250, was to reduce human-induced erosion within Redwood National Park and encourage the return of natural patterns of vegetation.

The main focus of the watershed rehabilitation program has been to reduce sediment delivery from abandoned logging roads and restore natural drainage patterns. Typical treatments include decompacting the road surface, removing drainage structures (primarily culverts), excavating road fill from stream channels and exhuming the original streambed and streambanks, excavating unstable sidecast fill from the downslope side of road benches or landings, filling in or draining the inboard ditch, and mulching and replanting the sites. An evolution of road rehabilitation techniques, beginning in 1978, will be discussed in more detail below. About 300 km of abandoned logging roads were treated between 1978 and 1996 (Figure 2.1).

The watershed rehabilitation program at Redwood National Park operated for many years under benign weather conditions, and between 1978 and 1996 Redwood Creek had no floods of greater than a five-year recurrence interval. In 1997, the treated roads received their first 'test' from a 12-year return period storm. Although storm damage reports documented many landslides and culvert failures on untreated roads (Redwood National and State Parks, unpublished report), the effect of the storm on treated roads was not known. An evaluation of treated roads was initiated to assess the success of the park's rehabilitation program in meeting its goal of sediment reduction from the road system following a large storm.

The purpose of this paper is to evaluate the erosion and sediment delivery from treated roads based on measurements after the 1997 storm. The format of the study is retrospective rather than experimental because the road treatments from 1978 to 1996 were not applied in an experimental design. Several questions are posed in this assessment: Is the amount of post-treatment erosion from removed roads related to hillslope position, hillslope gradient, or hillslope curvature? Did the type of underlying bedrock influence post-treatment erosion? Did the effectiveness of different road treatment methods vary significantly in terms of reducing sediment yields? Because the

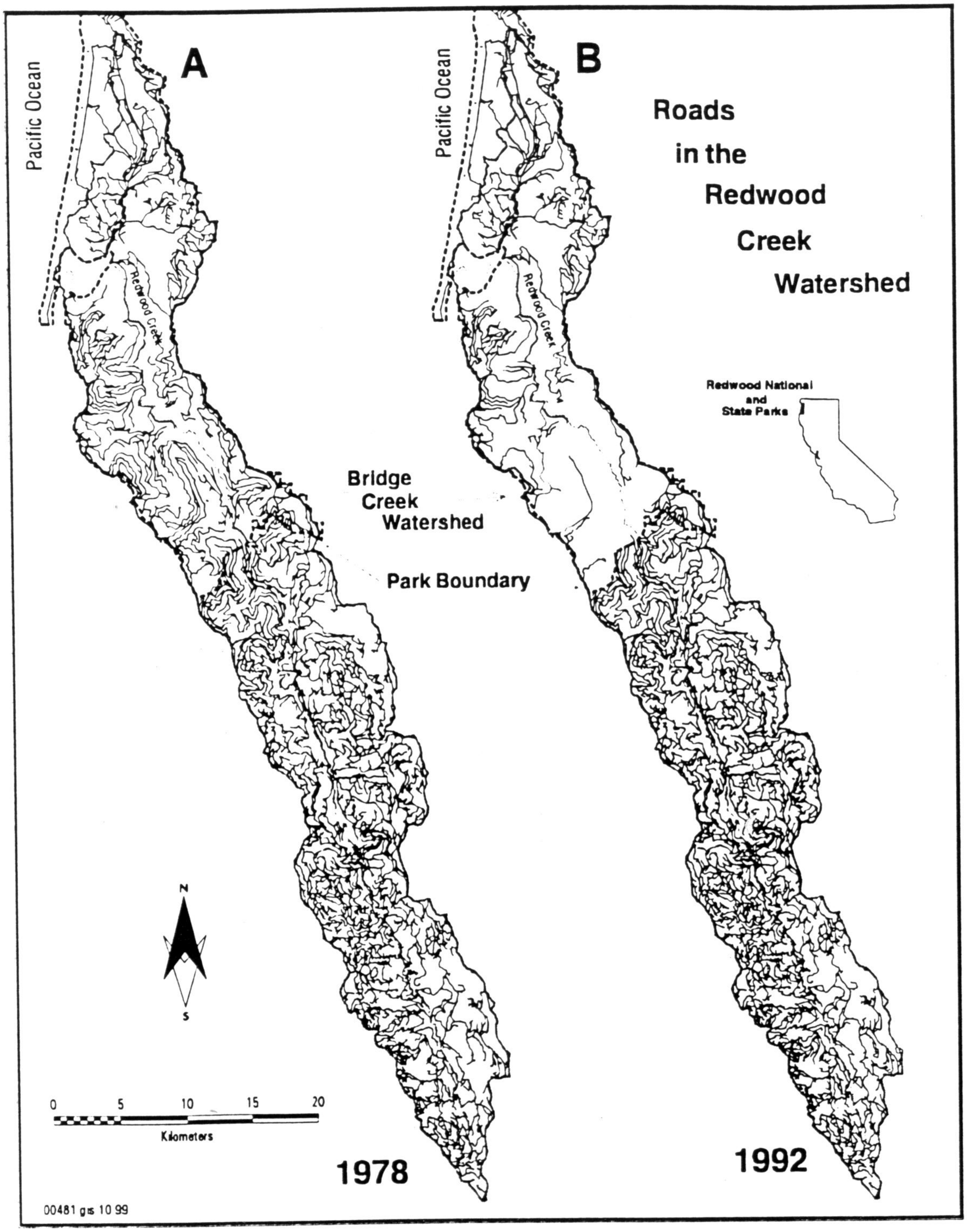


Figure 2.1: Location map of the Redwood Creek basin showing the distribution of roads in 1978 and 1992.

level of revegetation of treated sites increases with time, was post-treatment erosion related to time since rehabilitation? Was post-treatment stream channel adjustment related to stream power? From a basin-wide perspective, have road removal treatments significantly reduced sediment delivery from forest roads into streams?

2.2 Previous Studies

Many researchers have documented the effects of timber harvest and associated road construction in the Redwood Creek drainage basin. Janda et al. (1975) described watershed conditions in the Redwood Creek catchment, including the extent of timber harvest and the effects on the watershed. Their initial work spawned a series of more detailed studies of specific erosional processes. Marron et al. (1995) found that surface erosion from overland flow on forested and logged slopes in sandstone terrain was minor, but sheetwash on tractor-logged slopes in schist terrain can be a significant sediment source. Gullying was a major erosion process on roaded prairies and logged lands in the Redwood Creek basin, and most of the gullies originated on unpaved logging roads (Weaver et al., 1995). A sediment budget for Garrett Creek, a tributary to Redwood Creek, showed that road construction and logging accounted for almost all significant sources of hillslope erosion (Best et al., 1995). Landslides associated with roads and recently logged hillslopes accounted for nearly 80 percent of total landslide erosion measured in the Redwood Creek catchment (Pitlick, 1995). Finally, Nolan and Janda (1995) reported that synoptically measured values of suspended-sediment discharge were roughly 10 times greater from harvested terrain than from unharvested areas.

Although increased erosion rates and sediment yields following road construction and logging have been well documented in the Redwood Creek catchment, few studies address the change of erosion rates following road removal. Klein (1987) measured channel adjustments during the first year following excavations of 24 stream crossings in Redwood National Park. Following a five-year return interval flood, excavated crossings eroded an average of 0.8 m^3/m of length of stream through the road prism. Post-treatment erosion was most strongly related to stream power and inversely related to the percent of coarse material in stream banks and large wood in the channel. Surface erosion (dry ravel, rilling, and sheetwash) following road removal was minimal (Kveton et al., 1983). Luce (1997) found that road ripping (decompacting the road surface) was effective in increasing the hydraulic conductivities of road surfaces, but did not restore the conductivities to those of a forested slope. Bloom (1998) contrasted the erosion derived from treated and untreated road segments in Redwood National Park following the 1997 storm, and reported that storm-related erosion on untreated roads was four times greater than on treated roads, and that erosion was related to hillslope position and proximity to fault zones.

2.3 Field Area

The Redwood Creek catchment, located in the northern Coast Ranges of California, USA, is underlain by rocks of the Franciscan Assemblage, mostly sandstones, mudstones and schist. Redwood Creek drains an area of 720 km^2 and the basin receives an average of 2000 mm of precipitation annually, most of which falls as rain between October and March. The study area is located in the downstream third of the Redwood Creek basin, where elevations are primarily less than 700 m and rain-on-snow events are uncommon.

Average hillslope gradient is 26%. Typical hillslope profiles consist of broad, convex ridges with steeper streamside slopes, where streamside landslides are common. Locally, a break in slope separates the more gentle upper hillslopes and steeper (>65%) streamside hillslopes, which are called inner gorges (Kelsey, 1988). Floodplain development is limited in the Redwood Creek catchment, and the streams considered in this study are highly constrained (valley width is less than two channel widths). None of the roads included in this study was located on a floodplain or terrace. Stream gradients of excavated stream crossings averaged 25%.

Prior to timber harvest, a conifer forest dominated by coastal redwood (*Sequoia sempervirens)* and Douglas fir *(Pseudostuga menziesii)* covered most of the catchment, although scattered grasslands and oak-woodlands lined the eastern ridgetops. By 1997, 80 percent of the original coniferous forest had been logged, and parklands encompass the remaining old-growth forests. The primary silvicultural method was clearcut logging with tractor yarding, which resulted in extensive ground disturbance and large areas of bare soil. Widespread construction of haul roads and smaller skid trails accompanied the timber harvest activities.

2.4 Description of Road Treatments

The first step in treating forest roads was to map the geomorphic and hydrologic features of the road and adjacent hillslopes. Erosion features, drainage structures, the stream network, and the location of all roads, skid trails, seeps, and springs were identified on enlarged aerial photographs at a scale of 1:1200. Following the mapping phase, road removal treatments were designed and implemented. In the early 1980's, road treatment work focused on removing culverts and pulling back road fill from streambanks (Figure 2.2a-d). In some cases, newly excavated stream channels were protected with check dams or large rocks (Figure 2.2b). The crossing excavations surveyed in this study varied from 100 to 7500 m^3 in volume, and averaged about 1000 m^3.

On road reaches between stream crossings, a variety of techniques were used, which varied in the amount of earth moving involved (Figure 2.3a-e). Treatments in the early 1980's decompacted the road surface and constructed deep drains perpendicular to the road alignment to dewater the inboard ditch (a technique referred to as 'ripped and drained'). Typically, 200 to 500 m^3 of road fill was excavated for every kilometer of road treated with this method. This approach is the least intensive treatment (Figure 2.3b). Following this treatment, the roads were mulched, primarily with straw, and replanted with native vegetation (Figure 2.4a and b).

As the program progressed, park geologists began to use more intensive treatment methods, which included partially outsloping the road surface by excavating fill from the outboard edge of the road and placing the material in the inboard ditch at the

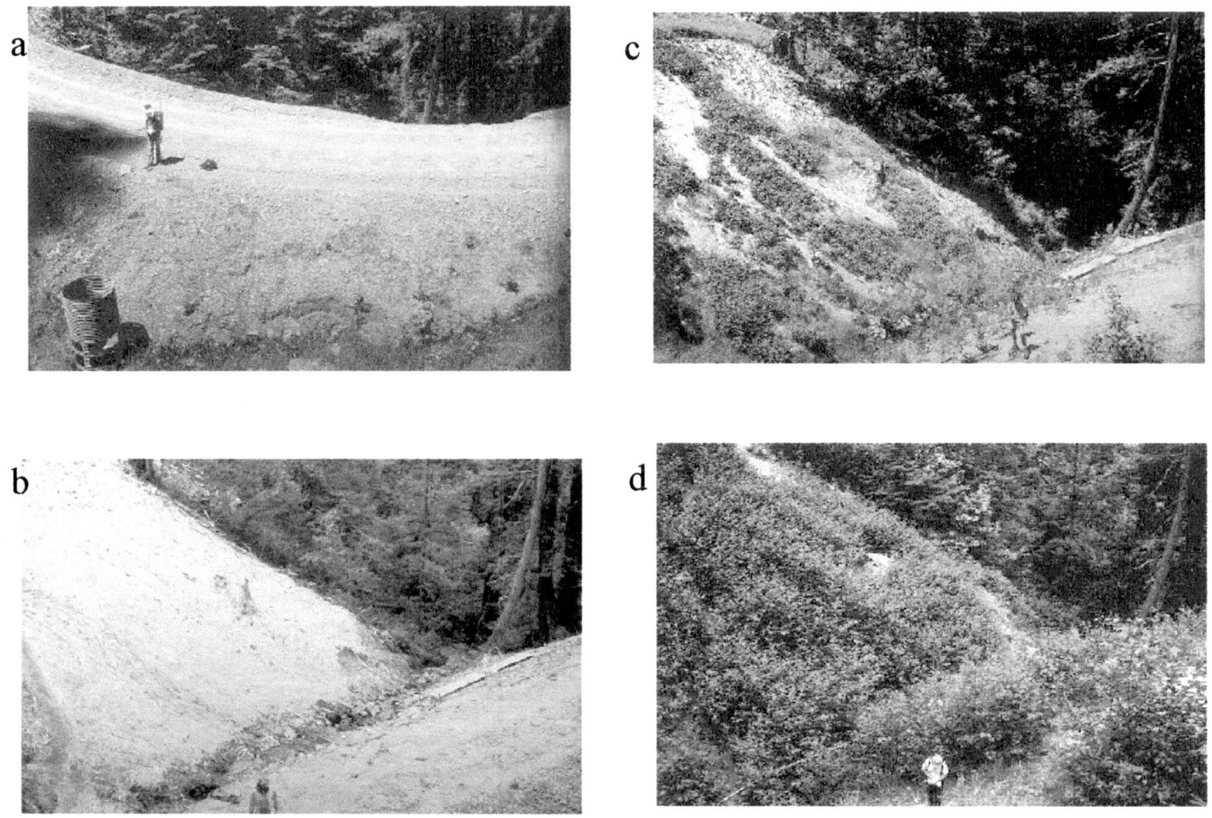


Figure 2.2. Typical stream channel excavation. a) Abandoned logging road with intact culvert before treatment. b) Immediately following stream crossing excavation. Note artificial rock armor placed on channel bed. c) Less than one year late, revegetation of the streambanks is well underway. d) Three years after treatment, alders have revegetated most of the ground disturbed during treatment.

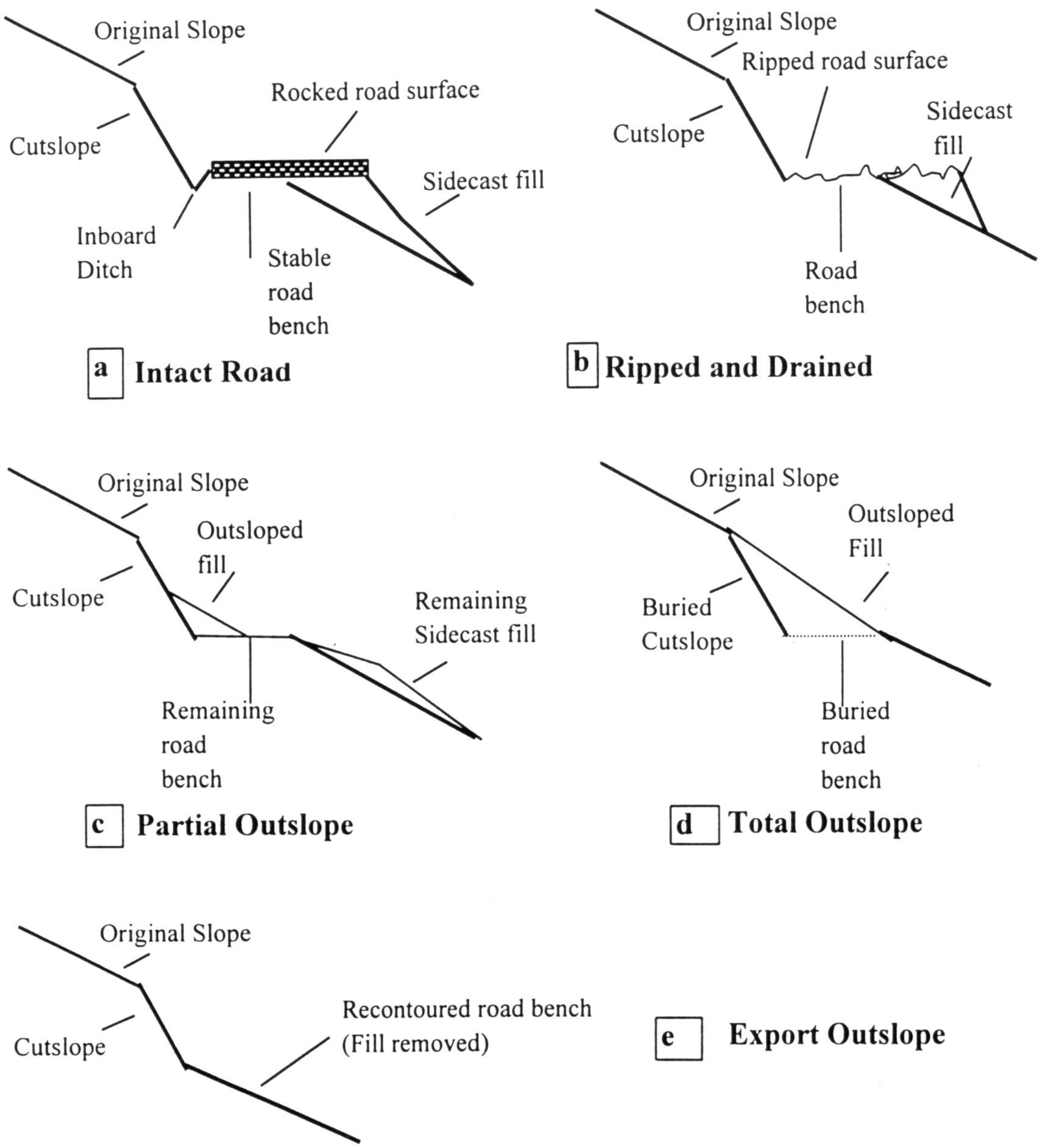


Figure 2.3: Schematic diagram showing the 'anatomy' of a road bench and various road treatment techniques. a) Intact road bench with rocked surface and inboard ditch. b) The road is ripped and drained, so the rocked surface is disaggregated and the function of the inboard ditch is eliminated. c) Partial outslope, in which the steepest sidecast fill is placed at the toe of the cutbank. d) Total outslope, in which all sidecast fill is placed at the toe of the cutbank. e) Export outslope, where all the sidecast fill is removed from the road bench entirely.

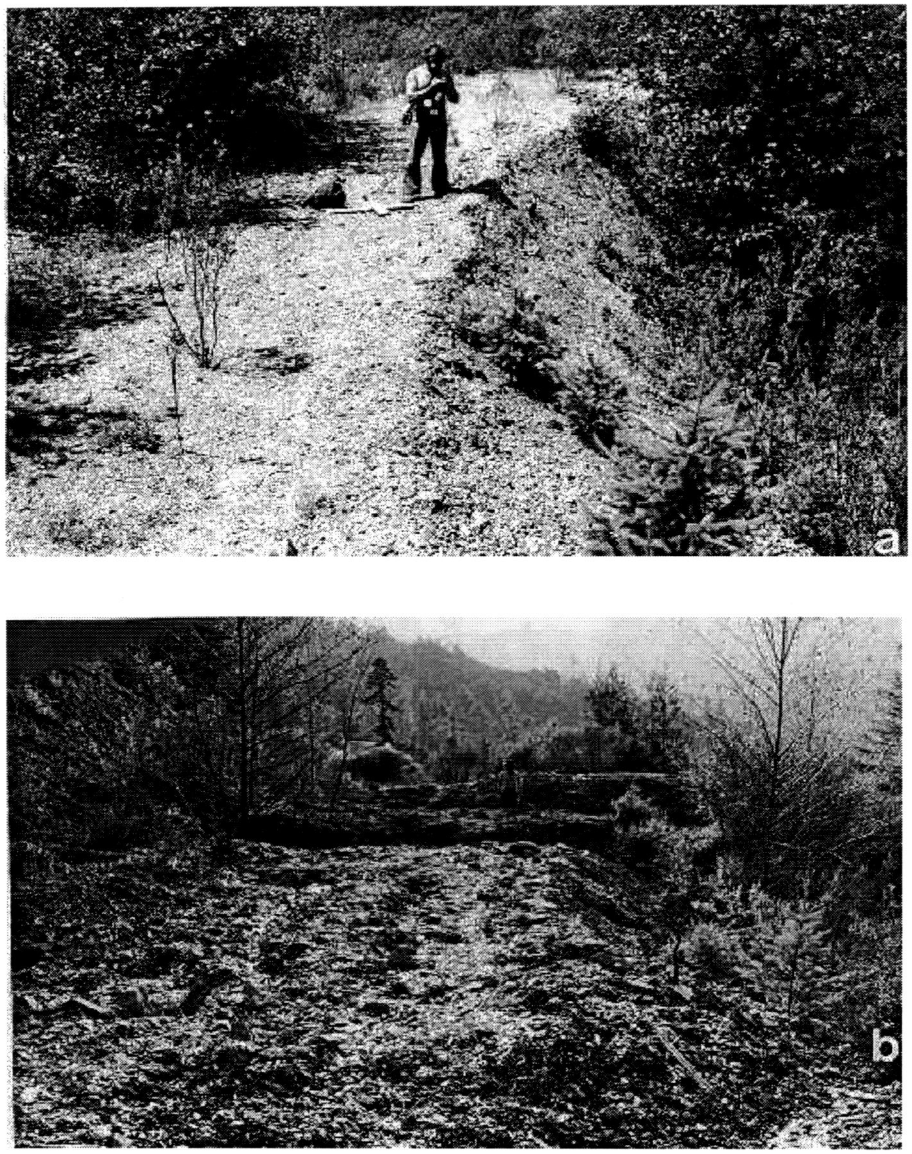
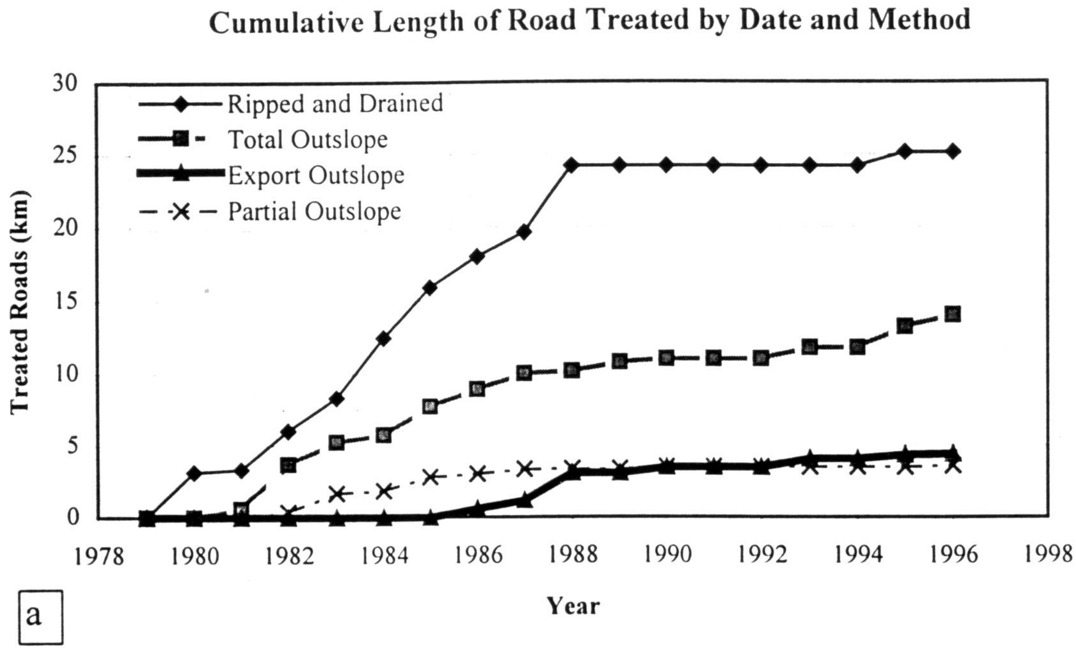


Figure 2.4. An example of the least intensive road rehabilitation technique. a) Abandoned logging road before treatment. b) The road surface is decompacted, and ditches are constructed perpendicular to the road alignment to drain the road. The road bench and road fill remain in place.

base of the cutbank (Figure 2.3c). This technique required more earth moving (1000 to 2000 m^3/km of treated road). By the 1990's, geologists commonly prescribed total outsloping and complete recontouring of the road bench, in which the outside edge of the road is excavated down to original ground and excavated fill is placed on the cutbank and shaped to follow the contours of the original topography. Stream channels were excavated to the original channel bed elevation and streambanks were extensively reshaped (Figure 2.3d, 2.5b). Total outsloping involved moving an average of 6000 m^3/km of treated road. Artificial channel armoring was seldom used in this phase, but trees felled during road treatment were later placed in the stream channels and on the treated road surface. On some road segments, excavated road fill was removed from the road bench and transported to a more stable location. This treatment was termed 'export outslope' (Figure 2.3e), and the locations where the road spoils were placed were called fill sites. Export outsloping removed the entire road prism, and involved the greatest amount of earth moving (15,000 to 20,000 m^3/km of treated road). Because surface erosion is not considered to be a major sediment source (Kveton et al., 1983), and natural revegetation is rapid in this region, little mulching or replanting has been done in recent years.

The cumulative length of road treated by the different methods is shown in Figure 2.6a. Most roads that were ripped and drained were treated prior to 1988, and most export outsloping occurred after 1988. This means that most minimally treated roads were subject to more storms than roads which had more intense levels of treatment. A greater length of road was treated in early years, when treatments were still

Figure 2.5: An example of the most intensive road rehabilitation technique. a) Abandoned logging road before treatment. b) The road bench is obliterated and the hillslope recontoured (total outsloping of the road bench, and total excavation of the stream channel). Note person for scale next to a stump that was exhumed during channel excavation.



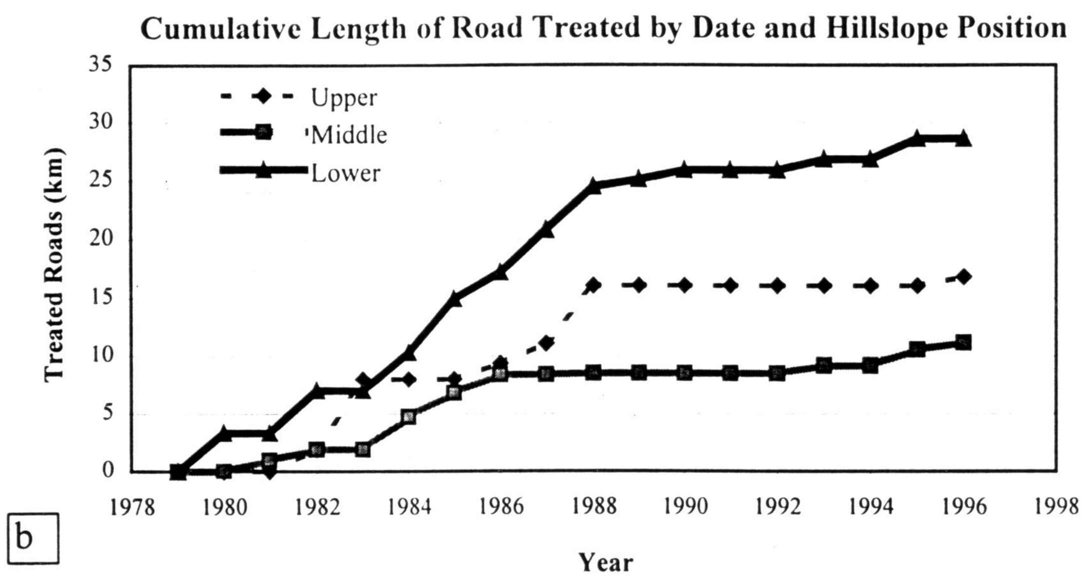


Figure 2.6: a) Cumulative length of sampled roads by date and method of treatment
b) Cumulative length of sampled roads by date and hillslope position

being refined. Due to budget constraints and more intensive treatments in later years, fewer road segments were treated in more recent years. Figure 2-6b shows the cumulative length of road treated by hillslope position. More lower hillslope roads were treated in the first few years of the restoration program than roads in upper and middle hillslope positions, and overall more lower hillslope roads were treated. The implications of these interactions among date of treatment, treatment method and hillslope position are discussed more fully later.

2.5 Methods

All treated roads within Redwood National and State Parks were subdivided into 1.6 km road segments. Because Bloom (1998) found that hillslope position was an important variable in evaluating erosion, road segments were stratified into three hillslope positions (upper, mid-slope and lower). The classification was based on the distance of the road from the adjacent ridgetop to the nearest high-order stream channel. In this catchment, hillslope position is related to slope gradient, with upper, middle and lower hillslopes averaging 25, 35, and 40 percent, respectively. It was difficult to accurately measure hillslope gradient at treatment sites, because thick vegetation and large road prisms obscured the original topography. For this reason, hillslope position is used as a surrogate for hillslope gradient. Because the streams in this study are highly constrained within steep, V-shaped valleys, ‘lower hillslope roads’ do not include any roads on floodplains or terraces, but are typically in the steepest topography.

Forty road segments were selected randomly for field mapping, but two segments, later deemed inaccessible, were not surveyed. During the field mapping phase each road segment was further subdivided into 'stream crossings' where a culvert had been removed, and intervening 'road reaches' that were treated by a variety of methods. Geomorphic maps that were constructed when the roads were first treated were used to supplement field observations to reconstruct site conditions at the time of treatment. Each sampled road segment comprised several treatment sites, representing both stream crossings and road reaches. Consequently, the inventory of 38 segments of treated roads (61 km) resulted in a data set consisting of 207 crossings and 301 road reaches. Each excavated stream crossing and treated road reach had a separate inventory form with pertinent site information, map and erosion measurements (Appendix).

Several types of post-road treatment erosion were measured: mass movement, bank erosion and channel incision, and gullying. Because previous studies had shown surface erosion from treated roads delivered a small proportion of the total sediment in this catchment, surface erosion on the treated road bench or crossing was not measured. Sediment delivery was estimated by measuring the void left by bank erosion or mass movement features and measuring the dimensions of the downslope deposit, if present. The estimated error of measuring the volume of voids and deposits was $\pm$ 25 percent. Commonly, the toe of the landslide entered a stream channel, and the eroded material had been transported from the site by the time of field mapping. Type, density, and ground cover of vegetation on the site were also recorded. Many road reaches were thickly vegetated, which obscured small, post-treatment erosion scars.

Regression analyses were used to evaluate which site factors were important in explaining post-treatment erosion. Factors used in the analysis of erosion and sediment delivery from treated road reaches were: hillslope position (upper, mid-slope, or lower); bedrock (schist, sandstone, or other); treatment type (ripped and drained, partial outslope, total outslope, export outslope, or fill site); time period of restoration activity (1980-1983, 1984-1987, 1988-1991, and 1992-1996); and hillslope curvature (convex, planar, or concave). For stream crossings, the factors used were: bedrock type, date of treatment, drainage area, channel gradient, volume excavated from channels, step frequency and elevation drop due to steps. Because road reach boundaries were based on the spacing between stream crossings, road reaches were of unequal length. Consequently, erosion from road reaches was normalized by the length of road reach (m^3/m of road). In contrast, crossing erosion was expressed as 'm^3 eroded per excavation.' It might also be preferable to express channel erosion volumes as a normalized value (m^3/m of channel), but in the field it was difficult to accurately determine the length of the excavated channel. Post-treatment channel adjustment upstream and downstream of the excavated channels blurred the boundaries of the excavated channel, and in many sites post-treatment erosion extended beyond the limits of the crossing excavation itself.

The treatment method for stream crossings (removal of culverts and reshaping streambanks) differed from that of road reaches (decompacting, draining or recontouring the road bench). For these reasons, the analysis considered data for stream crossings separately from road reaches. The results of the erosion measurements are reported as two values: 1) "total erosion since treatment" in cubic meters (a measure of the volume of voids from mass movement, channel erosion or gullying on the treatment site) and 2) "sediment delivery to streams," in cubic meters, (the volume of the voids minus the volume of downslope deposits). Although the measure of voids on the treatment site was fairly straightforward, the determination of how much of the eroded material actually reached a stream was somewhat subjective. Consequently, the estimates of sediment delivery from some sites are not as accurate as those of total erosion.

The date of treatment of the inventoried sites ranged from 1980 to 1996, and by 1997 when the sites were mapped, most road reaches and crossings were heavily revegetated with shrubs, hardwoods and some conifers. Thick revegetation (for example, Figure 2.2d) on most of the treated road reaches hindered a close inspection of the ground surface, and the minimum volume of erosion measured was 2 m^3. This was considered the detection limit for erosion on road reaches, and by this definition only 20% of the road-reach sites had detectable erosion. Helsel and Hirsch (1997) consider data to be severely censored when data sets have >50% of the values categorized as below the detection limit. In this situation, they recommend logistic regression as the appropriate analytical tool. The response variable on road reaches in this study used in the logistic regression was 'erosion' or 'no erosion'; the explanatory variables were bedrock type, hillslope position, type of treatment, hillslope curvature and date of treatment.

The explanatory variables are not necessarily independent. For example, the treatment technique of ripping and draining was more commonly used in the early time period of 1980 to 1983, than in later periods (Figure 2.6a). Another confounding factor is that the roads considered the most unstable were treated early in the program (Figure 2.6b). Contingency tables were used to check for independence among the variables, and several interaction terms were tested for significance in the regression analyses. Step-wise logistic regression with forward selection, including interaction variables, was used to determine which variables to include in the most reasonable regression model.

In contrast to road reaches, 96% of treated stream crossings exhibited detectable levels of erosion (although most channel adjustment was minor). The entire length and width of the excavated channel were surveyed, so detection of erosion was not a problem. In this case, standard multiple regression techniques were applied. An interaction term included in the regression analysis was (drainage area * channel gradient), a surrogate for stream power. Step-wise regression with forward selection, using an F-to-enter of 4 ($p=0.05$) determined which variables to include in the final regression model.

2.6 Results and Discussion

2.6.1 Distribution of Treated Roads across Sampling Strata

Due to the history of the watershed restoration program at Redwood National Park, not all road types and road treatment techniques are equally distributed across time and space. Contingency table tests showed that, at a 99% confidence level, several variables were not independent of one another: year of treatment, method of treatment, percentages of road length sampled in different categories. For example, 50 percent of and hillslope position. This fact is illustrated in Tables 2.1 and 2.2, which show the sampled road length was on lower hillslope positions. This does not mean there were originally more roads on lower hillslopes, but that the restoration program targeted such roads for early treatment, leaving more upper hillslope roads untreated. Export outsloping was more commonly prescribed on lower hillslope roads, so few of the randomly selected road reaches in upper and mid-slope positions had this treatment technique applied. Early in the program, more roads were minimally treated, and total outsloping was more common in later years. Because of budget constraints and the use of more expensive techniques, fewer roads were treated in the period 1992-1996, so the length of treated road in this category is less than for other time periods. Consequently, any extrapolation of the results of this study must consider the constraints placed by the distribution of sampled road reaches across the various strata.

Table 2.1: Percentage of sampled road length according to hillslope and treatment types

	Road Rehabilitation Technique					
Hillslope Position	Ripped and Drained	Partial Outslope	Total Outslope	Export Outslope	Fill Site	**Total**
Upper	13%	5%	9%	<1%	3%	**30%**
Mid-slope	8%	2%	9%	<1%	1%	**20%**
Lower	21%	6%	7%	12%	4%	**50%**
Total	**42%**	**13%**	**25%**	**12%**	**8%**	**100%**

Table 2.2: Percentage of sampled road length according to bedrock, hillslope curvature, and date of treatment

Bedrock Type		Hillslope Curvature		Date of Treatment	
Schist	72%	Concave	25%	1980-1983	30%
Sandstone	22%	Planar	19%	1984-1986	32%
Other	6%	Convex	56%	1987-1991	27%
				1992-1996	11%

2.6.2 Stream Crossings

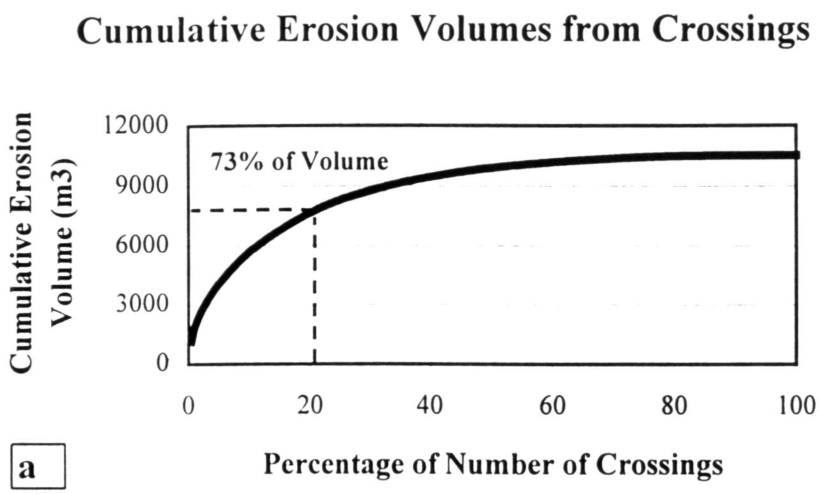
From 1980 to 1997, the total amount of material eroded from 207 crossings following treatment was 10,500 m^3, or about 50 m^3 /crossing. Although this represents a direct contribution of sediment to perennial streams, it is likely that, if these crossings had not been treated, much more sediment would have eventually been eroded and delivered into streams. For example, 220,000 m^3 of road fill was excavated from the crossings during treatment (1060 m^3/crossing) which represents the maximum volume of erodible material if those crossings had remained intact. In reality, not all the road fill actually erodes when a crossing fails. In the Garrett Creek catchment (a tributary outside the study area), Best et al. (1995) determined the average erosion from 75 crossings that had not been treated was 235 m^3/crossing. On the other hand, by excavating crossings and restoring natural drainage patterns, diversion of flow from the natural channel is prevented. Best et al. (1995) showed that diversions occurred at one-fourth of untreated crossings and here the average erosion was 2650 m^3/crossing. These lines of evidence suggest that the likely volume of erosion from the excavated crossings would have been at least four times greater, and probably more, if they had not been treated.

Most excavated stream crossings produced very little sediment. (Crossings which had debris torrents originating upslope and off-site of the crossing excavation were not included in this analysis because the purpose was to look at the effectiveness of the road treatment itself). Twenty percent of the excavated stream crossings produced 73 percent of the total volume eroded from stream crossings (Figure 2.7a). Klein (1987) and Bloom (1998) suggest that most channel erosion occurs in the first few years following treatment, and later adjustments of the channel form are smaller in magnitude. Virtually all the road fill eroded from the treated channels was transported off site by the time the crossings were inventoried.

Channel incision and bank erosion were the most common forms of post-treatment erosion in crossings. To determine a relationship between site characteristics and post-treatment erosion, many variables were used in the forward selection regression procedure (channel gradient, drainage area, drainage area*channel gradient (a surrogate for stream power), volume excavated during treatment, bedrock, date of treatment, number of boulder and log steps, and percent vertical drop due to steps). Only two explanatory variables were significant in the best-fit regression model:

$$\text{Volume eroded (m}^3\text{)} = 20.8 + 0.041\,(\text{drainage area*channel gradient}) + 0.009\,(\text{volume excavated, m}^3)$$

The surrogate for stream power (drainage area * channel gradient) ($p < 0.0001$) and the volume of material excavated from a channel during treatment ($p = 0.0085$) were



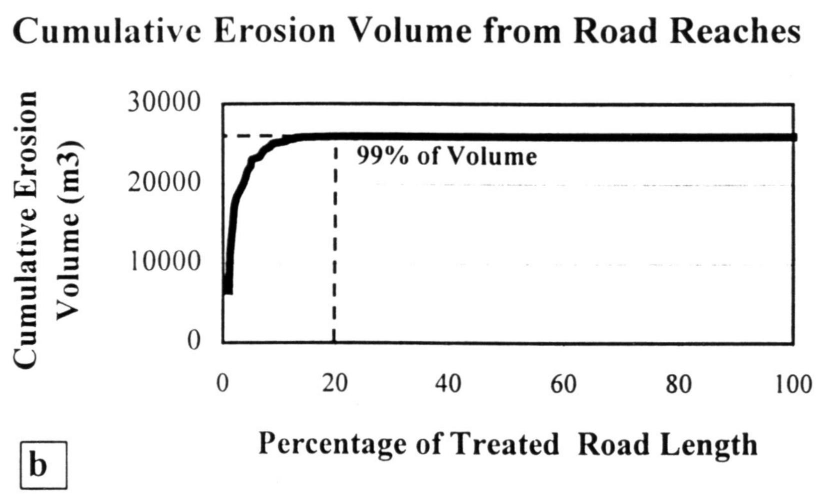


Figure 2.7: a) Cumulative plot of total erosion from excavated crossings
b) Cumulative plot of total erosion from treated road reaches

significant variables in explaining the volume of post-erosion in excavated stream channels. The greater the stream power and the larger the excavation, the more the channel eroded following treatment. Deeply incised channels that required more fill to be excavated were more vulnerable to post-treatment erosion than shallow crossings with less road fill because the reshaped streambanks were steeper, more extensive, and more likely to fail. The regression model was statistically significant at the 99% confidence level; however, the fitted model only explains 18% of the variability in post-treatment erosion. Erosion following treatment is highly variable, and many site-specific conditions (such as the presence of bedrock, springs, or poorly drained soils or incomplete excavations) can influence post-treatment erosion as well.

2.6.3 Road Reaches

The total amount of material eroded from treated road reaches was 25,900 m^3. Most (77%) of this erosion was attributed to mass movement processes, primarily road fill failures. Of the total erosion from road reaches, 74% of the eroded material was delivered to a stream channel. The cumulative distribution of erosion from road reaches is even more highly skewed than that for stream crossings (Figure 2.7b). Twenty percent of the treated road reach length produced 99% of the total erosion from treated road reaches, and most treated road reaches produced very little sediment. Total post-treatment erosion from 61 km of road, including both road reach failures and stream crossing erosion, was 36,400 m^3 (600 m^3/km of road); total sediment delivery was 29,500 m^3 (480 m^3/km of road).

A logistic regression model, based on 'erosion' or 'no erosion' of the treated road sites, resulted in four significant explanatory variables: hillslope position, date of treatment, treatment type, and an interaction term (hillslope position * treatment type). The results of the logistic regression can be expressed by the odds of failure (that is, erosion occurred on the road reach) (Table 2.3). For example, the odds of failure of roads treated in the early part of the program (1980-1983) were 6.7 times greater than the odds of failure for roads treated later (1992-1996). Similarly, the odds of failure for roads in lower hillslope positions were 5 times those of upper hillslope roads, and the odds of failure for mid-slope roads were 3 times those of upper slope roads. The logistic regression was rerun, redefining 'failure' to be erosion > 50 m^3 rather than only >2 m^3. The odds ratios were similar, in that lower slope roads treated early in the restoration program were the most likely to have failed.

Although the model was significant at the 99% confidence level, the percentage of deviance explained by the model is only 16%. Erosion on treated road reaches was highly variable, as it was for treated stream crossings. Besides the geomorphic variables considered in this analysis, road reach erosion is also influenced by site specific conditions, such as the presence of seeps, depth to bedrock, or history of past mass movement activity. Even though bedrock type was not a significant variable in this regression model, a finer distinction of bedrock based on the degree of fracturing, shearing and erodibility in individual units may be worth exploring in the future.

The interaction of hillslope position and treatment type was significant in the logistic regression model, and this interaction is described more fully in Table 2.4.

Table 2.3: Estimated odds ratios from logistic regression model relating post-treatment erosion on road reaches to date of treatment, hillslope position, type of treatment, and an interaction term.

Date of Treatment (p = 0.008)	Estimated Odds Ratio	**(Hillslope Position * Treatment)** (p = 0.006)*	Estimated Odds Ratio
1980-1983	6.7	Upper: Ripped and Drained	1.0
1984-1986	3.5	Upper: Partial Outslope	2.6
1987-1991	1.8	Upper: Total Outslope	7.0
1992-1996	1.0	Upper: Fill	0.0
Hillslope Position (p = 0.007)		Middle: Ripped and Drained	1.0
Upper	0.2	Middle: Partial Outslope	0.0
Middle	0.6	Middle: Total Outslope	0.8
Lower	1.0	Middle: Fill	0.3
Treatment (p = 0.052)		Lower: Ripped and Drained	1.0
Ripped and Drained	2.0	Lower: Partial Outslope	0.1
Partial Outslope	0.3	Lower: Total Outslope	0.1
Total Outslope	1.4	Lower: Export Outslope	0.2
Export Outslope	2.3	Lower: Fill	0.2
Fill	1.0		

* Results from (Upper* Export Outslope) and (Middle*Export Outslope) were not included because there were < 5 samples in each category.

Because the 'odds of failure' result defined by the logistic regression does not give information on the size of failure, Table 2.4 pertains to the magnitude of the failure, and contrasts sediment delivery under different treatment and hillslope conditions. On upper hillslopes, sediment delivery from all treatment types is low. Even minimal treatment seemed to be sufficient in preventing erosion on these sites. This suggests that, except for sensitive geomorphic locations such as headwater swales, a low intensity (and concomitantly, less expensive) treatment is adequate for upper hillslope roads. Sediment delivery from mid-slope roads was also low, except for those that had minimal treatment.

Table 2.4: Volume of sediment delivered to channels from treated road reaches, reported as m^3/km of road length.

	Road Rehabilitation Technique				
Hillslope Position	Ripped and Drained	Partial Outslope	Total Outslope	Export Outslope	Fill Site
Upper	10	10	10	N/A*	0
Mid-slope	310	0	20	N/A*	80
Lower	640	550	630	920	40

*Less than 5 samples in this category.

For effective sediment reduction, more intensive treatment, such as partial or total outsloping, is warranted on mid-slope roads. Lower hillslope roads, which were built on the steepest topography in the watershed, exhibited the highest erosion rates, no matter which treatment was used. It is interesting to note that the most intensive treatment method (export outsloping) was associated with the highest sediment delivery to streams from road reaches in lower hillslope positions.

The expectation of the road rehabilitation program had been that the more intensive the treatment, the less post-treatment erosion would occur. Nevertheless, this result should not be automatically interpreted as a general failure of the technique. Professional judgement is used when restoration treatments are formulated for a given road reach. Park staff who prescribed the high intensity treatment of export outsloping recognized some inherent instability of the road reach, based on evidence of past mass movement, the presence of seeps in the cutbanks, incipient failure of the road bench, etc. Consequently, these road reaches were among the most unstable and had the highest erosion potential even before road treatments were applied, and so might be expected to erode more following any type of treatment. On the other hand, because more land area is disturbed when using this treatment method, the buttressing effect of the road prism is lost, and the capacity of the road bench to store material from cutbank failures is eliminated, it may be that the treatment allows for greater sediment delivery than other treatments. A closer examination of the conditions under which export outsloped road reaches fail and deliver sediment is necessary to distinguish the causal mechanism.

Road rehabilitation efforts following road construction in steep, lower slope positions have a high failure rate and contribute much sediment to streams, no matter what type of treatment is used (Table 2.4). If sediment reduction from roads is the objective in a catchment, these observations suggest the need to avoid road construction (or improve road construction techniques) in these steep, streamside areas. Not only are these likely spots for erosion while the road is in place, but also subsequent treatment of the road may not be effective in eliminating road-related sediment production.

2.7 Basin-wide Perspective of Sediment Production

No direct measurements of sediment yield from treated roads during the 1997 storm are available; however, the values from the present inventory can be roughly compared with measurements made at the gaging station at the mouth of Redwood Creek (drainage area = 720 km^2). During the period 1980 to 1997, 11,100,000 Mg of suspended and bedload sediment were transported by Redwood Creek past this station. During this same period, 61 km of treated roads contributed 29,500 m^3 of sediment to streams (480 m^3 per km of treated road) If the randomly sampled roads are representative of all treated roads in the Park, and this rate is applied to the entire 300 km of treated roads in Redwood National Park, then 144,000 m^3 of sediment probably entered streams from treated roads. Consequently, sediment yield from treated roads represents a contribution of about 233,000 Mg to the basin's sediment load (assuming a bulk density of 1.62 gm/cm^3), which constitutes 2 percent of the total load of Redwood Creek during this period. Of the sediment contributed from treated roads, some of the coarse particles eroded from the road fill were transported as bedload, some broke to suspended size particles during transport, and some sediment was temporarily stored in small stream channels, but little is known about the specifics of sediment routing through these steep, low-order channels.

Without treatment, roads have some potential to eventually fail and contribute sediment to streams. Based on an inventory of 330 km of untreated roads in nearby basins, Weaver and Hagans (1999) estimated past road-related sediment delivery to be 720 m^3/km of road, and future potential sediment delivery without road treatment to be an additional 820 m^3/km, for a total sediment contribution of 1540 m^3/km of road. In a similar study based on 140 km of untreated roads in the Redwood Creek catchment, Bundros and Hill (unpublished data) reported past and potential sediment delivery from roads to be 1450 m^3/km. Untreated roads in the Garrett Creek catchment produced much more sediment (4670 m^3/km), most of which originated from debris torrents caused by stream diversions (Best et al., 1995). By removing culverts and restoring natural drainage patterns, park staff have removed the risk of stream diversions that would cause such debris torrents. None of the 207 excavated crossings examined in this study had diversions or debris torrents related to road treatment. These different lines of evidence suggest that, although road restoration in Redwood National Park did not completely prevent sediment production from removed roads, it does substantially reduce the long-term sediment risk from abandoned roads.

In contrast to the road inventories described above, a recent study by Rice (1999), also conducted in the Redwood Creek basin, reports an erosion rate of only 176 m^3/km of untreated logging road during the period 1995 to 1997. The hillslope position of these sampled road plots was not reported. The roads in Rice's study area were only subjected to a rainfall event of less than five-year return interval, based on rain gage records at Redwood Creek near Blue Lake and at Lacks Creek. Under these relatively low rainfall intensity storms, few culverts failed, as might be expected. Most road-related erosion in the past has been linked to culvert failures and diversions that occur during high intensity rainfall events. It is likely that the erosion rate reported by Rice (1999) does not represent the full erosion potential from untreated roads if these roads underwent a high intensity rainfall event.

Chapter 3

Temporal and Spatial Variability in Thalweg Profiles of a Gravel-Bed River

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3.1 Introduction

Flow resistance in gravel bed channels is influenced by the particle size present on the channel bed surface (skin friction) and by larger scale form roughness caused by bed irregularities, such as bed forms and pebble clusters. Deformation of the velocity field associated with larger-scale features of bed topography, flow obstructions, large woody debris, channel bends and abrupt changes in channel geometry also contribute to flow resistance (Dingman, 1984). The flow resistance of the channel increases as the sum of all sources of channel roughness increases.

Disturbances such as major floods and large sediment inputs can modify bed topography, and so influence channel roughness. In gravel-bed rivers, low gradient (<2%) reaches commonly display a pool-riffle morphology, and disturbances can decrease the size and frequency of deep pools. Consequently channel boundary conditions become smoother, and these changes in bed topography will be reflected in changes in velocity and shear stress distributions as well. Following input of a pulse of sediment and debris, a river channel processes and forms will adjust and evolve towards a new equilibrium state. The trajectories and timing of these adjustments involved in "recovery" are of interest to both geomorphologists and aquatic ecologists. Disturbance to a dynamically stable riffle-pool channel which results in aggradation leads to riffles becoming more extensive, pools becoming smaller and shallower, and bed material textures becoming finer (Lisle, 1982; Jackson and Beschta,1984). The fluvial system may be interpreted as exhibiting non-linear system behavior, and hence, system trajectories are dependent upon instantaneous system states (Lane and Richards, 1997).

Thus an understanding of the sequence of configurations (in this case, the sequence of development of longitudinal thalweg profiles) through which the system evolves is essential in order to explain system behavior (Lane and Richards, 1997).

The thalweg profile is influenced by the distribution of pools and riffles. The distribution of the gravel bar units that constitute riffles, and their associated pools, can be 'free' or 'forced' (Seminara and Tubino, 1989). Freely formed pools result from the fluival hydraulics of the stream and patterns of flow convergence and meander development. Several studies have shown that in alluvial self-formed channels, pools spacing is between five and seven times the channel width (Leopold et al.; 1964; Keller and Melhorn, 1978). Pools can also be 'forced' (Lisle, 1986; Montgomery and Buffington, 1997) by scour around obstructions such as large woody debris, boulders and bedrock outcrops. Forced pools may be spaced closer than pools in self-formed channels (Montgomery et al., 1995). The distribution of forcing elements (large woody debris, boulders and bedrock outcrops) in many catchments is random, and consequently no regular spacing between forced pools would be expected. It follows that different patterns of pool distribution (random or regular) may be used to determine the relative importance of different formative mechanisms.

The conceptual model proposed in this paper is that spatial structure in a longitudinal profile may be attributed to the type of material dominating channel structure (sediment, woody debris or bedrock), and time elapsed since the last major disturbance (due to floods or landslides, for example). Spatial structure in a thalweg profile is defined by several elements, including the presence of regular oscillations in bed topography (primarily due to pools and riffles), the strength of spatial autocorrelation between points in the channel bed, and the length of channel bed exhibiting autocorrelation (such as the length of a riffle crest). Immediately following disturbances, a river that can readily reorganize the dominant channel-forming materials in the channel bed may exhibit low variation in bed elevations and nor regular pattern in bed topography. This would be the case, for example, in rivers where the bed material size in much less than the bankfull depth, or the length of key elements of woody debris is less than the channel width. However, with increasing time since disturbance, variation in bed topography will increase and the arrangement of spatial structure in the bed profile will become more regular. In contrast, no regularly spaced structures in the bed will evolve in rivers that cannot readily reorganize the dominant bed materials. This would be the case, for example, in rivers where the bed particle size approaches bankfull depth, or the length of large woody debris is greater than the channel width, and forced pools dominate. A random pattern of bed topography would be expected in a stream with many forced pools, whereas a regular pattern would be expected if pools were freely formed by the hydraulics of converging flow in an alternate bar river.

3.2 Review of Existing Approaches Used to Quantify Bed Patterns

Several methods of quantifying longitudinal channel bed patterns, and especially the presence of pools, have been developed. A frequently used technique in the United States to determine the distribution of pools is "habitat typing" in which an observer walks the channel with a tape and measures the length of pools, riffles and other features

(U.S. Forest Service, 1992). There are several problems with habitat typing, including high operator variability, lack of replicability, and discharge dependency.

O'Neill and Abrahams (1984) suggested an objective method of identifying pools, but their approach determines only the numbers of pools and riffles and it is still based on a single threshold measure of the deepest part of the pool. Peterson et al. (1992) attempted to set target conditions for pool frequency, but they admitted that criteria used to define pools varied considerably among studies used in their analysis. Hogan and Church (1989) suggested that depth and velocity distributions across the entire channel area could be used to support more complete habitat assessments. In practice, these distributions are functions of river stage and they are, in any case, difficult to measure for high flows.

The problem with all these approaches is that they assume the pool is the only feature of interest in channel spatial structure, and that a pool can be objectively and consistently identified. In addition to pools, the degree of variation of channel bed elevations is an important component of channel boundary conditions, which cannot be derived simply from an analysis of maximum pool depths. In practice, two pools with equal maximum depths may have very different bed morphologies and may have been formed by different fluvial processes.

To monitor pool depths independently of discharge, Lisle (1987) adapted the concept of residual water depths that was first introduced by Bathurst (1981). The residual pool depth (d_r) is the depth of water in the pool below the elevation of the downstream riffle crest. This can be thought of as the water depth that would be present in the river if stream flow were zero and the riffle crest constituted a low head weir. The distribution of residual water depths along the entire longitudinal profile incorporates thalweg topography and provides more useful information than any analysis of pools alone. For example, Lisle (1995) found comparison of the standard deviation of residual water depths useful in identifying and assessing morphologic differences between two streams due to differences in their coarse woody debris loadings. However, to date, this approach has not been applied to larger rivers with different disturbance histories.

Spatial statistics provide an objective technique to detect the presence of channel bed features, such as pools or riffles. Richards (1976) used spatial series analysis to quantify oscillations in channel width and in the longitudinal bed profile. Robert and Richards (1988) showed the usefulness of semivariograms to model sand bedforms, and Robert (1988) used them to define micro-scale bed relief (5 mm spacing along a 6 m transect) in gravel-bed streams. Two fundamental problems exist in the use of the semivariogram to define bed topography, however. First, there is no simple way of determining confidence limits analytically (Robert and Richards, 1988), and second, they have limited utility in detecting areas of similar bed elevation, such as a riffle crest. Spectral analysis has been used to define patterns of bed elevation in sand bed channels, but it is difficult to place a physical interpretation on the results (Robert and Richards, 1988). Murray and Paola (1996) discuss the limitations of using spectral analysis and fractal methods to determine the downstream spatial structure of fluvial patterns. For example, similar power law spectral behavior can be produced by systems that are very different in character. Robison and Beschta (1989) used correlograms to define the spatial autocorrelation of low flow depths in several small streams with high woody debris loading. The results showed no significant pattern in the distribution of low flow depths for their study reaches, which were located in pristine, forested streams with many forced pools. Also, although spatial statistics have been used to characterize channel morphology at a given time, their use in monitoring temporal trends of morphological change following channel disturbance is much more limited.

On the basis of this review of past research, it may be concluded that changes in longitudinal profiles over decadal scales have not been addressed in systematically. To address this gap in knowledge, this paper evaluates several approaches to quantifying changes in thalweg morphology following disturbances due to large sediment inputs. The paper examines the potential for using distributions of residual water depths as a tool for monitoring the bed morphology of disturbed channels. It employs spatial autocorrelation analysis of the morphological data to depict temporal changes in the spatial structure of bed topography. Within the temporal framework, spatial statistics are used to characterize whether the longitudinal pattern of bed elevations is random or regular, and to estimate the maximum morphological variance or similarity in different parts of the channel.

3.3 Field Area

The Redwood Creek catchment is located in the northern Coast Ranges of California, USA (Figure 3.1) and is underlain by rocks of the Franciscan Assemblage,

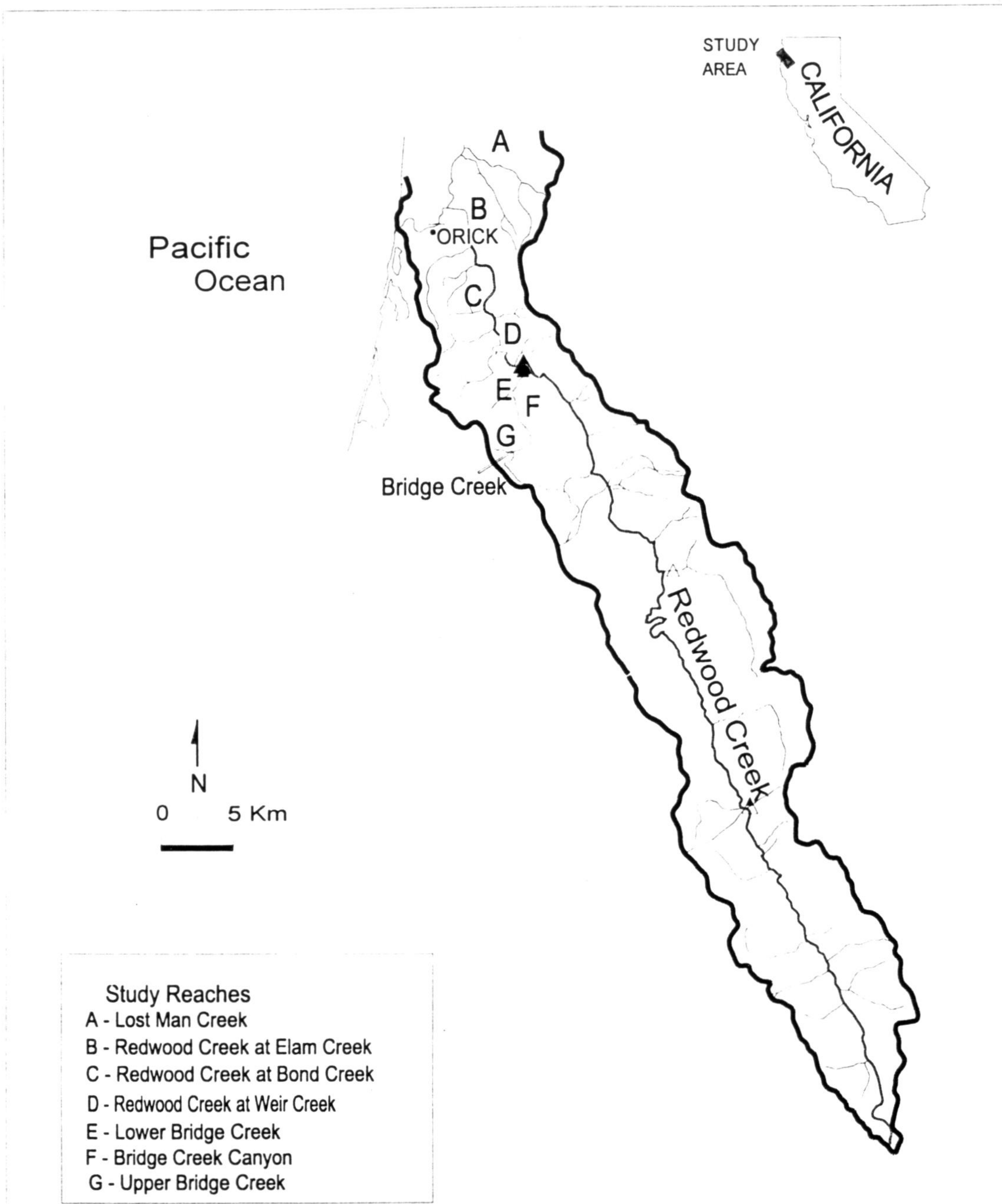


Figure 3.1: Location map of the Redwood Creek catchment showing the three study reaches on the mainstem of Redwood Creek, three in Bridge Creek and one in Lost Man Creek.

mostly sandstones, mudstones and schist. The 720 km^2 basin receives an average of 2000 mm of precipitation annually, most of which falls as rain between October and March. Total basin relief is 1615 m, average hillslope gradient is 26%. Redwood Creek is a gravel-bed river with a length of 100 km and channel gradients ranging from 12 per cent in the headwaters to 0.01 per cent in the lower reaches. Channel gradient is less than 2 per cent in the lowest 80 km of Redwood Creek and the bed morphology is characterized by pools and riffles.

Most tributaries are steep (> 4%), but the four largest tributaries have low-gradient reaches with well developed pool-riffle morphology like that in the main stream. Two tributaries, Bridge Creek and Lost Man Creek, are included in this study. There is no pristine, low-gradient 'control' reach with which to compare the disturbed reaches. However, Lost Man Creek has experienced no land-use disturbances since it underwent timber harvesting and road construction in the 1950's and 1960's. Hence, this stream was used for comparison with the study reaches.

Prior to 1945, 85 per cent of the Redwood Creek basin was forested with redwood (*Sequoia sempervirens*) and Douglas fir (*Pseudotsuga menziesii*) stands (Best, 1995). These trees can reach 100 m in height and 3 m in diameter, and the large woody debris contributed by fallen trees affects channel morphology in many streams. During the last four decades, large floods and extensive logging in the Redwood Creek basin has resulted in widespread channel aggradation and bank erosion (Madej and Ozaki, 1996). A 50-year flood in 1964 caused extensive streamside landsliding, but no channel surveys are available to quantify changes during that period.

Following a 25-year flood in 1975, the channel beds of Redwood Creek and Bridge Creek were almost flat and featureless in many reaches. Between1977 and 1997 longitudinal thalweg profiles of several reaches of Redwood Creek and its tributary Bridge Creek were resurveyed on several occasions to monitor the changes in pool distribution and depths as the morphology responded to the 1975 depositional event. The depth and frequency of pools in Redwood Creek increased between 1977 and 1995 (Madej, 1996; Madej and Ozaki, 1996), and pools are presently spaced at about three channel widths apart in most of the study reaches. Channel cross-sectional changes were also monitored, and these have shown systematic spatial patterns of bank erosion, aggradation and subsequent degradation (Madej and Ozaki, 1996). Between1977 and 1996, no flow exceeded a five-year recurrence interval. However, in 1997, a 12-year flood initiated many new debris flows that contributed large volumes of sediment to the rivers, which triggered renewed aggradation in several reaches.

Seven study reaches, representing a range of channel morphologies and types, were established on Redwood Creek (three), Bridge Creek (three), and Lost Man Creek (one) (Figure 3.1). Reach characteristics are listed in Table 3.1. Redwood Creek has low planform sinuosity (p = 1.03 to 1.10) displaying alternate bars. Typical bar lengths are 350 to 500 m. Mean particle size is small compared to depth, and the few pieces of in-channel large woody debris are much shorter than the channel width. Upstream reaches of Redwood Creek aggraded following the 1975 flood, but have subsequently degraded (Madej, 1996). The study reach 'Redwood Creek at Weir Creek' is within this degrading segment of river. Farther downstream, Redwood Creek at Bond Creek

Table 3.1: Study Reach Characteristics

	Redwood at Weir Creek	Redwood at Bond Creek	Redwood at Elam Creek	Upper Bridge Creek	Bridge Creek Canyon	Lower Bridge Creek	Lost Man Creek
Drainage Area (km^2)	523	585	605	25	27	30	20
Bankfull Width (m)	60	70	110	23	12	15	20
Bankfull Depth (m)	2.2	2.0	1.9	1.0	1.3	1.2	1.2
Channel Gradient (%)	0.24	0.18	0.15	1.24	1.66	1.12	0.71
Transect Length (m)	2500	2100	2530	550	670	400	810
D_{50} (mm)	22	18	15	30	60	32	45
Influence of large woody debris	Low	Low	Low	Moderate	High	Moderate	Moderate

and Redwood Creek at Elam Creek are two reaches that aggraded by an average of 0.6 m between 1975 and 1986, and subsequently degraded by about 0.3 m between 1986 and 1995 (Madej and Ozaki, 1996). The channel bed in these three study reaches aggraded slightly (0.1 m) after the 1997 flood (Ozaki and Jones, 1998).

Bridge Creek is a gravel-bed stream that presently exhibits an alternate bar planform, with typical bar lengths of 150 to 200 m. In 1954 and 1971 large woody debris was removed from the channel of Bridge Creek to salvage merchantable timber (Klein et al., 1987). Since 1971, the input of new large woody debris has been limited and, due to the extensive harvesting of streamside trees, the present debris loading is lower than it would be under pristine conditions. Although longitudinal profile surveys did not commence until 1986, field observations and examination of available aerial photographs indicate that Upper Bridge Creek received high sediment inputs in 1975. Cross-sectional monitoring began in 1974 showed that prior to 1986 a great deal of sediment was transported out of the upper reach, but that only 0.2 m of further degradation occurred between 1986 and 1995. In 1997 a debris flow delivered 13,000 m^3 of sediment and a great deal of large woody debris to the channel upstream of the upper surveyed reach and the channel aggraded locally as a result (Madej and Gibbs, 1998).

A narrow canyon, in which large woody debris, boulders and bedrock outcrops are common, separates the upper and lower reaches of Bridge Creek. In Lower Bridge Creek the channel degraded two meters between 1975 and 1986, but the rate of downcutting had decreased to 0.1 m/yr by 1996 (Madej and Gibbs, 1998). In 1986 woody debris loading was low in Lower Bridge Creek, but landslides generated by the 1997 flood contributed many new pieces of woody debris to this reach.

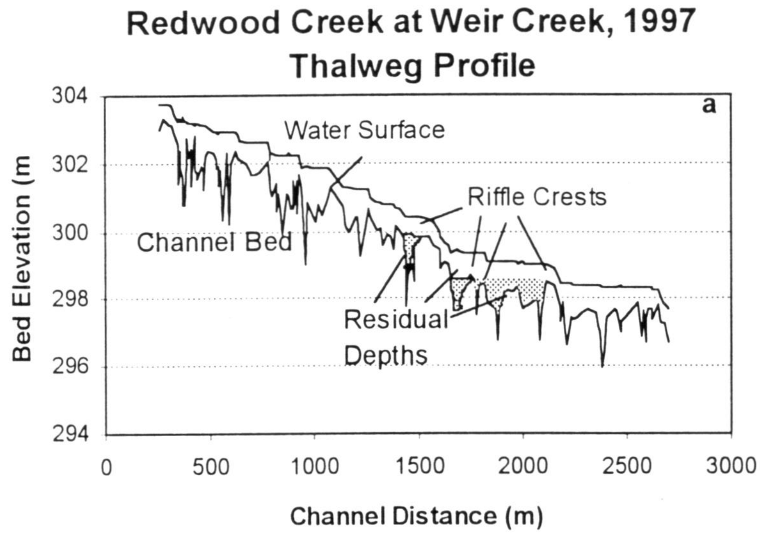
3.4 Field Methods

Three to five resurveys of the study reaches were performed between 1977 and 1997 to document t the development of bed morphology, and especially pools and riffles, following the 1975 flood. In the summer of 1977, the U. S. Geological Survey surveyed a longitudinal thalweg profile of the lowest 22 km of Redwood Creek The author resurveyed selected reaches of this area in 1983, 1986, 1995 and 1997. Surveys of Bridge Creek, reported by Klein et al. (1987), were conducted in 1986, and by the author in 1995 and 1997. Surveyed long-profiles began and ended at riffle crests and survey distances were measured along the centerline of the high-flow channel. Elevations of the thalweg and water surface were established using either an automatic level and stadia rod, or electronic distance meter and target. Survey readings were taken at all breaks in slope of the channel bed in order to characterize all major morphologic features (i.e., top, middle and base of riffles and pools) along the thalweg. The spacing of survey points averaged 15 m in Redwood Creek and 4 m in Bridge Creek. In Redwood Creek, surveyors used staff plates at three gaging stations and twenty permanent bench marks established for channel cross-sectional monitoring as a control on survey accuracy. The total error in elevation between the surveys was less than 0.2 percent (0.8 m). The length of each surveyed profile was 20 to 55 channel widths (400 to 2500 m, depending on the stream reach (Table 3.1)

Channel planform and bar lengths were mapped from two sets of aerial photographs (scale 1:6000) dating from 1978 and 1997. Unfortunately, bar lengths from the two dates could not be compared quantitatively because the discharge at the time of the 1997 photography was six times higher than that in the 1978 photographs. However, bar shape and location in the channel were compared qualitatively. Bar lengths measured on the 1978 photographs (taken during summer low flow) were used to calculate mean bar lengths in Redwood Creek.

3.5 Analytical Techniques

The distribution of residual water depths for each longitudinal survey was calculated using the method of Lisle (1989). First, bed elevations between survey points were linearly interpolated to obtain a common base from which to compare profiles for different years. A 5 m spacing was used for Redwood Creek, where channel widths vary from 60 to 110 m in Redwood Creek, in order to define all but the finest features of the longitudinal bed topography. A 3 m spacing was employed for Bridge and Lost Man Creeks, where widths vary from 12 to 23 m. A computer program was written to plot the profiles, convert the surveys into standardized data sets, calculate the distribution, mean and standard deviation of residual water depths, and compute the percentage of channel length occupied by riffles. For this purpose, riffle points were defined as points where the residual depth was zero. Figure 3.2a shows an example of a surveyed thalweg profile and Figure 3.2b illustrated the profile data transformed into residual water depths. Variability in bed elevations was evaluated using the standard deviations of residual



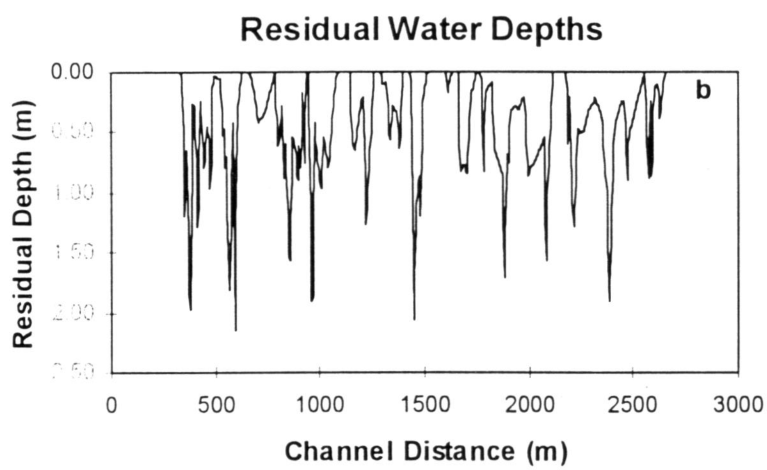


Figure 3.2: Examples of a longitudinal thalweg profile plot (a) showing how residual water depths are calculated, and (b) the corresponding residual water depth plot for Redwood Creek at Weir Creek.

water depth for each study reach. The significance of differences in the means, medians and distributions of residual water depth distributions from successive surveys was examined using the Student's *t*, Mann-Whitney and Kolmogorov-Smirnov tests, respectively.

The spatial distribution of pools and riffles is also of geomorphological interest, but the residual depth distributions do not contain information on the spatial ordering of pools within the fluvial system. To analyze spatial patterns in the distributions of pools and bed elevations, residual water depths were analyzed by the use of the Moran's I spatial autocorrelation coefficient (Legendre and Fortin, 1989). The formula for I at distance class d is:

$$I(d) = \frac{n\sum\sum w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{W\sum(x_i - \bar{x})^2}$$

where x = residual water depth at points *i* and *j* in the channel, and $\bar{x}$ = mean residual depth. All summations are for *i* and *j* varying from 1 to *n*, the number of data points, but excluded the cases where $i=j$. The w_{ij}'s take the value of 1 when the pair *(i,j)* pertains to the distance class d, and 0 otherwise. *W* is the number of pairs of points used in computing the coefficients for the given distance class. Moran's I may be positive or negative, with values usually ranging between -1 and +1. Moran's I compares values for pairs of points (residual water depths) at different distance classes (lag distance). The distance classes used ranged from 5 m (3 m in Bridge and Lost Man Creeks) to one-third of the long-profile length, or about 800 m in Redwood Creek.

Surveys from 1977 were not used in this analysis because the spacing of survey points was larger than in the other surveys, which would limit the ability of the correlograms to detect small bedforms.

The spatial structure of the channel bed profiles was examined using correlograms. Correlograms are plots of autocorrelation values (in this case, Moran's I) in the ordinate against distances between pairs of thalweg survey points (lag distances). The characteristics of the correlogram shape, such as the spacing between peaks and troughs and the width of a peak, are associated with particular spatial structures (Legendre and Fortin, 1989). Positive correlation (points plotted above the 95% confidence interval line on the correlogram) show distances at which residual water depths are similar to each other (for example, pools and pools, or riffles and riffles), whereas negative correlation (points plotted below the 95% confidence interval line on the correlogram) show distances at which residual water depths are significantly different from each other (for example, pools and riffles). It is common for the first few points in a correlogram to be positively correlated up to a short lag distance. This distance represents the length of channel in which neighboring points have similar residual water depths, such as the length of a riffle crest.

Correlograms were used in two ways. First, correlograms from different years were compared to identify temporal trends, through detecting the presence and scale of significant spatial autocorrelation of bed elevations. Second, correlograms were used to test whether the pattern of bed elevations was random or non-random. To test for spatial patterns, each set of residual water depths was randomized, and then a new correlogram was calculated. A chi-squared test was then used to compare the expected number of significant (positive or negative) and non-significant coefficients in the observed-values correlogram against the random correlogram.

3.6 Results and Discussion

3.6.1 Distribution of Residual Water Depths

Figures 3.3 to 3.5 present box plots of residual water depths in the study reaches on Redwood Creek, Bridge Creek, and Lost Man Creek, respectively. In Redwood Creek, the mean residual water depths were very low in 1977, due to the impacts of the 1975 flood. The mean, median, and maximum residual water depths then increased up until 1995, before decreasing, in response to the flood of 1997, to approximately their 1983 levels. Although the mean residual depths were not significantly different for some of the comparisons (for example, Redwood Creek at Bond Creek in 1983 and 1997; t-test with $\alpha = 0.05$), the distributions for all reaches are significantly different from one another (Kolmogorov-Smirnov test, 95% confidence levels). This finding demonstrated that consideration of the entire distribution of residual water depths can give a more complete picture of trends in the channel bed status than consideration of the means and maxima alone.

By the time of the initial profile survey in Bridge Creek, in 1986, Upper Bridge Creek had already recovered from the impacts of the 1975 flood, and only remnants of flood deposits remained stored in the channel. Channel cross sections show about

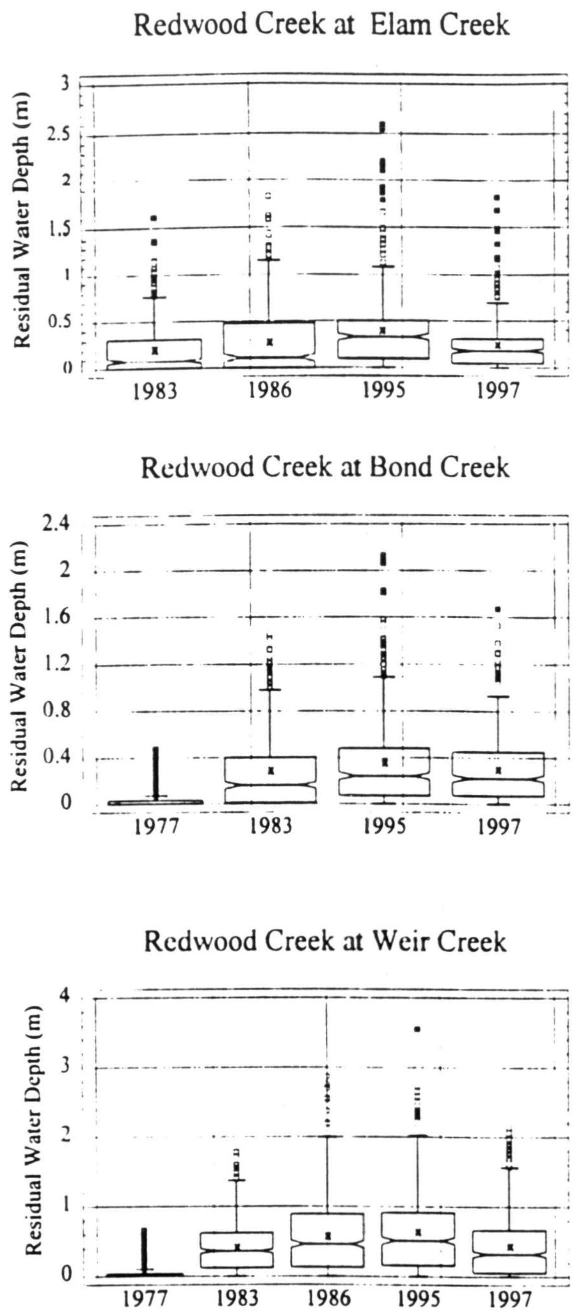


Figure 3.3: Box plots of residual water depths for Redwood Creek study reaches for the period 1977 to 1997. The upper and lower lines of the box are the 75 and 25 percentiles of the residual water depth distribution, the notches and centreline show the median values, and the "+" sign is the mean of the distribution. The lowermost horizontal line (whisker) is drawn from the lower quartile to the smallest point within 1.5 interquartile ranges from the lower quartile. The top whisker is drawn from the upper quartile to the largest point within 1.5 interquartile ranges from the upper quartile. Values that fall beyond the whiskers, but within three interquartile ranges are plotted as individual points (outliers).

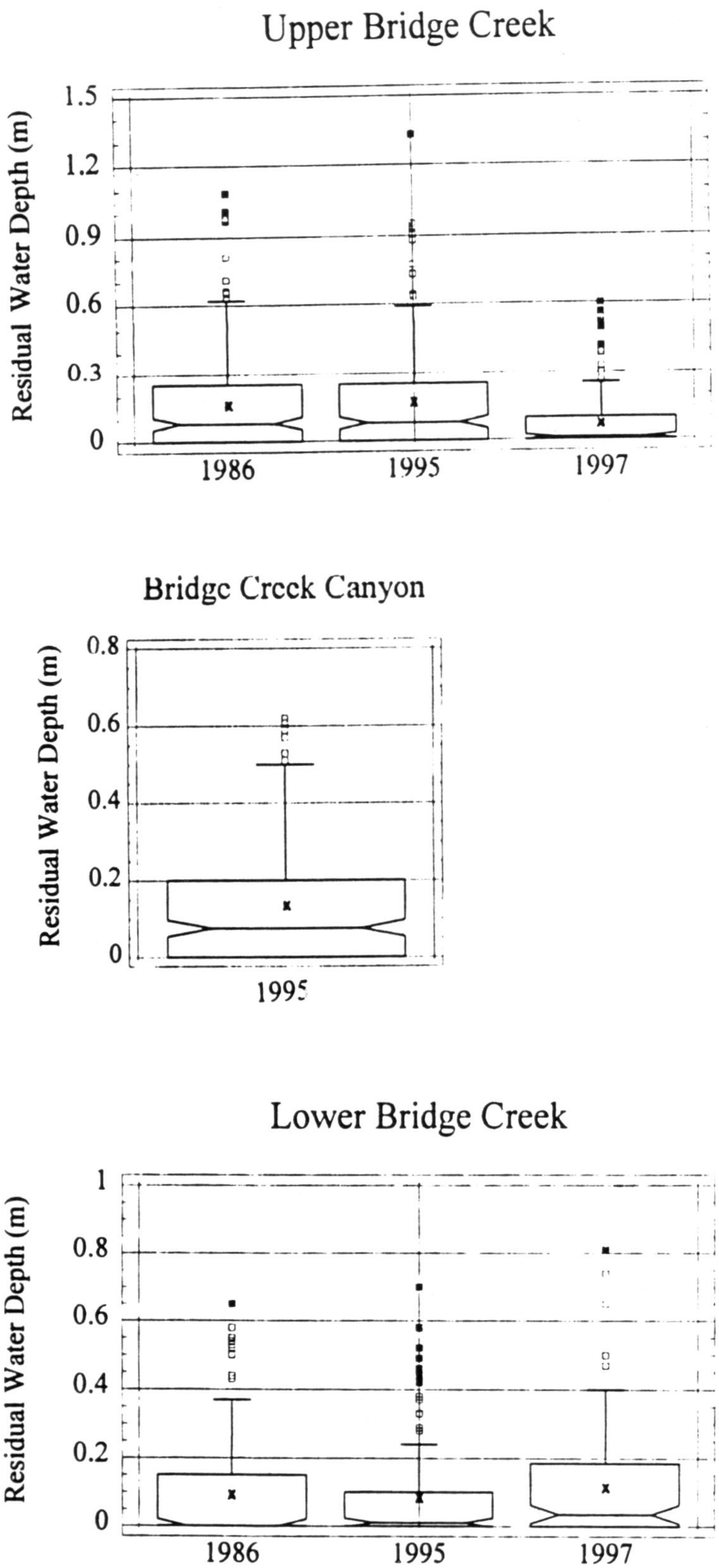


Figure 3.4: Box plots of residual water depths for Upper Bridge Creek, Bridge Creek Canyon and Lower Bridge Creek study reaches.

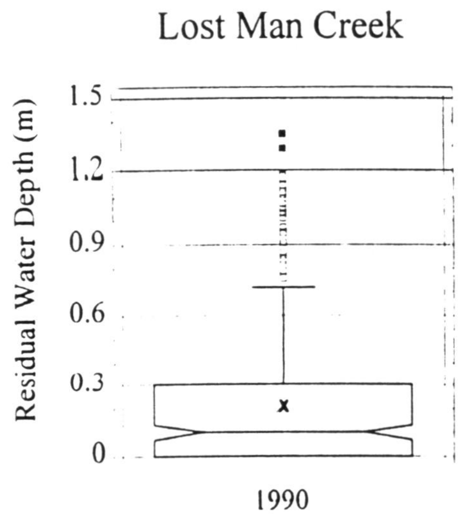


Figure 3.5: Box plot of residual water depths for Lost Man Creek study reach.

0.2 m of downcutting from 1986 to 1995, and show that a few pools had increased in depth. Following the flood-associated debris flows of 1997, mean residual depth decreased in Upper Bridge Creek and was significantly lower than in previous years (Figure 3.4). The Bridge Creek Canyon reach displays a similar distribution of residual water depths to Upper Bridge Creek, although the mean residual depth is smaller. In Lower Bridge Creek, cross-section monitoring shows that the channel incised into the flood deposits by 2 m between 1975 to 1986, but little further bed degradation occurred after 1986. Mean residual water depths were not significantly different during this period, although maximum depths increased through time.

Figure 3.5 shows the distribution of residual water depths in Lost Man Creek, a stream unaffected by timber harvesting activities since the 1960s. The shape of the distribution is the same as in the other streams. However, it should be noted that the mean residual water depth is greater than those of any of the Bridge Creek study reaches, even though Lost Man Creek drains a smaller catchment.

Figure 3.6 is a plot of mean residual depth of the study reaches during the period 1977 to 1997. Mean depths increased between 1977 to 1986, although the rate of increase slowed after 1986. Mean residual depths in all study reaches decreased to values typical of the early 1980s following the 1997 flood, which had a recurrence interval of 12 years.

Figure 3.7 shows a graph of the percentage of channel length classified as riffle (residual depth = 0) in the study reaches as a function of time. Trends in percentage riffle are the inverse of those in residual depths. Hence, the percentage of channel length occupied by riffles decreased in the years following the 1975 flood, rapidly up until the mid-1980s, and then more slowly. The percentage of channel occupied by riffles increased to about mid-1980s levels following the 1997 flood.

The variance of bed elevations was evaluated by using the standard deviation of the population of residual water depths (Figure 3.8). The underlying assumption is that increased variance in bed elevations reflects increased morphologic diversity in the channel bed. In Redwood Creek, standard deviations increased rapidly for 10 years following the 1975 flood, but between the mid-1980s and 1995 standard deviations increased only slightly. This flattening of the curve may indicate that bed variability was approaching the upper limit of morphological diversity that can develop in this river under the present flow and sediment regimes. Standard deviations decreased in all

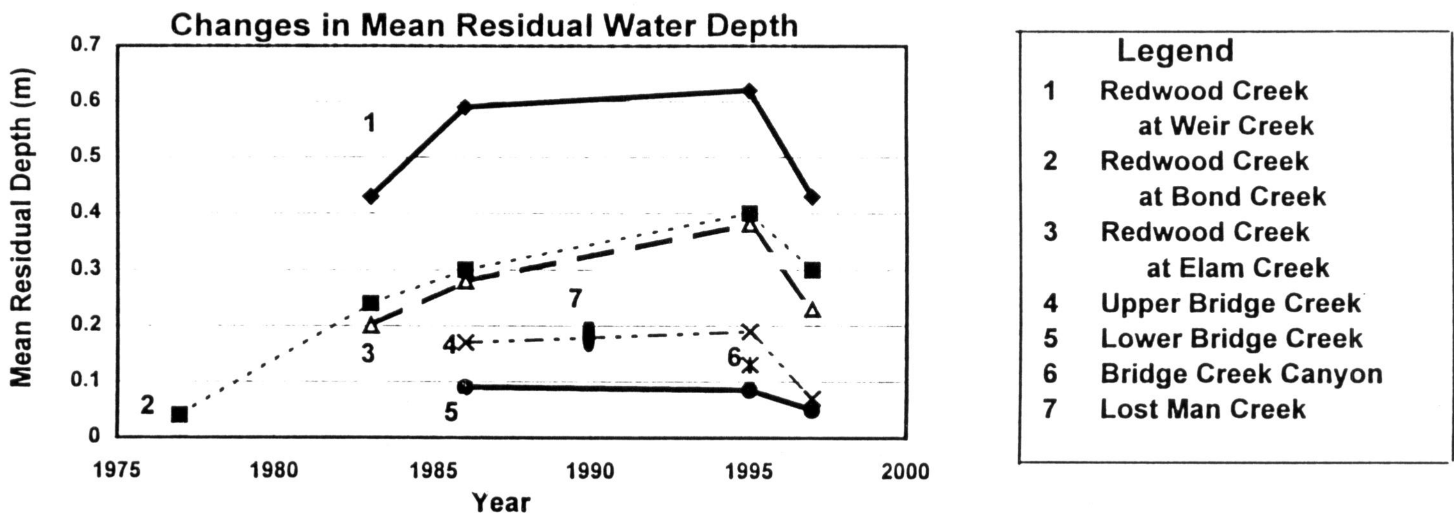


Figure 3.6: Mean residual water depth for each surveyed transect.

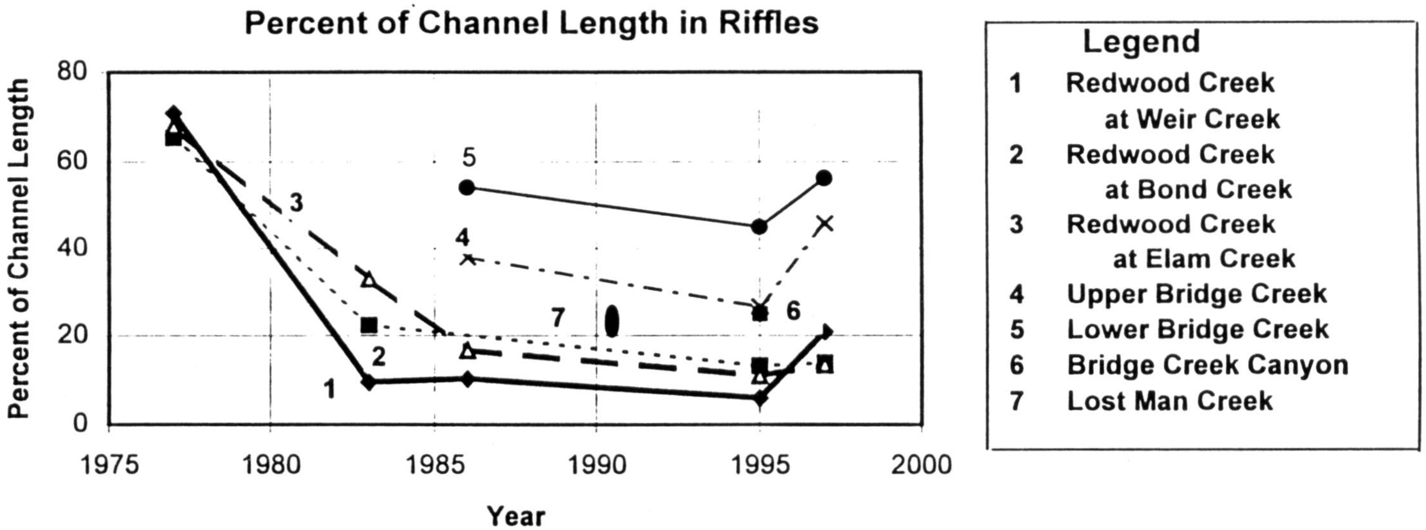


Figure 3.7: Percent of channel length classified as 'riffle,' in thalweg profile surveys. Riffles are defined as points where the residual water depth equals zero.

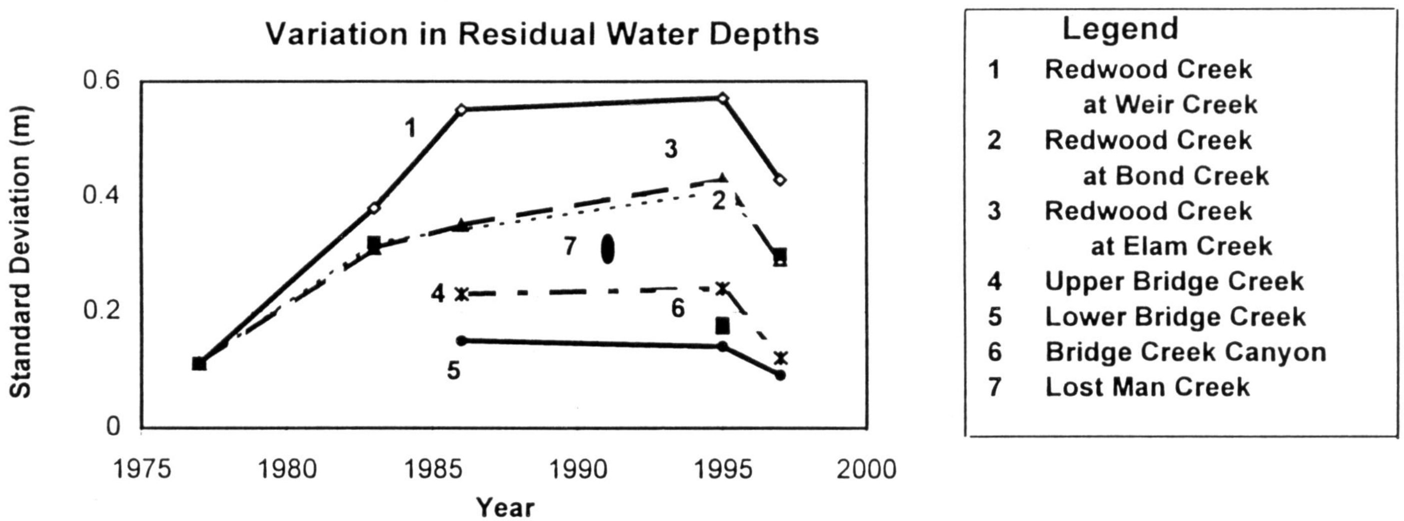


Figure 3.8: Variation in residual water depths in the thalweg profile surveys. The standard deviation of the population of residual water depths is plotted against time for the individual reaches.

reaches after the 1997 flood, although they remained higher than the levels observed in 1977 level (immediately following the larger, 1975 flood).

In addition to these within-reach comparisons, it would be useful to compare measurements made in all three creeks. However, to facilitate this the results must be standardized to remove scale effects. The statistic usually employed to allow scale-independent comparisons is the coefficient of variation [(standard deviation/ mean)]. However, plots of this statistic did not show any obvious pattern except that the magnitude of the standard deviation is frequently the same as the mean residual depth. Both mean residual depth and standard deviation change through time, but not necessarily at the same rate. As an alternative method to removing scale effects, bankfull depth was used to normalize residual depths. Although bed topography was changing through time, the reach-averaged bankfull depth could be considered to be constant during the study period. Figure 3.9 shows a plot of the resulting variation index [(standard deviation of residual water depth/bankfull depth) * 100] as a function of time. The stream reaches with the smallest quantities of flood deposits remaining from the 1975 event (Upper Bridge Creek, Redwood Creek near Weir Creek, and Lost Man Creek) all plot above a value of 20, although the values for all the study reaches decreased following the 1997 flood. The general trend that emerges is that values of the variation index are higher at sites with better habitat conditions.

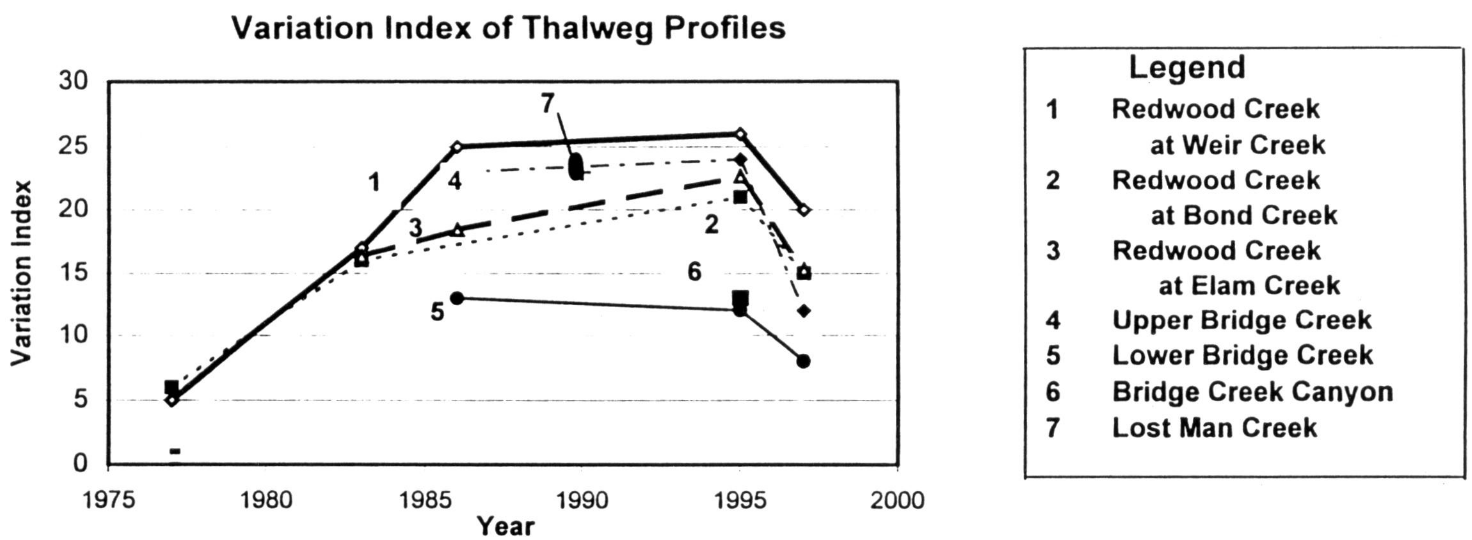


Figure 3.9: Variation index for study reaches plotted against time. The variation index is defined [(standard deviation of residual water depths/bankfull depth) * 100].

3.6.2 Spatial Autocorrelation in Thalweg Profiles

Figures 3.10 to 3.15 display correlograms for the repeat surveys of the study reaches. Most of the correlograms show significant positive correlation at short lag distances. This fine scale of correlation indicates the similarity of neighboring points, in other words, the length of channel bed with similar residual water depths (such as the length of a riffle). The length of this fine-scale correlation decreases through time in most study reaches. For example, in Redwood Creek at Weir Creek, this correlation distance decreases from 66 m in 1983 to 31 m in 1997 (Figure 3.10). Decreasing correlation distances may reflect reductions in the extent of riffles identified in the residual depth plot (Figure 3.7).

Significant positive or negative correlations in the correlograms at larger lag distances indicate the spacing of larger bed features. In 1983 the Redwood Creek at Weir Creek reach displayed positive correlation at 250 m , which is about four times the channel width (Figure 3.10a). This corresponds to the average bar length measured in the 1978 aerial photographs. In 1986, residual water depths were greater and two positive correlations occurred, at 200 m and 600-720 m (Figure 3.10b). Qualitative analysis of the aerial photographs revealed no obvious change in the planform of the river during this period, and it may be concluded that the second peak in the correlograms is probably an artifact due to the repetition of a 200-m long structure. The positive correlation at 200 m remained present through to 1997 (Figure 3.10c and d).

Farther downstream, in the aggrading reach, the pattern of bedform development is differs significantly. In 1983 in the Redwood Creek at Bond Creek study reach, there

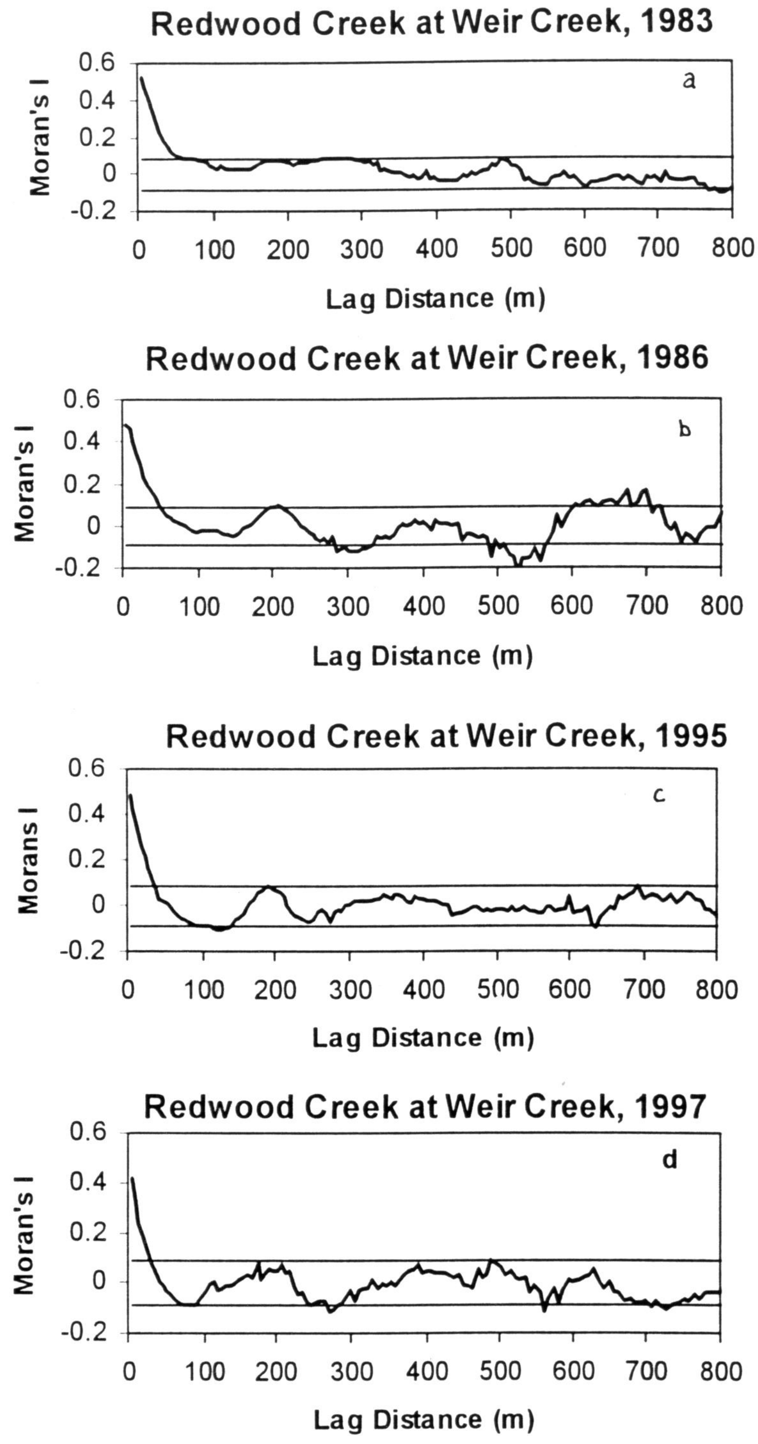


Figure 3.10: Correlogram based on Moran's I spatial autocorrelation coefficient for Redwood Creek at Weir Creek.

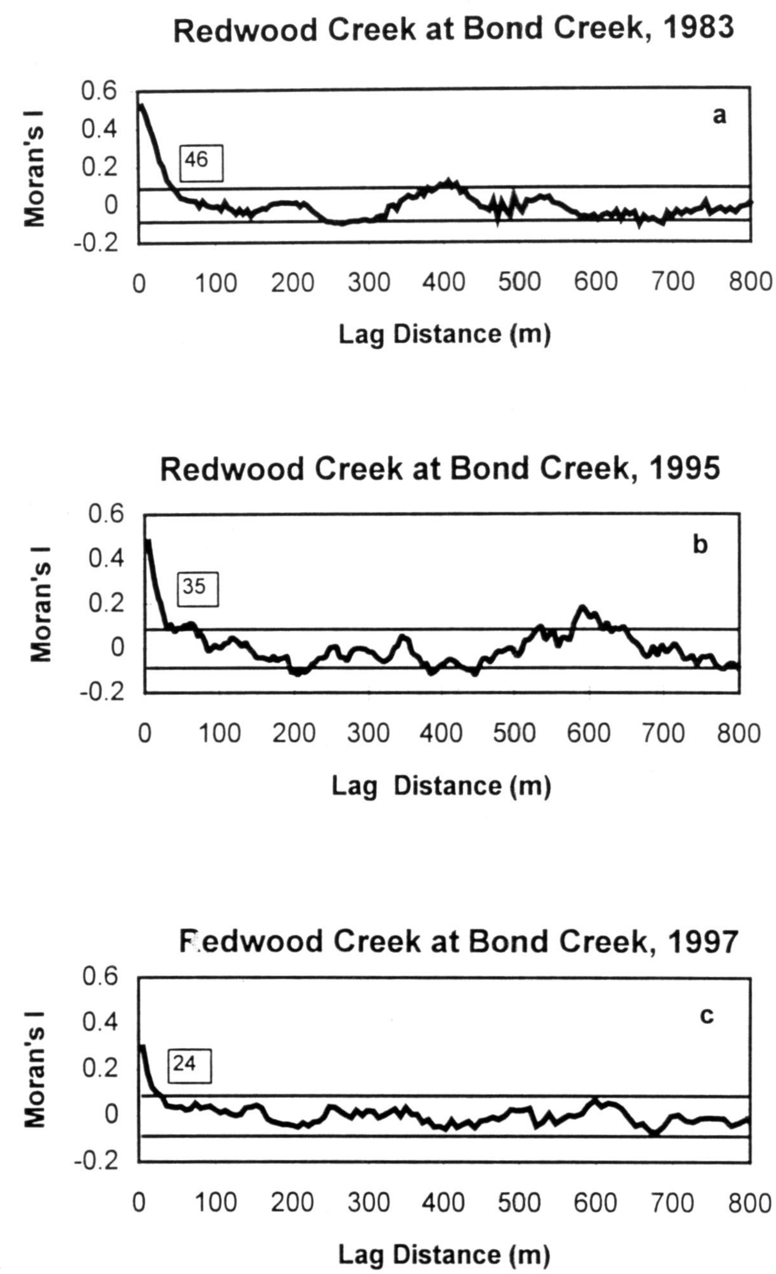


Figure 3.11: Correlogram based on Moran's I spatial autocorrelation coefficient for Redwood Creek at Bond Creek.

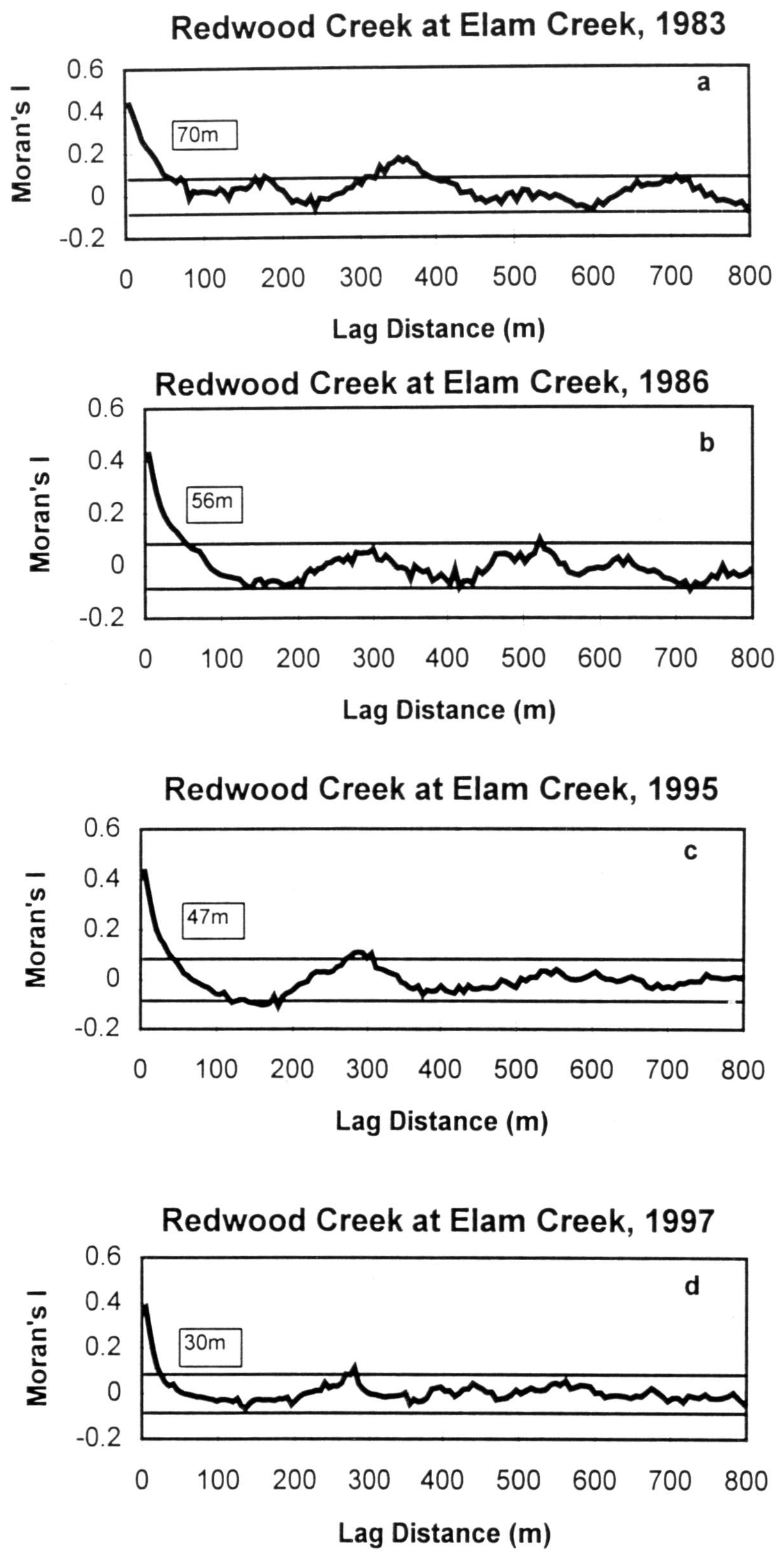


Figure 3:12: Correlogram based on Moran's I spatial autocorrelation coefficient for Redwood Creek at Elam Creek.

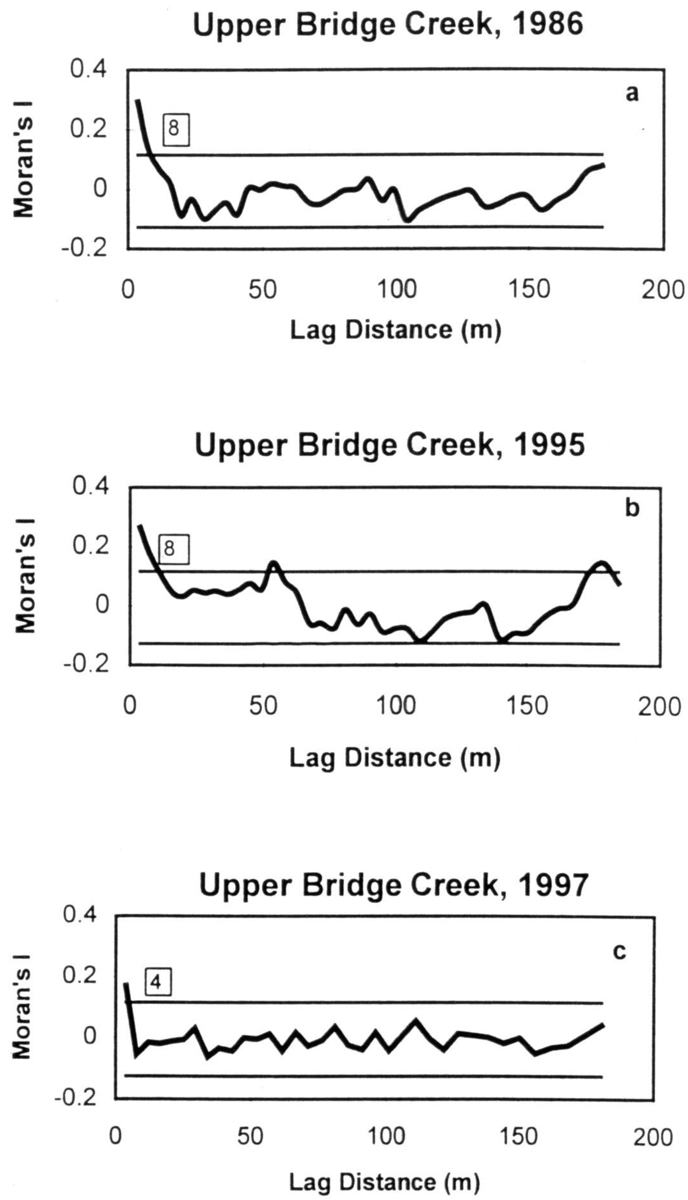


Figure 3:13: Correlogram based on Moran's I spatial autocorrelation coefficient for Upper Bridge Creek.

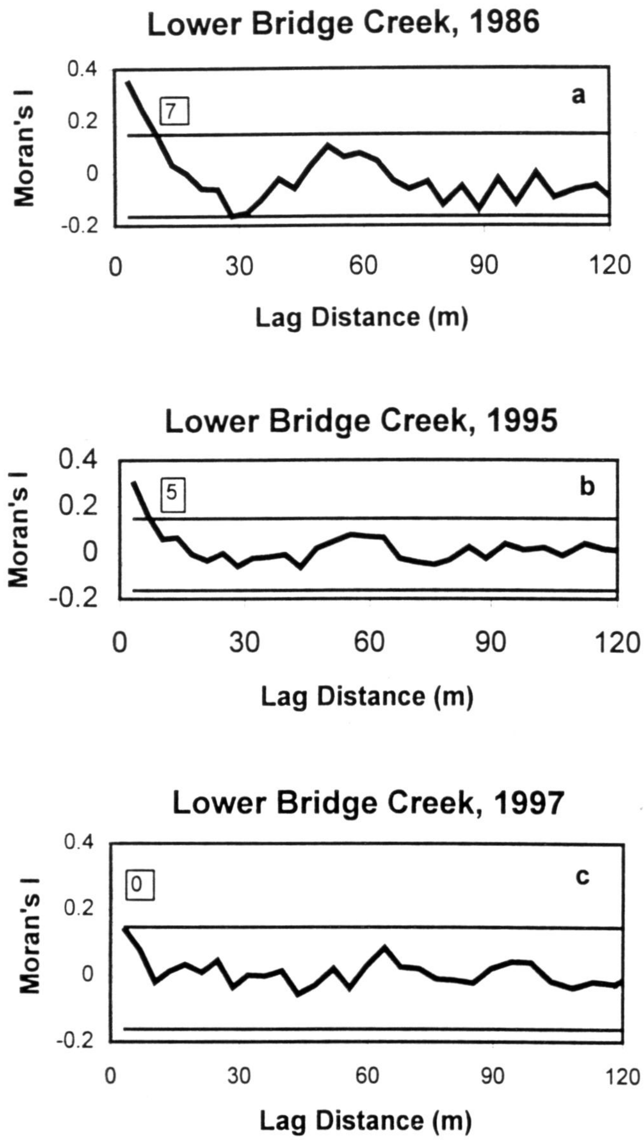


Figure 3.14: Correlogram based on Moran's I spatial autocorrelation coefficient for Lower Bridge Creek.

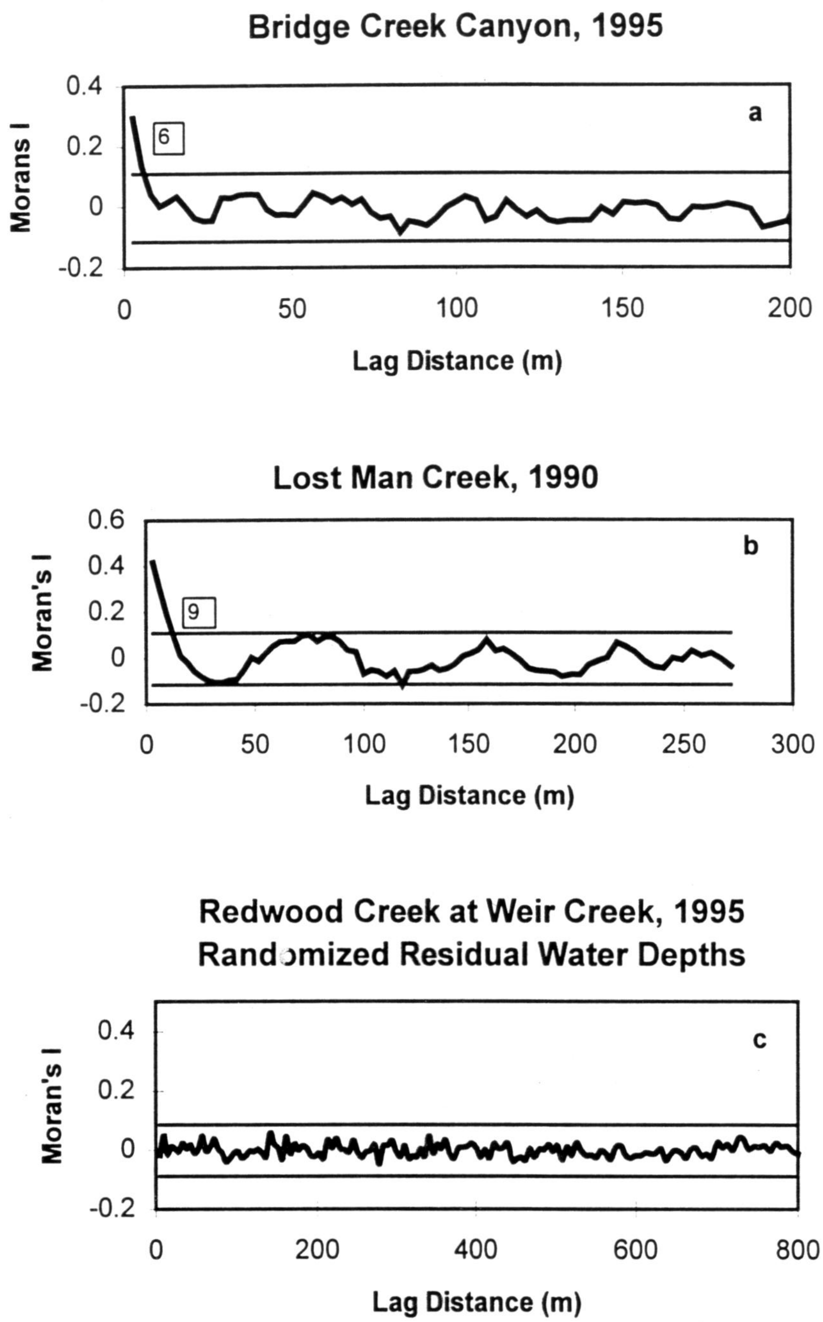


Figure 3.15. Correlogram based on Moran's I spatial autocorrelation coefficient for the Bridge Creek Canyon reach (a), Lost Man Creek (b), and a randomized set of residual water depths based on data from Redwood Creek at Weir Creek, 1995 (c).

was positive correlation was at 400 m, which is about five times the channel width (Figure 3.11a). This approximates to the average length of alternate bars in this reach measured on the 1978 aerial photographs. By 1995, the lag distance of the positive correlation increased to 600 m, or about eight times the channel width (Figure 3.11b), but following the 1997 flood, the distribution of residual water depths was more random. Aerial photographs taken in 1997 show that the planform still featured alternate bars, but expression of these bar units in the 1997 thalweg profile is weak (Figure 3.11c).

In 1983 the downstream-most reach, Redwood Creek at Elam Creek, exhibited a positive correlation at 180 and at 350 m, corresponding to 1.6 to three times the channel width, respectively (Figure 3.12a). The peak at 180 m had disappeared by 1986 (Figure 3.12b), but a significant correlation at 280 to 350 m was evident in all of the surveyed profiles. Examination of available aerial photographs indicates that the average bar length in this reach is 400 to 500 m. The finer scale of spatial autocorrelation in the thalweg profile actually corresponds to the pool spacing in this reach.

In Upper Bridge Creek the degree of organization of the channel bed (defined as detectable, regularly spaced features in the channel) increased between 1986, when no significant positive correlations were detected (Figure 3.13a) and 1995, when significant positive correlations appeared at 55 m and 180 m (Figure 3.13b). The correlation at 55 m corresponds to the most common spacing between riffle crests, and the correlation at 180 m corresponds to the length of alternate bar units in Upper Bridge Creek (150 to 200 m). The lack of regularly spaced alternate bars in this reach in 1986 is not surprising because, historically, the high loading of large woody debris would have generated numerous, random irregularities in the bed topography. More recently, inputs of woody debris have consisted of shorter, smaller pieces and the forced features produced by this type of debris have not persisted. This is the case because moderate flows have been competent to entrain the wood, either reorganizing it into regularly spaced features or transporting it downstream. By 1995 the abundance of large woody debris compared to natural conditions was reduced to the point that forced pools and bars were no longer prevalent, so a more regular structure emerged. However, the introduction of a great deal of sediment and large woody following the flood and debris flow of 1997 resulted in the distribution of residual water depths returning to a more random pattern in 1997 (Figure 3.13c). This residual depth distribution shows no significant correlations at lag distances greater than 4 m.

No strong bed features with lag distances greater than a few meters appeared in any of the correlograms for Lower Bridge Creek (Figure 3.14), which is consistent with the fact that its planform has never exhibited well developed bars. Following the 1997 flood, and its associated inputs of sediment and woody debris, even the fine-scale autocorrelation between neighboring points that was present in 1986 and 1995 had disappeared and the thalweg profile was completely random (Figure 3.14c).

Three further correlograms were formulated to characterize the patterns of autocorrelation associated with particular bed morphologies and to support statistical testing, using a chi-squared test, of the significance of autocorrelation patterns observed at the study reaches (Figure 3.15). The correlogram for the canyon reach of Bridge Creek (Figure 3.15a) has no significant correlations beyond a lag distance of 6 m. This indicates a lack of regular features in the bed that is consistent with the actual configuration of the bed, which exhibits a few small, irregularly spaced bars and forced pools scoured around boulders, bedrock outcrops and large woody debris.

At Lost Man Creek, neighboring points are significantly correlated up to a lag distance of 9 m, and a regular structure is apparent in the correlogram at a spacing of about 80 m or six times the channel width (figure 3.15b). These autocorrelations are representative of morphological features in the channel, which has only small pieces of woody debris and in which free riffle bars are well developed. It should be noted that under pristine, unlogged conditions large woody debris would probably be more abundant in this creek and this would influence channel morphology through generating more forced features and a more random pattern of bed topography.

Figure 3.15c shows the correlogram for a randomized set of residual water depths, based on the observed actual values plotted in Figure 3.10c. This is one example of the randomized sets were created in this study for each surveyed profile. A chi-squared test, with a significance level $\alpha = 0.05$, was used to establish whether the actual and randomized residual depth distributions were significantly different. The results confirmed that spatial organization in several profiles was not significantly different from a random pattern. This was the case at Redwood Creek at Weir Creek in 1983; Redwood Creek at Bond Creek in 1997, and all the Bridge Creek profiles.

Numerical modeling suggests there should be substantial elongation of alternate bar wavelength during the evolution from initial instability to fully developed stable bars (Nelson, 1990). The correlograms generated in this study demonstrate that the large flood and sedimentation event of 1975 initiated morphological instability in Redwood Creek and suggest that a regular bed topography was reestablished during the subsequent decade. They do not, however, provide clear evidence that the wavelength of alternate bars elongated during the recovery period. The trends towards development of regularly spaced bar features was interrupted by a further flood in 1997. In fact, following this event, the degree of organization in the bed topography was reduced and positive correlations were only found at shorter lag distances. In most study reaches positive autocorrelations were found at a spacing of about three channel widths apart, which corresponds to the average pool spacing, whereas alternate bar lengths were four to six times the channel width. It appears that, in this fluvial system, pools occur more frequently than the spacing of alternate bars would suggest. This is probably due to the presence of 'forcing' elements such as large woody debris.

Chapter Four

Development of Channel Structure, Organization and Roughness in Forested Mountain Streams Following Sediment Pulses

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In preparation for journal submission

4.1 Introduction

Watershed disturbances, such as mining, wildfires, landslides, and volcanic eruptions, can greatly increase the sediment load supplied to streams within short time periods. Associated mechanisms of increased sediment supply (sediment pulses) in a channel network, such as mass movements, surface erosion or release of stored sediments, are stochastic processes that can generate regions of high bedload transport and bed material storage in channels (Benda and Dunne, 1997a). In this paper, I define a sediment pulse to be an episodic input of sediment that is several times greater than the average annual sediment input to a channel. Depending on the characteristics of the channel and the input, the sediment pulse may or may not result in a distinct sedimentation zone or sediment wave in the channel. Many studies have addressed the magnitude and movement of sediment waves in natural channels (Gilbert, 1917; Pickup et al., 1983; Nicholas et al., 1995; Benda and Dunne, 1997b; Lisle et al., 1998), although these studies have not quantified the evolution of bed topography following the generation of a sediment wave.

In a general sense, the fluvial system has been considered as consisting of zones of sediment production, transfer, and deposition (Schumm, 1977). The formation of sediment pulses has also been documented by sediment budgets, which quantify changes in the mass of sediment input, storage and transport on a watershed scale (Swanson et al, 1982; Reid and Dunne, 1996). This mass balance approach is useful to define the timing, location, and magnitude of the sediment input to a channel, but a sediment budget does not address specifically how the channel rearranges and distributes the sediment input during subsequent sediment transport and storage phases. Other approaches to understanding sediment dynamics have been to study sediment transport processes on a finer scale (for example, initiation of movement, bed mobility, or sorting of bed particles). Still other studies have sought to generalize sediment transport and storage properties in different parts of the channel network (Montgomery and Buffington, 1997), but these classifications do not address the evolution of channel characteristics, specifically bed forms and channel patterns, through time.

This paper will explore changes in channel structure, organization, and roughness accompanying high supplies of coarse sediment to forested, mountain streams, based on the initial boundary conditions, the channel type and gradient, and the number and magnitude of flows capable of mobilizing bed material (called "organizing flows"). Under certain conditions channels display self-organizing behavior. Self-organization, as defined by Hallet (1990), results in "...periodic structures that form spontaneously on the substrate as water or air transports, erodes and deposits sediments. These spatial structures, often characterised by striking two-dimensional periodicity, include ripples and dunes, meanders and bar/pool topography of rivers, and rhythmic shoreline features." An example of such self-organizing behavior is the evolution of regularly spaced alternate bars of similar length following a perturbation of the channel bed (Nelson, 1990).

Organization of the channel bed does not only encompass alternate bars and pools, however. Bedforms in gravel-bed rivers can cover a range of scales from boulder clusters (microform) to unit bars (macroform) to sedimentation zones (megaforms)

(Church and Jones, 1982. Although the evolution of bedforms as a type of channel organization has been well studied over a range of hydraulic conditions in sand-bedded rivers (Jain and Kennedy, 1974), the development of regular bedforms with characteristic length scales in gravel-bed rivers following large sediment inputs is not well known. An understanding of bedform development at several scales is important because bedforms provide resistance to flow, and consequently influence flow properties. In addition, the development of gravel bars as bedforms provides major storage areas for coarse sediments as channels process their imposed sediment load, and sorting and organization of the sediment input into bedforms may contribute to the stability of an alluvial bed (Church et al., 1998)

A study of changes in channel structure and organization accompanying high supplies of coarse sediment to forested mountain streams must consider three aspects of channel morphology: the elements composing the channel, how those elements interact to form channel structures, and how those channel structures are organized. *Structural elements* in a channel (fine or coarse sediment, small or large wood, bedrock outcrops, bank material, etc.) provide the initial boundary conditions, and can be considered the building blocks of the channel and its bedforms. Common metrics of structural elements are particle size and distribution; bed and bank heterogeneity and composition; and presence and size of large wood. The combination of structural elements and the interaction of the elements with flow in the channel give rise to *channel structure*. In this paper, I consider channel structure as being analogous to the architecture of an individual building, in which structural elements are arranged to form higher-order features or patterns. Metrics used to describe structure range over several scales and include bed imbrication and sorting; and the size and type of channel units, such as pools, bars, steps, and riffles. At a higher order still, *channel organization* develops. By extension of the architectural analogy, channel organization is comparable to the arrangement of individual buildings in a community, and refers to the spatial arrangement or pattern of channel units or other bed features. This spatial distribution can be random, regular or clustered; the metrics used in quantifying channel organization in the channel are the spacing, frequency, variability, and regularity of features, and are measured by pattern analyses and various spatial autocorrelation techniques.

The premise of this paper is that in forested mountain environments, channels will organize sediment inputs to different degrees and different length scales based on the considerations shown in Figure 4.1. Only the cases in bold letters will be discussed in this paper. D_{50} is the median particle size.

Important factors influencing channel response to a sediment input are quantity and timing of the input (the definition of sediment pulse requires that a large sediment input enter the channel rapidly); the caliber of the input; whether or not in-channel wood influences subsequent sediment transport and storage; and the magnitude and frequency of flows capable of transporting and reorganizing the sediment input (organizing flows).

An organizing flow (defined as a discharge greater than the critical discharge required for bedload transport, $Q > Q_{cr}$) is considered a necessary condition for channel organization because bed particles must be mobilized in order to be rearranged and associated bedforms altered. For example, if a rockfall or earthflow delivers a large

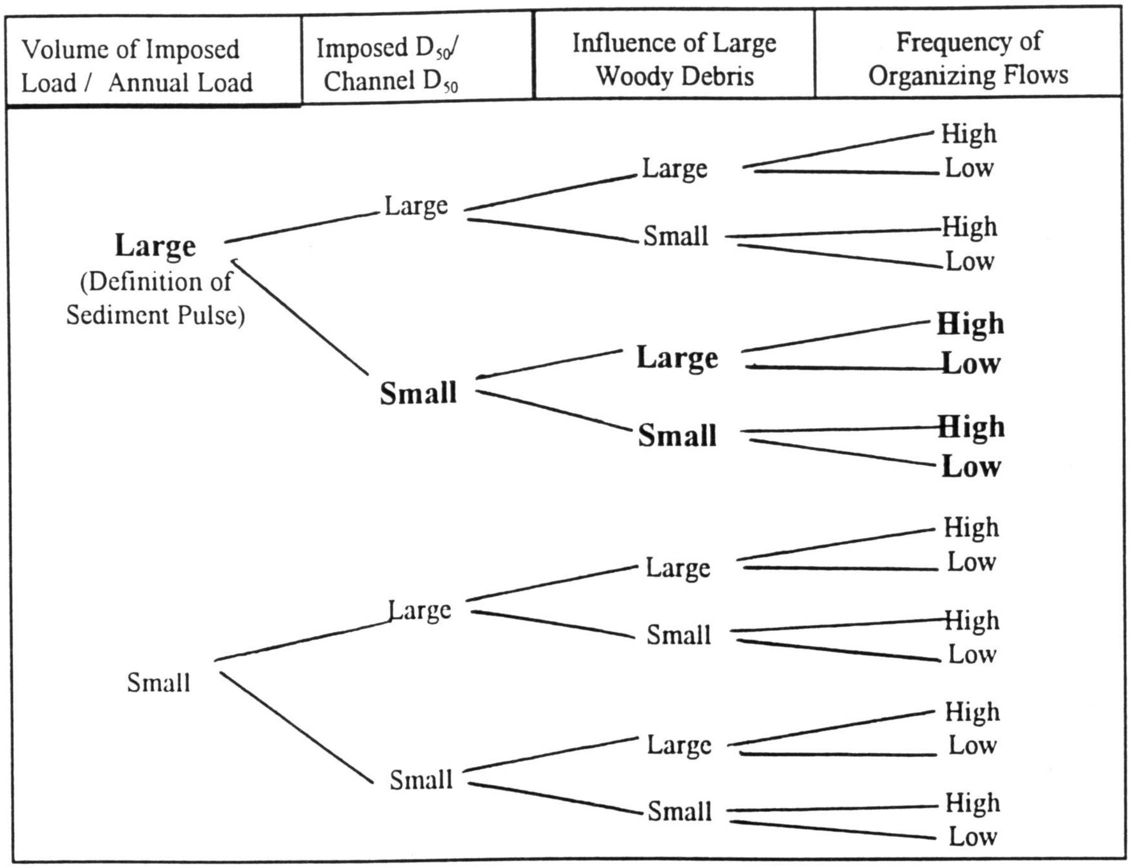


Figure 4.1: Factors influencing channel response to imposed sediment loads

volume of boulders to a cobble bed stream, the coarse particles will be deposited in the channel, but flows may not be competent to reorganize the boulders. In contrast, a large volume of more easily mobilized sediment entering a channel will be reorganized to various degrees, depending on the presence of in-channel wood and the frequency of organizing flows. Consequently, as a channel processes a sediment pulse, the signal of the pulse may be manifested through a change in structure, organization and roughness in the channel, although not necessarily by movement of a discrete wave. An additional premise is that the development of channel organization, through the formation of bedforms, should lead to higher channel roughness values due to form drag.

This paper will present a conceptual model of the development of channel organization following a sediment pulse. An analysis of channel structure, organization, and roughness in several channel types following different types of sediment pulses will be presented. Several case studies involving sediment pulses of various scales from rivers in the Pacific Northwest will be used to evaluate the conceptual model, as levels of bed organization in disturbed channels are documented by spatial autocorrelation analysis of bedform patterns.

4.2 Conceptual Model

Figure 4.2 presents a conceptual model of the development of bed organization following a sediment pulse. The x-axis represents different channel types typically found in a drainage basin, ranging from steep, headwater channels to low gradient, high order rivers. The arrows represent trajectories of change leading from a poorly organized state immediately following a sediment pulse to a more strongly organized channel. Channel bed organization is defined by variability in bed topography and regularity of bedform spacing. The degree to which a channel is organized is dependent upon the number of organizing events since disturbance (the y-axis).

Trajectories of channel change tending towards higher levels of organization are shown by the upward arrows. Initially following a sediment pulse, channels commonly are poorly organized, with low variability of channel bed elevations and irregular spacing of bedforms. Watershed perturbations that result in sediment pulses (floods, landslides, human modification of channels) can change the frequency, amplitude, and type of

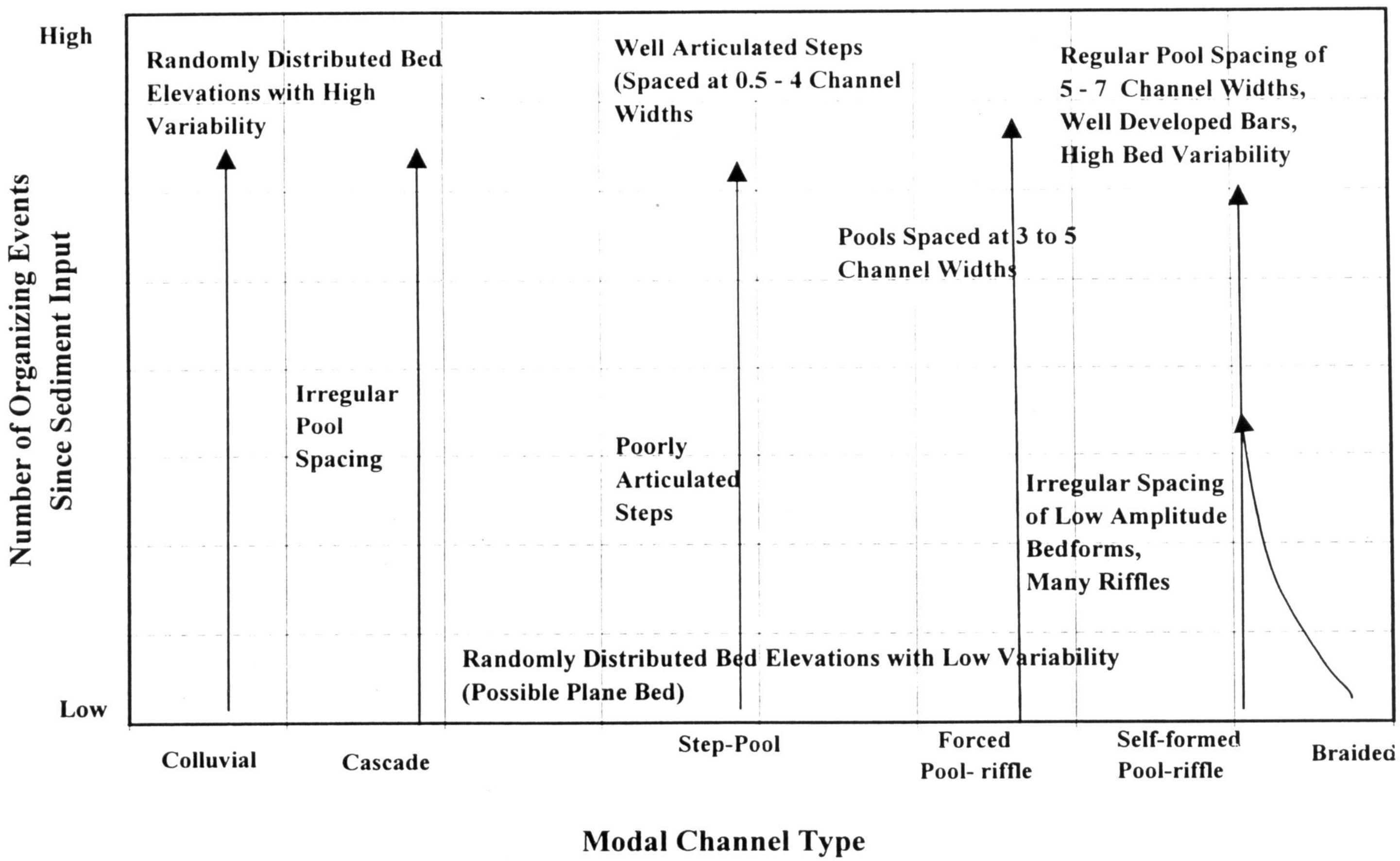


Figure 4.2 Development of channel bed organization following disturbances. Schematic shows expected trajectories of channel morphologic change following a pulse of coarse sediment in different types of streams.

channel bedforms. High sediment input can result in channel aggradation, filling of pools, burial of existing structure, or alteration of existing bedforms. Initially such perturbations will force the streams to have a more random structure with low heterogeneity in the channel bed. The variance of bed elevations will be low, and regularly spaced bedform patterns will either be subdued or eliminated.

The modal channel type influences the pattern of channel response and level of channel organization. Within a drainage basin, channels will tend to display certain morphologic forms (modal channel types) based on channel gradient and dominant grain size (Montgomery and Buffington, 1997). These channel types are not constant through time (Benda and Dunne, 1997b), because channel morphology changes in response to sediment input. Nevertheless, modal channel types represent the most probable state of a channel over a long time period (Benda et al., 1998). The modal channel type also influences the relative time required for channel organization (y-axis), because the frequency of bed mobilization varies across modal types. Within the constraints of channel gradient and particle size, the channel displays different levels of organization. For example, channels that experienced recent floods or landslides would be expected to exhibit a different channel structure and organization than channels with similar gradients and drainage areas that have not been disturbed for decades. Hogan et al. (1998) found this to be the case in British Columbia.

In colluvial channels recently subjected to debris flows, bed variability is initially low, or absent if scoured to bedrock, but the bed develops more complexity through time as additional wood and sediment enter the channel. In steep, low-order streams, the trajectory of changes leads to increased variability of the channel bed, with a few pools, but with no regular spacing or frequency of bedforms. Flows great enough to mobilize the wood and dominant sediment size (organizing events) in such channels are rare.

In step-pool streams, fine sediment following a pulse may initially bury the previous structure but can be transported through these channels quickly. In this case, channel structure and organization will be reestablished through exhumation of wood, boulders, and other structural elements. However, if the underlying step-forming clasts and wood are disturbed, as will be examined in this investigation, the development of steps with regular spacing, height and length characteristics will be slow, because the frequency of organizing flows is low. Initially, steps will be poorly articulated, that is, pools will not be well developed, steps will be weakly imbricated, and the steps will not display a regular spatial pattern for a given channel gradient. Through time, bed material is scoured from the pools and pools become deeper, and step-forming clasts become reorganized into more regularly spaced, stable, strongly imbricated steps with distinctive height and length characteristics (well articulated steps). Examples of well developed step structure are given in Whittaker and Jaeggi (1982), Grant et al. (1990), Abrahams et al. (1995) and Chin (1999).

In lower gradient, higher order streams, the modal type is a pool-riffle channel. Bar and pool topography generated by local flow convergence and divergence may be either freely formed by cross-stream flow and sediment transport, or forced by channel bends and obstructions (Lisle, 1986; Montgomery and Buffington, 1997). A sediment pulse in such channels can result in a more planar bed as pools fill, roughness elements are buried, and the channel aggrades. Subsequently the channel evolves from a random, low variability channel bed to one with forced bedforms caused by scour and deposition around obstructions, and finally to a well organized, highly heterogenous channel bed with regularly spaced bedforms. Depending on the abundance of forcing elements, a channel may not evolve to the end member of a channel formed only through alternating convergent and divergent flow patterns (a self-formed channel). In a pool-riffle channel, if the magnitude of the sediment pulse is great enough, a braided planform may emerge, which has no characteristic length scale (Sapozhnikov and Foufoula-Georgious, 1999). As the channel processes the sediment pulse, it will eventually revert to a single thread, pool-riffle system. The development of organization at any stage can be interrupted by the input of additional sediment or wood.

The concept of organizing flows depends on the initiation and transport of bed material in the channel, in order to rearrange and redistribute such material. The force required to initiate movement is usually stated in terms of a critical shear stress, τ_c, modelled by the Shields (1936) equation:

$$\tau_c = \tau^*_c (\rho - \rho_w)\, g\, D \qquad \text{Eqn. 4.1}$$

where ρ and ρ_w are the density of sediment and water, respectively, g is gravitational acceleration, and D is grain diameter. For streams less than one percent in slope, τ^*_c is generally between 0.030 and 0.073 (Buffington and Montgomery, 1997). At slopes greater than one percent, and relative submergence $d/D_{50} \leq 10$ (where d = water depth), the Shields approach is inadequate, and the Schoklitsch equation, based on a critical unit discharge q_c, provides more accurate predictions of sediment movement (Bathurst, 1987):

$$q_c = 0.15\ g^{0.5}\ D^{1.5}\ S^{-1.12} \qquad \text{Eqn. 4.2}$$

where S = slope.

Many other factors besides slope and bed particle size influence how easily bed material is transported, however, such as the degree of armoring, imbrication, sediment fabric, bed packing, grain protrusion, boulder clusters and bed relief. The purpose of this paper is not to define precisely the initiation of bedload transport in the channel network, as the data are not sufficient for this task. Rather, the purpose is to examine the role of organizing flows in a general sense, based on the conceptual model presented above.

The frequency of organizing flows varies in different parts of the channel network due to different dominant bed particle sizes and channel gradients. The frequency of flows large enough to rearrange the beds of colluvial or cascade channels is low, and in fact organization may depend more on mass movement processes than fluvial processes in these cases. In step-pool systems, channels may only be reorganized every 20 to 50 years, whereas the channel bed in a pool-riffle system can be mobilized several times a year. Consequently, the absolute times required for development along the separate trajectories depicted in Figure 4.2 are different for channels with diverse gradients and dominant particle sizes. In addition, the magnitude of an organizing flow should not be considered a constant through time at a given channel location. As the channel processes a sediment pulse, the channel bed commonly becomes coarser; thus the magnitude of an organizing flow increases through time, and the frequency of such flows decreases.

4.3 Previous Studies of Channel Organization

Many recent studies have addressed the phenomenon of spatial self-organization in physical systems (Hallet, 1990). Certain types of stream channels, such as those displaying pool-riffle or meander morphology, have long been recognized to have a regular structure. The spatial scale of this structure has usually been studied at a channel unit or reach scale. Such regular structure is a result of the interplay of two stochastic processes--the turbulent flow of water and the transport of many sizes of inorganic particles and large wood. Nelson (1990) considered alternate bar formation to be a natural self-patterning phenomenon, and showed that bar wavelengths increased following perturbations of a flat channel bed until eventually the bedforms stabilized. Both horizontal and vertical self-organization have been identified in braided rivers, which evolve towards a critical state (Sapozhnikov and Foufoula-Georgiou, 1999). The present study will only consider vertical and downstream self-organization in river profiles (development of bedforms), and not horizontal organization (meander development) because many steep mountain streams have limited channel migration zones and meander development. In addition, the degree of vertical organization can be compared across many channel types.

Quantifications of bedform spacing have covered a range of conditions. Regular spacing of pools and riffles, commonly at five to seven channel widths, has been documented by many researchers (Richards, 1976; Keller and Melhorn, 1978; Milne, 1982). Pools are not necessarily regularly spaced in streams with a high number of forced pools, such as those with high wood loading. Montgomery et al. (1995) documented higher pool frequency with increased large woody debris loading. Autocorrelation analyses in Alaskan streams with high wood loading showed no significant regularity in stream depth (Robison and Beschta, 1989), but Furbish et al. (1998) suggested that dominant wavelengths of alternate and mid-channel bars in steep, rough channels can be discerned. In Chapter 3, I used spatial autocorrelation coefficients to quantify the gradual development of regularity in a pool-riffle channel following the input of high sediment loads.

In rivers too steep to display a pool-riffle morphology, different types of channel organization have been described. Even in a gravel-bed stream without well defined bars, a coarse channel bed can develop stone cells (Church et al, 1998), stone lines (Laronne and Carson, 1976), boulder clusters (Brayshaw, 1984), or transverse ribs (Koster, 1978). On a microscale, Robert (1991) used spatial autocorrelation to document bed roughness due to skin friction in coarse-grained channels. Furbish et al. (1998) found both forced-bar topography and growth of freely formed bars in steep, rough channels. Kaufmann (1987) showed weak regularity in thalweg depths in streams subject to debris torrents.

In step-pool channels, morphologic characteristics and spacing of steps have been quantified by several researchers (Grant et al., 1990; Abrahams et al.,1995; Wohl et al., 1997; Chin, 1999). Grant et al. (1990) described the pattern and origin of step-pool topography, and found channel units were associated with distinct bed slopes and sequences. Billi et al. (1998) studied various levels of bed organization in step-pool, pool-riffle, and mixed reaches in steep mountain streams following a large flood, and attempted to define the recurrence interval of significant organizational events.

Montgomery and Buffington (1997) proposed a classification of channel reach morphology in mountain drainage basins that recognizes the important role of relative roughness and channel gradient in determining reach type (colluvial, cascade, step-pool, plane bed, pool-riffle, and dune ripple). They found characteristic slope, grain size, shear stress, and roughness ranges for different reach types. They further suggested that the response potential of different reach types to disturbances could be predicted, depending on such factors as channel confinement and geometry, in-channel wood, and riparian vegetation. They broadly define bedform patterns in various types of channel reaches to be either "multi-layered, laterally oscillatory, vertically oscillatory, featureless, random, irregular or variable." A rigorous analysis of bedform variability in different channel types is lacking, however, as is the concept of changes in channel structure, organization and roughness values through time.

Changes in channel morphology following large sediment inputs have been demonstrated in several regions. Lisle (1982) showed a decrease in pool depths following a large flood and associated channel aggradation. Madej and Ozaki (1996) quantified the decreases in both pool depth and frequency associated with a sediment pulse. A debris flow in a third-order mountain stream resulted in a reach with short, disordered channel units and decreased channel complexity (Lamberti et al., 1991).

Beschta (1984) documented changes in channel morphology due to increased sediment loads in both New Zealand and Oregon. Following a dam break flood, Pitlick (1993) documented aggradation that completely filled the channel downstream until subsequent flows eroded most of the sediment. Although these studies have documented changes in sediment flux and pool characteristics, they have not specifically addressed how bedforms reorganize in response to a sediment pulse.

Bedforms of all sizes provide resistance to flow, and hence, figure fundamentally in general considerations of flow properties. Increasing development of bedforms should lead to higher roughness values. Previous studies have addressed the relationship between bedforms and channel roughness. The form drag caused by dunes has been studied by Smith and McLean (1977). However, for more complex bedforms lacking pronounced regularity or even a characteristic length scale, such as those along some types of gravel-bed rivers, the connection between form drag and quantitative measures of boundary roughness is just starting to be explored (Robert, 1988).

4.4 Field Area

The conceptual model in Figure 4.2 will be evaluated using case studies of channels adjusting to sediment pulses, and most of these channels are located within the Redwood Creek basin. The Redwood Creek basin is located in the northern Coast Ranges of California, USA (Figure 4.3) and is underlain by rocks of the Franciscan Assemblage, mostly sandstones, mudstones and schist. The 720 km^2 basin receives an average of 2000 mm of precipitation annually, most of which falls as rain between

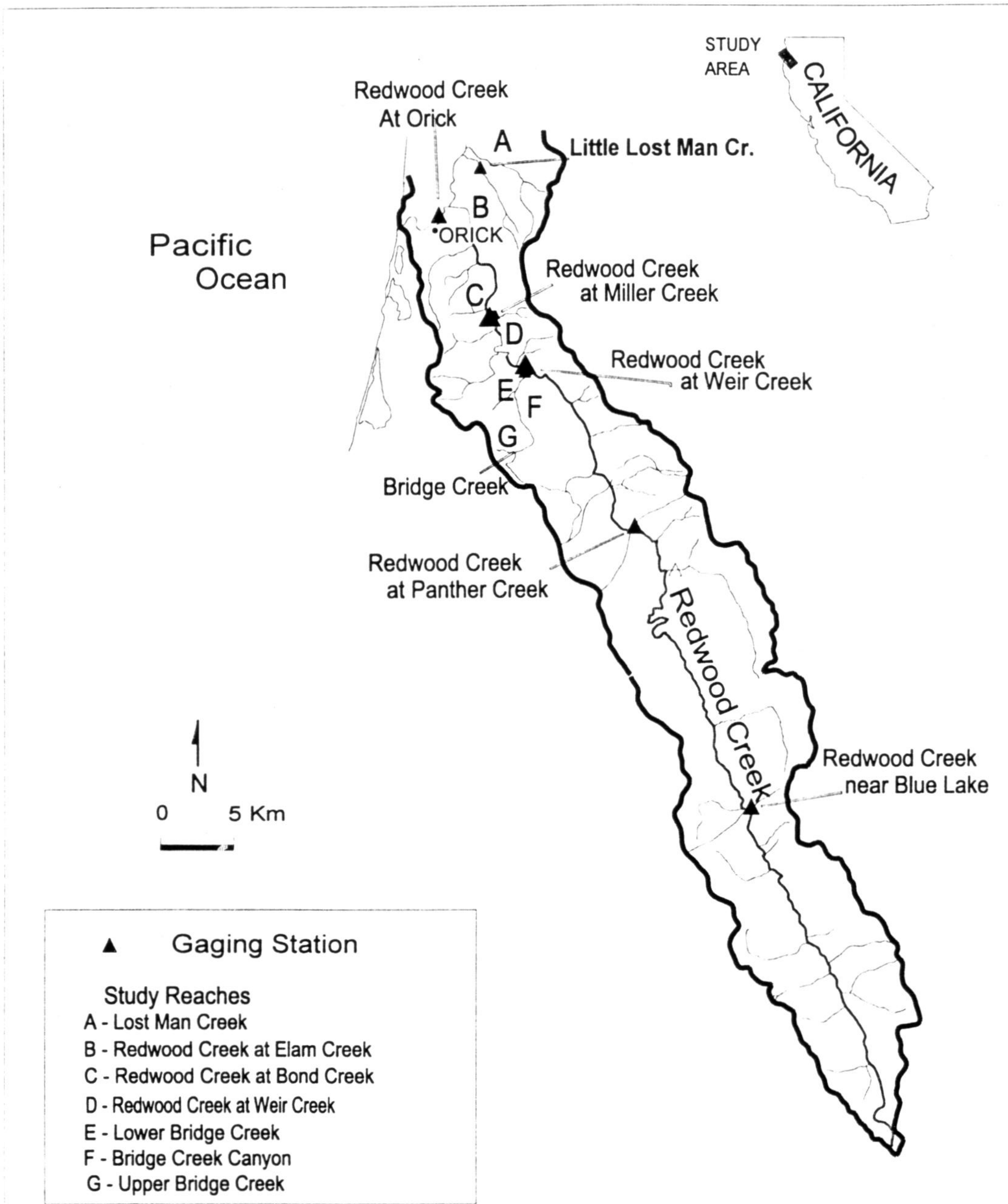


Figure 4.3 Location map of the Redwood Creek catchment showing the study reaches and gaging stations used in this study.

October and March. Total basin relief is 1615 m, average hillslope gradient is 26%. Redwood Creek is a gravel-bed river with channel gradients ranging from 12% in the headwaters to 0.01% in the lower reaches. The downstream-most 80 km of the 100-km length of Redwood Creek has gradients less than 2% and is characterized by a pool-riffle morphology.

Prior to 1945, 85 percent of the Redwood Creek basin was forested with redwood (*Sequoia sempervirens*) and Douglas fir (*Pseudotsuga menziesii*) stands (Best, 1995). By 1978, more than 80 percent of the coniferous forest was logged. In 1964, a 50-year flood caused widespread landsliding, bank erosion and channel aggradation throughout the Redwood Creek basin. In the 1970's, several more large floods (10 to 25-year recurrence intervals) initiated further landsliding and redistributed sediment. The downstream third of the Redwood Creek channel is still responding to the pulse of sediment introduced by past floods (Madej and Ozaki, 1996).

Most tributaries are steep (> 4%), but two large tributaries, Bridge and Lost Man Creeks, are low gradient streams with well developed pool-riffle morphology. A description of Bridge Creek is included in Chapter 3. The Lost Man Creek basin was heavily logged in the 1960's, so the amount of in-stream wood is probably much less than under pristine conditions. Since the cessation of timber harvest, land use disturbances in Lost Man Creek have been minimal. In 1989, the removal of a small dam released a supply of gravel to the stream. The details of this project are discussed later.

Between 1977 and 1999 longitudinal thalweg profiles of several reaches of Redwood, Bridge and Lost Man Creeks were surveyed several times to determine the changes in channel geometry, pool distribution and water depths through time. From 1977 to 1996, no flow exceeded a five-year recurrence interval, and channel changes were moderate. In 1997, a 12-year flood occurred, initiating many debris flows that contributed large volumes of sediment to the rivers and renewed aggradation in several areas.

In addition to the high order streams described above, 124 steep low order stream reaches associated with a watershed restoration program were inventoried. The watershed restoration program in the Redwood Creek basin was initiated in 1978. The focus of the program was to remove abandoned logging haul roads to restore natural drainage patterns and reduce sediment production from the roads. Descriptions and photographs of the road removal techniques can be found in Chapter 2. During road removal, road fill is excavated from stream crossings, and heavy equipment forms new channels through the former road prism. Sediment supply is high in these newly excavated channels, due to the availability of decompacted road fill. These new channels ranged from 4 to 52 percent in slope and drained between 0.1 and 3.2 km^2.

Figure 4.4 shows the distribution of study sites used in this paper according to two important variables: drainage area and stream gradient. Study reaches were chosen to represent a range of channel conditions and types, as well as by what surveys were available for analysis. To broaden the scope of study beyond Redwood Creek, analyses based on results from other studies (Lisle et al. (1998); Martinson et al. (1986); Maita (1991) and Sutherland (in progress)) were used. These examples included an artificial channel undergoing a sediment pulse (a flume experiment), a stream impacted by a

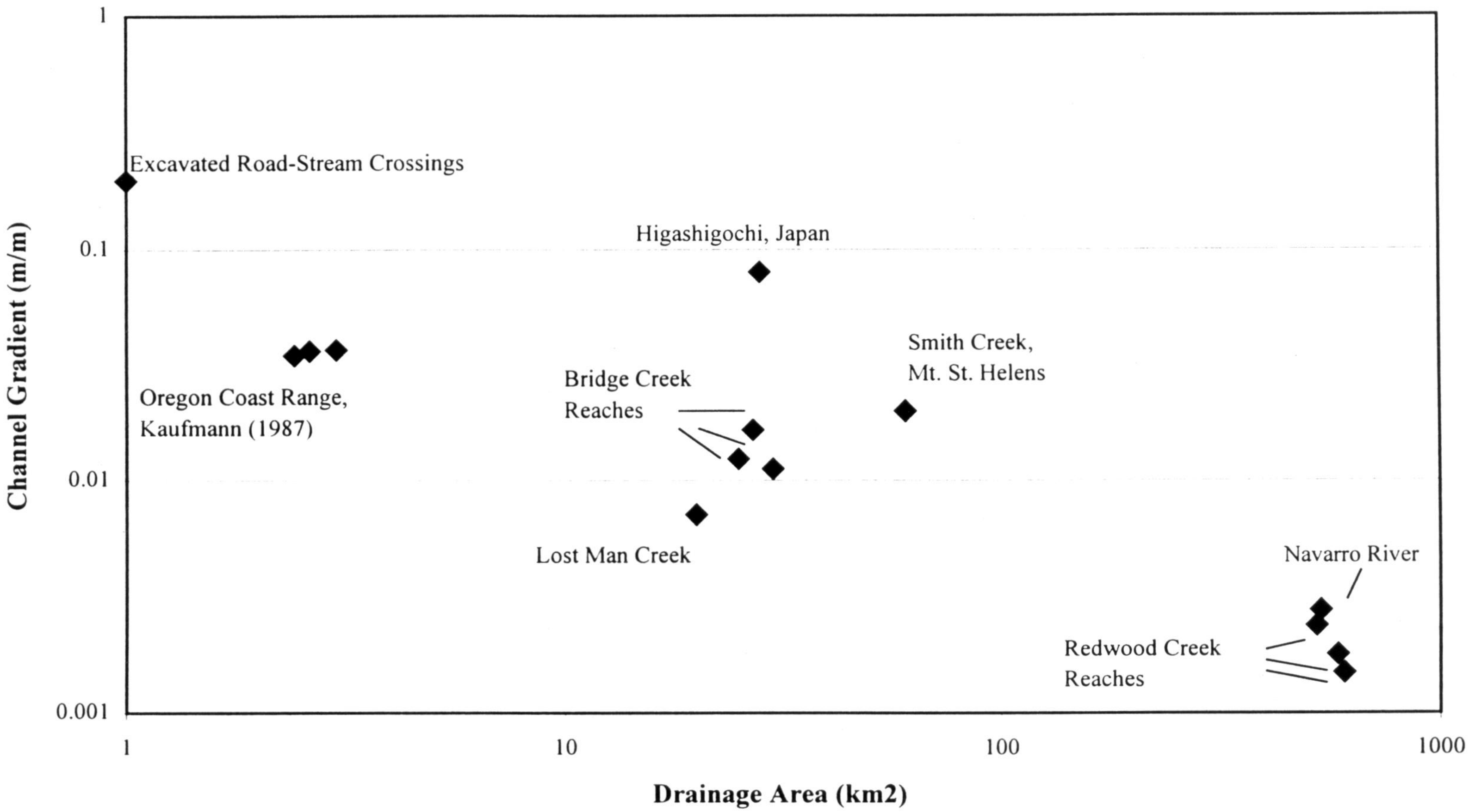


Figure 4.4: Distribution of study sites by drainage area and channel gradient.

volcanic eruption (Smith Creek), and two rivers affected by large landslides (Higashigochi and Navarro River). Channel characteristics of the study reaches are listed in Table 4.1.

The relative magnitude of the sediment pulse entering the study reaches is also listed in Table 4.1. The volume of sediment entering the channel was scaled as a ratio to mean annual sediment transport through that channel reach.(sediment pulse/annual sediment load). Because most streams did not have any associated sediment transport data, these are simply estimates based on regional trends and adjusted for drainage area. Although rough, these estimates are useful as indicators of the relative influence of a sediment pulse in a given channel network.

4.5 Methods

Longitudinal profile surveys formed the basis for much of the following data analysis. In Redwood, Bridge, Lost Man Creeks, elevations of channel bed and water surface were measured using a self-leveling level and stadia road. The spacing of survey shots was about 1/4 channel width, and all major breaks-in-slope were surveyed. Details of the method are given in Chapter 3. In the Higashigochi River and Smith Creek, longitudinal profile data were reconstructed from published survey plots, and the spacing of the survey shots is not known.

The distribution of residual water depths from longitudinal profile surveys was calculated using the method of Lisle (1987). Details are given in Chapter 3. A riffle was defined as a length of channel where the residual water depths were zero. Standard

Table 4.1: Channel characteristics of study reaches

Study Reach	Drainage Area (km2)	Bankfull Width (m)	Channel Gradient (percent)	D_{50} (mm)	Sediment pulse/ Annual sediment load
Little Lost Man Cr.	9	8	2.50	50	no pulse (control)
Lost Man Cr.	32	17	0.70	30	3
Upper Bridge Cr.	25	23	1.24	30	3
Bridge Cr. Canyon	27	12	1.66	60	3
Lower Bridge Cr.	30	15	1.12	32	3
Redwood Cr at Weir Cr.	523	60	0.24	22	25
Redwood Cr. at Bond Cr.	588	70	0.18	18	25
Redwood Cr. at Elam Cr.	605	110	0.15	15	25
Excavated road-stream crossings	0.1 - 3.2	1-2	4 - 52	~200	10
Higashigochi River	28	80	8.37	?	4
Smith Creek	30	70	2.21	?	10^4
Navarro River	535	60	0.28	?	0.3
Flume	N/A	1	1.00	0.57	N/A

statistics (mean, median, standard deviation) were calculated for the populations of residual water depths to document changes in channel structure. The standard deviation of water depths was used as an indicator of the variability of bed topography, and was normalized by channel width in comparisons across channel types. In channels that did not display well defined pools and riffles (Higashigochi River and Smith Creek), residual water depths could not be defined. In these cases, a linear regression was fit through the bed profile, and the magnitude of residuals from the regression line were used as an indication of bed variability. The greater the standard deviation of the residuals, the greater the variability of bed topography.

Channel organization was analyzed through spatial autocorrelation techniques that are described in Chapter 3. A spatial autocorrelation coefficient, Moran's I, documented the presence of regularity in the bed profiles, based on surveys of bed elevations. Two scales of spatial autocorrelation were studied. Short lag distance correlation represents the tendency of points close to one another in the channel bed to have similar elevations (i.e., neighboring points on a riffle crest). At longer lag distances, significant positive or negative spatial autocorrelation represents pairs of points that are more similar or more dissimilar from each other, respectively, than expected. A positive Moran's I represents regular spacing of channel units, such as between pool and pool, or riffle and riffle. I refer to this scale of autocorrelation as 'topographic regularity.' In this paper, the correlation distance is expressed in terms of channel width (CW) to compare regularity across channels of different sizes.

A different approach was used in evaluating channel bed patterns in newly excavated channels at restored road crossings. Excavated stream crossings were surveyed with a clinometer to measure stream gradient, and the number and type of steps, if present, were inventoried. Steps were defined as a distinct break in slope greater than 0.3 m high with a flatter tread upstream (to distinguish them from cascades, which are more continuous runs of turbulent water). In these small streams, pools downstream of steps, if present, were small and shallow (usually less than 0.1 m deep). Crossings that had secondary treatments following excavation (for example, imported large rock or wooden check dams to prevent incision of the channel bed) were excluded from the analysis. Of the 200 crossings inventoried, a total of 124 crossings, with a combined channel length of 2800 m, could be used to analyze channel development

To analyze changes in channel roughness values through time, U. S. Geological Survey water discharge records from five gaging stations (Figure 4.3) were used. The most complete record available was from the upstream most station, Redwood Creek near Blue Lake (1972 to 1997). Unfortunately, records from the longest operating gaging station (Redwood Creek at Orick) could not be used because of many man-made channel modifications. At this station the river was confined by construction of flood control levees in 1968, the river bed was disturbed by the commercial extraction of gravel in the 1980's, and vegetation on the gravel bars is removed frequently for flood control. At two stations, Redwood Creek at Miller Creek and Redwood Creek at Weir Creek, discharge was only measured during moderate to high flows. Records from a gaging station in an undisturbed, unlogged tributary, Little Lost Man Creek, were used as a control.

Gaging stations were purposely constructed in straight reaches to avoid complicated hydraulics due to bends, so roughness due to channel curvature is negligible. Channel bed profiles (surveyed at the gaging stations at low flow) show no change in channel grade during the study period. In addition, an analysis of sequential aerial photographs from these sites showed that other factors that could affect channel roughness, such as changes in channel planform, large in-channel wood, or streambank vegetation, were not important at the gaging stations.

Channel roughness was calculated using the Manning's equation:

$$n = \frac{(d^{2/3})(S^{1/2})}{v} \qquad \text{Eqn. 4.3}$$

where ' n' is the roughness coefficient Manning's n, 'd' is mean flow depth in meters, as an approximation of hydraulic radius, 'S' is the water surface slope (m/m), and 'v' is mean velocity (m/sec). Values for these parameters were obtained from gaging station records (U.S. Geological Survey (USGS) Form 9-207). Mean depth, not specifically listed on the USGS form, was calculated as 'area/width.' Water surface slope was assumed to be equivalent to the gradient of the channel bed surveyed at low flow. Water surface slope may change with discharge, so this value is only an approximation of the true energy grade at the gaging station. Because slope was used as a constant in all calculations at a given site, absolute values of roughness may be slightly off, but patterns in changing 'n' values should still be valid.

Before examining time trends in roughness values, roughness values must be adjusted for the influence of discharge. As an exploratory tool, discharge and Manning's n were related by linear regression, and the resulting residual plots were examined for possible trends through time. Extreme summer low flows, when water depth and bed particle size are equivalent, were not used in the analysis. To test whether trends in time were significant, I used the method described by Helsel and Hirsch (1992, p. 335). A multiple regression analysis was constructed using both time and discharge as variables in the model:

$$\ln(\text{roughness}) = B_0 + B_1(\text{Time}) + B_2(\ln(\text{Discharge}) + e.$$

The t-statistic for B_1 tests for significant changes with time.

The size distribution of particles on the streambed at the gaging stations was determined through pebble counts (Wolman, 1954). In this study, pebble counts consisted of a random selection of at least 100 particles from a riffle crest near each gaging station. The intermediate axis of each pebble was measured and tallied using Wentworth size classes. Cumulative size distribution curves were constructed, from which D_{50} (the median particle size) and D_{84} (the particle size that is coarser than 84% of the bed material) were calculated.

There are several limitations to this study of channel organization. First, many of the surveys used in this analysis were conducted for reasons other than documenting responses to sediment pulses, and the surveys were not necessarily located in the best stream reaches to analyze such responses. The spatial resolution of the surveys used (spacing of survey shots about 1/4 channel width apart) were useful to detect intermediate-sized bedforms, but cannot detect small scale structures and organization. Likewise, because the survey transects were generally 20 to 30 channel widths long, longer scale organization, if present, was not detectable by these surveys. Surveys were not available for all channel types, and only sediment pulses that could be easily mobilized by a stream were studied. There were gaps in data availability from basins with drainage areas in the 8 to 20 km^2 range and the 100 to 500 km^2 range. An area for future research would be to target streams with sediment pulses that fall within the areas of these data gaps.

4.6 Results and Discussion

Trajectories of changes in channel structure and organization following sediment pulses (Figure 4.2) were evaluated by measuring four aspects of channel bed topography: mean residual water depth, the standard deviation of distributions of water depths, the similarity of elevation between neighboring points on the channel bed (spatial autocorrelation at short lag distances), and the degree of regularity of bedform spacing (spatial autocorrelation at longer lag distances). Bedforms in step-pool channels were analyzed using the number, spacing, and height of steps. How quickly channel organization develops depends in part on the frequency of flows large enough to mobilize and rearrange bedforms. The following discussion examines these points using survey results from 12 types of stream reaches that experienced sediment pulses. Survey data, with various levels of detail and covering various time periods, are presented for step-pool, plane bed, and pool-riffle channels ranging in channel gradient from >20 percent to 0.01 percent.

4.6.1 Frequency of Organizing Flows

The vertical axis in the conceptual model (Figure 4.2) is "frequency of organizing flows." Initiation of bedload movement is, in itself, a topic of many studies with sometimes diverging results. The approach taken here is to use the general concept of bed mobility (based on Equations 4.1 and 4.2) as a necessary condition for changes in channel organization. The frequency of organizing flows will vary in different parts of the channel network due to the relationship between discharge and particle size. In lower reaches of Redwood Creek, for example, D_{50} is 16 to 22 mm, and bedload is mobilized frequently. Bedload is mobilized across most of the active channel when flows at Redwood Creek at Orick exceed 115 cms (Madej and Ozaki, 1996), and gravel bars scour significantly at flows greater than 300 cms (a flow with a 1.1 year recurrence interval) (Madej, 1995). Figure 4.5 shows the frequency of flows that exceeded 300 cms during the period of record. It is clear that some groups of years (the late 1970's, the early 1990's) had few organizing flows, while the earlier part of the record had many more organizing flows. Water Year 1997 had several organizing flows, which is reflected in many channel changes recorded in that year. Records of cross-sectional channel changes indicate that most scour and fill of channel beds occur in the years with the most organizing flows (Varnum and Ozaki, 1986); consequently, the ability of

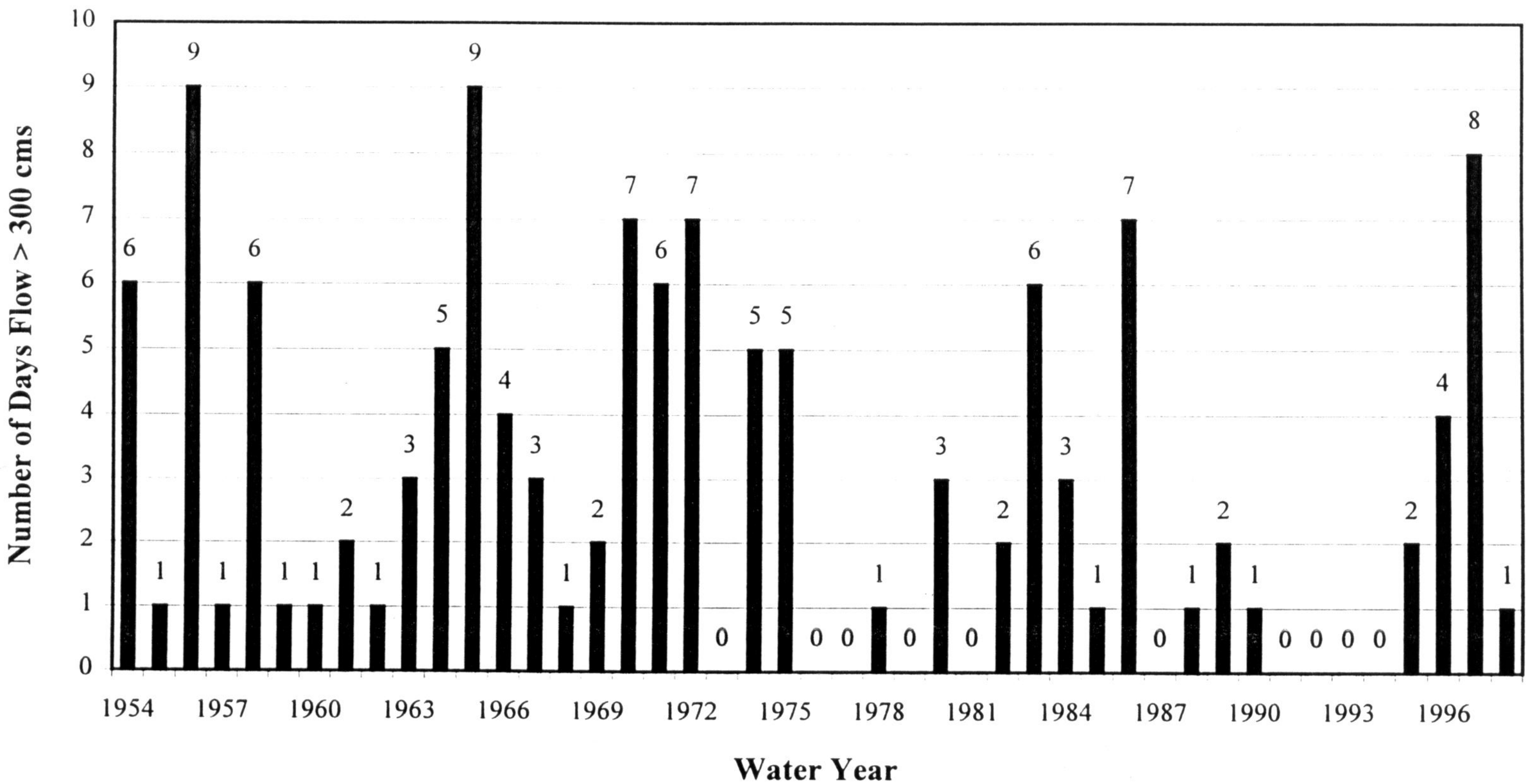


Figure 4.5: Frequency of mean daily flows that exceeded 300 cms (when extensive bed scour and filling occurs) at Redwood Creek at Orick during the period of record.

Redwood Creek to reorganize channel-stored sediment is probably greatest in these years as well.

Equivalent water discharge and sediment measurements are not available for subbasins within the Redwood Creek catchment. Through extrapolation, it is likely that tributaries of Redwood Creek experienced a similar pattern of high and low flow years. Nevertheless, an organizing flow in Redwood Creek does not mean that the same event produced an organizing flow in a small tributary because the critical discharge needed to transport larger bed material is greater. In small, steep tributaries where the dominant particle size is commonly 0.2 m or greater, flows capable of transporting bed material may only occur every decade or so. For example, Billi et al. (1998) suggest step-pool streams are only reorganized every 20 to 30 years. Hence, the magnitude of channel change needs to be interpreted in the light of the overall flow frequency during a given period.

4.6.2 Case 1: Sediment Pulses in Artificially Manipulated Step-Pool Channels

The following sections describe responses to sediment pulses in several types of channels. The first case involves the development of steps and pools in artificially manipulated channels. Since 1978 hundreds of kilometers of abandoned roads have been removed in Redwood National and State Parks, California. A major part of the road removal process is to excavate culverts and road fill from road-stream crossings using heavy equipment. When culverts and the overlying fill material are removed, the equipment operators form a smooth channel bed connecting the channel upstream of the old road bed to the channel downstream of the road prism. Although this newly excavated channel bed is in the same general location as the channel bed before the road was constructed, it is not necessarily in the same alignment or at the same elevation as the original streambed. The newly excavated channels can be considered to have undergone a sediment pulse because a large supply of poorly sorted road fill material remains in the channel bottom and forms the new channel banks.

Following excavation, channels adjusted by varying degrees of incision, headcutting, bank erosion, and transport of sediment. As a stream incised a freshly excavated crossing, fine-grained road material eroded, leaving a lag of coarser material in the channel bed. Depending on the particle size and stream gradient, these coarse particles became organized into steps. In some locations, previously buried boulders, tree roots, and wood were exhumed and formed steps. Nevertheless, in most cases the new channel was not simply an exhumation of the pre-road channel because of the degree of disturbance in these channels during the original road construction. Locally, rockfall and treefall from adjacent hillslopes contributed roughness elements to the channels following excavation.

Few survey data are available that document the longitudinal profiles of these newly created channels, but Figure 4.6 shows one such survey, in which the newly excavated channel was fairly smooth, and steps developed as the newly formed channel eroded. In this case, a bedrock outcrop at the downstream end of the excavation controlled the base level in both surveys. Photographs taken after the excavations provide additional evidence that most new channels were smooth and sloped evenly

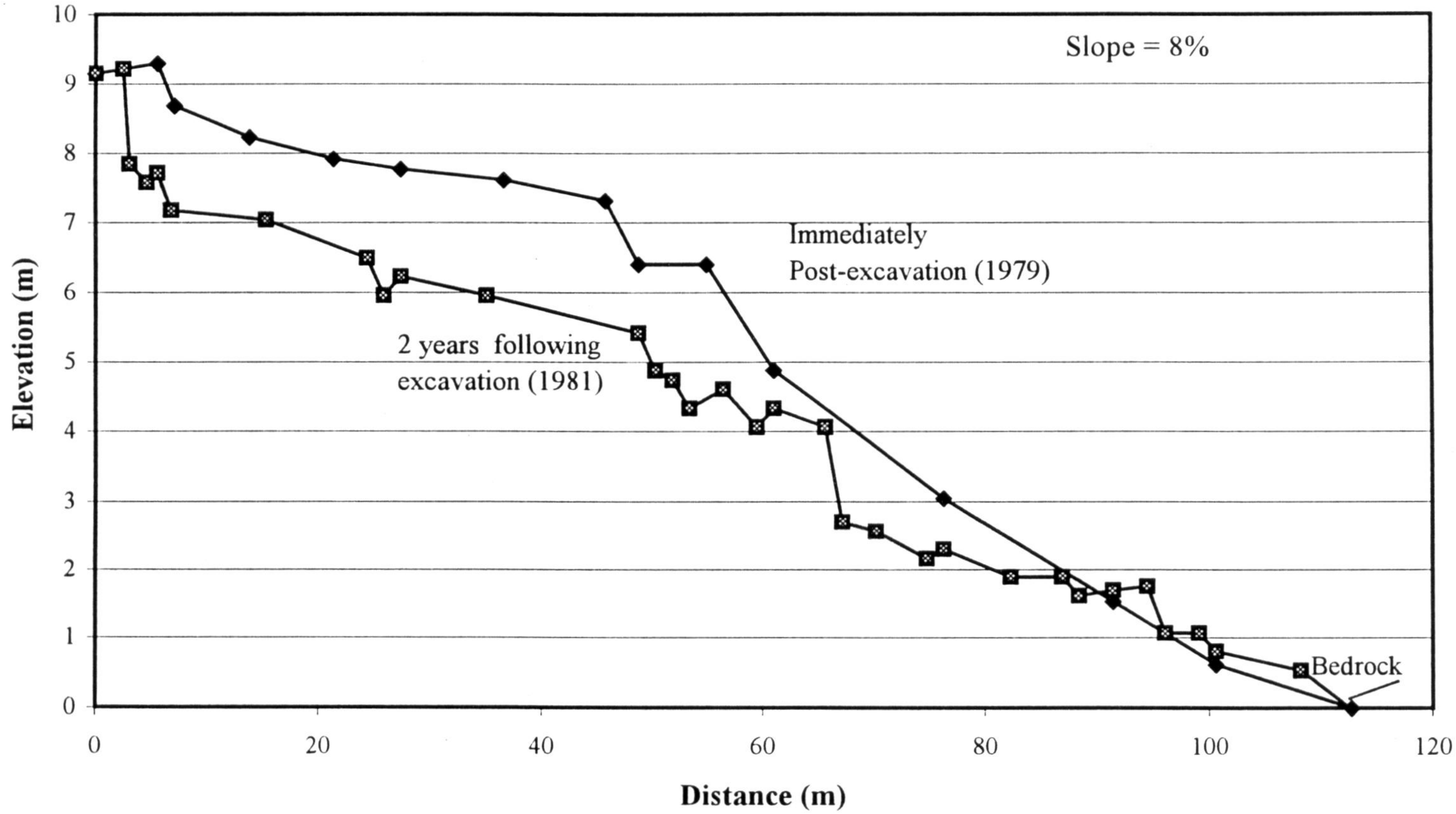


Figure 4.6: A survey of a stream crossing recently excavated during road rehabilitation work, and another survey two years later showing erosion of road fill and the development of stepped relief.

through the remaining road fill material. Moderate floods (3 to 5-year recurrence intervals) occurred in 1983 and 1986, and a 12-year flood occurred in 1997. By this time, many cobble, boulder and wood steps had formed. Of the 352 steps inventoried in this study, 38% were formed dominantly by wood, and 62% by cobbles or boulders. Many steps were formed by the interaction of inorganic and organic material, such as cobbles trapped by tree roots, forming a step. In a study of channel adjustments in 24 crossings one year after excavation, Klein (1987) found that 4 to 67% of the elevation drop was due to newly formed organic steps. The average step height (0.5 - 0.6 m) in the present inventory was similar for both wood and boulder steps, and was about twice the size of the dominant bed particle

The frequency of steps (number of steps per 30 m of channel length) was computed for each excavated crossing. The initial step frequency was assumed to be negligible, based on an analysis of photographs taken immediately after excavation, and measured step frequencies of <2 steps/30m. were considered to be within probable detection levels. Any step frequency of >2 steps/30m was considered significant development of bed variation following stream crossing excavation. According to this definition, 62% of the excavated crossings showed significant step development through time. Out of 124 crossings, mean step frequency was 3.4 steps/30 m of channel length. Step frequency was greatest in ranges of channel gradient of 15 to 35% (Figure 4.7).

Slope is probably a critical component of step formation in these excavated crossings. Below 15% slope, critical unit discharge (Equation 4.2) for a dominant bed

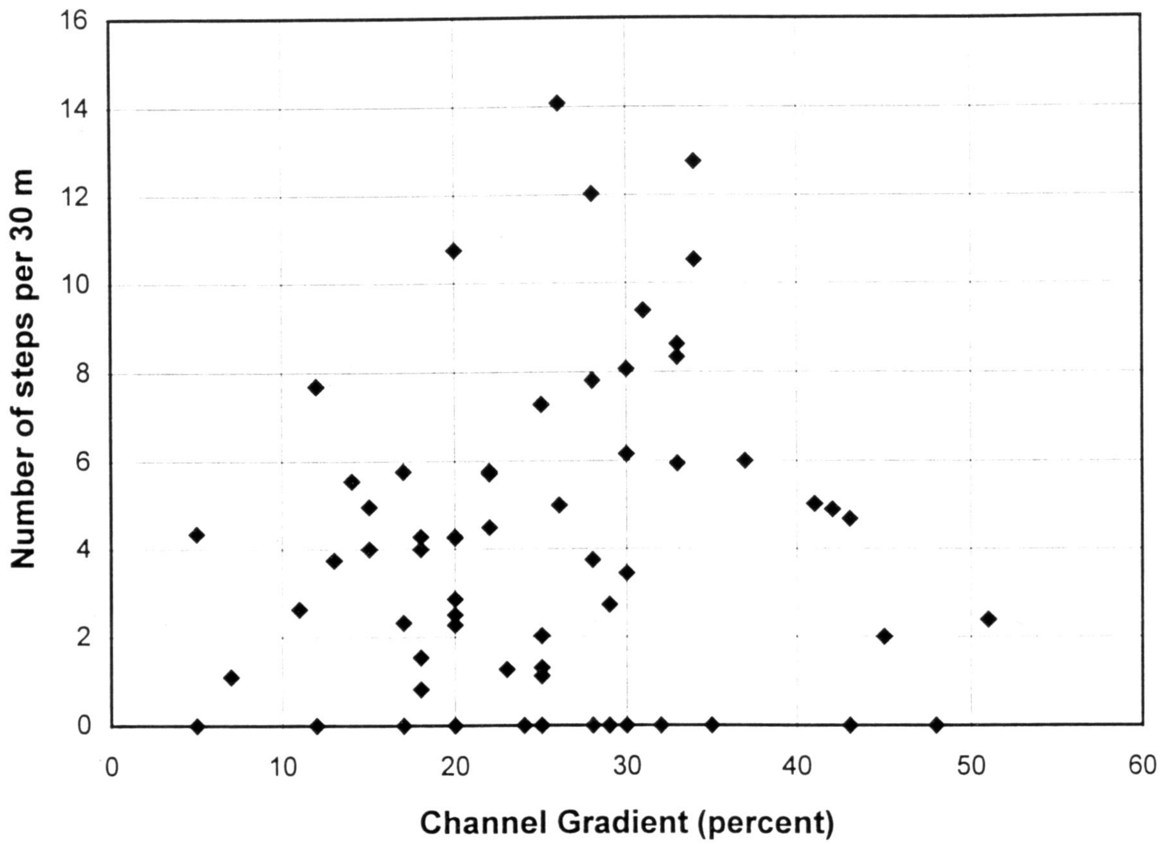


Figure 4.7: Frequency of steps (both organic and inorganic) that formed in excavated stream crossings, in relation to the channel gradient of the crossings.

particle size of 0.2 m is about 0.62 cms. I used the rational runoff method (Dunne and Leopold, 1978) to predict peak runoff rates in these crossings, which have a median drainage area of 0.11 km^2 and an average width of one meter. A 50-year flood for a 0.11 km^2 basin is 0.65 cms, similar to the critical discharge calculated for a crossing with 15 percent slope, so step-forming bed material would be mobilized infrequently in these crossings. In contrast, crossings with slopes of 20-25 percent have a calculated critical discharge of roughly 0.35 cms. This flow has about a 15-year recurrence interval, and so the dominant bed material might be expected to move more frequently than in the less steep crossings. It must be emphasized that these calculations are only meant to be rough estimates of the mobility of the bed material in these steep channels. More detailed field measurements would be needed to refine these numbers. In crossings with slopes of >35 percent, bedrock plays a greater role in limiting the ability of a stream to organize its bed into steps; bedrock chutes and boulder cascades are common; and steps are less frequent.

The relationship of step spacing and channel gradient was compared to that of another step-pool stream, Rio Cordon (Billi et al., 1998) (Figure 4.8). Although many of the excavated crossings fell within the range of Rio Cordon, many others had steps spaced significantly farther apart. The fact that there were fewer, more widely spaced steps in excavated crossings than in a natural step-pool stream is consistent with the idea that the frequency of organizing flows in step-pool channels is low, and that the organization of the channel bed into regularly spaced steps following road restoration will probably take several decades. At the time of the inventory in 1997 and 1998, steps

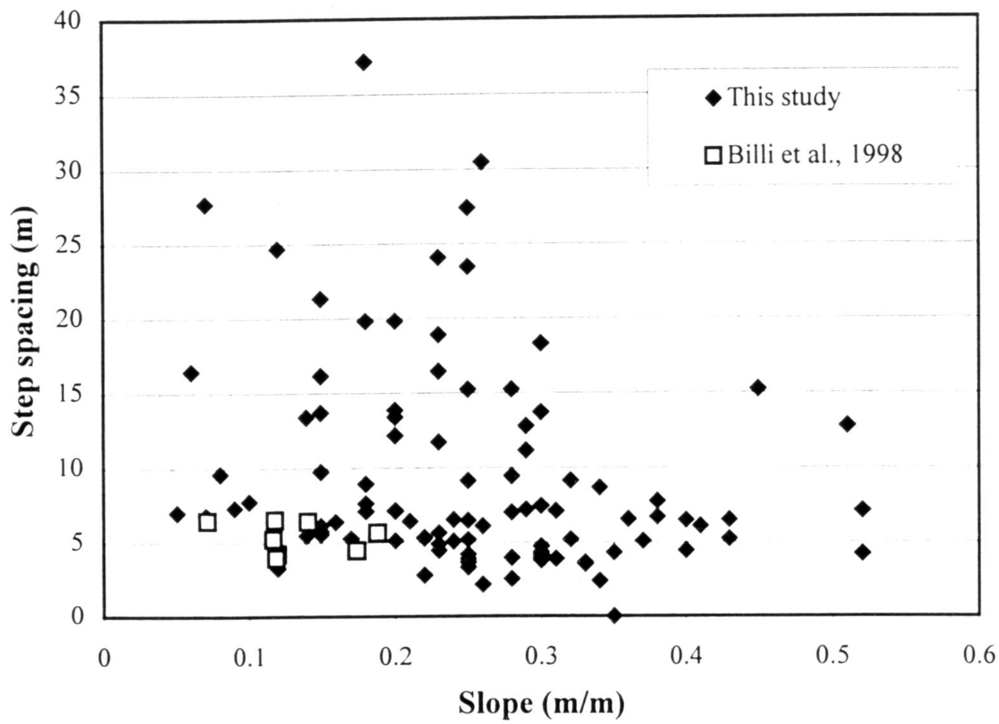


Figure 4.8: Step spacing in the Rio Cordon and in excavated stream crossings

were still randomly distributed, but channel beds showed increased heterogeneity since excavation, thus fitting the general conceptual model displayed in Figure 4.2. Eventually, after a period with several organizing flows, steps may become more regularly spaced, as the channel adjusts hydraulically to the size and type of bed material available in the channel.

Billi et al. (1998) found a characteristic length scale for steps to be a function of H/S, where H = height of step and S = slope. Their data are plotted on Figure 4.9 and are contrasted with the data from this study. Figure 4.9 shows a wide scatter in the length scale of excavated crossings. The channel development documented in this study does not yet show a characteristic length scale, but this may develop through time following more organizing flows.

The development of steps is an important component of energy dissipation in these excavated crossings. In the 124 crossings, the average percent of total elevation drop due to steps (which is assumed to be proportional to the percent of energy dissipated) was 35%. The roughness due to steps in newly excavated channels was compared to that in steps in well developed step-pool systems (Wohl et al., 1997) (Figure 4.10). In that study, the authors used Rouse's roughness concentration 'e', defined as the cumulative step height divided by the reach length (Rouse, 1965). Half the channels in the present study had roughness concentration values of < 0.05, whereas almost all of the channels with well developed step-pools (Wohl et al., 1997) had values of 'e' > 0.05. Although 62% of the channels in the present study showed step . development, and thus higher roughness values than in freshly excavated channels, they

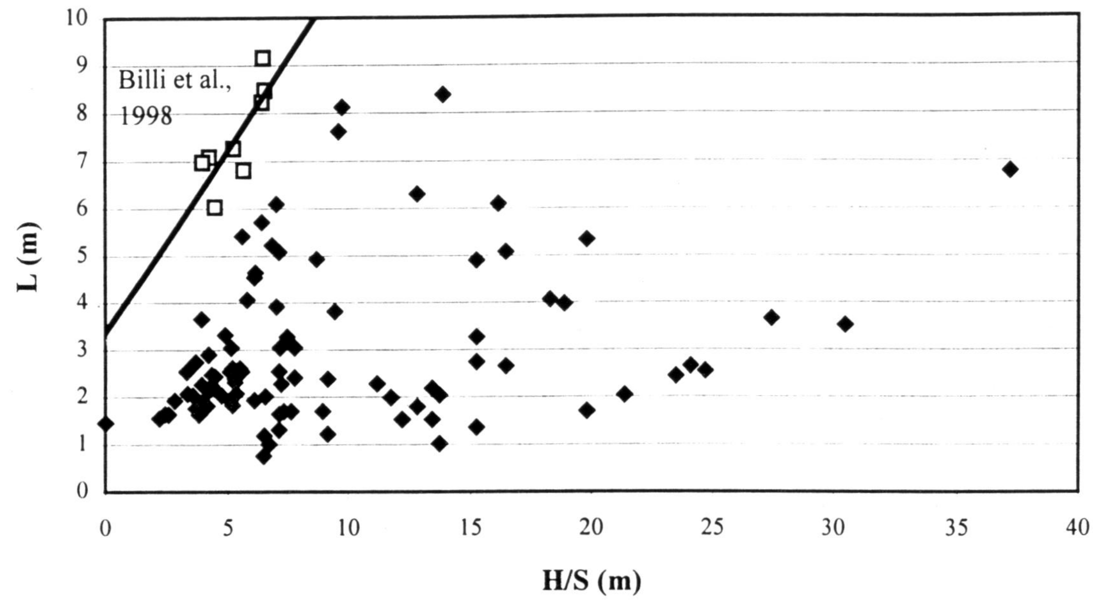


Figure 4.9: Step length, L, versus Height/Slope ratio, H/S

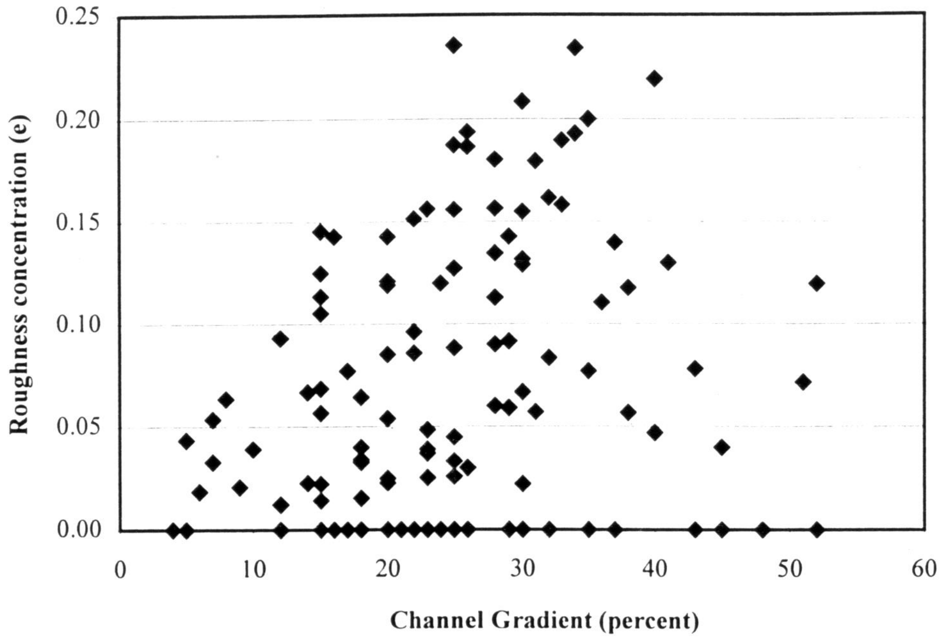


Figure 4.10: Roughness concentration, e, versus channel gradient

have not yet attained the roughness values typical of well articulated step-pool channels Plunge pools downstream of the steps in the present study were shallow (< 0.1 m), and may scour deeper with time, leading to further energy loss due to turbulence and hydraulic jumps over steps.

4.6.3 Case 2: Sediment Pulses in Steep (2 to 8 Percent Grade) Channels

Few studies document channel changes in steep channels following sediment pulses. In a steep gravel bed river in Japan, the Higashigochi, Maita (1991) surveyed several longitudinal profiles following a pulse of sediment caused by landslides. This river has the highest stream power (based on 'drainage area * slope,' Figure 4.4) of the sites considered in this paper. In August, 1982, a flood accompanied by extensive landsliding raised the stream bed from 3 to 8 meters, and this sediment was subsequently eroded from the reach. By May, 1983, the channel bed had returned to its former elevation. Almost no woody debris was observed in the surveyed reach, which is steep (average gradient is about 8 percent) and did not have a pool-riffle morphology. Initially, roughness elements were primarily boulders within the coarse gravel bed, and many of these were buried following the sediment pulse. Table 4.2 lists the standard deviations of the regression residuals based on the longitudinal profile surveys, which are an indication of bed variability. Immediately following the sediment pulse, the standard deviation decreased, and subsequently increased through time. The first survey of August, 1982 represents the peak of the deposition, whereas the second survey of August, 1982 followed the recessional flow when the river had partially eroded the flood

Table 4.2: Results of profile analysis for Higashigochi River, Japan

Date of Survey	r^2 from regression	Standard Deviation of Residuals
September, 1980	0.999	2.03
August, 1982 (a)	0.999	1.02
August, 1982 (b)	0.999	1.74
May, 1983	0.998	2.22

deposits (Maita, 1991). By May, 1983, the river had eroded down to its pre-flood level, and the standard deviation of residuals had increased to about the pre-flood level. These results support the conceptual model presented earlier, of high sediment loads initially leading to decreased heterogeneity, with an increase in bed variation through time. The resolution of these surveys was too coarse to examine trends in spatial autocorrelation.

Another example of response in steep channels following a sediment pulse is from Mount St. Helens, Washington, which erupted in 1980 and generated a lateral blast, and extensive lahars in the Lewis River drainage basin. The newly deposited bed material was very poorly sorted, and ranged from small bits of pumice to boulders. A tributary of the Lewis River, Smith Creek, was surveyed several times following the eruption, and the channel exhibited up to 10 m of aggradation (Martinson et al., 1986; and U.S. Geological Survey, unpublished data). Although there were many downed trees in the channel following the eruption, the influence of woody debris on Smith Creek morphology was dwarfed by the volume of volcanic deposits that obliterated the pre-eruption channel. Even though surveys were conducted during a relatively low flow period (1982-1995) when most floods were less than a 5-year recurrence interval, these flows can be considered organizing flows, because the fine-grained volcanic deposits were readily mobilized. Surveys were analyzed in a similar manner to the Higashigochi River data set (Table 4.3).

Table 4.3: Results of profile analysis for Smith Creek, Mount St. Helens

Date of Survey	r^2 from regression	Standard Deviation of Residuals
1983	0.999	0.23
1984	0.999	0.28
1995	0.999	0.45

The general trend in Smith Creek is of increasing bed variability through time. Cross-sectional surveys (Martinson et al., 1986) show a concomitant decrease in mean bed elevation during this period as well, as sediment was transported out of the reach. More detailed surveys could certainly shed more light on the development of channel organization in this system, which is responding to an extreme increase in sediment load from the eruption. The flood of record occurred in 1996, and the USGS is currently researching the effects of recent high flows on channel morphology.

4.6.4 Case 3: Channel Reorganization Following Debris Torrents

In 1997, a debris torrent that originated from a road fill failure deposited about 15000 m^3 of sediment and wood in Bridge Creek, a 30 km^2 tributary of Redwood Creek.

Profile surveys had previously been conducted (in 1986 and 1995) in three reaches of Bridge Creek downstream of the torrent site. These surveys were repeated in 1997 and 1999 to document channel changes following this sediment pulse. Formation and destruction of debris jams downstream of the debris torrent site have caused secondary effects in sediment routing in this stream. Although these debris jams were not within the surveyed reaches, storage of sediment behind a jam formed in 1997 may have moderated the volume of sediment reaching the downstream reach in Bridge Creek.

Table 4.4 reports the results of the surveys. The upstream reach of Bridge Creek, which was directly impacted by the debris torrent deposition, responded immediately with decreases in channel bed variation (standard deviation of residual water depths) and increases in length of channel in riffles. The channel downcut through the debris torrent deposits rapidly (mean channel bed elevation had dropped about 0.5 m by 1999, following the increase of 0.7 m in 1997). Although mean residual water depth and standard deviation recovered quickly (by 1999 the values approached the pre-debris torrent levels), the pattern of regularly spaced bars that was present in 1995 disappeared in 1997 and had not reappeared by 1999. Large woody debris in this channel, much of it deposited by the debris torrent, strongly affects channel morphology in this reach, and contributes to the irregular bedform spacing by causing many forced pools.

The canyon reach, which is narrow, steeper and bouldery, showed little response to the release of sediment from erosion of the debris torrent deposit upstream and the release of sediment from a debris jam that broke upstream of the canyon. Cross sections

Table 4.4: Results of profile analysis for Bridge Creek study reaches

Bridge Creek	Mean Residual Water Depth (m)	Standard Deviation (m)	Percent of channel in riffle	Short Lag Distance Correlation (m/CW*)	Topographic Regularity (m/CW)
Upstream Reach, 1986	0.17	0.23	38	0.4	none
Upstream Reach, 1995	0.19	0.24	27	0.4	3
Upstream Reach, 1997	0.07	0.12	46	0.2	none
Upstream Reach, 1999	0.17	0.24	32	0.6	none
Canyon Reach, 1995	0.13	0.15	25	0.5	none
Canyon Reach, 1999	0.14	0.21	39	0.8	none
Downstream Reach, 1986	0.09	0.15	54	0.5	none
Downstream Reach, 1995	0.08	0.14	45	0.3	none
Downstream Reach, 1997	0.05	0.09	56	0	none
Downstream Reach, 1999	0.10	0.18	51	0.4	none

*CW = channel width

showed little change in mean channel bed elevation, and, except for an increase in the length of riffles in the channel, channel morphology did not seem much affected by the flux of reworked debris torrent sediment. No bedform regularity was apparent either before or after the debris torrent. This is not surprising because the reach was characterized by boulders and bedrock outcrops, as well as large woody debris, both before and after the debris torrent. The possibility of exceeding the critical discharge to move such boulders to rearrange the bed is negligible.

The downstream reach, also with high woody debris loading, did not have well developed alternate bars. This reach responded to the debris torrent in 1997 by a decrease in depth and standard deviation and an increase in percent riffles. The lack of significant short and long lag distance autocorrelation in this reach in 1997 indicates that the channel bed topography was random, and not organized into any regular bedforms. By 1999, channel variability had increased, short lag distance correlation had returned, but no significant regularity at a longer scale was apparent. A newly formed debris jam upstream of this reach which trapped some sediment from the debris torrent may have assisted in the recovery of channel variation in this reach through the metering of sediment supply and transport. In-channel wood plays an important role in this stream, and as wood from the debris torrent is redistributed during future flows, channel morphology will likely continue to change.

Results from Bridge Creek are consistent with those from another study involving channel surveys in streams affected by debris torrents. Kaufmann (1987) substituted space for time, and studied morphologic characteristics in three channels subjected to debris torrents of various dates. Channel beds were surveyed every meter in a 100-m reach in three channels: Gwynn, Cape and Little Cummins Creek, Oregon. Kaufmann showed that channel complexity increased with time, due to the creation of transverse bars, glides, riffles, pools and side channels. In Gwynn Creek, which had a torrent two to three years prior to the study, mean depth and standard deviation of bed elevation were low, pools were infrequent, and roughness values were low. Both Cape and Little Cummins Creeks, which had not experienced torrents for about 12 and 120 years, respectively, water depth, standard deviation of water depths, pool frequency, and roughness values were significantly higher. In terms of spatial autocorrelation, Kaufmann found short lag distance autocorrelation at about two channel widths, and weak regularity in the profiles at ten channel widths in the more recently disturbed channel and at five channel widths in channels with older debris torrents.

Hogan et al. (1998) report similar trends in streams in British Columbia, where debris torrents are an important mechanism leading to woody debris jams in channels. Here, they recognized that initial response to jam formation was a loss of stream channel complexity, less variable water depths, and more prevalent riffles. In some cases, channels became braided. In more recently disturbed channels, the distance between stable riffle-pools was greater than in channels with older disturbances. Through time, pools became more extensive, a single thread channel developed, previously buried large wood was exhumed, and channel morphology became more complex.

4.6.5 Case 4: Reorganization of a Channel Bed Following Dam Removal

In 1989, a 3-m high dam was removed from Lost Man Creek, a 32 km^2 tributary of Redwood Creek, and roughly three-fourths of the 4000 m^3 of sediment stored upstream of the dam were also removed. A new straight channel was excavated by equipment through the remaining sand and gravel in the bed, at an elevation about 2 m lower than the channel bed that existed when the dam was in place. This remaining accumulation of loose, easily mobilized sediment upstream of the old dam site can be considered a sediment pulse because it represents a large sediment supply suddenly available for reworking by the stream. Longitudinal profile surveys were conducted at the dam site in 1990 and 1996 to document channel development in this area. In addition, a 1990 survey of Lost Man Creek upstream of the dam-influenced reach was used as a control, to evaluate what the channel condition may have been without the influence of a dam.

Following dam removal and one high flow season (1990), Lost Man Creek at the dam site exhibited low values of mean residual water depth and standard deviation when compared to the control reach located upstream of the dam influence (Table 4.5). No regularly spaced bedforms had appeared. By 1996, the variability of the channel bed had increased, indicated by increases in mean residual water depth and standard deviation of water depths, and a decrease in short lag distance autocorrelation, and bars were spaced about 7.2 channel widths apart. The percent of channel length in riffles was initially high, but rapidly approached the value of the control reach. Some channel structure in terms of pool formation was attained quickly by scour around bedrock

Table 4.5: Results of profile analysis for Lost Man Creek study reaches

Lost Man Creek	Mean Residual Water Depth (m)	Standard Deviation (m)	Percent of channel in riffle	Short Lag Distance Autocorrelation (m/CW*)	Topographic Regularity (m/CW)
1990 Post Dam	0.08	0.13	54	0.7	none
1996 Post Dam	0.19	0.24	20	0.5	7.2
1990 Control Reach (Upstream)	0.23	0.30	25	0.6	5.7

* CW = channel width

outcrops and boulders, but the larger scale of channel organization with regularly spaced bars is beginning to emerge at a wider spacing than in the control reach. Because of previous logging activity along this stream and the dam construction activities, the supply of in-channel wood is low, and so the influence of large wood on channel morphology is also low in this reach.

4.6.6 Case 5: Reorganization in Low Gradient, High Order Streams Following Landslides

Three reaches of Redwood Creek were studied intensely from 1977 (immediately following a large sediment input from a flood and associated landsliding) to 1997. Results from these longitudinal profile surveys are reported and discussed in Chapter 3. Spatial autocorrelation results are reported in Table 4.6.

In general, short lag distance autocorrelation in Redwood Creek decreased with increasing time since the 1975 flood and associated sediment input. This is consistent with results reported in Chapter 3 of increasing variation of the channel bed with time. Although the three reaches of channel display alternate bars, bar spacing is not completely regular. Long lag distance autocorrelation (topographic regularity) is generally less than the five-to-eight channel width spacing frequently reported in the literature. This probably reflects the influence of other forcing mechanisms in the channel, such as channel bends, bedrock outcrops, boulder deposits, etc.

In the Navarro River basin, a single landslide contributed about 60,000 m^3 of sediment to the channel in 1995 and dammed the river. Subsequent surveys (Sutherland, in progress) showed several meters of downcutting in the channel at the landslide site. A

Table 4.6: Results of profile analysis for Redwood Creek study reaches

Study Reach	Short Lag Distance Autocorrelation (m/CW*)	Topographic Regularity (m/CW)
Redwood Cr. at Weir Cr., 1977	1.2*	7.8*
1983	1.1	4.5
1986	0.8	3.4
1995	0.6	3.4
1997	0.5	8.2
Redwood Cr. at Bond Cr. - 1977	1.7*	1.8*
1983	0.6	5.3
1995	0.5	7.9
1997	0.3	none
Redwood Cr. at Elam Cr. - 1983	0.6	1.5
- 1986	0.5	2.5
- 1995	0.4	2.5
-1997	0.3	2.4

* Resolution of survey was coarser than later surveys, so short lag distance correlation or the presence of regular, but short bedforms, if present, were not detectable.

preliminary analysis of longitudinal profile data shows results consistent with the other rivers in this study (Table 4.7). Mean water depth and standard deviation increased with time since the sediment pulse. The channel bed had no significant topographic regularity immediately following the sediment pulse, but it developed regularity at a scale of about 8.7 channel widths within a year of the landslide.

4.6.7 Case 6: Sediment Pulse under Controlled Channel Conditions (Flume Experiment)

The previous cases of channel organization involved forcing mechanisms of channel development due to the presence of wood, bedrock outcrops, boulders, etc., to various degrees. To examine bed organization without such factors, data from a flume experiment were analyzed. The experiment was conducted by Lisle et al. (1998) in a flume one meter wide, 160 m long, with a slope of 0.01 and a bed composed of a poorly sorted mixture of sand and fine gravel. First the flume was run until a series of migrating alternate bars formed. Next, sediment was introduced over a section of flume 60-80m downstream of the flume entrance. The flume was run at steady water discharge until the sediment accumulation dispersed and seemed to disappear. Bed elevations were measured at 0.5 m intervals down three longitudinal profiles, one located over the channel's center line and the other two located half the distance to either bank. From these data I constructed thalweg profiles for four runs: one before the sediment input, two during the dispersal of the sediment wedge, and one at the conclusion of the flume run. The thalweg profiles covered the distance 80 to 140 m downstream of the flume entrance (downstream of the sediment introduction).

Table 4.7: Results of profile analysis for Navarro River

Navarro River	Mean Residual Water Depth (m)	Standard Deviation (m)	Percent of channel in riffle	Short Lag Distance Autocorrelation (m/CW*)	Topographic Regularity (m/CW*)
1995	0.3	0.33	10	1.1	None
1996	0.7	0.77	11	1.2	8.7
1997	0.7	0.76	12	1.1	8.7

The methods used to analyze these longitudinal profiles using mean residual water depth, standard deviations, and spatial autocorrelation coefficients are described in Chapter 3. Points in the longitudinal profile were linearly interpolated to form a data set with thalweg elevations spaced 0.3 m apart, and results are reported in Table 4.8. Mean residual water depth and standard deviation initially decreased after the sediment input, and then increased through time. The percent of channel in riffles increased after the sediment input, and decreased through time. Short lag distance autocorrelation remained about the same through the run.

Figure 4.11 shows the destruction and subsequent development of structure and organization in the thalweg profiles during this experiment. Before the sediment wave was introduced, bed elevations spaced 8 m apart (8 channel widths) were significantly positively correlated (Figure 4.12a). After the introduction of the sediment wave, the mean thalweg elevation was 12.9 cm higher than the original channel (Figure 4.11) the periodic structure was destroyed (Figure 4.12b), and there were no significant correlations beyond 0.9 m. This trend held while the "excess" sediment was being transported through the flume (Figure 4.12c), and reorganized into regularly spaced structures. Visually, the experimenters noted a change in bar spacing and migration of bar fronts that corresponded to the results in Figure 4.12 (Lisle, personal communication). The experimenters stopped the flume run when it seemed that the sediment wave had disappeared. At this point the bed had reorganized into distinct periodic bedforms, and significant positive correlations of bed elevations were noted at distances 8 m and 16 m apart (Figure 4.12d). It is interesting to note that the mean

Table 4.8: Results of profile analysis for flume experiment

Flume Run	Mean Residual Water Depth (cm)	Standard Deviation (cm)	Mean thalweg elevation (cm)	Percent of channel in riffle	Short Lag Distance Correlation (m/CW*)	Topographic Regularity (m/CW)
Before wave	10.3	6.3	13.8	2.5	0.9	8
During wave - first survey	9.7	5.3	26.7	4.5	0.9	none
During wave- second survey	9.2	4.0	22.0	2.5	0.9	none
After wave	11.4	6.0	18.0	1.0	1.2	8 and 16

* CW = channel width

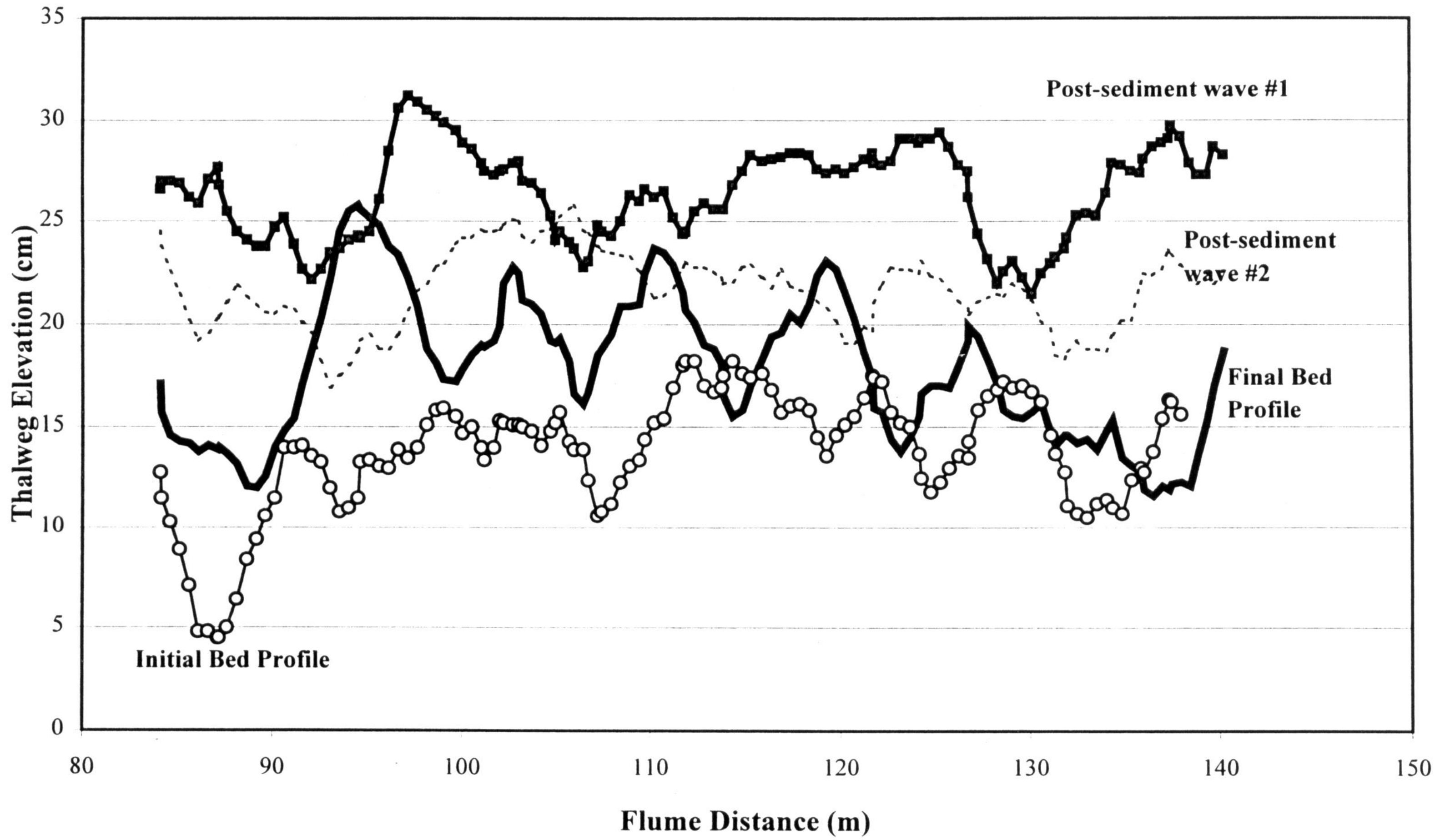


Figure 4.11: Thalweg profiles assembled from flume data collected by Lisle et al. (1998) representing four surveys: before, during (2), and after a sediment pulse which entered the flume between Distance 60 and 80 m.

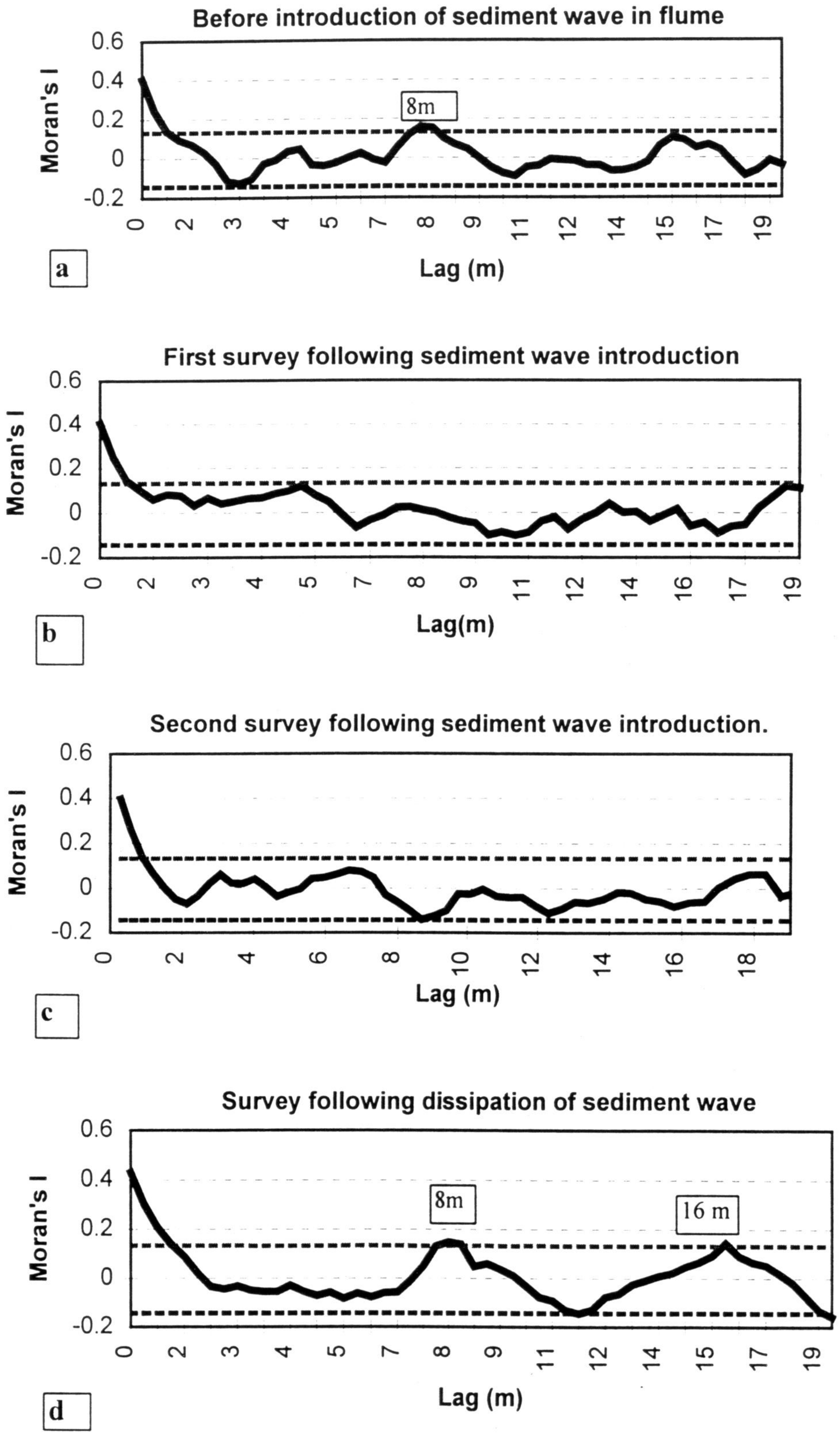


Figure 4.12: Correlograms for the four thalweg profiles shown in Figure 4.11.

thalweg elevation was still 4.2 cm higher than at the beginning of the run (Figure 4.11), indicating that there was still a net increase in the amount of sediment stored in the channel bed. Nevertheless, the channel had reorganized this excess sediment into regularly spaced bedforms, on the same scale as the original spacing, and a sediment wedge was no longer visually detectable by the researchers.

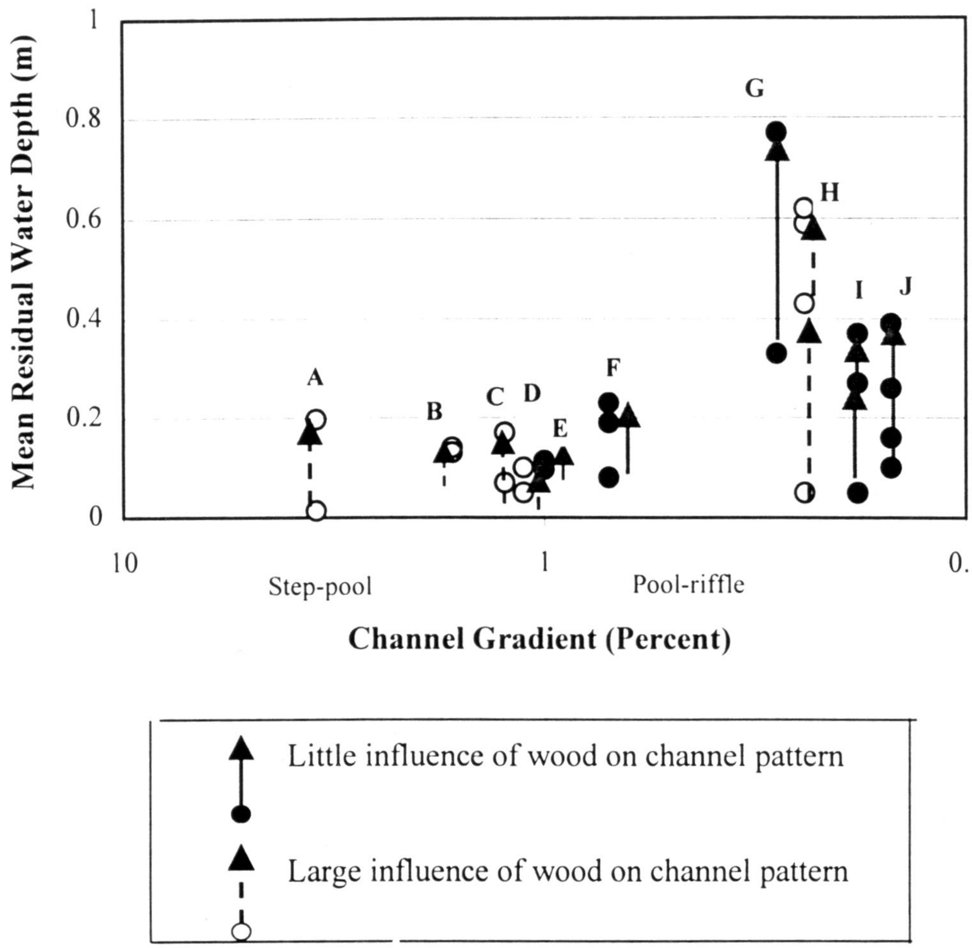
In this case study, the trajectory of stream channel evolution did not go through a phase of primary scale organization due to forced bars and pools (Figure 4.2), because the flume was devoid of such forcing mechanisms. In the absence of wood or bank irregularities, the channel reestablished its original structure and organization, and this occurred at a higher bed elevation than the original bed. The channel in the flume was able to reorganize the input of sediment into regularly spaced bedforms, with the appearance of the total dissipation of excess sediment, even though the in-channel supply of sediment was still elevated over the initial conditions, based on mean thalweg elevation. The processing of the sediment pulse in the flume was detectable through changes in channel organization, although not necessarily through tracking the movement of a distinct wave down the flume. This situation is similar to that of the downstream reaches of Redwood Creek, where cross-sectional surveys show the streambed is still elevated above 1975 levels, but where pools and alternate bars are developing regular patterns in this elevated channel (Madej and Ozaki, 1996).

4.6.8 Trends in Channel Structure and Organization

The results of the case studies presented above support the concept of increasing channel structure and organization with time since disturbance. Figure 4.13 summarizes the trends in mean residual water depth, in streams with various channel gradients. Initially following a sediment pulse, water depth was low, but depth increased with time following disturbance in all study reaches, whether or not wood was abundant.

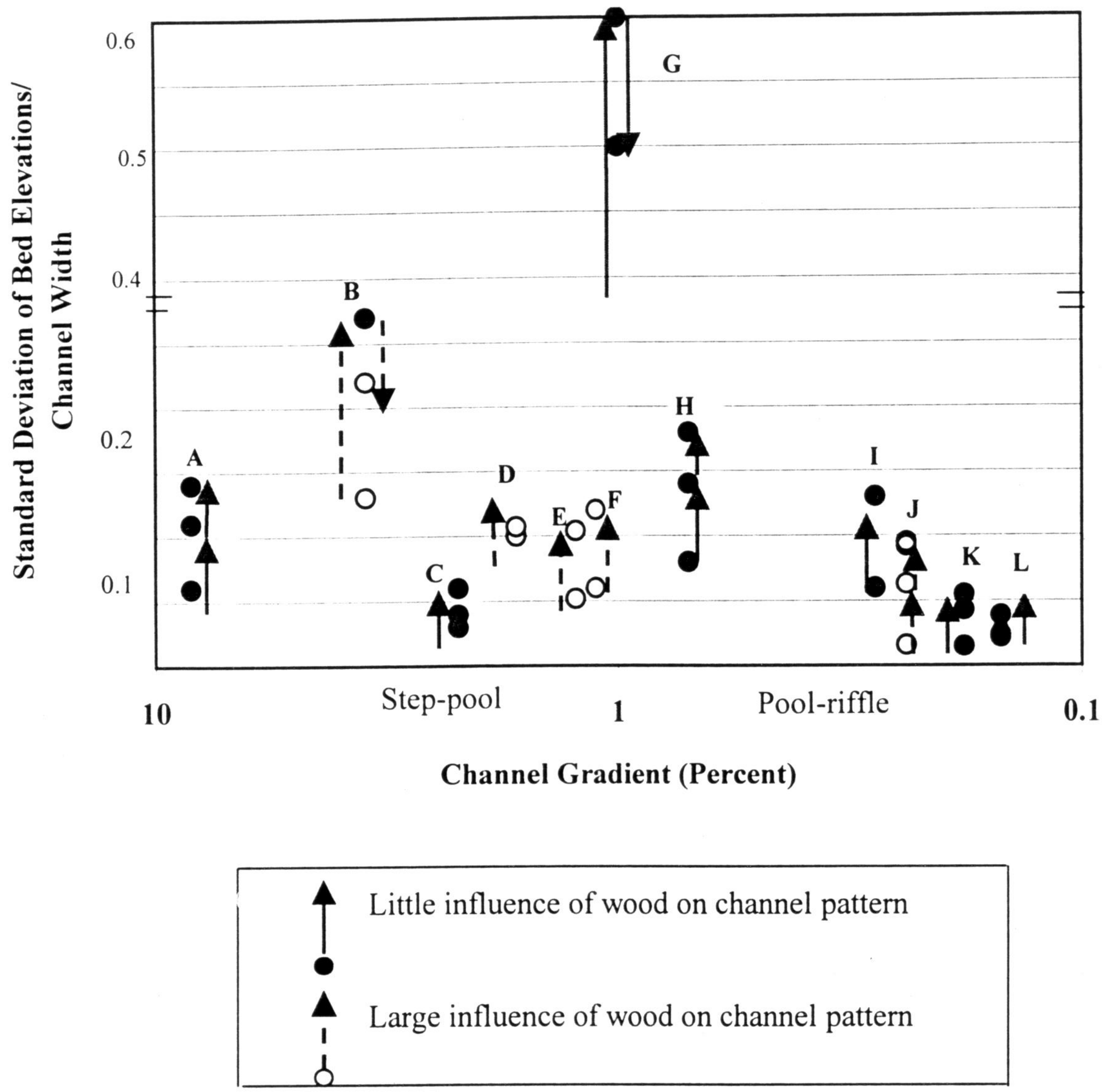
Figure 4.14 shows trends in the variability of bed topography through time. In almost all cases, variability of bed topography increased with time since a sediment pulse. Bed variability increased in most streams, both with and without high wood loading. One exception was in the study of three streams in the Oregon Coast Range ('B' in Figure 4.13). Kaufmann (1987) found that variability in a channel in which a debris torrent had occurred about 120 years ago was less than in another channel that experienced a debris torrent about 12 years before. This finding may be due to the fact that data of morphologic changes through time were not available from a single channel, and three different channels were used in the study. Another possibility is that much of the channel bed variability was influenced by large wood in the channel. As the wood decayed, there was a loss of structure, and thus variability, in bed topography.

In the flume, variability decreased in the runs following the sediment input, but at the end of the run, variability had again increased to pre-sediment input levels. The normalized value of bed variability in the flume plots much higher than for other reaches, but since the value of variability is scaled by channel width and the width of the flume channel was artificially controlled, this result is not surprising.



A - Oregon Coast Range Rivers
B - Bridge Creek Canyon
C- Bridge Creek, Upstream Reach
D - Bridge Creek, Downstream Reach
E- Flume
F - Lost Man Creek
G - Navarro River
H - Redwood Creek at Weir Creek
I - Redwood Creek at Bond Creek
J - Redwood Creek at Elam Creek

Figure 4.13: Trends in mean residual water depth with increasing time since sediment pulse

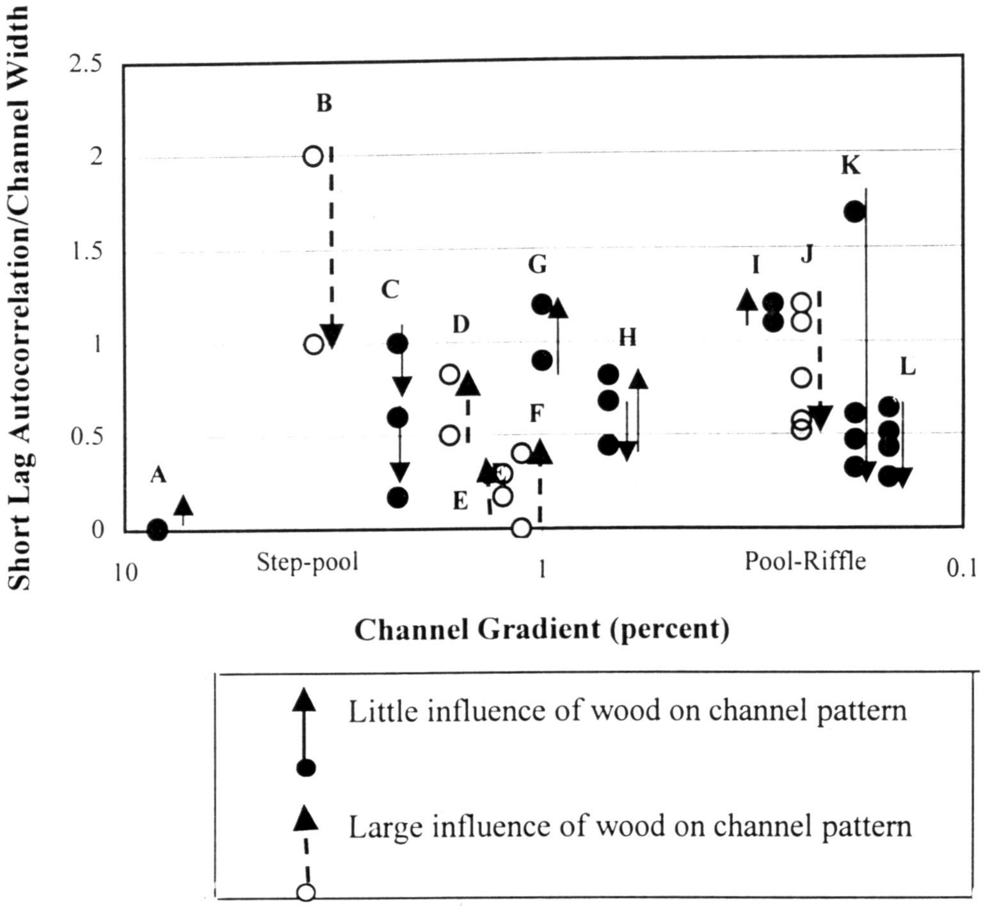


A - Higashigochi River
B - Oregon Coast Range Rivers
C - Smith Creek, Mt. St. Helens
D - Bridge Creek Canyon
E - Bridge Creek, Upstream Reach
F - Bridge Creek, Downstream Reach
G - Flume
H - Lost Man Creek
I - Navarro River
J - Redwood Creek at Weir Creek
K - Redwood Creek at Bond Creek
L - Redwood Creek at Elam Creek

Figure 4.14: Trends in variability of bed topography with increasing time since sediment pulse.

In the three Redwood Creek reaches, bed variability increased through time, but the increase was less in downstream, wider reaches ('K' and 'L' in Figure 4.14) than a narrower, steeper reach ('J'). This may be because continued channel aggradation in the downstream reach indicates that the channel is still processing high sediment loads, and topographic variability may not have yet reached the stage of development as the upstream reach. Alternatively, the variability of bed topography may not increase in a downstream direction as quickly as channel width increases, and so the normalized value of variability is smaller in downstream reaches. Bed variability also increased in the excavated stream crossings, but those results are not shown on this graph because a different survey procedure was used.

Figure 4.15 summarizes another indicator of channel organization, that of the short lag distance autocorrelation, scaled by channel width. This index represents the length of channel in which neighboring points are more alike than points farther apart. If the distribution of bed elevations is random (the bed elevation of adjacent surveyed points are not related) the value of the index is about zero. Two trends in this index were noted. One is illustrated by channels 'A', 'E', and 'F', which initially exhibited a random bed topography following a sediment pulse. Subsequent pool and bar development resulted in areas of the channel bed having similar elevations; i.e., there was an increase in the short lag distance of significant autocorrelation. The more common trend was that in which channels responded to a sediment input by a smoothing of the channel (filling in the pools) and a greater channel length in riffles, as in 'B', 'C', 'H', 'J', 'K', and 'L'. In these cases, there were initially long stretches of channel bed with

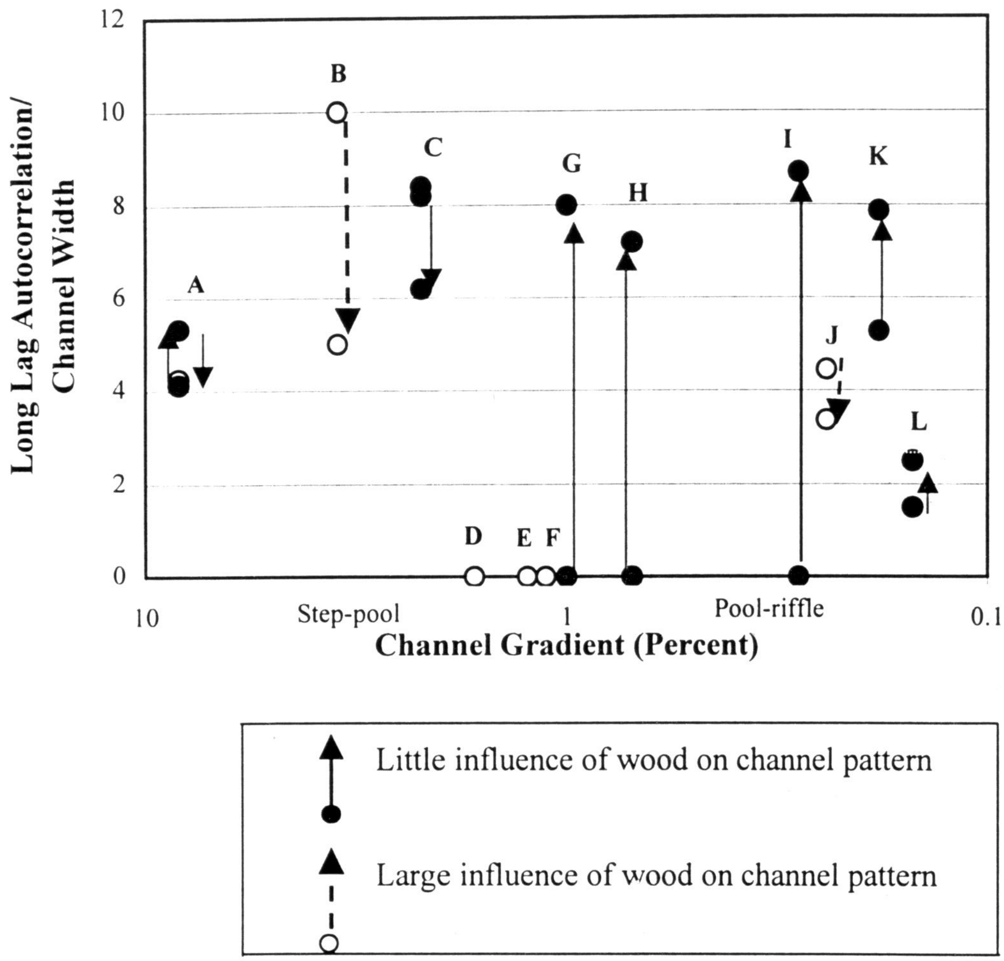


A - Higashigochi River
B - Oregon Coast Range Rivers
C - Smith Creek, Mt. St. Helens
D - Bridge Creek Canyon
E - Bridge Creek, Upstream Reach
F - Bridge Creek, Downstream Reach
G - Flume
H - Lost Man Creek
I - Navarro River
J - Redwood Creek at Weir Creek
K - Redwood Creek at Bond Creek
L - Redwood Creek at Elam Creek

Figure 4.15: Trends in short lag distance autocorrelation with increasing time since sediment pulse

similar bed elevations, with correspondingly high values of short lag distance autocorrelation. As the channel developed more pools and complex bed topography, the similarity between adjacent points diminished, and the lag distance of significant autocorrelation decreased with time. Both types of channel evolution, that from a random (low value) state and from a more uniformly flat (high value) state tended towards intermediate values of 'short lag autocorrelation/channel width' between 0.2 and 0.7. The flume channel 'G' did not follow either of the two types of trajectories, perhaps due to the lack of forcing mechanisms to add to bed complexity. Wood did not seem to be an important factor influencing the short lag distance autocorrelation. However, a limit in this type of study using many channel surveys is the resolution of the surveys themselves. It is difficult to compare values of short lag distance correlation without knowing the level of detail of the surveys, because the spacing between survey shots determines the scale of feature and autocorrelation that can be detected. For this reason, profiles from the Higashigochi River were not used in spatial autocorrelation analyses.

A fourth index used to describe channel structure and organization is 'topographic regularity,' defined by regularly spaced features such as steps, pools, and bars. At longer lag distances than the previous index, positive autocorrelation reflects the distance between similar channel units, such as pools and pools, or riffles and riffles. Figure 4.16 shows the trends in long lag distance correlation, which represents the degree of regularity of these types of bed features. In cases where surveys documented bed conditions immediately following a sediment pulse ('G', 'H', and 'I'), the channel bed initially showed no regularity (a value of zero), and subsequently regularity of



A - Higashigochi River	G - Flume
B - Oregon Coast Range Rivers	H - Lost Man Creek
C - Smith Creek, Mt. St. Helens	I - Navarro River
D - Bridge Creek Canyon	J - Redwood Creek at Weir Creek
E - Bridge Creek, Upstream Reach	K - Redwood Creek at Bond Creek
F - Bridge Creek, Downstream Reach	L - Redwood Creek at Elam Creek

Figure 4.16: Trends in long lag distance autocorrelation (topographic regularity) with increasing time since sediment pulse

bedforms developed through time. In channels 'K' and 'L', the length scale of regularity also increased through time. Theses streams, with well developed alternate bars and low wood loading, showed the most widely spaced regularity. Forcing elements in these five channels were absent or rare. In contrast, in channels 'D', 'E', and 'F', in which the bed was dominated by boulders and wood, no obvious regularity had developed within two years of a debris torrent. In channels 'B' and 'C' the initial surveys were conducted a few years following the sediment pulse, and bed conditions immediately following the pulse were not quantified. In these channels, the length scale of regularly spaced bedforms decreased with time, as forced pools and bars were formed by scour around obstructions. Channel 'J', with many forced pools around boulders and wood, followed this pattern as well.

In excavated stream crossings, not shown on Figure 4.16 because a different survey methodology was used, regularity in step spacing was developing in some of the channels, but was still less than that reported in the literature for other step-pool channels. Crossings without wood or coarse clasts, or with boulders too coarse to transport, showed little or no step development.

Channel organization can also be compared to the relative size of the sediment pulse entering the channel, as estimated in Table 4.1. Streams which had relatively small sediment pulses to process in relation to their mean annual load and did not have high wood loading ('H' and 'I') quickly regained widely spaced topographic regularity. In contrast, streams with larger sediment pulses in relation to their mean annual load ('C', 'J', 'K', and 'L') exhibited some degree of channel organization, but not the magnitude of change as in the other streams. (No data are available on the size of the sediment pulse for streams represented by 'B').

These results from many types of channels suggest that the degree of regularity and organization that develops in a channel depends on the time since disturbance and the presence of forcing elements that can influence channel morphology. Several surveys displayed no autocorrelation at longer lag distances, although these same surveys did show increased water depth and variability in bed topography through time. This observation suggests that the development of channel structure occurs more quickly than channel organization, which is consistent with the conceptual model introduced earlier.

4.6.9 Changes in Roughness Values Through Time

Both skin friction and form drag contribute to flow resistance in a channel. If a channel bed becomes coarser, the roughness due to boundary materials (skin friction) increases. In addition, as bed topography becomes more complex, and the heterogeneity of the channel bed increases, form roughness should also increase. Increases in form roughness should have the most influence at low to moderate flows, whereas the roughness due to bed topography would be drowned out at very high flows, when mean depth of water is much greater than the vertical dimension of bed topography. The hypothesis tested here is that an increase in bed form development detected in the study reaches should manifest itself in a concomitant increase in Manning's n roughness coefficient at low to moderate flows. Water discharge measurements collected at five gaging stations along Redwood Creek were used to test this idea. Up to twenty-five years of water discharge measurement records (1972 to 1997) were examined, using the relationship defined by the Manning's equation (Equation 4.3).

Besides bed topography, other factors, such as in-channel wood, meanders, abrupt changes in channel geometry and hydraulic jumps can theoretically contribute to flow resistance, but field observations show these factors are not important at the gaging stations used in this study. The channels at the gaging stations are highly confined, and have no floodplains; consequently energy loss during overbank flow is not a factor.

The trend exhibited by Little Lost Man Creek (Figure 4.17a), the control stream, is typical of gravel-bed channels (Barnes, 1967). Manning's n decreases with increasing discharge, and a residual plot based on Figure 4.17a (Figure 4.17-b) shows no time trend during the period of record (1973 to 1990); the coefficient for time is not statistically significant (Table 4.9).

At the upstream-most gaging station along Redwood Creek (Redwood Creek near Blue Lake), Manning's n also decreases with higher discharge ($r^2 = 0.50$) (Figure 4.18a). As might be expected, there is more variability at summer low flows when skin friction dominates than at high flows when both grain and form roughness are low. Figure 4.18b is a plot of the residuals based on the regression shown in Figure 4.18a. In contrast to the control stream, this plot suggests roughness increases through time at this gaging station (statistically significant at the 99% confidence level, Table 4.9).

Farther downstream, the gaging station 'Redwood Creek above Panther Creek' also shows an increase in roughness through time, but the relationship between roughness and discharge displays a somewhat different pattern. Manning's n decreases

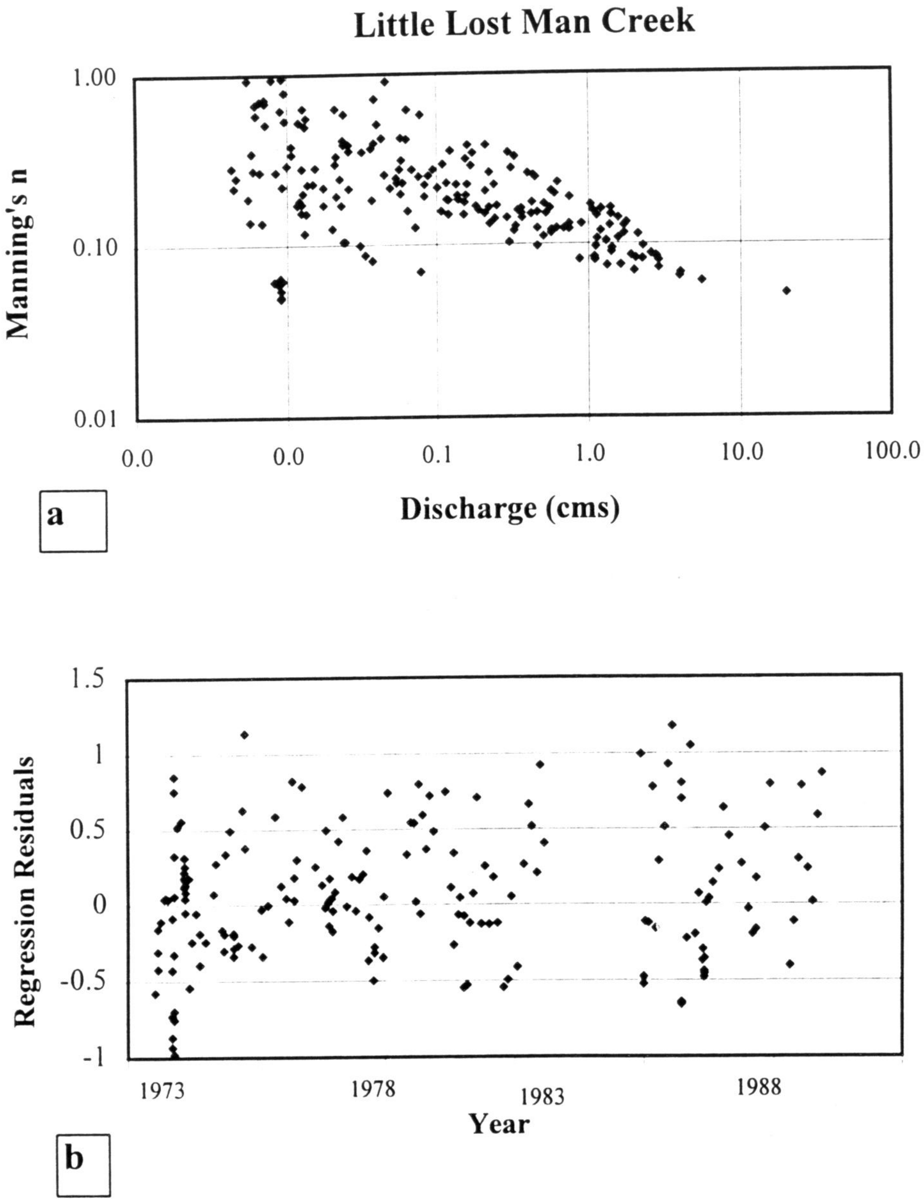


Figure 4.17a: Manning's n versus discharge at Little Lost Man Creek gaging station
b) Regression residuals versus time.

Table 4.9: Results of multiple regression analysis relating roughness values to discharge and time

Gaging Station	Period of Record	Number of Measurements	Adjusted r2	p-value for Discharge	p-value for Time
Little Lost Man Creek	1974-1988	133	0.48	0.0001*	0.7024
Redwood Creek at Miller Creek	1977, 1982	13	0.63	0.0022*	0.9414
Redwood Creek at Weir Creek	1977-1982	13	0.72	0.0004*	0.0922*
Redwood Creek at Panther Creek (Q < 10 cms)	1980-1988	41	0.66	0.0001*	0.0003*
Redwood Creek at Panther Creek (Q > 10 cms)	1980-1988	57	0.62	0.0001*	0.0001*
Redwood Creek near Blue Lake	1972-1997	287	0.72	0.0001*	0.0001*

* Variable is statistically significant at the 90% confidence level or better

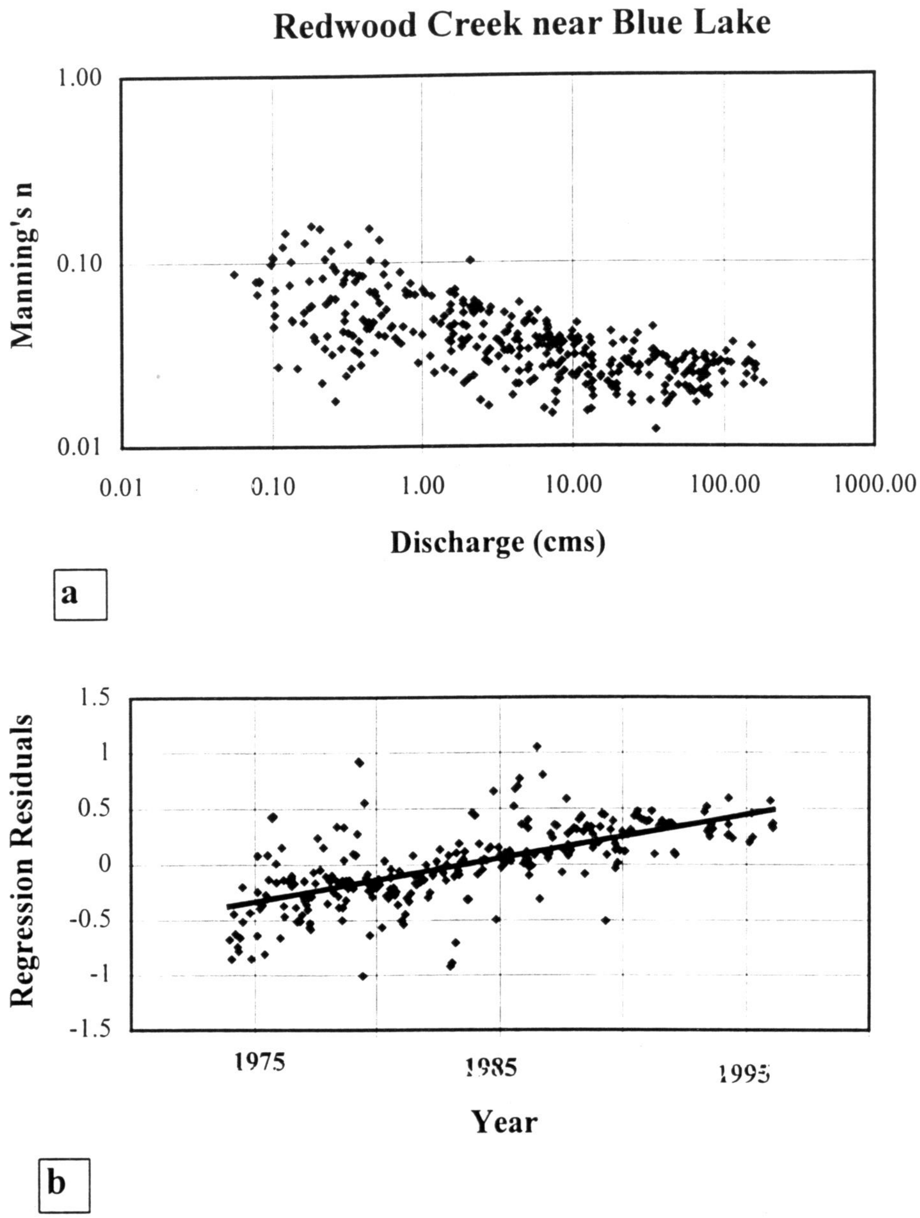


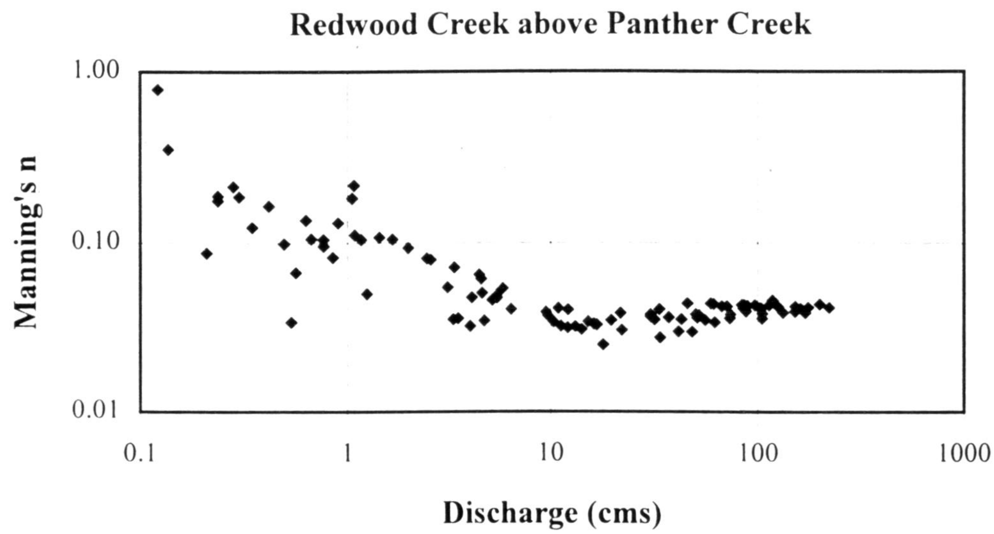
Figure 4.18a: Manning's n versus discharge at Redwood Creek near Blue Lake gaging station

b) Regression residuals versus time.

with discharge, but only until about 10 cms (average annual flow at this station is 16 cms). (Figure 4.19a). At higher flows, roughness actually increases slightly with increasing discharge. Because of the strong non-linearity in the discharge-roughness relationship, flows < 10 cms were analyzed separately from those > 10 cms. Over the period of record (1980 to 1988), the time variable in the multiple regression model was indeed significant at this gaging station for both analyses, and channel roughness increased through time across the full range of flows (Table 4.9).

The remaining two gaging stations used in this analysis were only monitored during high winter flows during 1977 to 1983, and no low flow measurements were available. Roughness did show an increase through time at Redwood Creek at Weir Creek (Figure 4.20a and b, Table 4.9), but the increase was not statistically significant at Redwood Creek at Miller Creek (Figure 4.21a and b, Table 4.9). The much smaller sample size at these stations hinders a complete analysis. Unfortunately, the gaging stations were discontinued and the cableways for sampling were dismantled, so additional high flow measurements were no longer possible.

At three stations, the expected pattern in gravel-bed rivers of decreased flow resistance at high discharges was actually reversed There are two possible explanations for this. First, at two of those stations, old-growth redwood trees up to 3 m in diameter line the streambanks. Although there is no floodplain in these confined reaches, as the stream stage increases, some flow resistance is contributed by the very large trees growing on the inundated banks. Nevertheless, channel widths are 35 to 60 m at these



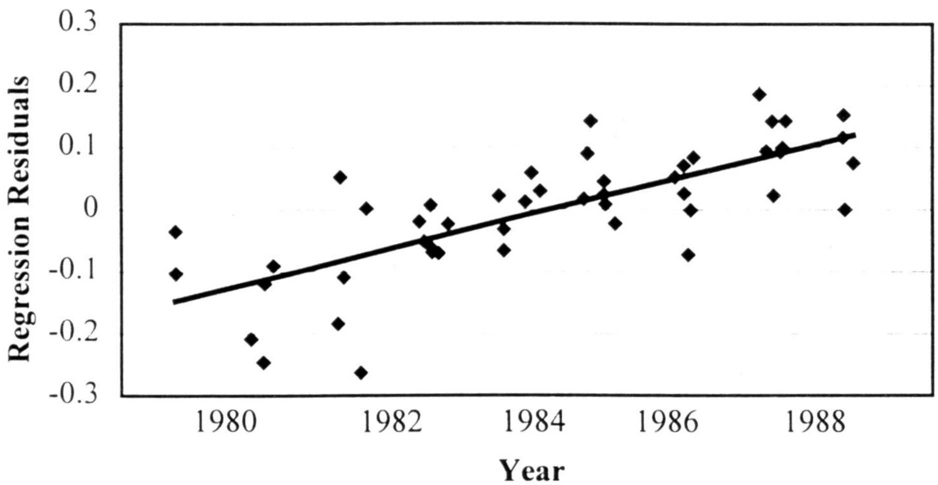


Figure 4.19a: Manning's n versus discharge at Redwood Creek above Panther Creek gaging station
b) Regression residuals (for Q > 10 cms) versus time.

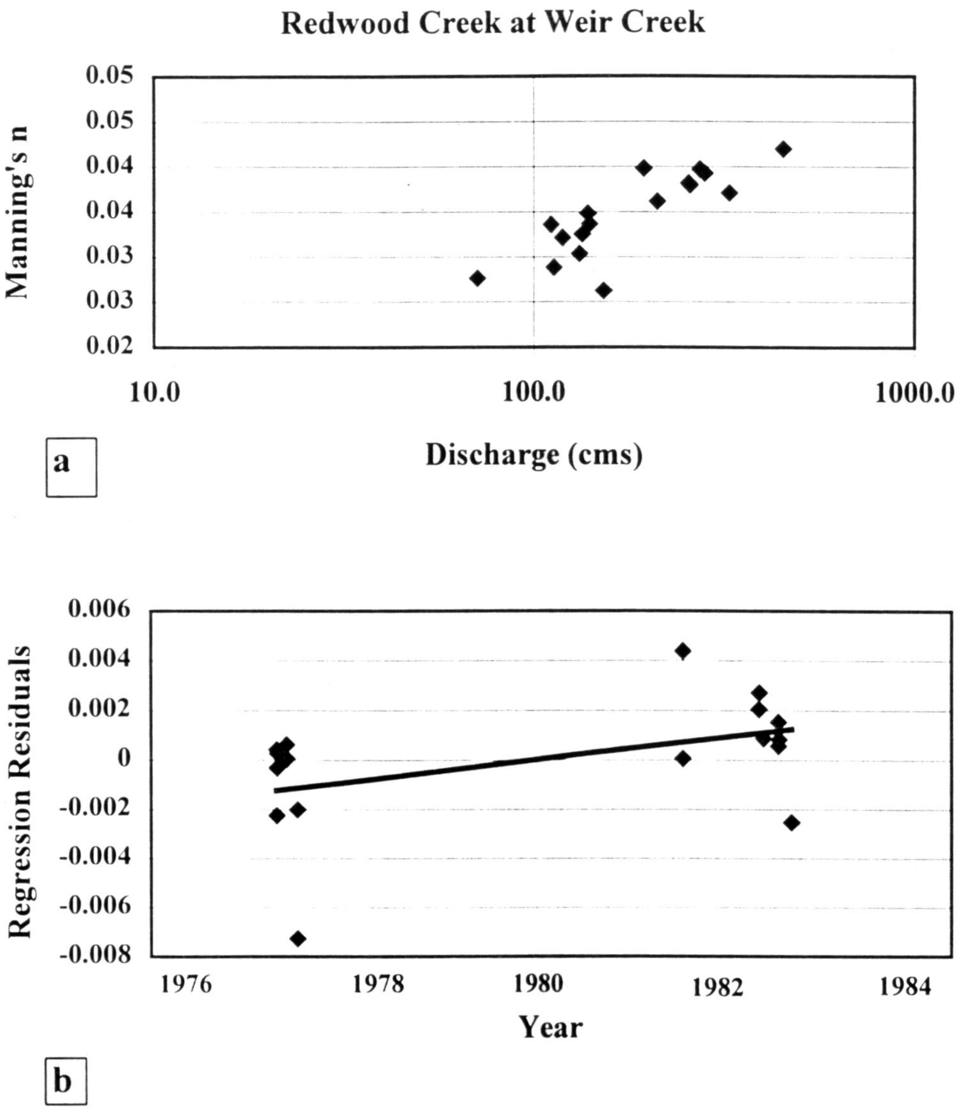


Figure 4.20a: Manning's n versus discharge at Redwood Creek at Weir Creek gaging station.
b) Regression residuals versus time.

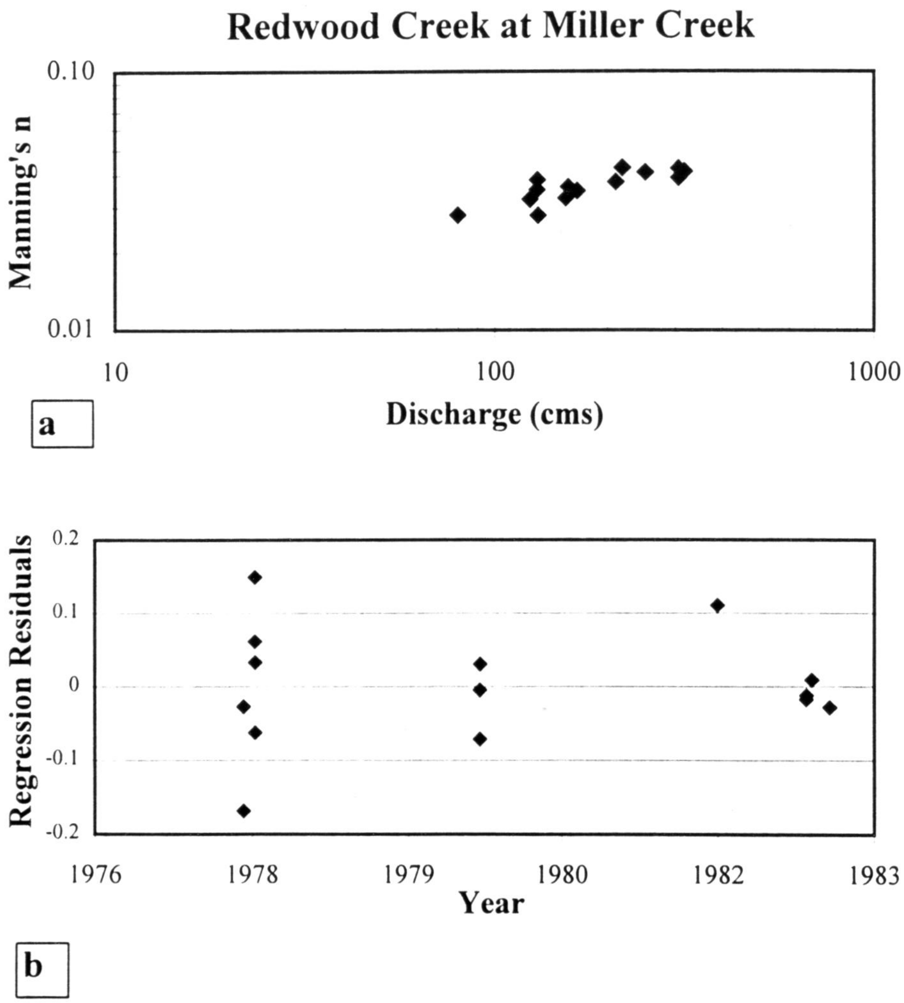


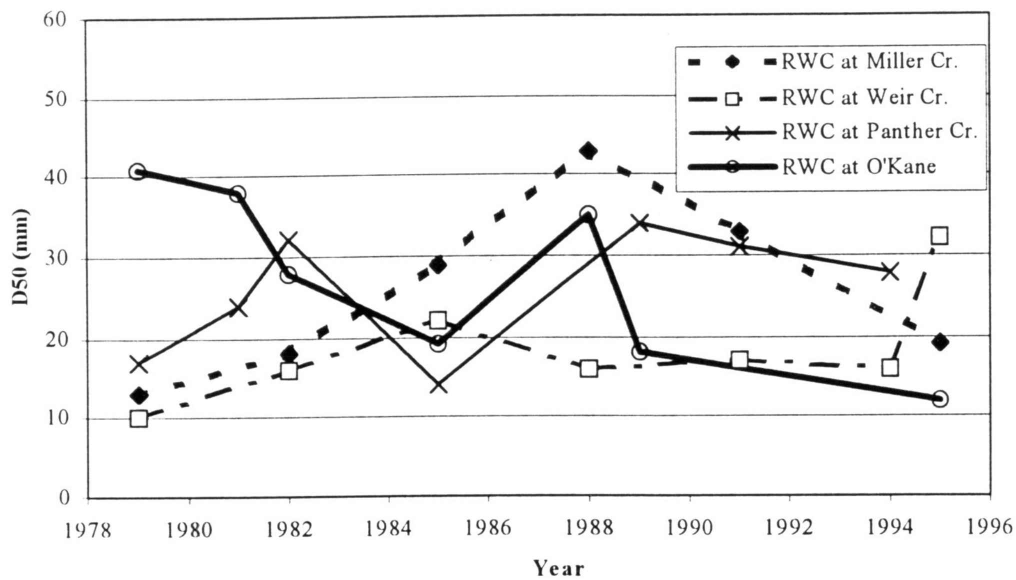
Figure 4.21a: Manning's n versus discharge at Redwood Creek at Miller Creek

b) Regression residuals versus time.

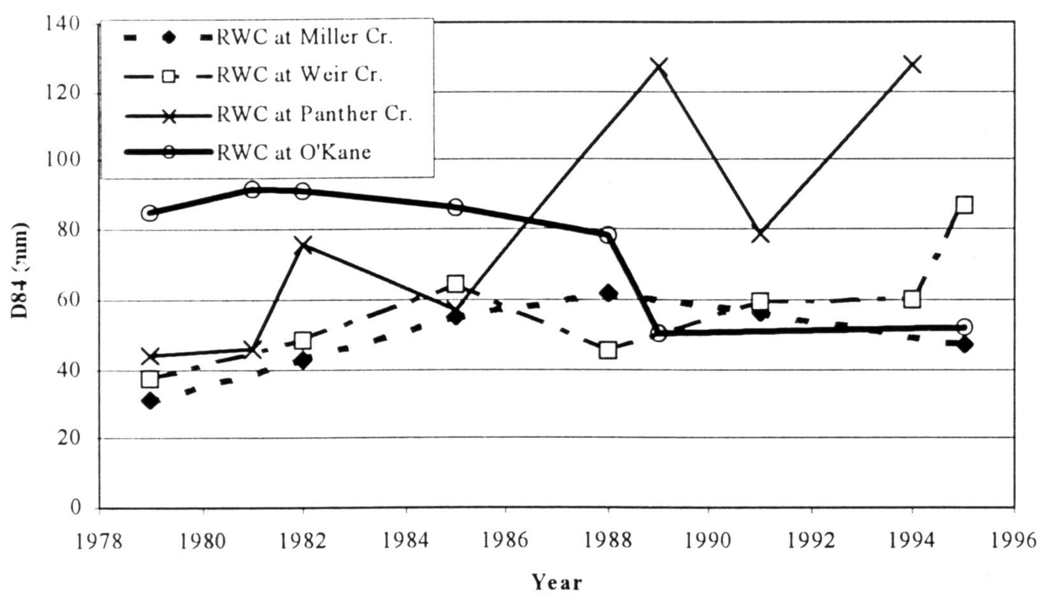
stations, so the influence of streambank vegetation on flow hydraulics across the entire channel is probably minimal.

Another explanation for increases in flow resistance is the change in bed topography at high discharges. Madej (1995) used soundings of water depth at gaging stations during floods to determine the depth of scour of the channel bed. The increase in cross-sectional relief of the bed topography during a single flow event varied from 0.6 m at Redwood Creek at Weir Creek to 1.2 m at Redwood Creek at Miller Creek. Following the flood wave, the channel bed returned to its pre-flood configuration. This suggests that changing bed forms, analogous to ripples and dunes in sand-bed rivers, contributes to flow resistance in the easily mobilized, gravel-rich reaches of Redwood Creek at high flows. This topic warrants further investigation

Channel roughness increased through time at three of the Redwood Creek gaging stations, whereas there was no significant change in roughness values in a pristine, unlogged stream used as the control reach (Table 4.9). The increases in flow resistance are consistent with either a coarsening of the channel bed through time or increased development of bed topography, or both. To analyze the possible effects of increased particle size on roughness values, size distribution data based on pebble counts at the gaging stations were analyzed. These results show mixed trends (Figure 4.22a and b). Although pebble counts were centered on a given channel cross section each year, the total area of channel bed area sampled each year varied with different survey crews. This causes a problem in interpreting the results because, for example, a crew may have sampled a fine-grained eddy deposit one year, but not have included it in the sample area



a)



b)

Figure 22a: Changes in D_{50} based on pebble counts at gaging stations
22b: Changes in D_{84} based on pebble counts at gaging stations

another year. Because the pebble counts were not necessarily conducted in a standardized manner, these results should be used cautiously.

Although the pebble count data have these constraints, some generalizations can be made. Redwood Creek near Blue Lake, which had a significant increase in roughness values through time, actually showed a decrease in surface bed particle size during the same period. Other factors, such as more pronounced bed relief, must be responsible for the increase in flow resistance. At the two other stations exhibiting increased roughness values through time (Redwood Creek above Panther Creek, and Redwood Creek at Weir Creek), the channel bed surface did coarsen during the same period. Skin friction at the gaging stations has the vertical dimension of 30 to 130 mm (range of D_{84} in the channel bed). In contrast, the vertical dimension of bed topography (the depth of pools and heights of bar faces) is 1 to 3 m. Because the increase in flow resistance is seen at all stages, not just low flow, it is probably due to the development of bed topography as well as coarsening of the bed. This idea is supported by Prestegaard (1983), who showed that bar resistance accounts for 50 to 75% of total resistance in wide, low sinuosity gravel-bed streams.

4.7 Geomorphic and Biological Implications of Research

There are several geomorphic and biological implications of this study. For example, the development of channel structure and organization influences the roughness of a channel. Increasing bed variation and development of bedforms should lead to higher roughness values due to form drag. Increased development of bedforms and increased variability of bed topography will influence the distribution and magnitude of secondary flows within a channel. An understanding of the spatially varied conditions of the channel bed may further the understanding of non-uniform flow. Increased development of channel structure can decrease the mobility of the channel bed (Church et al., 1998) and hence influence the sediment transport regime. Models of sediment routing could benefit from a knowledge of channel organization, because how a channel processes its sediment load in one part of the channel network obviously influences the timing and magnitude of sediment input to reaches farther downstream. The sequential linking of different types of channel organization in a drainage network is related to the 'disturbance cascade' model proposed by Nakamura et al. (in review) which considers shifts in disturbance patches along channels. Channel structure plays an important role in providing aquatic habitat, and the types and scales of roughness elements influence the distribution of microhabitats, benthic invertebrates, and channel complexity. Some aspects of aquatic habitat can be defined by the degree of spatial variation and structure of the channel bed.

Chapter 5

Conclusions

5.1 Summary

In this research, several aspects of hillslope and channel recovery following watershed disturbances were examined. Some disturbances are natural, such as floods, volcanic eruptions, debris flows and fires. In this study, however, the primary disturbances that were explored (increased rates of sediment production from roads, landslides, and timber harvest activities) were anthropogenic. Two aspects of recovery following disturbances were explored: reductions in sediment production from disturbed hillslopes, and the development of channel structure and organization.

The recovery of hillslopes and streams was documented following two types of restoration. Active restoration involved excavation of road fill and culverts from stream crossings, and reshaping road benches. Extensive heavy equipment work and earth moving were involved in this restoration work of hillslopes and low order channels (Chapter 2). The approach used in larger stream channels was one of passive restoration, in which streams were allowed to process the imposed sediment load naturally, without intervention by heavy equipment dredging, in-channel structures, or streambank reconfiguration (Chapter 3). At both active and passive restoration sites, channel structure, organization, and roughness increased through time (Chapter 4).

The analysis in Chapter 2 examined post-treatment erosion of both stream crossings and road reaches during the two decades following removal of forest roads.

Post-treatment erosion of both crossings and road reaches was highly variable. Almost 80% of the treated road reaches had no detectible erosion following a 12-year recurrence interval storm. Even though most treatment sites were heavily vegetated within a few years of treatment, road fill failures still occurred on 20% of the road reaches. Hillslope position was an important variable in explaining post-treatment erosion of road reaches. Sediment delivery from treated roads in upper, middle and lower hillslope positions was 10, 135, and 550 m^3 of sediment/kilometer of treated roads, respectively. On steep, lower hillslopes, no treatment method was totally effective in preventing erosion, and both minimal (ripped and drained) and more intensive (export outsloped) road treatments were associated with high sediment yields to streams. In contrast, in upper, convex hillslope positions, all treatment styles worked well. In stream crossings, post-treatment erosion was most strongly correlated to a surrogate for stream power (drainage area * channel gradient) and the amount of road fill excavated from the stream crossing during treatment. By eliminating the risk of stream diversions and culvert failures, road treatments significantly reduce the long-term sediment risk from abandoned roads.

Chapter 3 employed a statistical analysis of series of residual water depths as a method to quantify changes in channel bed variation and bed pattern on a reach scale. During the 22 years following a large flood and associated landsliding in 1975, the distributions of residual water depths changed significantly, and the degree of bed heterogeneity was related to the time since disturbance. Mean residual water depth and depth variability increased through time, while the length of channel occupied by riffles decreased. Following a 12-year return period flood in 1997, and its associated sediment inputs, these trends in recovery reversed, and variation in the thalweg profiles decreased.

A variation index [(standard deviation of residual water depths/bankfull depth)*100] was developed to compare the variation of residual water depths in streams of different sizes. Increased variation of residual water depths was indicative of increased spatial heterogeneity of the physical environment, which is assumed to contribute to increased diversity in biological communities. The variation index was highest (> 20) in the study reaches with the smallest quantities of remaining flood deposits, and the index shows promise as a tool to indicate more favorable stream habitat conditions.

The use of spatial statistics to define channel structure and organization was also explored, and was found to be a promising technique for objective monitoring of changes in bed topography following disturbance. Study reaches represented a range of channel types, and scales of autocorrelation were identified through spatial analysis. Short lag distance autocorrelation decreased through time, which is consistent with the observed decrease in the length of channel in riffles documented by the thalweg profiles. Autocorrelation at longer lag distances corresponded to the length of alternate bar units in the channels (five to eight channel widths) and to pool spacing (about three channel widths in systems with many forced pools). Pools are more frequent in Redwood Creek than might be expected in a simple alternate bar system because of the presence of large woody debris and other obstructions which form forced pools.

Variation in both residual water depths and their spatial characteristics can be used to characterize the development of channel bed pattern following large inputs of sediment. The ability of the channel to reorganize inputs of woody debris and sediment determines the degree of subsequent bed organization. Stream reaches which could readily reorganize hillslope inputs (particle size was much less than bankfull depth, length of large woody debris was less than channel width, and frequency of organizing flows was high) developed both increased bed heterogeneity and organization within two decades following disturbance. Streams that had a lower frequency of organizing flows (step-pool systems) also displayed increased bed variability and roughness due to step development within 10 to 20 years of channel excavation. Nevertheless, they have not yet developed the characteristic length scales and spacing that are typical in natural step-pool systems, and development of channel organization is slower in these streams. Although the planform in low gradient channel reaches remained about constant during the monitoring period, the longitudinal expression of alternate bar units became stronger with increasing time since the last flood.

The results presented in Chapter 4 support a conceptual model which proposes trajectories of channel recovery following sediment pulses in streams over a range of channel gradients. A sediment pulse commonly diminishes channel structure, organization, and roughness. All the case studies presented in this paper followed this general pattern of decreased bed variability following a sediment pulse. Bed variability and development of forced pools and bars subsequently increased with the number of organizing flows (flows greater than critical discharge). The model also suggested an increase in spatial organization of the channel bed through time. The results of this study provide evidence that more time is required to organize the channel into regularly spaced bedforms than to develop an increase in bed variability and structure.

The development of regularity in the beds of Redwood and Bridge Creeks from 1977 to 1995 indicates the self-adjusting nature of channels. Fluvial processes were able to organize previously random hillslope inputs into regularly spaced bed forms; the reverse happened in response to a flood and debris torrent in 1997. Regularity in streams with forcing mechanisms, such as large in-channel wood and bedrock outcrops, develops at a shorter scale (two to five channel widths) than in streams without such forcing mechanisms (five to eight channel widths). Because of randomly distributed bedrock outcrops, wood, and other obstructions, rivers in nature will not display as regular a spacing as a channel in a flume. A channel in a flume experiment exhibited self-organizing behavior that processed sediment inputs into regularly spaced bedforms, even without transporting all the 'excess' sediment out of the reach and attaining previous bed elevations.

Geomorphic recovery, as proposed by Wolman and Gerson (1978), requires the attainment of a pre-existing landform. Geomorphic work in stream channels not only entails a transport of material and a change in form, but also a reorganization of bedforms. Through this research, I suggest that measures of geomorphic effectiveness can include not only channel form, but also the arrangement of channel features following a disturbance.

Roughness increased through time at several gaging stations in Redwood Creek during the same time period as the relief of bed topography was increasing. Because neither bed material size nor riparian vegetation changed significantly at these sites, the development of bedforms probably plays an important role in the observed increase in flow resistance in the channel. The development of bed topography in a gravel bed river contributes to channel roughness and flow resistance, and can influence bed particle mobility. By identifying scales of longitudinal bedforms, we may increase the understanding of sediment transport and alluvial sedimentation.

5.2 Land Management Implications

Adaptive land management involves monitoring the effects of management activities, and modifying land management approaches and techniques based on what is found to be effective. The results of Chapter 2 can be used by land managers in designing future road removal work in the most cost-effective manner. Minimal treatment is sufficient in reducing sediment production from low risk sites (in this basin, convex, upper hillslope roads), whereas more intensive treatment is needed for high risk sites (in this case, steeper lower hillslope roads. By identifying factors associated with road failures, these results also can help prioritize roads for treatment. In conjunction with mapping of existing roads, the results from this research can be used in an evaluation of erosional risks from forest roads across a landscape. In addition, the assessment presented here can serve as a framework for evaluating the success of other watershed restoration programs. Although erosion rates measured in this study are specific to the site conditions of the Redwood Creek catchment, this approach can be adapted to other regions. Accelerated erosion rates are a widespread problem in many regions of the world, and road treatments can be effective in significantly reducing sediment yields from forest roads. A study of changes in sediment production is important in interpreting cumulative effects in a watershed as well.

An issue of concern in the Pacific Northwest regarding management of forested lands is the range of morphological diversity in natural systems. Under many ecosystem management activities, land managers attempt to replicate the range of natural variability in watershed processes. To date, variability in the magnitude and frequency of many processes has not been adequately quantified. The disturbance regime in a watershed effects the range of variability in channel conditions. The results presented here provide a basis upon which to compare variability of longitudinal profile patterns in different sized streams and in response to large floods and associated sediment loads.

The development of channel structure and organization has important biological implications. Changes in sediment inputs and resulting changes in channel morphology are important considerations in ecosystem studies. Increased bed heterogeneity and organization cause increased channel complexity and form a variety of aquatic habitats. Ecosystem influences of such channel changes include: the availability and connectivity of aquatic habitat and refugia, quality of spawning and rearing areas, channel sediment textures, fish migration barriers, nutrient and organic matter exchanges between rivers and floodplains, frequency of overbank flooding with associated fine sediment deposition, the creation of off-channel habitat and sites for plant colonization, distributions of riparian and floodplain communities, the magnitude and frequency of bedload transport, stream temperature regimes, hyporheic flow patterns, links between abiotic and biotic factors in the ecosystem and the links of upslope watershed conditions to channel disturbances. An understanding of the trajectories of physical recovery in disturbed stream systems will thus help predict the biological response to disturbances.

The development of channel bed structure and organization through changes in bed topography also affects the hydraulics of a river. Increased bed relief may cause increased flow resistance, turbulence in the flow, and secondary circulation patterns. This study of channel morphologic changes in a gravel-bed river will help future efforts in modeling hydraulics in gravel-bed rivers.

Sediment pulses are of concern to land managers because they influence sediment routing, sediment input to downstream reaches and reservoirs, and the stability of infrastructure features, such as bridge crossings and buried pipelines. The effect of sediment pulses on a channel may not always be detectable by a distinct sediment wave moving downstream. Instead, this research showed that more subtle changes in channel structure and organization can also accompany sediment pulses.

5.3 Future Research

This research focused on two scales in the channel network. Road restoration work focused on hillslopes and low-order channels, whereas sediment pulses were studied in higher order channels. In the future, road restoration techniques could be applied according to an experimental design, which would help sort out the confounding variables present in this study. Locations of erosion on treated roads were highly variable, and a closer examination of site specific conditions underlying erosional problems is warranted. The hydrologic effects of road removal should be studied in addition to changes in sediment production. Finally, more information on the linkage of sediment routing from small to large channels is needed

The present work examined stream channel variation in the downstream direction. It would be useful to consider interactions of sediment pulses, channel morphologic changes, and the formation of floodplains and side channels, which provide critical refuge for juvenile fish. Although this particular fluvial system is constrained by narrow valley bottoms and bedrock outcrops, studies of cross-channel changes following sediment pulses in more unconstrained rivers would be worthwhile.

Not all stream systems are expected to perform as the conceptual model in Chapter 4 suggests. For example, a low-variability bedrock-dominated stream that receives a sediment pulse may actually respond by an increase in variability with the addition of movable material. Likewise, a sediment pulse accompanied by large amounts of woody debris could conceivably cause many forced pools and increased channel complexity. However, channel changes in many types of situations followed the trajectories proposed by the conceptual model. As a sediment pulse is processed by a stream system, the channel structure, organization, and roughness will change, and the manifestation of a sediment pulse may be reflected in changes in these elements. Future research will focus on examining such changes under a wider range of field conditions.

Fluvial systems may be ordered, complex or chaotic. The relevance of self-organization of fluvial systems has been addressed in the formation of channel networks (Turcotte, 1997), but it is just beginning to be explored on the scale of channel reach dynamics. For example, a single thread channel with a high imposed sediment load can become a braided system, which has been shown to be chaotic (Sapozhnikov and Foufoula-Georgious, 1999). As a braided river processes sediment pulses and transports its imposed load, the river can revert back to a single thread, ordered channel. The phase transition between a chaotic, braided system and a deterministic, self-organized, alternate bar system needs to be explored more fully. The present research suggests that scales of organization can be identified in disturbed fluvial systems, and that much more work can be done in this area.

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Appendix

Field Form for Inventory of Roads on Past Watershed Rehabilitation Sites

SITE INFORMATION AND SUMMARY

1. Rehab Project #____________ 2. Work Site #__________
3. Rehab Project Leader_____
4. Date Mapped:_____________ 5. Mapped By: ________________
6. Watershed:____________________________ 7. Quad ID:_________
8. Site type: [**1**]Crossing, [**2**]Landing, [**3**] Road Reach, [**4**] Ditch/Road Relief, [**5**] Skid trail [**6**] Other
9. Erosion Process: [**1**]Fluvial (Sec.I) [**2**]Mass movement (Sec. II) [**3**] Both [**4**] None

ROAD INFORMATION

10. Road Name:__________________________________
11. Year of Construction______________ 12. Year of Rehab.__________

CONDITION OF FILL:

13. [**1**]Intact, [**2**]Sag, [**3**]Ponded H_2O, [**4**]Cracks, [**5**]Scarps, [**6**]Holes, [**7**]Gully/Rills [**8**] Seeps
14. Fill Failure Potential? [**1**]Yes, [**0**]No

REHABILITATION INFO.

15. Primary Treatment [**1**]Total Outslope, [**2**]Partial Outslope, [**3**]Export Outslope [**4**] Total Excavation [**5**]Partial Excavation [**6**]Ripped [**7**] Drained, [**8**]Fillsite [**9**]None [**10**]Other
16. Secondary Treatment [**0**] None [**1**] Rocked Channel [**2**] Straw Mulch [**3**] Wattles [**4**] Check dams [**5**] Contour Trench [**6**] Other
17. Top Soil Restored? [**1**]Yes, [**0**]No [**2**] Unknown

Vegetation:

18. Revegetation Treatment: [**1**] Conifer seedlings, [**2**]Grass Seed, [**3**]Willow [**4**] Alder seed [**5**]Alder seedlings [**6**] Other

Existing Vegetation:	Avg. Ht.	Avg. Stem Spacing	RANK
Redwood	19________ft.		20 ________
Douglas Fir	21 ________ft.		22 ________
Alder	23 ________ft.	24_______ft.	25 ________
Tanoak	26________ft.		27________
Madrone	28________ft.		29________
Shrubs	30 ________ft.		31________
Herbaceous-Mesic/Xeric	32 ________% cover		33 ________
Herbaceous-Hydrophytic	34________% cover		35________

36. Exotics present: [**1**] Foxglove [**2**] Pampas Grass [**3**] Scotch Broom [**4**]Tansy Ragwort [**5**]Other

SOIL CHARACTERISTICS

37. Bedrock: [**1**]Schist **[2]** Sandstone **[3]** Other

38.Soil Code (see list)___________________

39. Soil Depth: [**1**]<50cm, [**2**]50-100cm, [**3**]>100cm

SECTION I: FLUVIAL EROSION SITE

EXISTING FEATURE:

40. [**1**]Gully, [**2**]Bank Erosion, [**3**]Channel Incision **[4]**Rilling/Surface Erosion, [**5]**Spring

CHANNEL DESCRIPTION

41. Grade of crossing______% 42. Grade: Upstream______%

43. Downstream______%

44. Channel Width: at crossing ______ ft. 45. Upstream._______ ft.

46. Downstream._______ ft.

47. Length of excavated crossing _________ ft.

48. Total Drop ___________ft.

49. Drop due to wood: _____________ft.

50. Drop due to rock: ____________ ft.

51. Number of wood steps ___________

52. Number of rock steps __________

53. Dominant Bed Material: [**1**]Sand, [**2**]P/C, [**3**]Bldrs, [**4**]BedRk, [**5**]SmOD, [**6**]LrgOD **[7]**Fill

54. Bedload Transport [1]High, [2]Moderate [3] Low

SITE DESCRIPTION

55. Diversion Potential? [**1**]Yes, [**0**]No

56. Now Diverted? [**1**]Yes, [**0**]No

57. **Comments**:

SECTION II: MASS MOVEMENT SITE

FEATURE TYPE:

58. [**1**]Earthflow, [**2**]Shallow debris slide, [**3**]Rotational Slump
[**4**]Debris Torrent, [**5**]Cutbank Failure, [**6**]Fill Failure
[**7**] Failure of Excavated Fill

SLOPE POSITION AND FORM

59. Hillslope: [**1**] Upper, [**2**] Middle, [**3**] Lower, [**4**] Inner Gorge
60. Topographic: [**1**] Concave, [**2**] Planar, [**3**] Convex
61. BIS? [**1**]Yes, [**0**]No
62. Slope Above__________ %
63. Slope Below__________ %
64. Distance to stream ________ ft.

FEATURE DESCRIPTION

65. Level of Activity: [**1**]Active, [**2**]Waiting, [**3**]Totally Evacuated

66. Average Scarp height:_______________ ft.
67. Range of scarp heights:_______ ft.
68. Features Present: [**1**]Cracks, [**2**]Scarps, [**3**]Ponded Water,
[**4**]Sagging, [**5**]Holes, [**6**]Leaning Trees, [**7**]Spring, [**8**]Stream Channel Undercutting, [**9**]Excess H_2O Diverted onto Feature
[**10**] Buried Wood Exposed

69. **Comments**:

SECTION III: TOTAL EROSION VOLUMES

EROSION VOLUMES I. FLUVIAL EROSION ON-SITE	Eroded Before Rehab	Excavated in Rehab.	Erosion Since Rehab	Erosion Potential (In 20-yr flood)
Road Fill at Crossing:	70 ____ yd^3	71. ____ yd^3	72. ____ yd^3	73 ____ yd^3

OFFSITE i.e., from a diversion, or upstream or downstream impacts of crossing failure.

Offsite	74. ____ yd^3		75. ____ yd^3	76. ____ yd^3

II. MASS MOVEMENT

Total Volume-Onsite	77 ____ yd^3	78. ____ yd^3	79 ____ yd^3	80 ____ yd^3
-Offsite	81 ____ yd^3		82 ____ yd^3	83 ____ yd^3

TOTAL VOLUME:

Total Volume Moved:	84 ____ yd^3 (70+74+ 77+81)	85 ____ yd^3 (71+78)	86 ____ yd^3 (72+75+ 79+82)	87 ____ yd^3 (73+76+ 80+83)

Percent Delivery to Channel	88 ____ %	89 ____ %	90 ____ %
Total Yield to Channel	91 ____ yd^3 (% x 84)	92 ____ yd^3 (% x 86)	93 ____ yd^3 (% x 87)

94. Road Type: [1] Cut and Fill [2] Full Bench

Comments: (For example, provide comments on Extreme Erosion: Nature & Likelihood)