STREAM CHANNEL ADJUSTMENTS FOLLOWING LOGGING ROAD REMOVAL IN REDWOOD NATIONAL PARK

REDWOOD NATIONAL PARK

WATERSHED REHABILITATION

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TECHNICAL REPORT 23

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WATERSHED REHABILITATION PROGRAM

In 1978, under the authorization of P.L. 95-250, the National Park Service implemented a program of watershed rehabilitation within the Redwood Creek basin. The goals of the program are to reduce sources of man-induced erosion and to restore naturally-functioning redwood and related ecosystems on logged lands within the park. Results are presented in technical reports, journal articles, and symposia proceedings.

NOTICE

This document contains information of a preliminary nature, and was prepared on an interim basis. This information may be revised or updated.

STREAM CHANNEL ADJUSTMENTS
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Redwood National Park Watershed Rehabilitation

Technical Report Number 23

by

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National Park Service
Redwood National Park
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ABSTRACT

The excavation of road fill from stream crossings on former logging roads is a major focus of the watershed restoration program in Redwood National Park. Channel adjustments in response to winter stormflows were measured on 24 newly excavated stream crossings to identify the relative importance of on-site independent variables.

Two dependent variables, channel erosion and surficial channel bed armor size, were statistically related to sets of independent variables measuring stream hydraulics and stream bank material properties in two series of regression analyses. In the channel erosion series, the final regression equation incorporated as significant predictors (in order of decreasing predictive importance) total stream power, the percent boulder and cobble content of streambank materials, and the percent stream elevation drop composed of organic debris steps.

Of primary importance in explaining the variability in channel erosion was total stream power of the peak flow of the study period, which was directly related to channel erosion. The boulder and cobble content of stream bank materials, inversely related to channel erosion, was second most important among predictors. Because the best fit was obtained using the square of this quantity, it is inferred that the potential for erosion decreases as a power function of increasing coarse fragment content of eroding materials, all other factors being equal. The percent of stream elevation drop composed of organic debris steps was inversely related to channel erosion because it provided for energy dissipation and hydraulic resistance.

In the channel bed armor size regression series, the final regression equation incorporated (in order of decreasing predictive importance) total stream power and percent of the stream elevation drop composed of organic debris steps as significant predictors. Being inversely related to channel bed armor size, the presence of organic debris steps partially offset the channel armoring demands of total stream power.

To minimize channel erosion following stream crossing excavation, consideration must be given to the relative magnitudes of driving forces (stream power) and resisting forces (coarse fragment content of bank material and level of organic debris control of the stream profile). In proposed excavations where resistance to erosion is anticipated to be low and stream power is expected to be high, excessive channel adjustments may be avoided by use of channel protective measures such as installation of check dams, importation of rock armor, or emplacement of organic debris.

ACKNOWLEDGEMENTS

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Finally, I would like to extend my gratitude to my graduate committee members Dr. William Weaver, Dr. Robert Ziemer, Dr. Andre Lehre, and Dr. Carl Yee, for their excellent reviews of the thesis drafts. In particular, I am greatly indebted to Dr. Weaver for once again allowing me to benefit from his uncanny powers of constructive review, a talent for which he is frequently called upon, but one for which he receives only infrequent recognition.

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INTRODUCTION

Watershed Restoration Program

In 1978, in compliance with a congressional authorization in the Redwood National Park Expansion Act (P.L. 95-250), a large-scale watershed restoration program was initiated in the lower one-third of Redwood Creek basin (Figure 1). The congressional action authorized, among other things, the implementation of a watershed restoration program designed to correct erosional damage caused by timber harvest and road building activities which occurred prior to public acquisition of park lands. In total, nearly 36,000 acres of logged timberland and over 200 miles of logging roads will be treated in the restoration program. Because of the unique goals and unprecedented scale of the watershed restoration program, it provides an important opportunity to evaluate the success of various restoration techniques applied.

When roads are constructed across streams, a large amount of fill material (soil) is bulldozed into the stream channel to build the road bed up to grade. A major part of the ongoing watershed restoration program includes the removal of this road fill material from skid trail and haul road stream crossings (Figure 2). Excavation of road fill from stream crossings is given high priority because of the relatively high potential for significant erosional damage. For example, during extreme runoff events, plugged culverts may divert streamflow and cause gullying of hillslopes and road beds while saturated stream crossings can fail as destructive debris torrents.

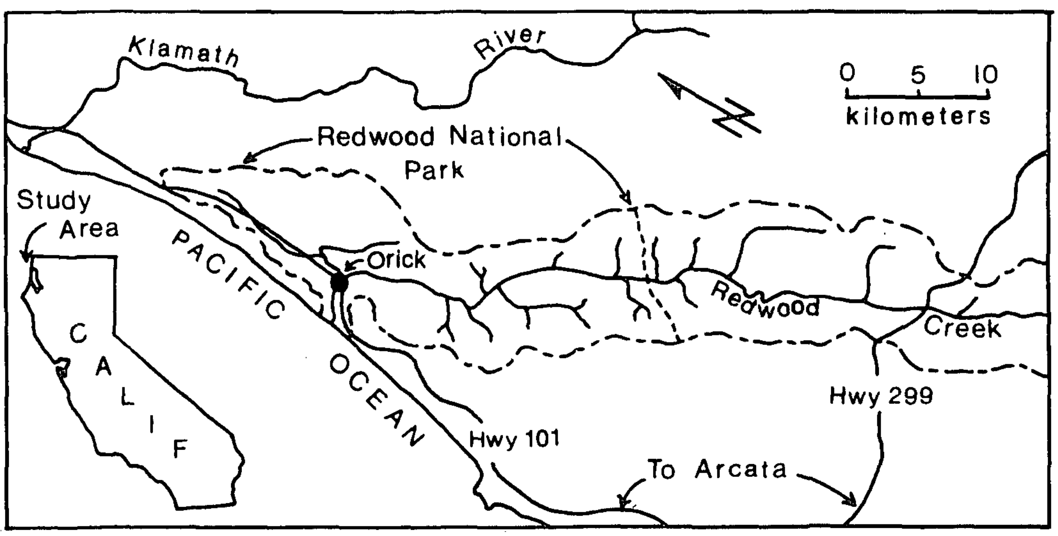
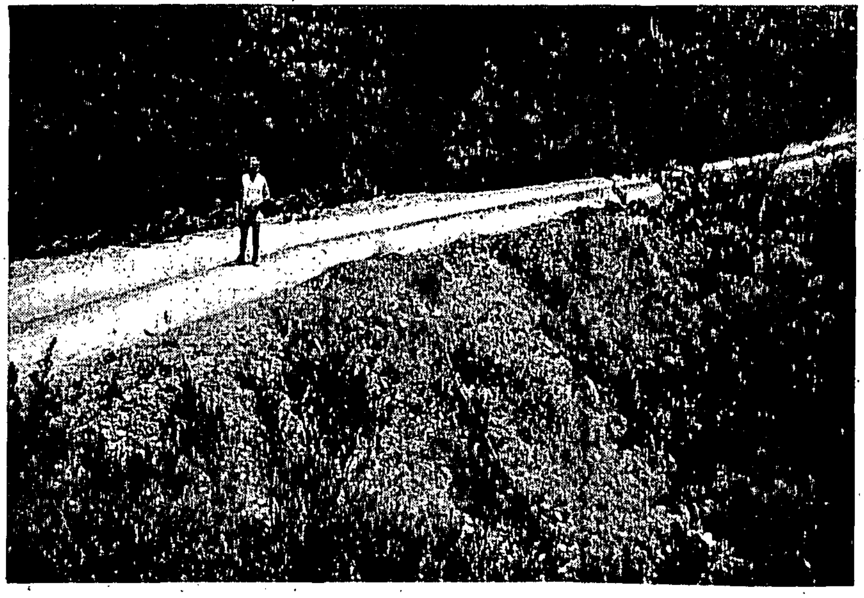


Figure 1. Location map of lower Redwood Creek showing Redwood National Park lands in the lower one-third of the basin.

A.



B.

Figure 2. Logging road stream crossing before (A) and after (B) excavation. Excavation has uncovered cobbles and boulders that composed the original stream bed.

Statement of the Problem

Past experience has shown that significant amounts of channel erosion often occurs in recently excavated stream crossings (data on file at Redwood National Park, Orick, CA). Excavated channels are sometimes armored with quarried rock, or check dams are constructed to prevent channel erosion. These protective measures are costly and, in many cases, have not proven cost-effective (Weaver and Sonnevil, 1984). For this reason, most stream crossings excavated since 1981 in the park have been left unprotected.

Because the erosional stability of unprotected excavations is derived from the presence of original stream channel structure (e.g., organic debris and coarse inorganic sediments), excavations are designed to uncover the original channel bed, leaving the stream's structural elements intact. During excavation, earth moving equipment is used to exhume the buried stream channel. The design of the excavation is guided by projecting adjacent hillslope and channel geometries into the fill prism. The unearthing of channel structure, in-place stumps, and zones of subsurface water seepage also aids in determining the alignment of the original streambed. The presence of unanticipated meanders or abrupt changes in gradient of the buried channel, however, sometimes results in poor alignment of the excavated channel with the original streambed. Where this occurs, channel segments are exposed which lack the continuity of stabilizing materials prevalent in adjacent undisturbed reaches.

To design stable excavations, it is useful to quantify the importance of the factors controlling channel scour. Consequently, a study was undertaken with the following objectives: 1) to examine in detail the process of channel adjustment subsequent to stream crossing excavation, 2) to determine the relative importance of on-site physical variables affecting channel adjustments, and 3) to develop technical criteria to be used in designing more stable stream crossing excavations. To accomplish these objectives, the first winter's channel adjustments were measured on 24 reaches consisting of exposed channels beneath stream crossings excavated in the summer of 1982. Site-specific variables contributing to erosivity and erodibility were quantified for the purpose of explaining the variability of observed channel adjustments.

STUDY AREA

Location

The Redwood Creek drainage lies in the coastal mountains of northwestern California and is centered at approximately 41 degrees north latitude and 124 degrees west longitude. The basin is 74 km long and 725 km^2 in size. Redwood National Park (Figure 1) constitutes a large portion of the lower one-third of this elongated watershed, as well as other areas along the coast between Crescent City and Orick.

Geology

Regional geologic structure is strongly influenced by the triple junction of the Gorda, Pacific, and North American tectonic plates a short distance off the northwestern California coast. Combined forces of the plates against one-another results in a general northeastern-southwestern compression. Faulting and folding has occurred normal to compression, and subsequent drainage basin evolution exhibits a strong northwestern trend.

Lithologies predominant in the northern California Coast Ranges consist of a complex assemblage of Franciscan sedimentary, volcanic, intrusive, and metamorphic rocks (Bailey et al. 1964). Tectonic deformation of the region has resulted in pervasive faulting, folding, and shearing to the degree that lithologies are considered to be structurally weak. Relatively rapid rates of tectonic uplift in this setting have allowed accelerated stream incision, creating extremely steep mountainous topography.

Within the Redwood Creek drainage, different lithologies on either side of the basin are separated by the Grogan Fault, a northwest trending feature which is followed by almost the entire length of the main channel of Redwood Creek (Figure 3). Northeast of the fault, slopes are underlain by highly sheared, faulted, and folded sandstones and mudstones. This sedimentary terrain can be divided into two units on the basis of lithologic coherency and the proportion of sandstone to mudstone. The Coherent Unit of Lacks Creek (CLC) is characterized by a more coherent structure and a higher sandstone: mudstone ratio than in the Incoherent Unit of Coyote Creek (ICC) (Harden et al. 1982). The CLC occurs higher on the hillslopes than the ICC and is more competent, and hence less prone to mass wasting than the ICC.

Of the 24 stream reaches studied within Redwood National Park, four are located on each of these two units on the northeastern side of the basin (Figure 3). Reaches 1 through 4 (Appendix A) occur on stream crossing excavations on Rehabilitation Site 82-1 in the upper slopes of the Emerald Creek tributary watershed. This site is situated within the Coherent Unit of Lacks Creek. Reaches 5 through 8 (Appendix A) occur on unnamed tributaries within Rehabilitation Site 82-5. Located in a

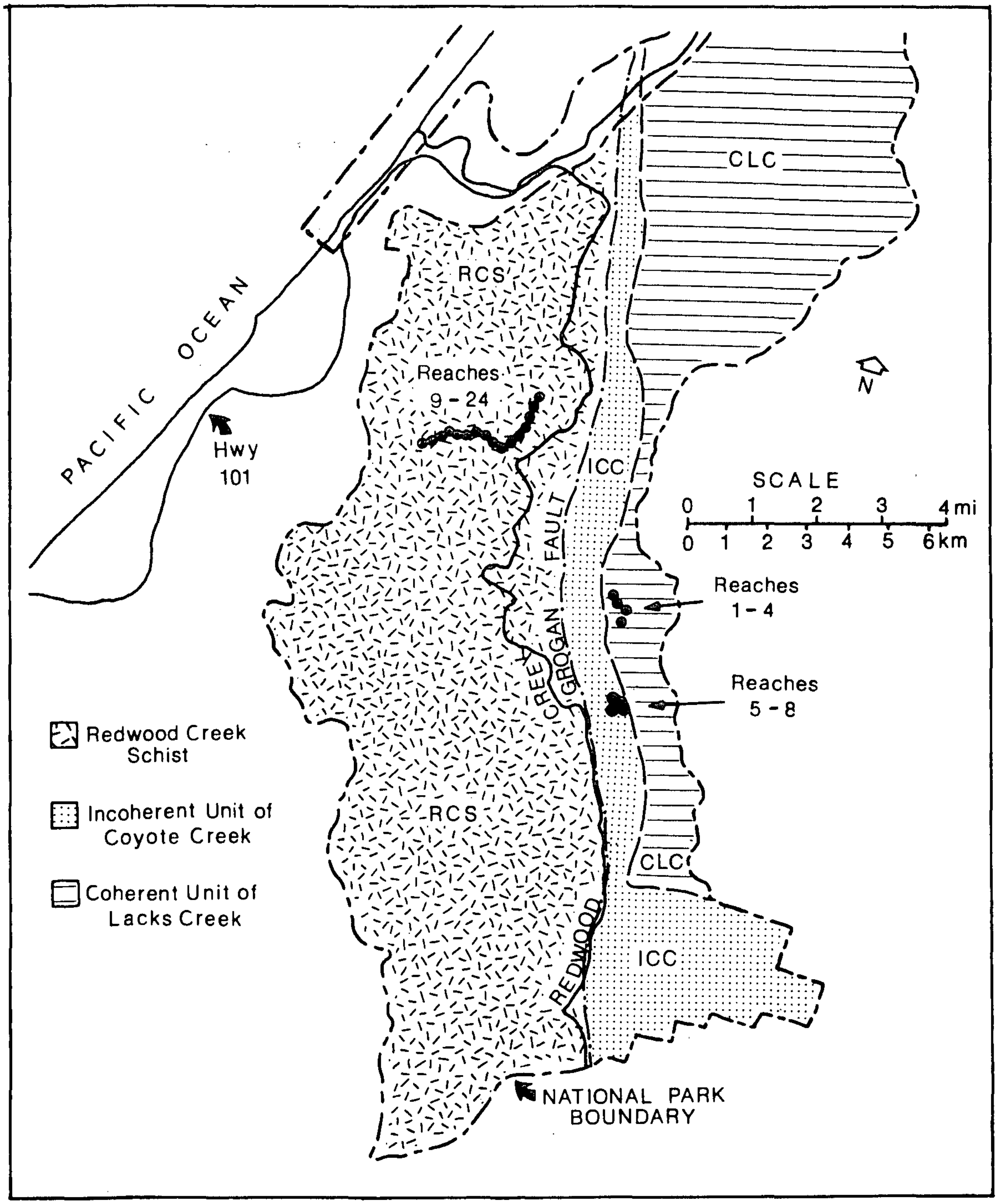


Figure 3. Geologic map of the south area of Redwood National Park showing locations of study reaches within the Redwood Creek Schist (RCS), the Incoherent Unit of Coyote Creek (ICC), and the Coherent Unit of Lacks Creek (CLC).

mid-slope position draining directly into Redwood Creek, these excavations lie within the less competent Incoherent Unit of Coyote Creek.

On the southwestern side of the basin, slopes are underlain by the Redwood Creek Schist (RCS) (Figure 3). Rocks in this unit consist of schists of variable metamorphic grade and are highly sheared and folded (Harden and others, 1982). The remaining 16 study reaches (Reaches 9 through 24, Appendix A) occur in stream crossing excavations of Rehabilitation Site 82-4 in Bond Creek, a tributary watershed located in schist terrain.

Climate

Average annual precipitation in the lower one-third of Redwood Creek is approximately 200 cm, most of which falls as rain from October through the following April. Snowfall occasionally covers the ridges at elevations higher than 700 m. Because of the mild, Mediterranean-type climate characteristic of the northern California Coast Ranges, significant snowpack development is rare and ephemeral.

Intense rainfall events commonly occur several times during the seven month rainy season. Table 1A lists rainfall depth-duration-frequency data for the lower Redwood Creek area. Table 1B contains depth-duration-frequency data for the rainstorm of December 15, 1982. Comparison of the two tables shows that for 6- and 24-hour durations, the return frequency of the 1982 storm was three and seven years, respectively. The December 15, 1982 storm was the largest magnitude precipitation event of the study period, and was therefore assumed to be the most erosive runoff event of the season. Overall precipitation for the study period was 35 percent above normal at 270 cm (data on file at Redwood National Park, Orick, CA).

Topography

High rainfall, combined with structurally weak lithologies and rapid uplift rates, have sculpted the region into rugged terrain. Across the lower Redwood Creek basin, about 600 m of vertical relief occurs over 3000 m of horizontal distance from drainage divide to valley bottom. Hillslope gradients commonly exceed 30 degrees and may exceed 45 degrees. Hillslope configurations are most often complex, although simple convex, concave, and planar hillslopes can also be found. Valley bottoms of basins in the area are rarely wider than the active channel because of geologically rapid stream incision and hillslope encroachment due to mass movement processes. Exceptions within the lower Redwood Creek drainage include alluvial flats inside meander bends and discontinuous terrace remnants along the main channel of Redwood Creek.

Table 1A. Rainfall depth, duration, and frequency data for lower Redwood Creek basin. Data tabulated from isohyetal maps in Miller et al. (1973).

Return Period (years)	Rainfall Depth (cm)	
	Duration = 6 hours	Duration = 24 hours
2	6.1	14.0
5	7.1	15.2
10	7.6	17.8
25	9.7	20.3
50	10.2	22.9
100	11.4	25.4

Table 1B. Rainfall depth, duration, and frequency data for storm of December 15, 1982 (data on file at Redwood National Park, Orick, CA). Return periods were interpolated from isohyetal maps in Miller et al. (1973).

Duration (hours)	Depth (cm)	Return Period (years)
1.0	1.8	2
6.0	6.3	4
12.0	9.1	2
24.0	16.0	6

Stream Channel Morphology

Stream form and structure are a function of the geologic, geomorphic, and biologic setting of coastal northern California. Low order streams in the area are typically very steep, deeply incised, and exhibit concave-upward profiles. The highly erodible lithologies and geologically rapid rates of tectonic uplift favor rapid stream incision, while this process is attenuated by the constant routing of organic debris through the fluvial system.

Organic debris, consisting of tree limb, root, and trunk fragments introduced to the stream from the surrounding forest, provides important structure in low order streams (Keller and Tally 1979). Organic debris accumulates in channels to form discrete "dams", or steps, in the longitudinal profile (Figure 4). By exaggerating the variability in local channel gradient, organic debris steps cause much of a stream's potential energy to be expended at localized points along the profile. Energy dissipation by vertical waterfalls over organic steps results in less energy available for channel erosion and sediment transport (Heede 1972, Curry 1976, Swanson and Lienkaemper 1978, and Marston 1982).

Figure 4. Small stream in an undisturbed, old-growth setting. Note that organic debris accumulations form steps in the stream's longitudinal profile.

In addition to providing for non-erosional energy dissipation, significant amounts of transportable sediment may be trapped and stored behind organic steps. Both Megahan and Nowlin (1976) and Swanson and Lienkaemper (1978) have estimated organic debris-stored sediment to exceed mean annual sediment yield by an order of magnitude in watersheds in Idaho and Oregon, respectively.

Land Use History

By 1978, when the study area was included in the National Park, most of the old-growth forest had been clearcut logged and tractor yarded. Road building associated with timber harvest activities occurred mostly between 1960 and 1978.

Effects of road building, clearcutting, and tractor yarding in Redwood National Park are well documented (Janda 1977, Nolan et al., in press). Ground disturbance due to tractor yarding is estimated to exceed 80 percent of the harvest area (Weaver et al. 1979). The most persistent effect of timber harvest operations, however, is erosion associated with logging road and skid trail stream crossings. The potential for significant sediment inputs to the fluvial system at stream crossings may be realized upon: 1) catastrophic failure of stream crossings, or 2) gully erosion from surface water diversions (Weaver et al., in press).

Logging road and skid trail construction alters surface and shallow subsurface hydrology by: 1) causing interflow emergence at road cuts, 2) diverting small streams out of their natural flow courses and onto logged hillslopes, and 3) adding road surface and inboard ditch runoff to existing streams. These alterations of hillslope drainage patterns result in increased surface water discharges and can lead to gullying or accelerated channel erosion. Weaver et al. (in press) have shown that 40 percent of total sediment discharge from the lower Redwood Creek basin is due to gullying caused by stream diversions which result from plugged or undersized culverts at stream crossings. During high runoff events, ponding above stream crossings may lead to saturation of the road fill, thereby increasing the likelihood of debris torrents.

The current land use in the study area is the ongoing watershed restoration program begun by the National Park Service in 1978. The major focus of the program has been to restore natural drainage patterns and to eliminate the potential for diversions and stream crossing mass failure by removal of abandoned logging roads. Since 1978, an average of about twelve miles of logging roads and skid trails, including about one hundred stream crossings, have been treated annually.

MATERIALS AND METHODS

Variables Quantified

Ten variables were measured in an attempt to explain the nature and degree of channel adjustments in 24 study reaches composed of recently uncovered channels at excavated stream crossings (Table 2). The two dependent variables, unit scour (SCOUR/M) and diameter of channel bed sediments (D65), were chosen because they represent the most profound channel adjustments observed to occur in stream crossing excavations in previous years. The remaining eight variables were selected as being representative of forces, or components of forces, either driving or resisting channel adjustments.

Table 2. Variables quantified for the study reaches, and their acronyms or symbols.

Acronym or Symbol	Variable Description
SCOUR/M	Volume of channel erosion per meter of channel length (m^3/m), or unit scour
D65	Diameter (mm) of channel bed sediments of which 65% is finer (by weight)
Ω	Total stream power (joules/sec./meter of bed length)
%B+C	Percent by volume of bank material composed of sediment in the boulder and cobble size classes (>64 mm diameter)
%ORGDROP	Percent of total stream elevation drop composed of organic steps
AVOSTPHT	Average height (m) of organic steps
AVORGDIS	Average horizontal distance (m) between adjacent organic steps
%CLAY	Percent clay in the finer than 2 mm fraction of bank material
QPK	Peak discharge (m^3/sec) for the study period
SLOPE	Slope of a line of best fit through a plot of the profile of each study reach (unitless).

The variables peak discharge and channel gradient were used to calculate total stream power (Bagnold 1973), a measure of the maximum erosive force of water flowing through the study reaches. Organic debris in the study reaches was quantified in several ways to assess its degree of influence on providing hydraulic resistance to stream power. Finally, two properties of the soil material composing the erodible channel substrate, percent clay and percent boulders and cobbles, were also quantified. Percent clay was measured as an index of the cohesiveness of the soil matrix. Percent boulders and cobbles in the soil was chosen as being indicative of the self-armoring capability of erodible materials.

Channel Erosion

Total channel erosion in the study reaches consisted of both fluvial scour and small bank slumps. Fluvial erosion (channel widening and downcutting) was estimated by surveying monumented cross-sections which were installed perpendicular to the channel alignment in the study reaches. Four cross-sections were installed in most reaches, however, in several considerably shorter reaches, three cross-sections were considered sufficient. Spacing of the cross-sections was determined by longitudinally dividing the reaches into thirds or fourths (depending on overall length), and placing cross-sections in the middle of each division. The intervening distance between cross-sections ranged from six to 17 m, averaging 10 m.

Cross-section endpoints consisted of metal rods which were driven securely into the upper channel banks. Cross-sections were established and first measured following stream crossing excavation in September, 1982 (prior to any significant runoff events). Cross-sections were measured by stretching a level line and measuring tape between the two endpoints and, at slope breaks, measuring the distance from the string to the ground surface with a surveying rod. Horizontal distance from the left endpoint was measured by reading the tape at the intersection of the rod and tape. Data pairs were recorded in this manner for all significant slope breaks. Plotting data pairs as X,Y coordinates yielded a two dimensional representation of channel dimensions on each cross-section.

Following the rainy season of 1982-83, the cross-sections were remeasured. Cross-sectional fluvial scour was calculated as the net increase in area on each cross-section. Total scour volume was calculated by averaging scour areas of adjacent cross-sections, multiplying by the intervening horizontal distances, and then summing the volumes between cross-sections in each reach (commonly referred to as the double-end-area method).

Mass erosion was computed by measuring the width (W), length (L), and depth (D) of bank slumps (Figure 5) adjacent to the study reaches and estimating the volume by using the formula:

Volume of Prism = (Basal Area x Height) /3
where: Basal Area = (Width x Depth) /2
Height = Length of Slump

Where bank slumps intersected the cross-sections, the cross-sectional area attributable to the slump was subtracted from the net scour area so that only fluvial erosion was estimated from the cross-sections. The delineation of the boundary between mass and fluvial erosion on cross-sections having both was made by placing a vertical line at the edge of channel bottom at the base of the slump (Figure 6). Separation of fluvial and mass erosion this way was somewhat subjective in cases where slump deposits infringed on the active channel cross-section. However, it was considered more accurate to partition out mass erosion before averaging scour area between cross-sections because of the localized irregularity in eroded channel shapes due to slumping. Eroded void shape transitions between adjacent cross-sections tended to be regular when only fluvial scour was present and irregular when bank slumps were present. Because the double-end-area method is most accurate for cases where regular transitions between end areas exist, it was considered advantageous to calculate mass and fluvial erosion volumes separately, and then sum them to estimate SCOUR/M.

Variations in length of the excavated reaches were considerable, ranging from 18 to 70 m (Appendix A). For comparison of channel erosion volumes between the study reaches, unit erosion volumes were calculated as quotient of total erosion (m^3) divided by channel length (m).

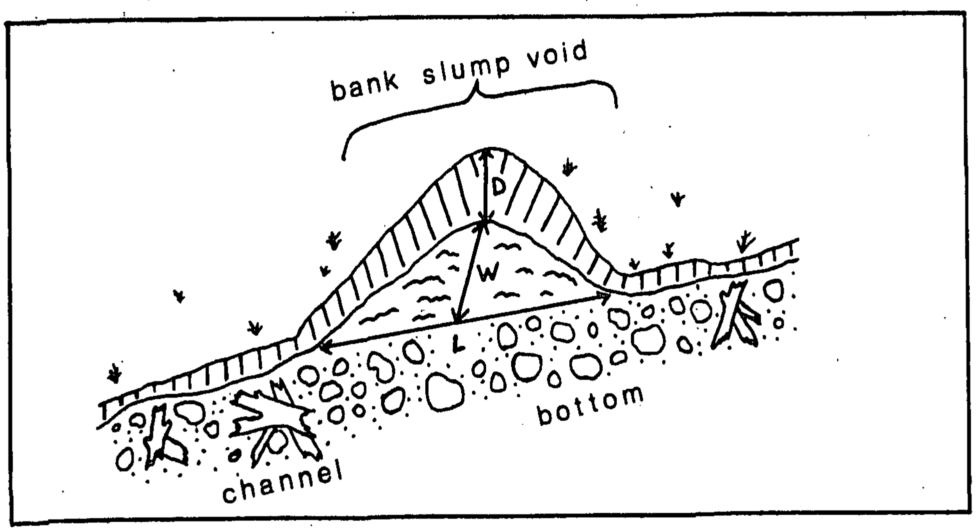


Figure 5. View from across channel of a bank slump void adjacent to the stream channel. Measurement axes for slump volume calculations are shown as D (depth), W (width), and L (length).

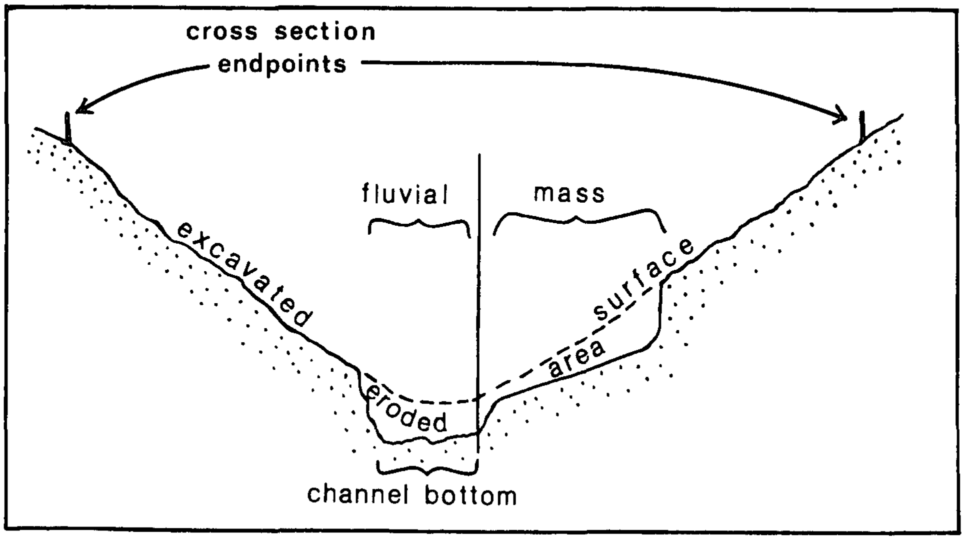


Figure 6. Diagrammatic delineation of boundary between mass and fluvial erosion on a cross-section intersected by a slump. Boundary is set by a vertical line drawn up from the edge of the channel bottom adjacent to the toe area of the slump.

Channel Bed Armor

Size distributions of surficial channel bed sediments were measured immediately after stream crossing excavation and again after the rainy season. An adaptation of the photographic method described in Kellerhals and Bray (1971) was used, whereby vertical photographs of the channel bed were taken from eye level. In each photo, a measuring rule was placed on the channel bottom so that individual scales could be computed for each photo to allow for variations in camera height. Color slides (35mm) were taken of the channel bed at each cross-section and midway between cross-sections.

After developing, the slides were projected onto a sampling grid mounted on an electronic digitizer surface. The scale of each photo was set first by digitizing the image of the measuring rule within the photo. Then, the shorter of the two visible axes was digitized for all particles falling under grid intersections (35 per photo). All particles finer than coarse pebbles (less than 16 mm in diameter) were not individually measured, but were simply lumped in a size class of finer than 16 mm diameter. This sampling method, referred to as grid-by-number, is equivalent to bulk sieve analysis by weight without numerical conversion (Kellerhals and Bray 1971).

An assumption necessary for use of the photographic method of measuring particle size distribution is that the shorter of the two visible axes of each particle represents the intermediate, or b-, axis. This assumption seemed reasonable in the study reaches because most particles were platy in shape, resulting in a strong tendency to lie flat, rather than on edge, on the channel bottom.

After digitizing all particles sampled in a study reach, diameters were tallied into size ranges as described by Leopold (1970). Particle size distributions of cumulative percent finer versus diameter (mm) were plotted (example shown in Figure 7), and the diameter at which sixty-five percent of the sample was finer (D65) was determined from the plot for each reach. The post-winter D65 was used as an index of the degree of channel bed armoring which occurred during the study period.

Size distributions of channel bed sediments present immediately following excavation (prior to significant runoff) were not a result of any morphological phenomena. Measurement in this condition was necessary, however, to assure that channel armoring did in fact occur, as documented by post-winter size distributions which were much coarser than those measured pre-winter.

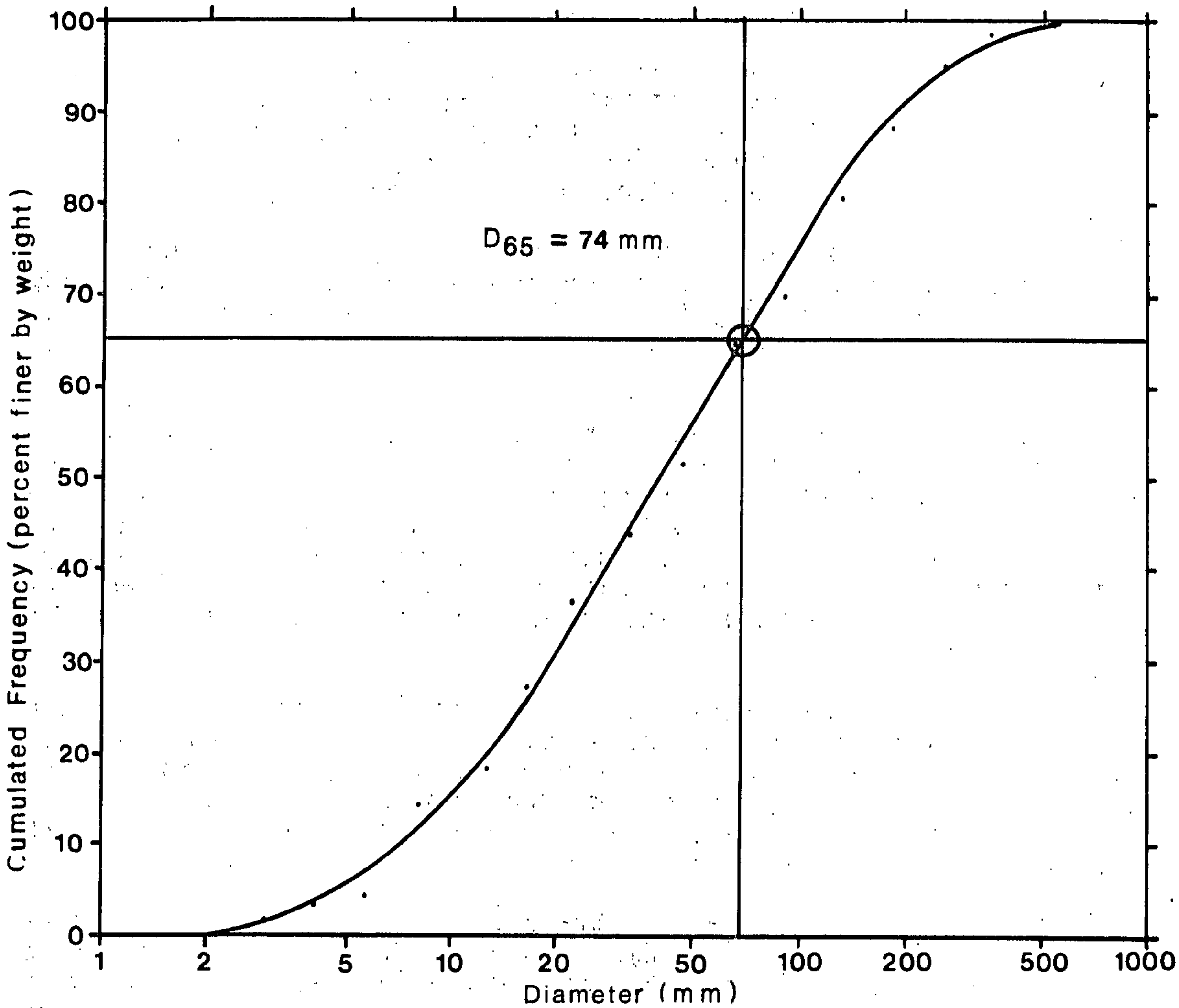


Figure 7. Sediment size frequency curve for channel bed material showing graphic determination of the diameter at which 65 percent of sampled particles were finer (D65). The D65 from this curve is 74 mm.

Stream Power

Total stream power is a measure of the total power available for sediment transport (Bagnold 1973). Although originally developed for prediction of sediment transport rates in alluvial channels, Bull (1979) used the concept in discussing landscape evolution. His use of the ratio of stream power (driving forces) to critical power (resisting forces) is analogous to the factor of safety method for slope stability analysis. Similarly, in this study, total stream power is treated as an independent variable representing the driving forces operating in the study reaches.

Stream power is calculated by the formula:

$$\Omega = \rho g Q S$$

where:
Ω = total stream power (joules/sec/m)
ρ = density of water (1000 kg/m^3)
g = acceleration due to gravity (9.81 m/sec^2)
Q = discharge (m^3/sec)
S = water surface slope (unitless)

which requires field measurements of discharge and water surface slope. Total stream power of the largest magnitude discharge event of the study period was used in the analysis.

Peak Stream Discharge

Each study reach was equipped with a crest-stage gage (Figure 8) for measuring peak stages during discharge events with the intentation of developing stage-discharge rating curves for the study reaches to estimate peak seasonal discharges by extrapolation. However, aggradation and scouring in the gaged reaches rendered most of the stage data unusable. The few crest-stage gages that functioned well were at least useful for determining the relative magnitude of flow events of the season.

Streamflow was measured during several storms in the study period. Due to the cascading nature of the streams, excessive turbulence made accurate measurement of discharge with a pygmy current meter impossible. Discharge measurement by dilution methods, however, are well suited to turbulent streams. The salt slug injection method described in Church and Kellerhals (1970) was satisfactorily used in the study.

Unfortunately, discharge was not measured during the largest event of the season (December 15, 1982). However, discharge of the second largest event (January 26, 1983) was measured and was used to estimate streamflow of the largest event. Depth-duration data for both storms were examined (Table 3), and a depth ratio mean of 1.5 was determined

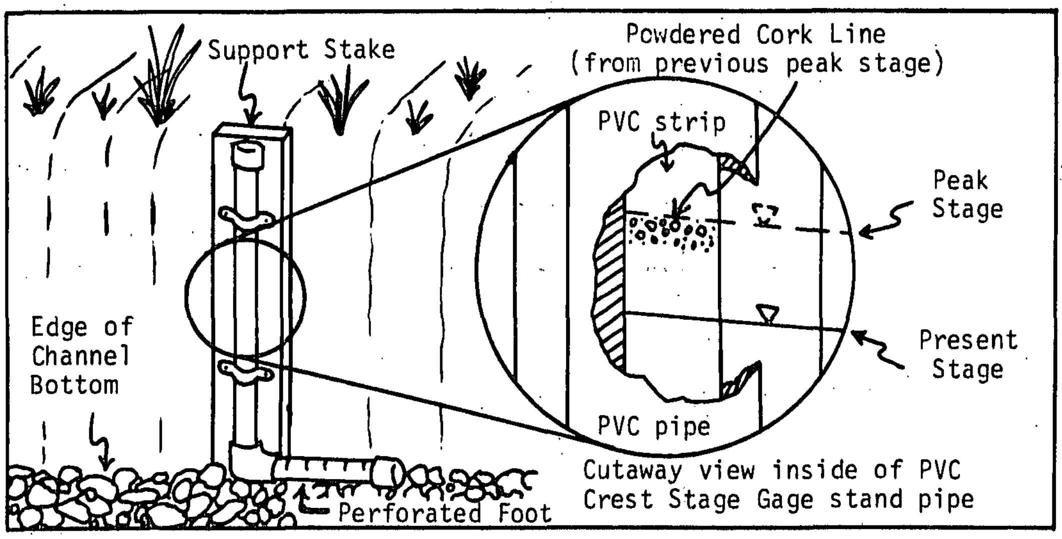


Figure 8. Schematic diagram of a plastic crest stage gage used for recording peak stages of storm flows of the study period. After the height of the cork line left from the previous peak stage is recorded, the cork is washed down to the bottom of the gage to prepare it for the next storm event.

for a variety of durations. To estimate differences in antecedent soil moisture between the two storms, daily antecedent precipitation indices (API) were calculated for the study period. Daily API values are calculated by Chow's (1964) equation:

$$API_i = K \cdot API_{i-1} + P_i$$

where: i = day number of calculation period
K = recession factor
P = precipitation occurring on day "i" (inches)

The recession factor (K) represents an estimate of the rate of decay of rainfall inputs (the higher the K, the slower water leaves the hillslope hydrologic system as runoff). A recession factor of 0.90 was selected because it is approximately the middle of the range normal values according to Chow (1964). Using a recession factor (K) of 0.90, API depths for the days of the first and second largest storms of the study period were 3.83 and 3.84 inches, respectively. Because of the very similar antecedent moisture conditions, streamflow differences between the two storms were assumed to be largely a function of precipitation intensity differences. Using this rationale, discharges measured during the second largest event were simply multiplied by the rainfall depth ratio mean of 1.5 to generate estimates of discharge for the largest event of the study period.

Table 3. Rainfall depths and depth ratios at various durations for storms of Dec. 15, 1982, and Jan. 26, 1983.

Duration (hours)	Rainfall Depth (cm)		Depth Ratio (A/B)
	Dec. 15, 1982(A)	Jan. 26, 1983(B)	
1.0	1.8	1.1	1.6
2.0	2.8	1.9	1.5
4.0	4.5	3.1	1.5
6.0	6.3	4.0	1.6
12.0	9.1	6.0	1.5
24.0	16.0	11.0	1.5
			$\bar{x}$ = 1.5

Channel Gradient

For stream power calculations, the slope value commonly used is water surface. The extreme turbulance of water flowing through the study reaches, however, precluded reliable measurement of water surface slope, necessitating the use of channel bed gradient instead. Detailed theodolite and electronic distance meter surveys of the thalweg (point of maximum depth) through each study reach provided data on channel profile configurations. A line of best fit was drawn through a plot of each profile and the slope of this line was used in the computation of stream power.

Organic Debris

The importance of woody debris has only recently been widely recognized in the literature on channel morphology. Zimmerman et al. (1967) investigated relationships between channel width, drainage area, and in-stream organic debris accumulations in Vermont streams. Later, Heede (1972) studied the effects of log steps on the hydraulic characteristics of two Rocky Mountain streams. He quantified the proportion of stream elevation drop composed of organic steps and found it to be positively related to potential energy dissipation by turbulence and inversely related to surficial channel bed material size.

More recent work (Keller and Swanson 1979, Swanson and Lienkaemper 1978, Keller and Tally 1979, Marston 1982) focused on the role of large organic debris in channel form and process of streams of the Pacific Northwest, including tributaries to Redwood Creek. The nature of these studies included: 1) quantification of in-stream organic debris and debris-stored sediment, 2) processes of introduction of sediment and debris to streams, 3) longevity of sediment and organic debris in streams, and 4) the function of woody debris in anadromous fish habitat. In addition, Marston (1982) investigated the role of organic steps in potential energy dissipation by application of thermodynamic principles.

In this study, the influence of organic debris on channel adjustments was measured in three ways. Thalweg surveys through the study reaches yielded information on both the height of individual organic steps and their longitudinal spacing. Averages for organic step height (AVOSTPHT) and horizontal distance between steps (AVORGDIS) were two independent variables calculated from the surveyed profiles. A third variable derived from the profiles was the percentage of total elevation change in each reach composed of organic steps (%ORGDROP) calculated as:

$$\%ORGDROP = \frac{\text{Cumulative Height of Steps}}{\text{Total Elevation Change}} \times 100$$

Bank Material Properties

Composition of streambank material in the study reaches was quantified in order to estimate resistance to scour from two perspectives: 1) clay content (contributing to shear strength by increased cohesion) and 2) boulder and cobble content (increasing the potential for the eroding material to accumulate a coarse lag deposit). To accomplish this, several methodologies were employed to determine particle size distributions over a wide range of sizes.

Coarse Fragments

Following the scour-inducing runoff events of the study period, coarse fragment content of the exposed streambanks was quantified using the grid-by-number approach discussed by Kellerhals and Bray (1971). Four linear "grids" were established on exposed banks within each study reach: one in each of four quadrants composed of left and right banks of the upstream and downstream halves of the reach. Endpoints for each grid were established by inserting a surveying pin into the streambank. Then, a measuring tape was strung along the contours of the bank between the two endpoints, and eighteen sampling points were established along the tape at distances determined from a table of random numbers. At each sampling point, the diameter of the exposed particle was measured and tallied. Where sampling points fell on particles less than 16 mm in diameter, particles were classified as such without actual measurement, and a small sample (about 100g) was removed from the bank and placed in a composite sample bag for laboratory analysis of the finer size ranges.

Upon analysis of bed material size properties (discussed earlier), it was recognized that channel armoring materials were composed of sediments in the cobble and boulder size ranges (greater than 64 mm in diameter). For this reason, coarse fragment content of streambanks was expressed as the percent by volume of bank material in the size fraction coarser than 64 mm in diameter (%B+C).

Clay Content

Shear strength of the streambanks due to soil cohesion was indirectly assessed by using clay content as a surrogate variable. The composite samples obtained during the grid sampling of coarse fragments were wet sieved to remove the fraction coarser than 2 mm. Hydrometer analysis, as described by Bowles (1978), was then used to determine clay content (%CLAY) of the finer than 2 mm fraction of bank material. An assumption necessary for application of the methods chosen for bank material sampling is that the material exposed in eroded streambanks was representative of the material that was eroded away. Although the validity of this assumption cannot be tested "ex post facto", there was no visual evidence in the field to suggest spatial heterogeneity of material properties within the study reaches.

Regression Analysis

Computer-assisted multiple linear regression analysis was accomplished using the MINITAB (Ryan et al. 1976) statistical package available on Humboldt State University's CDC Cyber computer system. Two separate series of regressions were performed: one using unit channel scour (SCOUR/M) as the dependent (Y) variable and the other using channel armor (D65) as the dependent variable. In each series, the stepwise regression procedure (Draper and Smith 1981) was selected from among the options available in MINITAB. In this procedure, predictor (X) variables are added to successive iterations of the regression in order of descending partial correlation coefficients. At each iteration, all predictor variables (including those within and outside the current regression equation) are F-tested for significance of partial correlation coefficients at the 0.05 level. Those variables already in the equation which are found to be insignificant are removed, and the next significant variable not yet in the equation is inserted. The stepwise regression is halted, and the current equation adopted when no predictor variables can be either removed from or added to the equation on the basis of partial correlation coefficient significance tests.

RESULTS

Channel adjustments in response to winter stormflows varied widely between the 24 study reaches (Table 4). Unit channel erosion (SCOUR/M) ranged in excess of an order of magnitude, with maximum scour of about three cubic meters per meter of channel length. Channel armoring (D65) differences between the study reaches were also quite large. Over a five-fold difference was observed between the minimum and maximum D65 values for the study reaches in the post-winter condition.

Inferences drawn from the multiple linear regression results reported here are founded primarily on interpretation of significant partial regression coefficients. Because the validity of interpretations of the relative importance of predictor variables can be questionable if multicollinearity exists between them (Neter et al. 1974, pp. 339-347), the correlation structures for predictor variables from both the SCOUR/M and D65 regressions were examined (Appendix B). Multicollinearity may be indicated by: 1) high correlation coefficients between predictor variables, 2) disagreement between the signs of the partial regression coefficients and those of the simple correlations between the dependent and independent variables, and 3) inflated standard errors of the partial regression coefficients (Neter et al. 1974, pp. 339-347). Upon examination of the correlation structures and standard errors of partial regression coefficients from both final regression equations (Appendix B), it was concluded that multicollinearity was not a problem for the predictor variables incorporated.

Table 4. Ranges, means, and standard deviations for the variables quantified.

Variable	Units	Range	Mean	Standard Deviation
SCOUR/M	m^3/m	0.1 - 2.8	0.8	0.9
D65	mm	20 - 110	50	24
Ω	joules/sec/m	41 - 594	227	140
%B+C	percent	4 - 25	14	6
%ORGDROP	percent	4.1 - 67.2	34.1	20.2
AVOSTPHT	m	0.3 - 1.0	0.5	0.2
AVORGDIS	m	2.1 - 13.4	4.5	3.0
%CLAY	percent	9.1 - 29.3	21.1	5.5
QPK	m^3/sec	0.013 - 0.229	0.107	0.065
SLOPE	unitless	0.138 - 0.319	0.228	0.058

Channel Erosion Regression

The stepwise multiple linear regression of channel erosion (SCOUR/M) on the six predictor variables progressed through three iterations to derive an equation which satisfied the partial correlation coefficient significance criteria. The equation:

$$SCOUR/M = 1.29 + .0047\,\Omega - .0783\ \%B{+}C - .0136\ \%ORGDROP$$

explained 82.2 percent of the variability in SCOUR/M (79.5 percent when adjusted for degrees of freedom).

Of the six independent variables on which unit scour was regressed, three were found to be significant predictors of channel erosion. They are (in order of descending predictive importance): 1) total stream power (Ω), 2) coarse fragment content of streambank materials (%B+C), and 3) percent stream elevation drop composed of organic steps (%ORGDROP). The signs of regression coefficients are indicative of the type of relationship each independent variable has with the response variable (SCOUR/M). The positive sign associated streampower affirmed the expected positive relationship between channel scour and erosional stress. The negative signs associated with %B+C and %ORGDROP were indicative of inverse relationships with SCOUR/M. The inverse nature of these relationships was also in agreement with intuitive judgement (they are components of resisting forces in the factor of safety analogy). The three predictor variables not incorporated into the regression equation were: 1) average intervening distance between organic steps (AVORGDIS), 2) average height of organic steps (AVOSTPHT), and 3) percent clay in the finer than 2mm fraction of streambank materials (%CLAY).

Two outliers in the data set were indicated by standardized residuals exceeding 2.0 in absolute value. No measurement, calculation, or data entry errors could be found which could account for incongruity of these observations with the rest of the data set. However, a review of the field notes recorded during the profile surveys of these reaches (Reaches 17 and 20, Appendix A) indicated the presence of bedrock exposures in the channel bottoms of both reaches, a condition which makes these two reaches unique. The standardized residuals of Reaches 17 and 20 were -2.08 and -2.27, respectively, indicating significantly less scour than expected. The presence of bedrock in the channel bottom was a likely cause for the low scour volumes experienced by these reaches due to the resistance to downcutting provided. For this reason, Reaches 17 and 20 were considered anomalous among the 24 observations.

The stepwise regression was rerun, excluding Reaches 17 and 20 from the exercise. The resulting equation:

$$SCOUR/M = 1.09 + .0054\,\Omega - .0758\ \%B{+}C - .0105\ \%ORGDROP$$

explained 91.2% of the variability in unit channel scour (89.7% when adjusted for degrees of freedom). By omission of Reaches 17 and 20, the multiple correlation coefficient was improved by about ten percentage points using the same predictor variables. The standardized residual for Reach 23 in this regression exceeded 2.0 in absolute value; however, no justification for removing this observation could be found.

A diagnostic tool commonly used in regression analysis is an examination of plots of the standardized residuals (r_i) against the predicted values of the response variable (y_i) and against each of the predictor variables (Cook and Weisberg 1982, pp. 37-40). Such plots are useful for indicating the need for data transformations to linearize non-linear relationships. A plot of r_i versus predicted SCOUR/M for the second regression (n=22) revealed a trend of convex upward curvature. Residual plots of the predictor variables were then examined, and a similar trend was observed in the plot of r_i against %B+C (Figure 9A). In an effort to straighten this curvilinearity, SCOUR/M regressions were rerun with %B+C raised to powers between one and three at increments of 0.5. The best r-squared was achieved when %B+C was raised to a power of two. This transformation resulted in the regression equation:

$$\text{SCOUR/M} = .621 + .0058\,\Omega - .0028(\%\text{B+C})^2 - .0111\ \%\text{ORGDROP}$$

This regression explained 93.0 percent of the variability in SCOUR/M (91.8, adjusted for degrees of freedom). Although the r-squared percentage was only improved by about two by the transformation of %B+C, curvature of the residual plot was reduced appreciably (Figure 9B). Reaches 5 and 23 had standardized residuals exceeding 2.0 (2.27 and -2.56, respectively) in the regression, however no justification for their removal from the data set could be found.

Channel Armor Regression

The stepwise regression of channel armoring (D65) on the four predictor variables selected resulted in the equation:

$$\text{D65} = 15.6 + 1.51\,\Omega$$

This regression explained 77.2 percent of the variability in D65 (76.2 percent adjusted for degrees of freedom). Of the four predictor variables, only total streampower (Ω) was allowed to remain in the regression by the partial correlation coefficient significance tests.

A plot of the residuals did not indicate the need for transformation of the data. The residual plot did, however, reveal the presence of an outlier in the data set. No errors in calculations or data entry could be found which might explain the high standardized residual (-2.77) associated with the observation (corresponding to Reach 6, Appendix A.)

The excessively high standardized residual for Reach 6 was due to a finer than predicted D65 (indicated by a negative sign of the standardized residual value). The most striking difference observed in

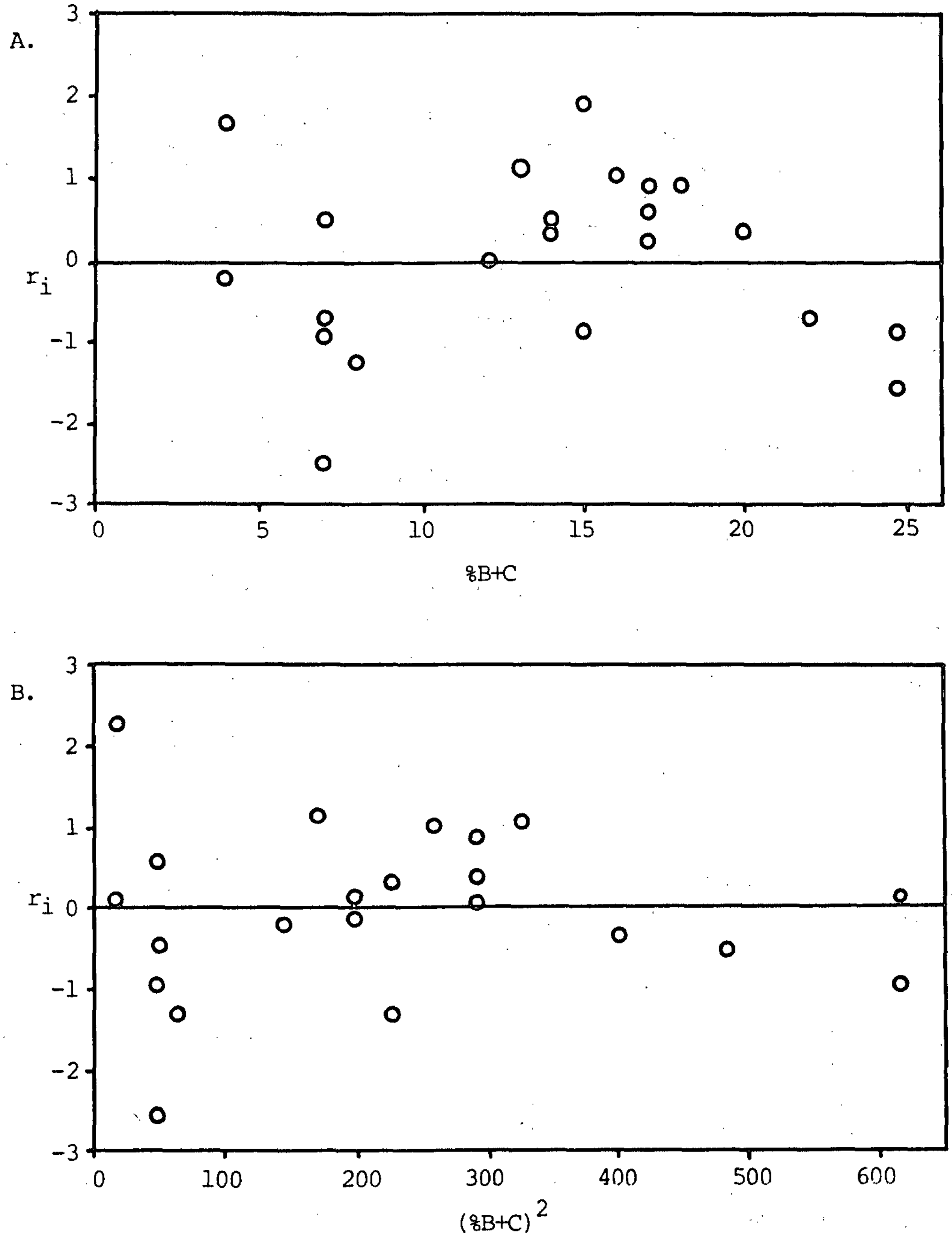


Figure 9. Plots of standardized residuals (r_i) from the SCOUR/M regressions before (A) and after (B) transformation of %B+C by squaring. Note that the curvature in the plot of r_i versus %B+C (A) is greater than in the plot of r_i versus $(\%B+C)^2$ (B).

the field between Reach 6 and the other 23 reaches was the extremely saturated condition and resultant instability of streambanks along the upper portion of the reach (see Figure 10). It was noted during frequent visits to the study reaches that the streambanks adjacent to Reach 6 continued to slough and supply fine sediment to the channel well after stormflows had receded. In other reaches, banks appeared less mobile, allowing more opportunity for lag development by winnowing away of fines while storm discharges receded. From these observations, it was concluded that Reach 6 could be considered anomalous with respect to channel armoring due to the persistence of bank sloughing.

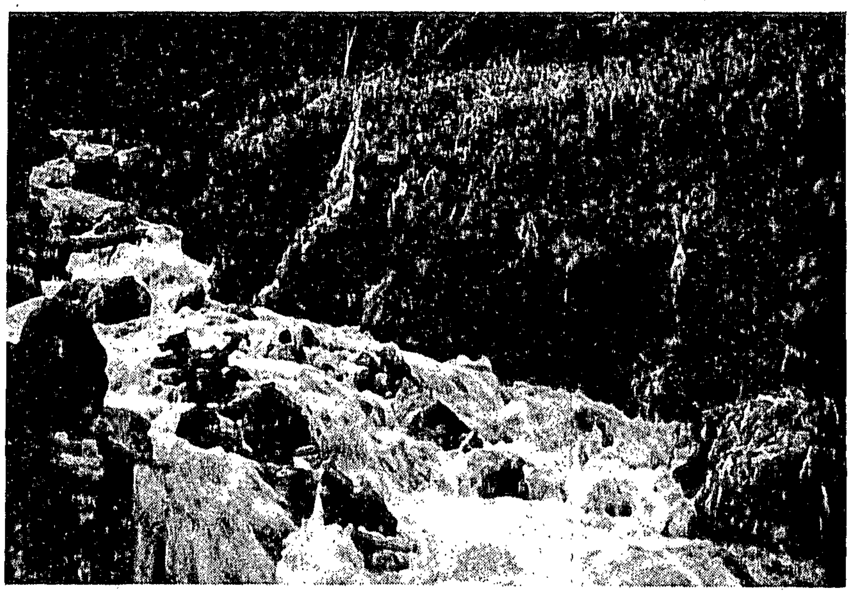


Figure 10. Left bank in Reach 6 following the storm of December 15, 1982. At the time this photo was taken (December 17, 1982), bank slumping continued to supply fine sediment to the channel, precluding or masking the development of a channel bed armor layer.

The channel armoring stepwise regression was re-run with a data set which excluded the anomalous observation (Reach 6). The equation:

$$D65 = 27.0 + .149\ \Omega - .268\ \%ORGDROP$$

explained 89.2 percent of the variability in the D65 (88.1 percent when adjusted for degrees of freedom). By exclusion of Reach 6, the multiple correlation coefficient was improved by 11 percentage points. Regression coefficient signs indicated a positive correlation of D65 with stream power, and a negative correlation with %ORGDROP. The nature of these relationships was consistent with rationales used in variable selection. In this regression, Reaches 8 and 14 exhibited high standardized residuals (-2.37 and 2.17, respectively), but no reasons could be found for considering these observations to be anomalous.

DISCUSSION

Channel Erosion

Although the process of channel erosion is complex, the independent variables selected for the stepwise regression analysis worked well in explaining its variability. Only 8 percent of the variability in SCOUR/M remained unexplained by the final equation generated using total stream power (Ω), the square of percent boulder and cobble content of bank material ($(\%B+C)^2$), and percent stream drop composed of organic steps (%ORGDROP) as predictors.

Of primary importance in explaining channel erosion variability was total stream power. Although observed volumes of channel erosion were probably a function of cumulative short-term peak powers attained during several high discharge events during the study period, peak seasonal stream power, averaged over the reach, was a good index for estimating the erosional stress (driving forces) experienced by the study reaches.

The coarse fragment content of streambanks in the study reaches (%B+C) was second in importance as a significant predictor of channel erosion. As shown in Table 5, study reaches located on the Incoherent Unit of Coyote Creek (ICC) were much lower in %B+C than those located on either the Coherent Unit of Lacks Creek or the Redwood Creek Schist. The pronounced lack of coarse fragments in materials sampled in the ICC is consistent with the findings of Weaver et al. (in press) which demonstrate a low capability for negative feedback through self-armoring of subsoils on this terrain.

Table 5. Comparison of boulder and cobble contents of streambanks on different lithologies in the study area.

Lithologic Unit	Number of Reaches	Mean %B+C
Redwood Creek Schist	16	15.1
Coherent Unit of Lacks Creek	4	18.5
Incoherent Unit of Coyote Creek	4	5.5

In the channel erosion regression analysis, an improved fit was accomplished by squaring %B+C. This suggests that, all other factors being equal, the potential for channel erosion diminishes as a power function of increasing coarse fragment content of eroding materials. Perhaps a more appropriate measure of the negative feedback (armoring) potential of materials subject to fluvial erosion might be the percent by volume of particles coarser than a diameter equal to the largest size transportable by maximum expected (design) stream power. Such a competency-dependent variable would eliminate the need for using arbitrary size distinctions.

Third most important of the independent variables included in the regression equation was percent stream drop composed of organic steps (%ORGDROP), which ranged from 4.1 to 67.2 percent. Organic debris in the channel was responsible for reducing total stream power available for channel erosion and for providing bed resistance. Much of the literature concerning the role of organic debris in streams reports high percentages of potential energy dissipation due to vertical waterfalls over organic steps. Potential energy dissipation ranged from 30 to 80 percent and 32 to 52 percent in Oregon streams investigated by Keller and Swanson (1979) and Swanson et al. (1976), respectively. Keller and Tally (1979) report a range of 18 to 60 percent of potential energy dissipated by organic steps in tributaries to Redwood Creek.

For the study reaches investigated herein, percent stream drop composed of organic steps is analogous to what has been referred to in the literature as percent potential energy dissipation. The use of this phrase is avoided in this study, however, because such a quantity is affected by discharge rate. During high flows, relatively small organic steps may become submerged and rendered less effective as potential energy dissipators. Because channel profiles were surveyed at low flows, some uncertainty exists as to the utility of all sizes of organic steps for energy dissipation at peak flows. This uncertainty may explain why %ORGDROP was of only tertiary importance in the regression equation. If possible, potential energy dissipation by vertical falls over organic steps should be measured at the flow rate of interest to assure accurate quantification.

In the stepwise regression analysis, three independent variables were excluded on the basis of partial correlation coefficient significance tests. They are: 1) average vertical height of organic steps (AVOSTPHT), 2) average horizontal distance between steps (AVORGDIS), and 3) percent clay in the finer than 2 mm fraction of bank material (%CLAY).

It may be speculated why the two variables calculated from the arrangement of organic debris in the profiles (AVOSTPHT and AVORGDIS) were not significant predictors of SCOUR/M. Selection of these variables was based on the assumption that the greater the spacing of organic steps in the profile (both horizontally and vertically), the less continuity of channel structure present and the greater the exposure of erodible materials to erosional forces. Support for the validity of this reasoning was drawn from qualitative field observations made during the study period. However, because the averages used were not particularly representative of extreme values of organic step height and intervening horizontal distance, the variables calculated were not as sensitive as they might otherwise have been. In retrospect, perhaps a calculation method which gives more weight to high values of organic step height and horizontal spacing would have been more appropriate.

Of the two bank material properties quantified, only percent boulders and cobbles (%B+C) was a significant predictor. Percent clay in the soil fraction (%CLAY) failed to meet the significance criteria. A possible explanation may be that the bank material in the study reaches varied not only in the quantity, but also in the quality of clay-sized particles present. The hydrometer analysis estimates clay content only on the basis of particle size, not mineralogy. Because cohesion in clays is, at least in part, a function of clay micell minerology, the simple particle size analysis was probably not the best surrogate variable for cohesion. Although clay content of the bank material in the study reaches failed to be a significant predictor of channel erosion, it is possible that some other material property (such as Atterberg Limits or shear strength) could have improved the regression model.

Channel Armor

The development of a channel bed inorganic armor layer occurred to some degree in all 24 study reaches. In the first regression (n=24), total stream power (Ω) alone explained over 77 percent of the variability in D65. Percent stream drop composed of organic steps (%ORGDROP) became a significant predictor of D65 only after an anomalous observation (Reach 6) was deleted. For the 23 remaining observations, Ω and %ORGDROP explained over 89 percent of the variability in D65.

As was the case with channel scour, the relative magnitudes of driving and resisting forces operating in the study reaches determined the degree of armor development. The driving force (stream power) was partially offset by the resistance provided by organic debris. Particle size distributions of channel bed armor in Reaches 13 and 20 (Figure 11) graphically demonstrated the effects of organic debris on armoring requirements. As shown in Figure 11, Reaches 13 and 20 experienced similar peak seasonal stream power, but had different levels of %ORGDROP. Surficial bed material in Reach 20 became coarser than that in Reach 13 during the study period. This reflects the dampening effects of organic debris on stream power. Organic steps exaggerate the variability in local channel gradient, causing lower gradients in channel segments between adjacent steps and higher gradients at steps (vertical slopes). Local gradient extremes are responsible for similar extremes in local stream powers. In reaches having a relative abundance of organic steps, the areal influence of high local stream powers is small in proportion to that of low local stream powers, resulting in surficial sediment sizes more reflective of the latter.

In the stepwise multiple regression analysis, the explained variability increased from 77 to 88 percent after the exclusion of Reach 6 from the data set. Having just 6.9 percent of total elevation drop composed of organic steps, Reach 6 was fourth lowest in organic debris influence among the study reaches. With a moderately high stream power (367 joules/sec/m), the predicted D65 was 74 mm; 85 percent larger than the observed D65 of 40 mm (Appendix A) for this reach. While included in

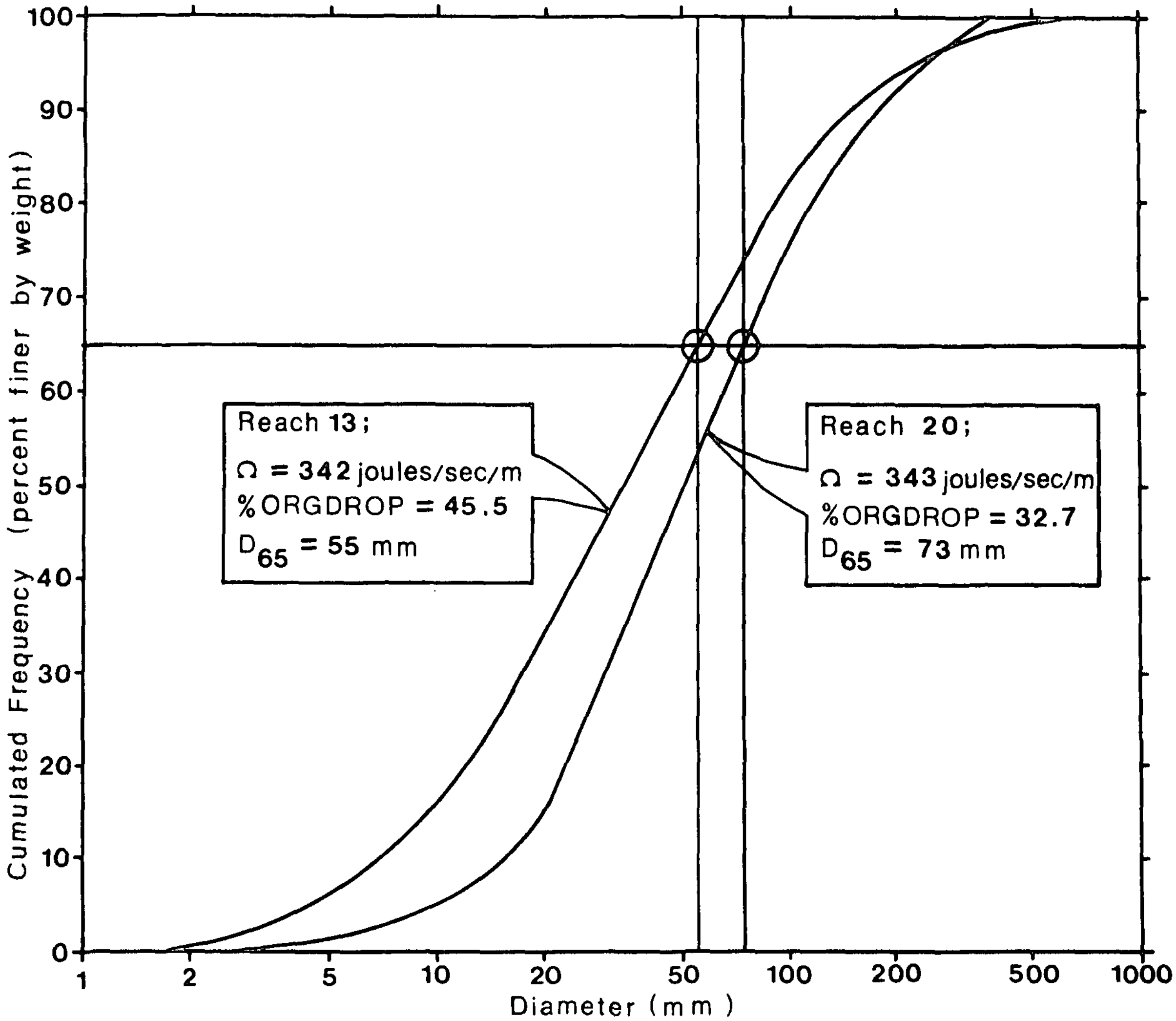


Figure 11. Particle size distribution curves for Reaches 13 and 20 showing values of D65 and predictor variables. Note that although these reaches experienced similar total stream powers (Ω), armoring requirements were more effectively offset by the greater organic debris influence (indexed by %ORGDROP) in Reach 13 than in Reach 20, resulting in a finer D65 in Reach 13.

the regression data set, the influence of Reach 6 was sufficient to mask the significance of organic debris in attenuating armoring requirements. The phenomenon attributed to the non-conformity of Reach 6 (persistent bank sloughing) may have been present (although to lesser degrees) in other study reaches exhibiting negative standardized residuals. If this was the case, %ORGDROP might have increased in significance relative to stream power if bank sloughing persistence were quantified as a predictor variable.

As in the SCOUR/M regression, the two independent variables based on the vertical height and horizontal spacing of organic steps (AVOSTPHT and

AVORGDIS) were not significant predictors in the D65 regression analysis. And, as mentioned earlier, these variables were averages, and so tended not to adequately reflect extreme values of organic step height and spacing. Hypothetically, two very dissimilar reaches with respect to arrangement and abundance of organic steps could yield identical values of AVOSTPHT and AVORGDIS. Because the nature of energy dissipation provided by organic steps is a function of not only the proximity of steps to one another, but also the continuity of steps within an entire reach, the averages for organic step height and horizontal spacing were poor predictors of bed material size.

CONCLUSIONS

Stream channel adjustments following removal of logging road stream crossings were dependent upon the magnitude and duration of erosive forces applied (stream power) relative to the resistance provided by organic debris and coarse inorganic sediments. The observed adjustments reflected increases in channel structural stability (resistance) in response to stream power. Total stream power of the largest discharge event (Ω) can only be considered as an index of erosive forces because of the variability of stream power in time and space. Fluctuating discharge rates and adjustments in local channel gradient caused sudden changes in stream power over time, while within-reach gradient variations accounted for spatial heterogeneity. Temporal changes in the volume and size distribution of the sediment supply (both from upstream sources and within-reach scour) and in the size of channel bed material further complicated fluvial responses. Although channel adjustments occurred in concert as complex feedback mechanisms, the simple models generated from the net seasonal adjustments explained high percentages of variability.

The abundance of organic debris in excavated stream crossings was a function of the amount of original channel structure composed of organic debris relocated upon excavation and the amount of organic debris removed from or placed in the road fill during construction.Reach 23 (Figure 12) provided an example of successful excavation to abundant organic channel structure. Channel adjustments in this reach were minimal.

In reaches where structural organics were sparse, channel adjustments were greater. Resistance to channel erosion was derived primarily from coarse sediments armoring the channel bed and banks. If a sufficient amount of coarse sediment was not present at the onset of large stream power events, channels responded with slope reductions by scouring their beds and accumulating a coarse lag from the eroding channel bed and banks. The potential for armor development (a form of negative feedback) varied among the different lithologies present in the study area. Bank material adjacent to reaches within the Incoherent Unit of Coyote Creek displayed approximately one-third the boulder and cobble content of that in either the Coherent Unit of Lacks Creek or the Redwood Creek Schist unit. Reach 5 (Figure 13) represents a rather extreme case of erosional response due to lack of both original channel structure (organic debris) and negative feedback (armor) potential of the eroding material. This reach was located in the Incoherent Unit of Coyote Creek.

The self-armoring capability of bank materials only becomes important when existing channel structure is inadequate. Although the amount of structure that will be found in buried channels is impossible to determine prior to excavation, observation of undisturbed channel characteristics in adjacent reaches above and below road crossings may

A. B.

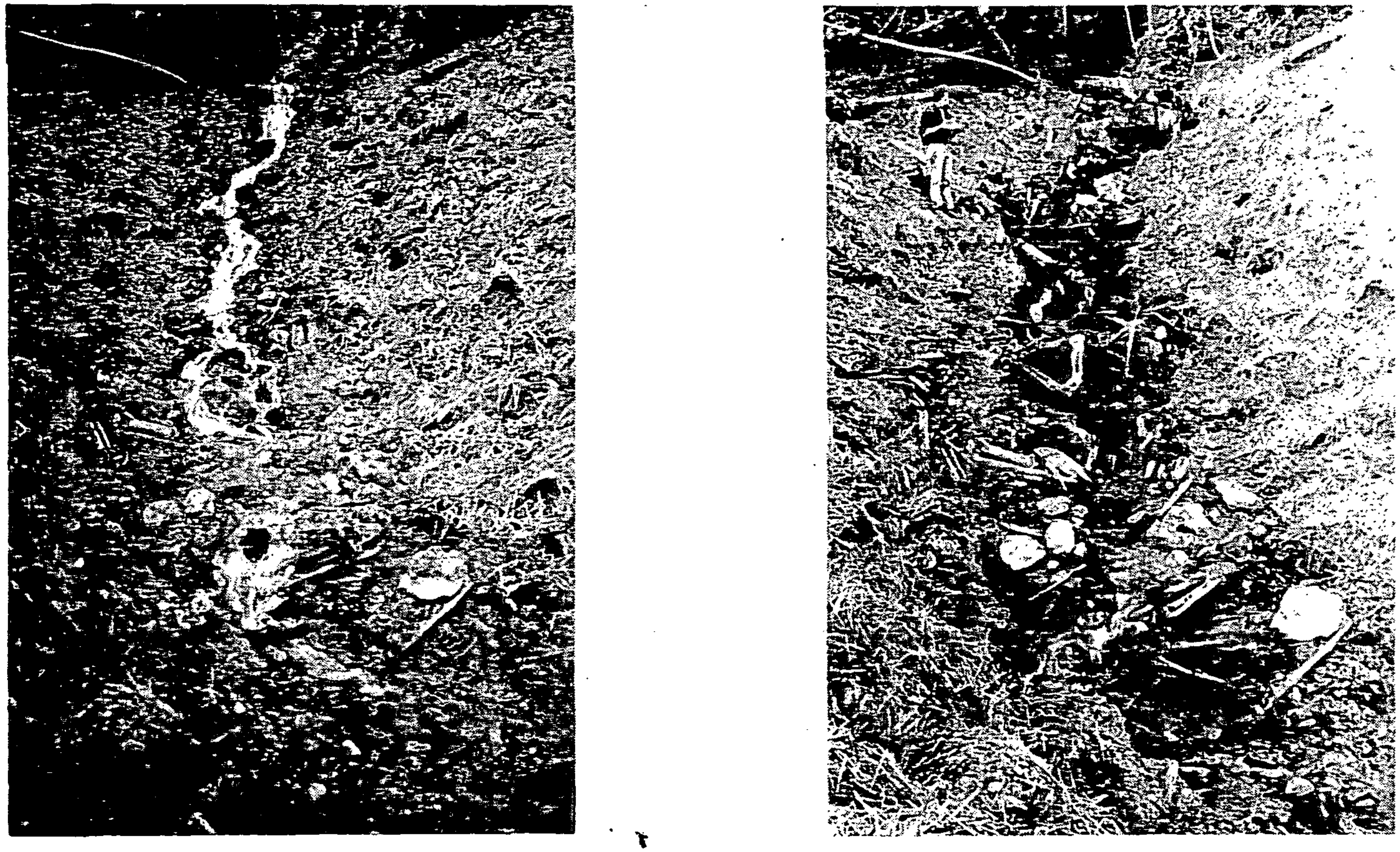


Figure 12. Before (A) and after (B) season photos of Reach 23 showing development of numerous steps composed of organic debris accumulations. Percent stream drop composed of organic steps (%ORGDROP) in this reach was relatively high at 45.5%.

A. B.

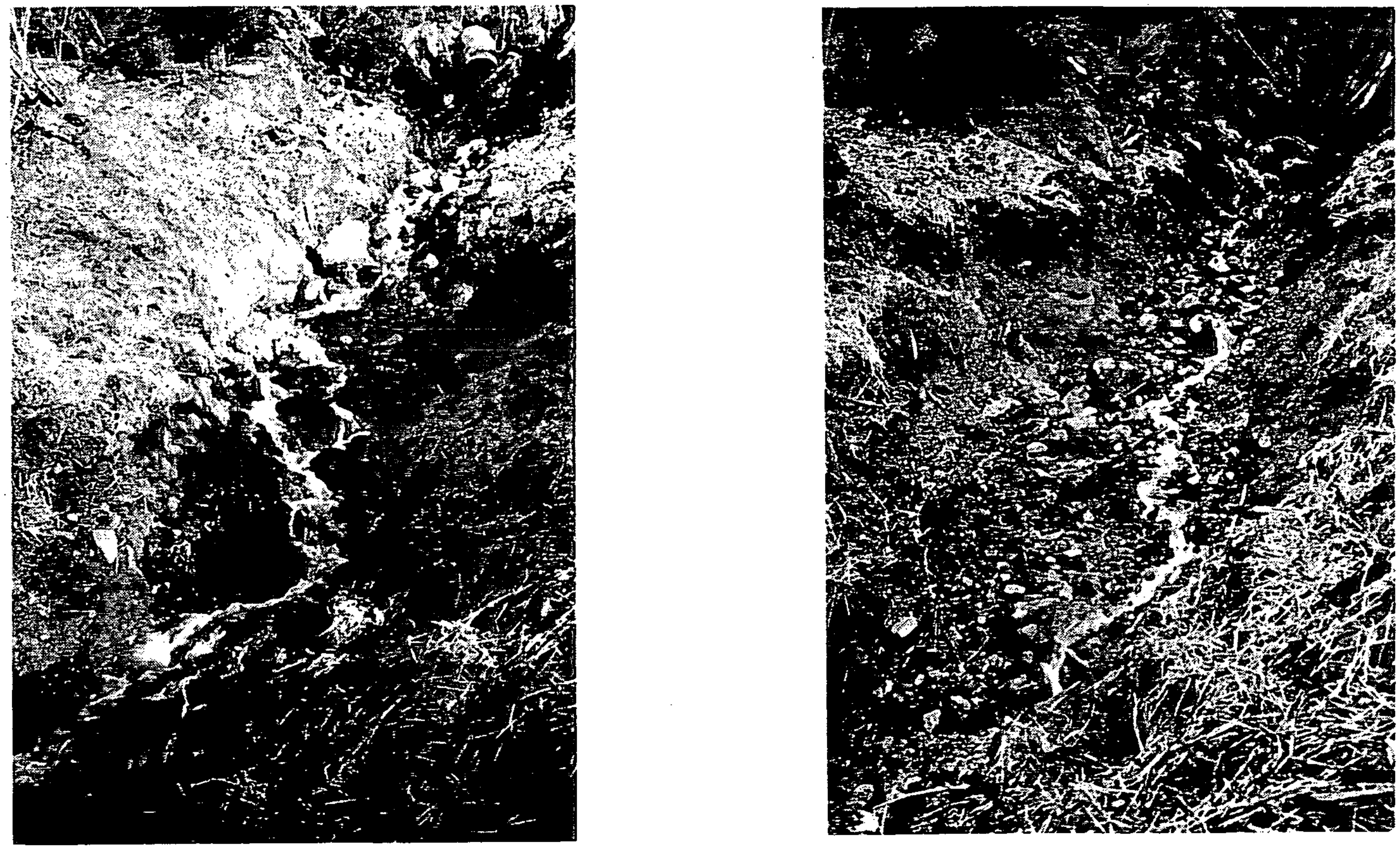


Figure 13. Before (A) and after (B) season photos of Reach 5 showing extensive scour and channel bed armor development. Percent stream elevation drop composed of organic steps (%ORGDROP) was relatively low (6.9%), as was the percent streambank material composed of boulders and cobbles (%B+C), accounting for the severe erosion occurring in this reach.

suggest the nature of the channel beneath the road fill. Where sufficient organic debris and inorganic armor is anticipated, care should be taken not to dislodge these materials during excavation.

In stream crossing excavations where organic channel structure is anticipated to be sparse, resistance to erosion will be derived primarily from coarse inorganic sediments. Some inorganic armoring materials may be exhumed upon excavation of road fill, however these materials are often difficult to recognize, and are thus more likely to be removed or disturbed by heavy equipment activities. Resistance to channel erosion in the absence of organic structure may be conservatively assessed by considering the coarse fragment content of bank materials adjacent to excavated channels. Low percentages of cobbles and boulders, a condition conducive to accelerated scour, may be anticipated in stream crossings underlain by shale and mudstone, or their metamorphosed equivalents. Although found on other terrain, these highly erodible materials are especially common on areas within the Incoherent Unit of Coyote Creek.

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APPENDIX A. Table of data for variables quantified (symbols and acronyms are explained in Table 2, page 10).

Variable: Reach No.	SCOUR/M	D65	Ω	%B+C	%ORGDROP	AVOSTPHT	AVORGDIS	%CLAY	QPK	SLOPE	LENGTH (m)
1	0.3	57	311	25	30.1	0.7	4.2	21.6	0.229	0.138	26
2	2.8	110	594	20	5.4	0.6	3.0	19.0	0.212	0.285	32
3	2.0	88	385	15	23.6	0.6	5.4	21.5	0.212	0.185	24
4	1.5	67	294	14	25.0	0.5	2.9	24.7	0.208	0.144	18
5	2.6	74	278	4	6.9	0.7	12.9	26.3	0.105	0.270	32
6	2.6	40	367	4	6.8	0.6	8.2	18.8	0.136	0.275	62
7	0.1	20	88	7	67.2	0.4	3.3	20.0	0.059	0.150	19
8	0.8	23	178	7	40.9	0.5	3.2	25.7	0.076	0.237	29
9	0.8	75	395	25	10.0	0.4	3.2	9.1	0.166	0.243	30
10	0.3	25	41	8	7.7	0.4	13.4	23.5	0.013	0.319	32
11	0.1	35	77	18	23.1	0.3	2.1	18.0	0.029	0.271	27
12	0.3	26	151	17	55.3	0.5	2.1	18.0	0.029	0.271	35
13	0.6	55	342	22	45.5	1.0	3.6	11.0	0.143	0.244	28
14	1.6	69	276	7	59.4	0.8	4.6	11.7	0.149	0.189	26
15	0.4	32	123	14	42.4	0.3	3.0	20.3	0.063	0.199	45
16	0.2	44	100	15	4.1	0.3	2.5	25.6	0.035	0.293	25
17	0.3	67	344	15	47.0	0.5	2.4	19.0	0.123	0.285	39
18	0.7	57	208	17	37.6	0.6	5.2	22.0	0.127	0.166	31
19	0.2	48	130	17	29.5	0.4	3.7	27.8	0.043	0.308	24
20	0.2	73	343	18	32.7	0.5	3.6	29.2	0.135	0.259	28
21	0.2	29	104	16	46.1	0.4	4.7	29.3	0.076	0.138	36
22	0.2	28	94	12	49.7	0.4	2.6	25.6	0.034	0.279	35
23	0.1	35	158	7	62.2	0.5	4.2	16.4	0.079	0.205	40
24	0.1	22	69	13	61.4	0.4	3.9	24.5	0.043	0.163	70

APPENDIX B. Correlation matrices for variables incorporated into the final SCOUR/M and D65 regression equations.

Correlation matrix for the final SCOUR/M regression:

Predictor Variable	Partial Regression Coefficient		Simple Correlation Coeff.		
	Coefficient	Standard Error	SCOUR/M	Ω	%B+C
Ω	0.0057972	0.0004730	0.698	------	------
$(\%B+C)^2$	-0.0028288	0.0003407	-0.256	0.317	------
%ORGDROP	-0.011062	0.002995	-0.523	-0.385	-0.139

Correlation matrix for the final D65 regression:

Predictor Variable	Partial Regression Coefficient		Simple Correlation Coeff.	
	Coefficient	Standard Error	D65	Ω
Ω	0.14875	0.01375	0.922	------
%ORGDROP	-0.26770	0.09706	-0.510	-0.346

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