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Authors

Keller, Edward A
MacDonald, Anne

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LARGE ORGANIC DEBRIS AND ANADROMOUS FISH HABITAT IN THE COASTAL REDWOOD ENVIRONMENT: THE HYDROLOGIC SYSTEM

by

EDWARD A. KELLER and ANNE MacDONALD

Department of Geological Sciences
University of California, Santa Barbara

Office of the Director
CALIFORNIA WATER RESOURCES CENTER
University of California Davis, California 95616

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ABSTRACT

This research on effects of large organic debris on stream channel form and process relevant to anadromous fish habitat was along three lines of inquiry. First, new ways to evaluate discrete hydrologic environments, such as pools, riffles and debris accumulations were developed. Experiments completed provided basic data to test a model useful for predicting hydraulic geometry of pools and riffles. These experiments will help managers develop design criteria for construction or improvement of fish habitat in channel restoration projects. Similar hydrolgic experiments in Redwood National Park, have been completed to evaluate the stream power associated with organic steps and defines a sediment buffer system that modulates the movement of bedload through the fluvial system.

A second line of inquiry involved debris removal experiments in Redwood National Park. Significant hydrologic and morphologic changes occurred as a result of the debris removal. Results of the debris pulling experiment suggest that the stream now is more sluggish and has less hydrologic variability than prior to the debris removal.

The third line of inquiry was a comparative study between undisturbed streams flowing through old growth redwood forest with those impacted by timber harvesting. Large organic debris (greater than 10 cm in diameter) is equally effective on controlling gross channel form in both undisturbed and disturbed channels, but there is a difference in the size and quantity of debris, channel morphology, and thus anadromous fish habitat. There is a higher percentage of unstable stored sediment in disturbed basins and sediment storage sites tend to be filled more often. Once storage sites are full, sediment may be transported more directly through the channel to downstream sites, producing a sediment pollution problem.

Introduction

Studies of short-term modification of the earth's surface cannot ignore the effect vegetation has on the processes involved in weathering, transport and deposition of earth materials, and this interaction is nowhere better developed than in the coastal forests of northwestern North America. One aspect of this is the relationship between large organic debris (LOD), defined as all woody material greater than 10 cm in diameter, and stream channel form and process. Recent work by Heede (1972, 1981), Swanson and others (1976), Swanson and Lienkaemper (1978), Keller and Swanson (1979), Keller and Tally (1979), Tally (1980), Mosley (1981), and Marston (1982) suggest that LOD plays a crucial role in determining the morphologic and sediment routing characteristics of undisturbed forest streams. Debris steps and jams act as local base levels, producing stepped-bed profiles and enhancing pool development, and are therefore responsible for much of the hydrologic variability found in steep forest streams. In addition, these effects are sufficiently long-lived to be considered "geologic". Residence time of redwood debris in stream channels can exceed 200 years (Keller and Tally, 1979), and accumulations of Douglas fir are known to remain in channels for more than 100 years (Swanson and others, 1976).

Since debris accumulations are effective barriers to sediment movement, they should also be important components of streams draining forests which generally have high sediment loads as a result of logging and road building activity. Sediment pollution is particulatly high in northwestern California, where the combination of seasonally intense rainfall, very erosive substrate (rocks of the Franciscan assemblage), and high uplift rates result in the largest suspended sediment yields per unit area reported in any non-glaciated terrain in North America (Janda and Nolan, 1979). Research by Bilby and Likens (1980), Bryant (1980), and Pitlick (1982) indicates that large organic debris in disturbed channels functions much the way that it does in undisturbed channels; it produces pools, stepped long profiles, often stabilizes stream banks, and buffers sediment delivery to trunk streams.

Study Areas and Methods

Our research on the role of large organic debris on stream channels has been concentrated in the northern Redwood Creek drainage, specifically on Prairie Creek, Little Lost Man Creek, Hayes Creek, Lost Man Creek, and Larry Damm Creek (figure 1), and on the North Fork of Caspar Creek on the Mendocino Coast south of Fort Bragg (figure 2). Where studied, Little Lost Man and Lost Man Creek are predominantly underlain by shales, thin-bedded to massive

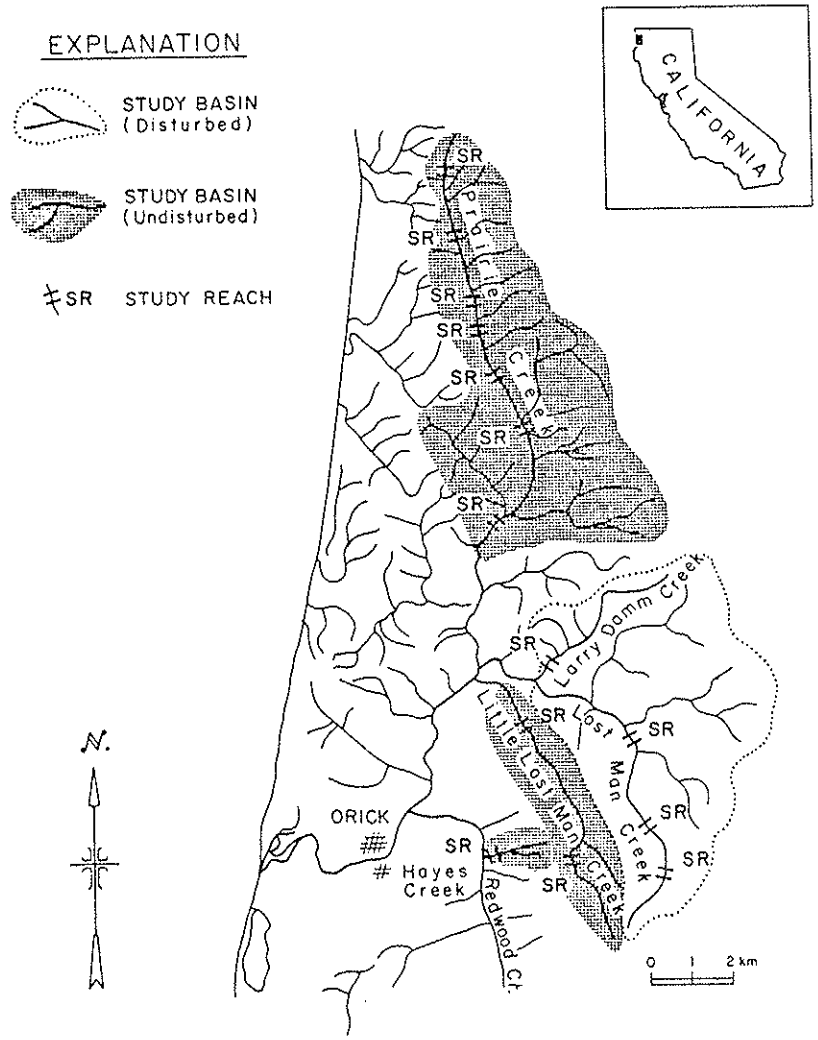

Figure 1: Location of study reaches in the Redwood Creek watershed.

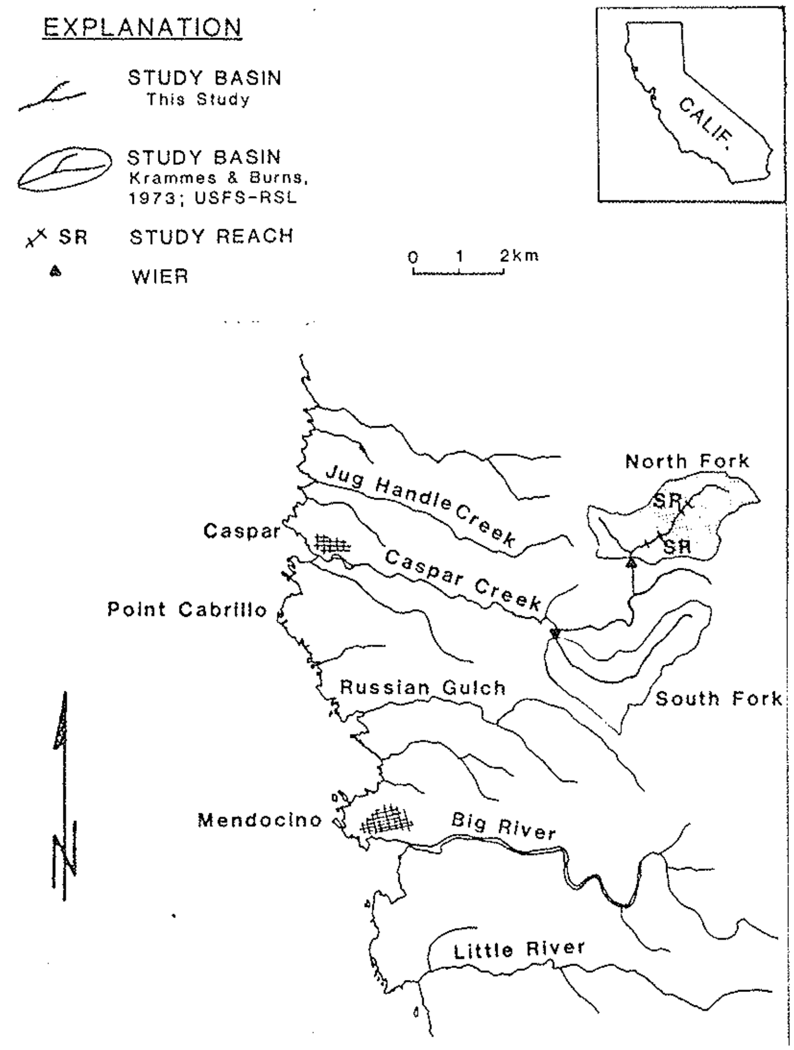

Figure 2: Location of study reaches in the Caspar Creek watershed.

sandstones, and pebble conglomerates of the Mesozoic Franciscan Assemblage. Their valleys trend NNW-SSE and lie parallel to major Quaternary and older faults in the area (Herd, 1978; Kelsey, 1982). The entire Prairie Creek watershed and Larry Damm Creek above the study reach are underlain by consolidated sands and gravels of the Plio-Pleistocene Gold Bluffs Formation, which are interpreted to be riverine and littoral deposits of a proto-Klamath River. Hayes Creek drains Franciscan sediments in its upper reaches, crosses the Grogan Fault, and drains pelitic schists in the lower reaches.

Watersheds of Little Lost Man, Hayes, and Prairie Creeks support extensive old-growth redwood forest (*Sequoia sempervirens*) with minimal recent disturbance. In contrast, the Lost Man Creek basin above the USGS gaging station was 97% logged between World War II and the creation of Redwood National Park in 1968 (Iwatsubo and others, 1976). A similar percentage of Larry Damm Creek was logged between 1954 and 1968. The North Fork of Caspar Creek, draining shales and sandstones of coastal belt Franciscan, was logged and burned in the 1890's. It now supports an eighty-plus year old forest dominated by redwood (*S. sempervirens*), hemlock (*Tsuga heterophylla*), grand fir (*Abies grandis*), and tanoak (*Lithocarpus densiflorus*).

Two separate approaches to the study of large organic debris have been taken in this project. First, in order to determine the role of organic debris found in stream channels draining logged basins, the comparative morphology of both undisturbed and distubed basins was assessed. The study of undisturbed basins was completed in 1980, and reported on by Keller and Tally (1979) and Tally (1980). Because many of the same principles apply in both cases, the work by Keller and Tally will be discussed in this report along with the findings of the study of logged basins. Study reaches were established on channels draining Franciscan sediments (Little Lost Man, Lost Man, and Caspar creeks) to give a range of drainage basin areas, and time since disturbance in the case of Lost Man and Caspar creeks. For each study reach of 20 - 30 channel widths, a morphologic map was constructed to estimate the relative proportion of channel area in the major environmental categories: pools, riffles, undercut banks, debris stored sediment and non-debris stored sediment. In addition, the control of plan morphology (width, sinuosity, pool-to-pool spacing) by large organic debris could be assessed from these maps. The long profile and representative cross-sections were surveyed in each reach to determine average channel dimensions (especially depth) and the percent of elevation drop due to debris. The second portion of this study was centered on Larry Damm Creek, and consisted primarily of a debris removal experiment. Data similar to that collected on other study reaches was gathered repeatedly on Larry Damm Creek from September 1979 to

August, 1982, both before and after debris removal in August, 1980. Channel bed material, bed and suspended load were also sampled, and travel times of water through selected sub-reaches was determined with salt tracing techniques over a range of discharges up to roughly 40 percent of bankfull flow.

Residence Time and Loading of Large Organic Debris

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

Large organic debris loading, measured in cubic meters of woody debris per square meter of active channel (m3/m2), is determined by measuring the length and diameter of all large organic debris found within the limits of active bedload transport. In general, there is an inverse relationship between the stream size (measured in terms of upstream drainage basin area) and debris loading. This results because small streams tend to have narrow valleys, steep valley slopes, and a relatively high frequency of landslides, all of which tend to increase the debris loading. Marston (1982) reports a peak in the frequency of log steps (not total debris loading) in third order streams, resulting from the fact that the headward portions of streams often have narrow, V-shaped valleys in which there is little likelihood of trees actually falling in and blocking the thalweg. Examination of table 1a, however, suggests that there is a great deal of variability in the debris loading of a particular stream. Much of the variability can be explained in terms of the proximity of large redwood trees to the stream channel: where the density of large trees is relatively high, the debris loading is correspondingly higher. Tally (1980) indicates a good correlation (r= 0.88) between debris loading and frequency of large trees within 50 m on either side of the channel.

Movement of large organic debris through the stream system is primarily by flotation during high flows or perhaps, in very steep section of stream channels, by debris torrents (Swanson and Lienkaemper, 1978; Keller and Tally, 1979). Large organic debris in streams draining old-growth forest, such as Prairie, Hayes, and Little Lost Man creeks,

Table 1a. Comparison of Morphologic Data for Undisturbed Watersheds, (Tributaries to Redwood Creek) Northwestern California (a)

Study Reach	Hayes Creek	Little Lost Man Creek Upper	Little Lost Man Creek Lower	Prairie Creek Hope Creek Reach	Prairie Creek Little Creek Reach	Prairie Creek Forked Creek Reach	Prairie Creek Zig Zag No. 2	Prairie Creek Natural Tunnel	Prairie Creek Brown Creek	Prairie Creek Campground
Upstream basin area (km^2)	1.5	3.5	9.1	0.7	3.5	6.6	8.2	11.2	16.7	27.2
Stream order	2	2	3	2	2	2	2	2	3	4
Slope	0.12	0.033	0.048	0.02	0.014	0.012	0.009	0.01	0.01	0.005
Debris loading (m3/m2)	0.340	0.283	.098	0.436	0.025	0.026	0.043	0.212	0.170	0.039
Pool to pool spacing (in channel widths)	2.4	(b) 1.9	(b) 1.8	(b) 6.2	(b) 4.7	2.6	6.6	2.7	6.0	4.0
% channel area pool	12	22	18	49	34	46	36	41	26	25
% channel area riffle	26	15	21	21	46	49	20	15	18	25
% channel in debris stored sediment	40	39	39	30	18	30	15	21	29	13
% channel area undercut banks	4	3	1	1	4	3	4	1	<1	1
% pool morphology influenced by debris	83	100	90	86	71	87	50	80	67	50
Debris controlled drop in elevation of the channel (%) (c)	38	59	30	43	27	34	8	<1	18	<1

(a) Total percentages in stream environments may be less or greater than 100% due to overlaps such as pools that contain debris stored sediment or existence of other environments not listed.

(b) Spacing controlled by organic debris.

(c) Ratio of cumulative loss of channel elevation associated with large organic debris to total fall of the stream reach.

may be very large, often several meters in diameter, and as a result moves only rarely. This was determined by examining "nursed" trees such as hemlock, spruce, and other redwood trees growing on in-channel debris. Coring of these "nursed" trees indicates a minimum time that the debris has been in the stream channel. In all, more than 30 pieces of debris have been dated; half of these have been in the channel in excess of 100 years, with the oldest exceeding 200 years. Based on this evidence, it is apparent that large organic debris can reside in stream channels for several centuries and, thus, is a permanent part of the fluvial system. In larger streams, such as the lower portions of Redwood Creek, flood discharges are sufficient to float even the largest debris, and the residence time is therefore shorter. However, debris sufficiently attached to the banks may still contribute to the formation of large pools.

Because of the substantial alteration of stream channels and banks in disturbed watersheds, due to the combined effects of timber harvest and major storms in 1955, 1964, 1972, and 1975, none of the debris dams studied in Lost Man or Caspar creeks supported nursed logs greater than 20 years in age; vegetation-stabilized sediment stored behind these jams generally dates from 2 to 5 years after major storms based on dendrochronolgy. The presence of numerous large logs in the channel with sawn ends also suggests that debris loading and spacing in stream draining logged watersheds is related to the road construction and timber harvest practices employed, and time since timber harvest, as well as local geologic and hydrologic conditions affecting mass-wasting. In general, pieces of woody material introduced to the stream channels during timber harvest are smaller and more numerous than those delivered by natural processes. They are therefore more mobile and have a greater destabilizing effect on the channel because they "caulk" large, open, pre-existing debris accumulations; the resulting jam is more susceptible to catastrophic failure (Bryant, 1980). Subsequent local additions of debris are likely to be from early successional tree species which are generally smaller than the climax species (Bilby and Likens, 1980; Bryant, 1980). In northwestern California, these are also less rot-resistant than redwood, and therefore shorter-lived in the channel. This can be seen in Caspar Creek, where no natural, pre-logging jams remain following sluicing of the channel used to move cut logs downstream. Most of the in-channel debris is composed of hemlock and tanoak boles, and the total loading is quite low (table 1b). In contrast, substantial numbers of logs have been added to Lost Man Creek for use as stream crossings during yarding of felled trees and from failures of roads near the channel. Only on Larry Damm Creek has a major log jam been shown to pre-date timber harvest, based upon a "nursed" redwood tree with an age of 68 years (lower debris jam in figure 3a). This jam was subsequently removed

Table 1b. Morphologic Data for Disturbed Watersheds, Northwestern California (a)

Study Reach	North Fork Caspar Creek Upper	North Fork Caspar Creek Lower	Lost Man Creek Upper	Lost Man Creek Middle	Lost Man Creek Lower	Larry Damm
Upstream basin area (km^2)	1.6	3.9	1.1	3.4	9.8	3.7
Stream order	2	2	2	3	4	3
Slope	.016	.013	.048	.024	.047	.014
Debris loading (m^3/m^2)	.042	.048	.210	.181	.142	.152
Pool to pool spacing (in channel widths)	(b) 3.5	3.8	(b) 4.1	(b) 2.6	1.3	2.2
% channel area pool	24	36	33	43	14	27
% channel area riffle	30	30	25	14	11	14
% channel in debris stored sediment	44	34	43	31	41	59
% channel area in undercut banks	2	1	4	2	1	2
% pool morphology influenced by debris	82	43	79	100	57	59
Debris controlled drop in elevation of the channel (%) (c)	57	37	69	33	30	17
Approximate period of timber harvest	1890's	1890's	Post WW II-~1960?	Post WW II-~1960?	Post WW II-1968	1954-1968

(a) Total percentages in stream environments may be less or greater than 100% due to overlapping environments and/or existence of non-listed environments.

(b) Spacing controlled by organic debris.

(c) Ratio of cumulative loss of channel elevation associated with large organic debris to total fall of the stream reach.

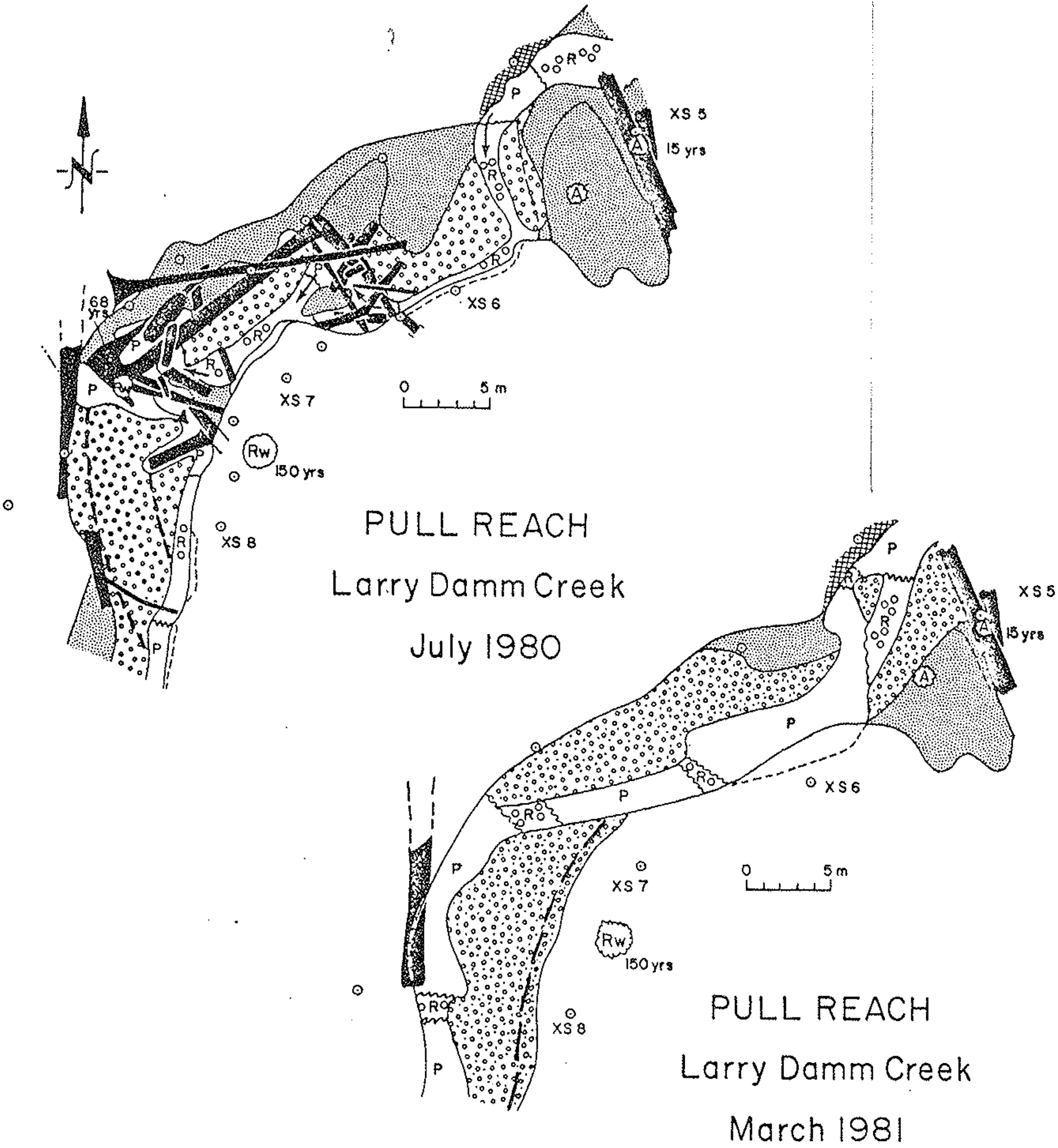

Figure 3: Morphologic maps of the upstream portion of the "Pull" reach, Larry Damm Creek, a) before and b) after debris removal.

in a debris removal experiment, discussed elsewhere in this report.

Nature and Extent of Large Organic Debris Control on Sediment Storage Patterns

Large organic debris plays an important role in the routing and storage of sediment. Debris accumulations such as organic steps produce storage compartments for sediment, ideally shown in figure 4. Data contained in tables 1a and 1b suggest that such storage sites account for a significant portion of the total channel area. In undisturbed basins, debris stored sediment is strongly correlated with channel slope (rank sum correlation r = 0.90). This indicates the importance of debris in providing storage sites in steep channels, as well as the locally high production of sediment associated with steep channel slopes. Elsewhere in the Redwood Creek basin, Pitlick (1980) found than organic debris was responsible for storing a substantial percentage of all sediment stored in tributary channels, ranging from 39 percent in streams draining Douglas fir dominated forest, to 74 percent when the basin was originally forested with redwood.

Studies by Megahan and Nowlin (1976) and Swanson and Lienkaemper (1978) suggest that annual sediment yields

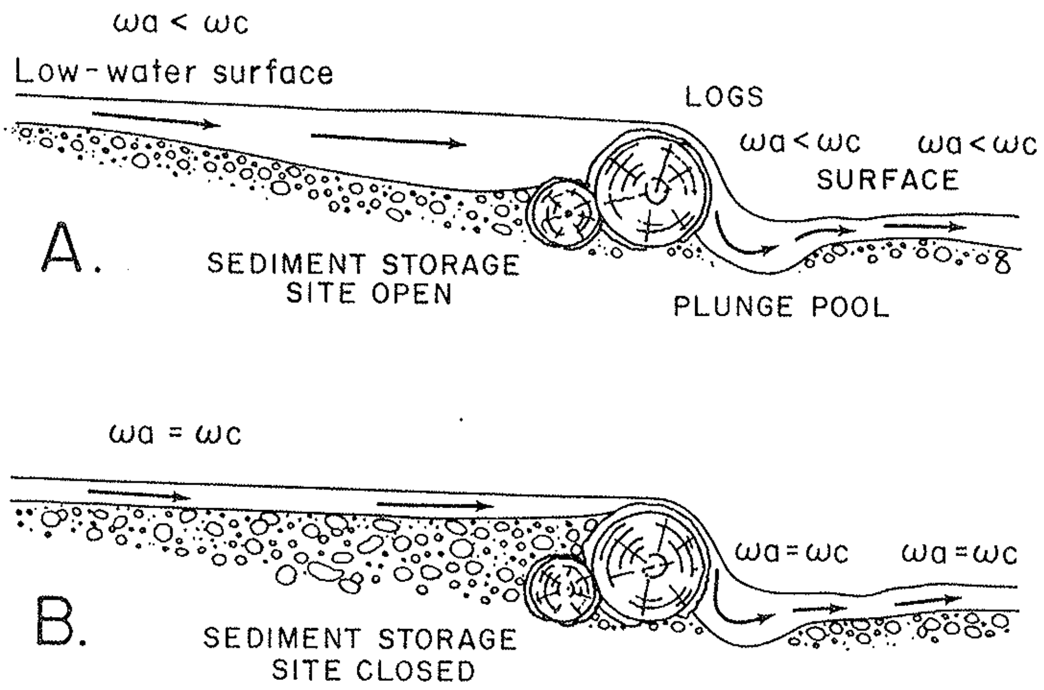

Figure 4: Distribution of stream power over an idealizd organic step with the upstream storage compartment a) empty and b) full.

in small forested watersheds are generally less than 10 percent of the sediment stored in channels. In comparison, in Little Lost Man Creek, 40 percent of the channel is in debris stored sediment. This reflects the difference in size of organic debris producing the sediment storage compartments. The average annual suspended sediment yield for the Little Lost Man Creek basin is about 450 metric tons and approximately 25 percent of this is bedload, providing an average annual bedload yield of 116 metric tons. The total debris related volume of potential storage capacity in Little Lost Man Creek is estimated at 14,000 m^3; roughly 64 percent, or 8950 m^3 of this is presently filled (Tally, 1980). Assuming a unit weight of debris stored sediment consisting of gravel and sand to vary between 1.36 and 2.00 tons per cubic meter (Geiger, 1965), approximately 100 to 150 years of average annual bedload sediment is stored in debris-related sites along Little Lost Man Creek and about 50 to 100 years of average annual bedload yield is available for future storage. Thus, if the storage system were filled to capacity, it would contain from 150 to 250 years of average annual bedload yield. This should not be interpreted to mean that the sediment storage compartments associated with large organic debris effectively trap all of the bedload that moves into a particular reach. In fact, debris stored sediment tends to be significantly finer gravel than that found on riffles on Little Lost Man Creek (Tally, 1980). Furthermore, because it is finer sediment, it tends to be transported more frequently in response to moderate flow (50 percent of bankfull), whereas coarse material on riffles tends to armor the bed and is probably moved only during extreme events (Tally, 1980). Evidence from streams in New Zealand suggest that sediment that moves out of a debris stored site will usually only move a short distance before being redeposited behind downstream debris accumulations (Mosley, 1981).

More specific explanation of sediment transport rates in forest streams is difficult. To date, only Mosley (1981), in a carefully controlled channel, has published bedload transport rates in debris-laden channels, and found tremendous temporal and spatial variation in sediment movement. He related this to disruption of existing jams from rotting of logs or differential scour at high flows. This process is difficult to predict and measure, and "although sediment is transported along the channel by mechanisms which are universal and in principle describable in terms of physically-based theories, knowledge of these laws and theories alone cannot provide a full understanding of the behavior and form of this stream," (Mosley, 1981, p. 579). For this reason, the following discussion will be confined to observed patterns of erosion and depostion within the stream reaches studied. Comments regarding the causes of these patterns will be summarized in subsequent sections of this report.

In comparing undisturbed and disturbed watersheds, disturbed systems have a greater amount of debris stored sediment. Mean channel area in debris-stored sediment is 27 percent and 42 percent, respecitvely; the Mann-Whitney test shows this to be a significant difference at the 0.01 percent level. This is reflects the greater extent to which available storage compartments are filled in disturbed stream channels.

In order to better assess the effect of large organic debris on sediment storage, all woody material greater than 10 cm in diameter was removed from a 100 m stretch of Larry Damm Creek in August, 1980. This amounted to removing greater than 60 m^3, or approximately 25,500 board feet of logs and debris, contained primarily in two discrete jams at the head of the 100 m reach (DJ1, upstream, and DJ2, downstream, on figure 3a). No sediment was removed from the channel.

Prior to debris removal, 31 cross-sections were established in a 300 m reach of Larry Damm Creek, with 6 located in the 100 m above the reach from which debris was removed, 8 located in the 100 m reach below the "pull" reach, and the remainder within the central 100 m "pull" reach. In addition, the long profile was surveyed three times (September, 1979; January, 1980; August, 1980), and the channel mapped by tape and compass twice to establish magnitudes of variation in scour and fill in this stream channel. These surveys were also used to estimate the amount of debris-stored sediment within the "pull" reach. An estimate of 90 m^3 of debris-stored sediment within the "pull" reach was made assuming that material was stored 1) against the right bank between the two log jams 2) above DJ1 in the vicinity of cross-section (XS) 6 on the right bank 3) above DJ1 in the vicinity of XS5, left bank, and 4) in 30 percent of the gravel bar below DJ2, above an average winter low-flow water level for the entire reach (Q = 0.05 cms).

Most local adjustment of sediment to debris removal was complete by November 1, 1980, following peak discharges of approximately 12.5 percent of bankfull. Subsequent storms in early December, late January, and mid-February of winter 1980-1981 affected the most substantial changes in sediment storage patterns. These are demonstrated in figures 3, 5, and 6, comparing pre- and post-debris removal morphologic maps, cross-sections and long profiles, respectively, within the reach. The most notable changes in sediment storage patterns are: 1) erosion along the left bank above DJ1, seen in increased bank undercutting at XS6, 2) removal of a substantial part of the sand bar at XS5, left bank, which had previously been stable in the backwater of DJ1, 3) the formation of a point bar between cross-sections 7 and 8, and 4) the formation of substantial pools at XS6 and below the location of DJ2 (best seen in figure 6). Approximately 60 percent of the debris-stored sediment (of 70 m3 scoured) was removed from the reach, much of it redeposited upstream of

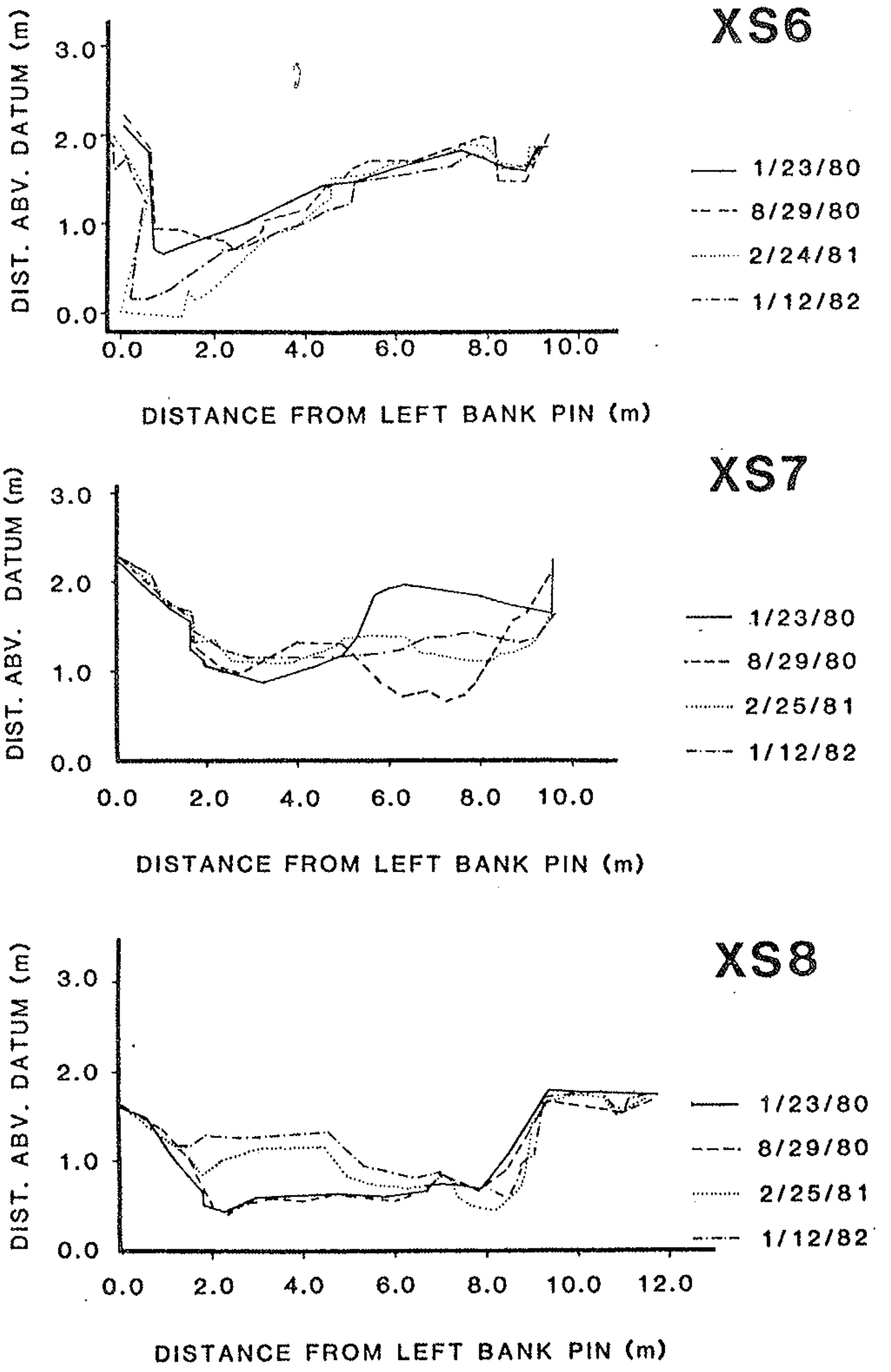

Figure 5: Cross-sections XS6, XS7, XS8, "Pull" reach, Larry Damm Creek. Cross-section locations shown on map, figure 3.

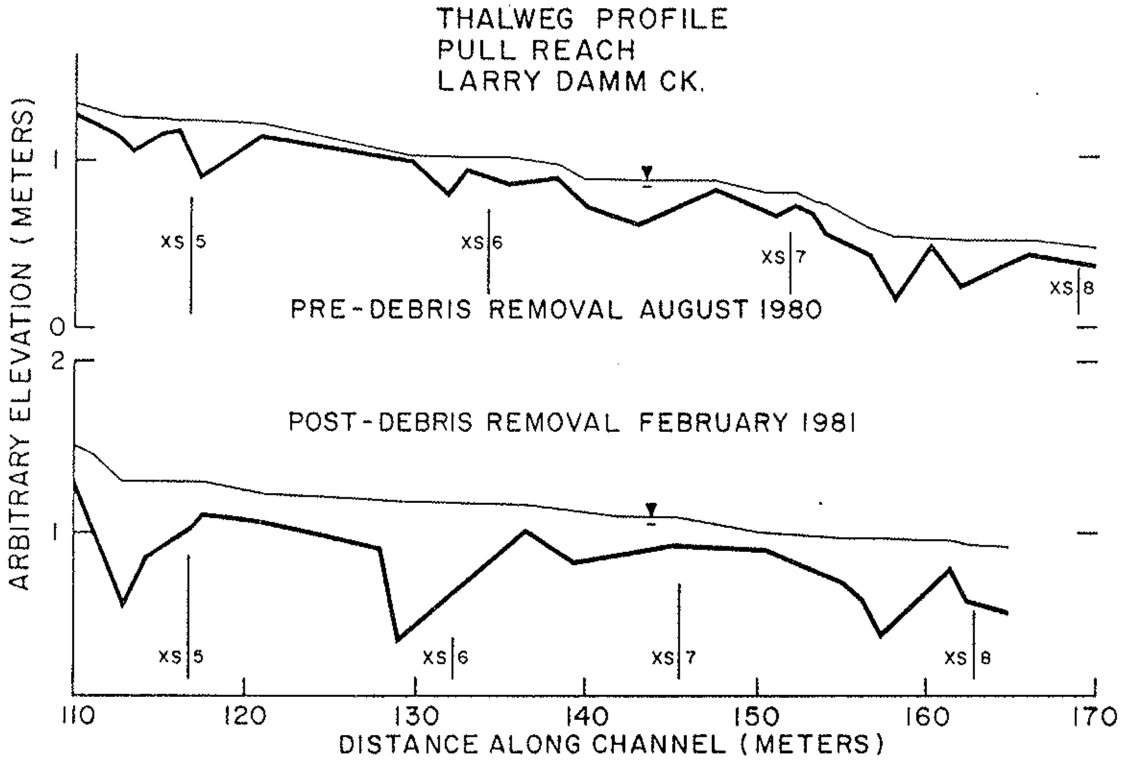

Figure 6: Long profile, "Pull" reach, Larry Damm Creek, before and after debris removal. Cross-section numbers are those on figures 3 and 5.

the next two large debris jams. This can be seen by aggradation at cross-sections 11 (above the next debris jam downstream, DJ3), and 12 (between DJ3 and the following jam, DJ4; figure 7). The remaining material eroded from banks and destabilized sediment bars within the "pull" reach combined with material scoured from above this reach, and appears to have been deposited as the aforementioned point bar. The general patterns of readjustment conform to those expected in an alluvial channel with a meandering course. Further adjustment in the reach will probably enhance the pools and point bar described above and continue bank erosion of the left and right bank at XS6 and the left bank at XS5. These latter areas constitute the remaining 28 percent of sediment originally estimated as being debris stored prior to debris removal, and are still present in the reach as of August, 1982.

The caliber of sediment within the reach has also increased following debris removal, as seen by the comparison of areas of fine (d50 <10 mm) and coarse (d50 generally >10 mm, with the surface layer d50 >30 mm) bed material shown as fine and coarse stipple on figure 3. Limited freeze coring of sediments within the channel thalweg at XS8 shows insignificant differences in sediment size before and after debris removal, with post-removal bed material being slightly finer throughout the 0.4 m deep core (mean d = 16.2 mm in 1980, 15.4 mm in 1981) though coarser at the surface (mean d = 44.0 mm in 1980, 45.5 mm in 1981).

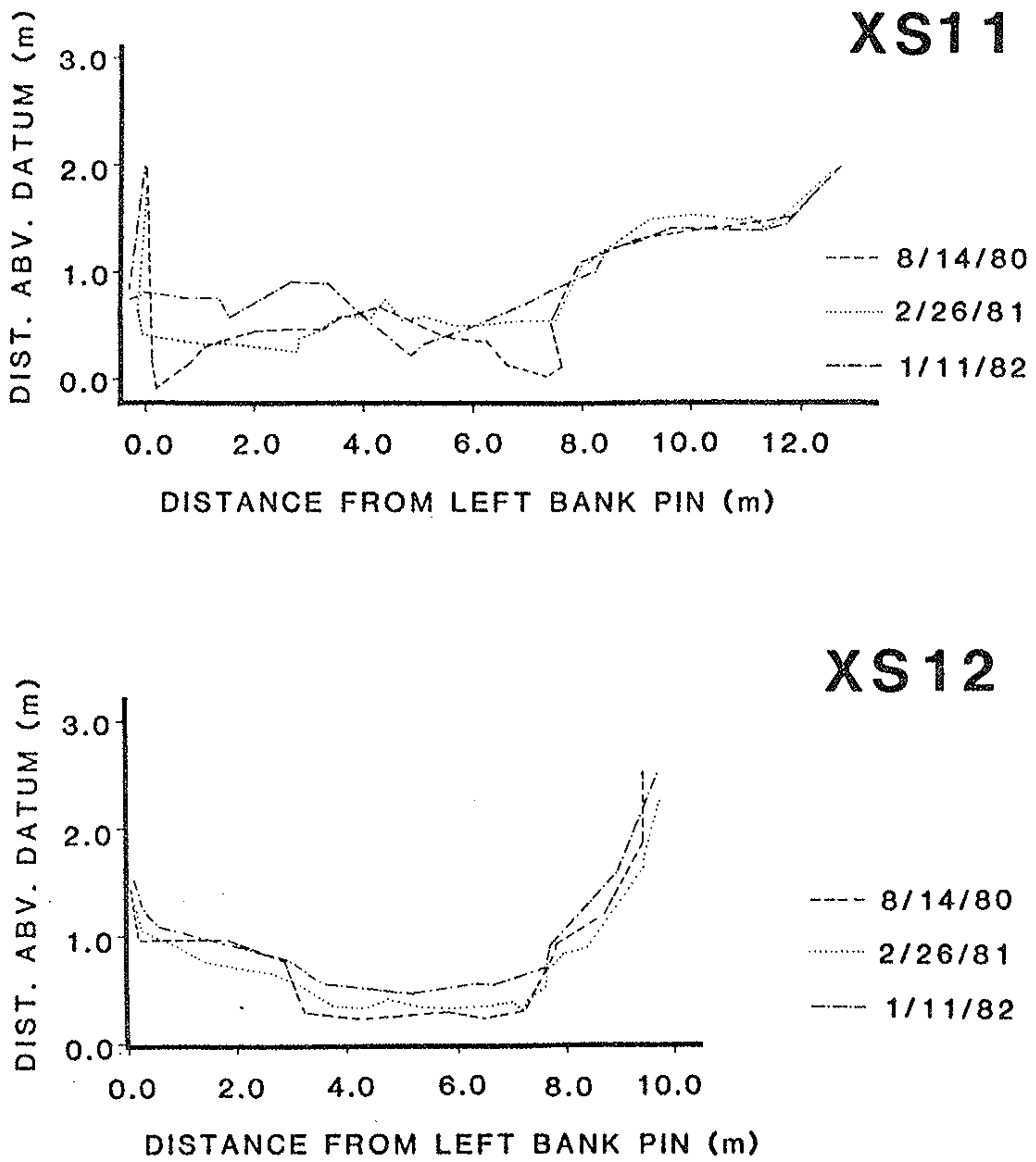

Figure 7: Cross-sections XS11, upstream of debris jam 3, and XS12, downstream of debris jam 3.

More pronounced differences can be found at the head of DJ3, where thalweg sediments are substantially finer following debris removal. The mean particle size throughout this core decreased from 10.0 mm in 1980 to 2.87 mm in 1981, and the mean particle size of the top 7 cm of the core decreased from 6.7 mm to 4.8 mm.

Large Organic Debris Control of Morphologic Environments

Debris control of channel morphology can also be seen in the spacing of pools and riffles vis-a-vis the location of in-channel debris. In alluvial stream channels (those which flow in valleys with floodplains composed of unconsolidated sediments, as compared to mountain streams, with no floodplains and non-homogeneous substrate, or bedrock streams), pool spacing is generally 5 to 7 channel widths. It results from the same flow irregularities which give rise to channel meanders. In contrast, the small (second to fourth order) streams chosen for this study have little or no floodplain, and often flow on bedrock (Little Lost Man and Lost Man creeks) or have bedrock exposed in the channel banks. In addition, their plan patterns and gross channel slopes are generally reflective of underlying bedrock structures, (Tally, 1980). Lost Man and Little Lost Man creeks both parallel major Quaternary faults mapped to the north and west, and lower Larry Damm Creek, from the study reach to its confluence with Lost Man Creek, flows parallel to the trends of conjugate joint patterns mapped 0.5 km upstream in the Gold Bluffs Formation (Kelsey, 1982). There is some suggestion that the high slope of Prairie Creek in the Brown Creek reach may also be related to neotectonics of the region.

On a smaller scale, the locations of pools in mountain streams are fixed by large roughness elements (LRE´s) such as bedrock outcrops, sharp bends in the stream course, or large organic debris. Pools form due to continued scour around these LRE´s (Lisle and Kelsey, 1982). Organic debris is the dominant LRE in all the stream channels studied here, and is virtually the exclusive LRE in many of the study reaches. The low pool-to-pool spacing in these streams is indicative of their non-alluvial character. The mean pool spacing is 3.9 channel widths in undisturbed channels and 2.9 channel widths in disturbed channels, clearly well below the 5 to 7 channel widths common in alluvial channels. Pool spacing decreases with increasing stream order in disturbed channels, contrary to expectations if these stream channels were becoming more "alluvial" in nature downstream. Nearly half of the study reaches exhibited control of pool spacing by large organic debris alone (tables 1a and 1b). Control of the pool-riffle sequence by large organic debris can also be seen by the percent of pool morphology controlled by debris (tables 1a and 1b). Generally, more than 70 percent of the pools are created or significantly enhanced by the presence of large organic debris, irrespective of previous disturbance history. This is particularly noticeable in the smaller stream channels: there is a significant negative correlation between the percentage of morphology created by debris and drainage basin area (Spearman rank-sum correlation, $r = -0.71$, $p = 0.89$). Pools created by organic debris are often plunge pools; as a result, they are deep and well aerated at low flow, providing excellent fish habitat.

The debris removal experiment on Larry Damm Creek, introduced in the previous section, also allowed direct documentation of the effect of organic debris on pools and riffles. Prior to debris removal, three of the five pools in the debris reach were created or significantly enhanced by organic debris, while the remaining two were associated with channel bends. Presently, eight pools can be distinguished within the reach; six are associated with channel bends, and the remaining two are not associated with any non-alluvial large roughness element, but occur as chutes opposite side channel bars (at XS7 and XS8, figure 4b). Exhumed debris has slightly enhanced pools at XS5 and XS6, and the pool above XS8 has enlarged against a bank now more significantly defended by a large redwood bole. Nonetheless, the effect of debris on pool morphology is significantly reduced.

Pool-to-pool spacing within the "pull" reach has decreased from 2.5 to 1.6 channel widths, has remained constant in the upstream reach, and increased slightly in the downstream section, from 1.9 to 1.7 channel widths. This decrease in pool spacing is due to the greater number of pools within the "pull" reach following debris removal. The increased development of pools is also reflected in the increased areal extent of pools relative to riffles (71 to 76 percent) and to the active channel as a whole (17 to 26 percent). At high, channel forming flows (generally at or above bankfull, 4.1 cms on Larry Damm Creek), pools form due to scour brought about by flow convergence. Flow is now directed against the erodible bed and banks rather than on in-channel debris, causing scour until some equilibrium of shear stress exerted by the flow vs. shear strength of the bed and banks is realized. An increase in the number of pools in the "pull" reach is indicative of the extent to which debris may decrease flow convergence above a jam, and direct flow, in this case away from channel banks, at or below the jam.

Channel Slope and the Distribution of Energy

Erosion and deposition patterns related to the presence of large organic debris can be understood as the result of the expenditure of potential energy on the stream bed and banks in the form of work. In steep mountain streams, organic debris jams often act as a local base level, producing stretches of the channel where water surface slope, representing potential energy loss per unit length of channel, is locally decreased above the jam and increased over the jam relative to the mean. Generally, a pool and/or ponded sediment is present above the jam, and a plunge or scour pool is found under or downstream of the jam, depending upon the porosity of the jam to sediment. This is the characteristic "stepped bed" profile (Keller and Swanson, 1979; Heede, 1981; Marston, 1982), where a significant amount of a stream's potential energy may be dissipated at debris created falls and cascades which occupy a relatively small percentage of the total stream length. Thus, energy is expended at these locations rather than producing an incised channel with unstable and eroding channel banks.

As much as 70 percent of the elevation loss within stream reaches surveyed can be controlled by debris (tables 1a and 1b). This form of debris control is most pronounced in headwater reaches and decreases downstream and in undisturbed reaches with relatively low channel slope. Drop in elevation associated with debris is also greater in disturbed channels than it is in undisturbed channels over the same range of drainage basin areas (< 9.5 km^2). The mean elevation loss is 40.5 and 34.1 percent, respectively. This reflects the lower porosity of jams in logged basins from the combined effects of "caulking" and high sediment loads.

The simplest debris accumulation is an organic step, such as the one shown in figure 8, consisting of a single log set perpendicular to flow in the stream bed. The longitudinal profile shows debris-stored sediment above the step and a plunge pool below it. Since the pool upstream of the step is associated with a bend, secondary circulation will maintain a pool in this location regardless of sediment load (Dietrich, Smith and Dunne, 1979). Therefore, the sediment storage compartment associated with this step is full or nearly so. One of the largest differences in sediment routing between streams draining disturbed and undisturbed watersheds is the amount of available storage space (Tally, MacDonald and Keller, 1980), which is a function of differences in sediment loads in the two cases. A hypothesized comparison of unit stream power through organic steps with filled vs. non-filled upstream storage sites was shown in figure 4. The critical power threshold, defined as the point where available stream power meets of exceeds that required for entrainment of bed material (Bull, 1979), will be met at lower discharges if the storage compartment is filled, all else being equal. The hypothesized relationship for filled compartments is borne out by data collected at the step shown on figure 8, and is summarized in figure 9. The dashed line represents a discharge of 95 percent of bankfull. At this discharge, flow depths were approximately 0.7 m throughout the reach

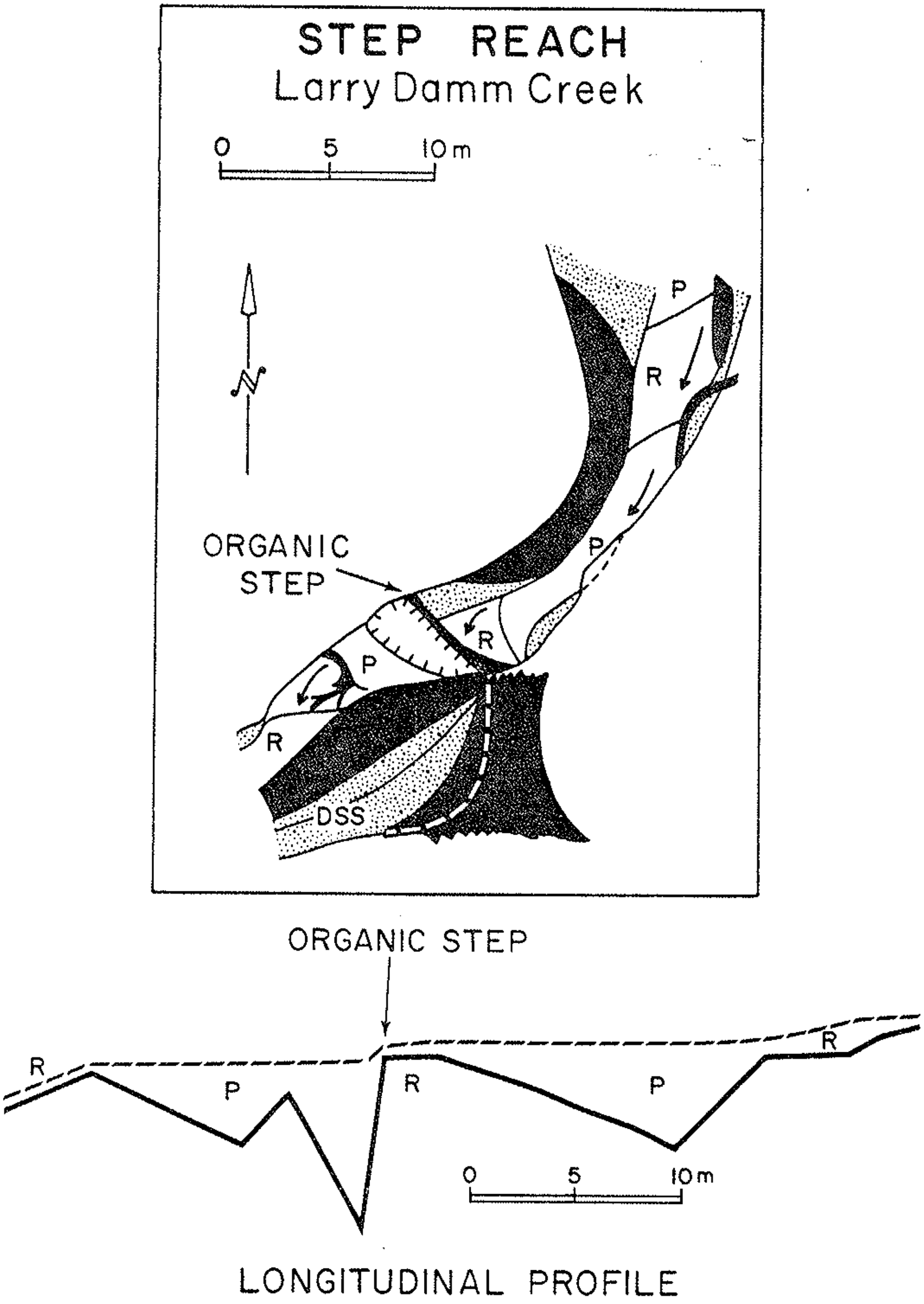

Figure 8: Morphologic map and long profile of simple organic step, Larry Damm Creek.

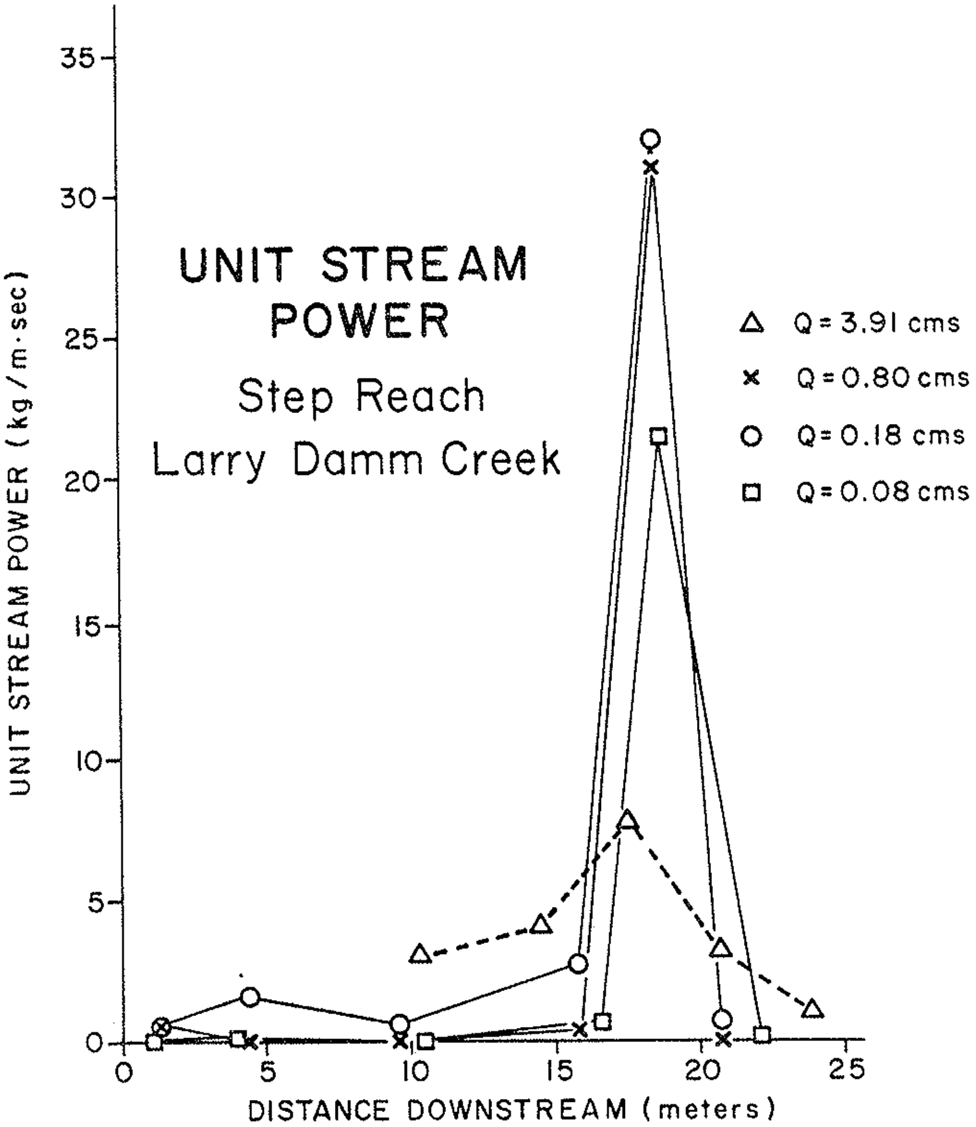

Figure 9: Distribution of unit stream power with discharge over organic step shown in figure 8.

(except in the upstream pool, where depths exceeded 1.0 m) and predominantly sand-sized sediment was being transported across the entire width of the active channel.

The dissipation of energy by debris jams was also investigated in conjunction with the debris removal experiment. Since the overall channel slope was not altered by debris removal, changes in mean velocity through the pull reach should reflect adjustments in channel roughness. On the scale of subreaches, channel slope can also adjust to changes in roughness and both can account for changes in water velocity (Prestegaard, 1983). Salt tracing techniques, outlined by Church and Kellerhals (1970) and Calkins and Dunne (1970), were used to measure mean travel time of water through selected reaches before and after debris removal. A quantity of salt water was introduced sufficiently upstream to be vertically and horizontally mixed within the desired reach. The passage of this salt-impregnated water was traced at the reach endpoints with conductivity meters. The mean travel time of water through the reach is the difference between the mean travel times to each endpoint. Mean velocity through each reach was calculated by dividing the centerline length of the wetted channel by the mean travel time. The results are shown on figures 10 through 13. Although complicated by changes in channel morphology as the "pull" reach adjusted following debris removal, mean velocity is generally higher with no debris in the channel over the range of discharges sampled

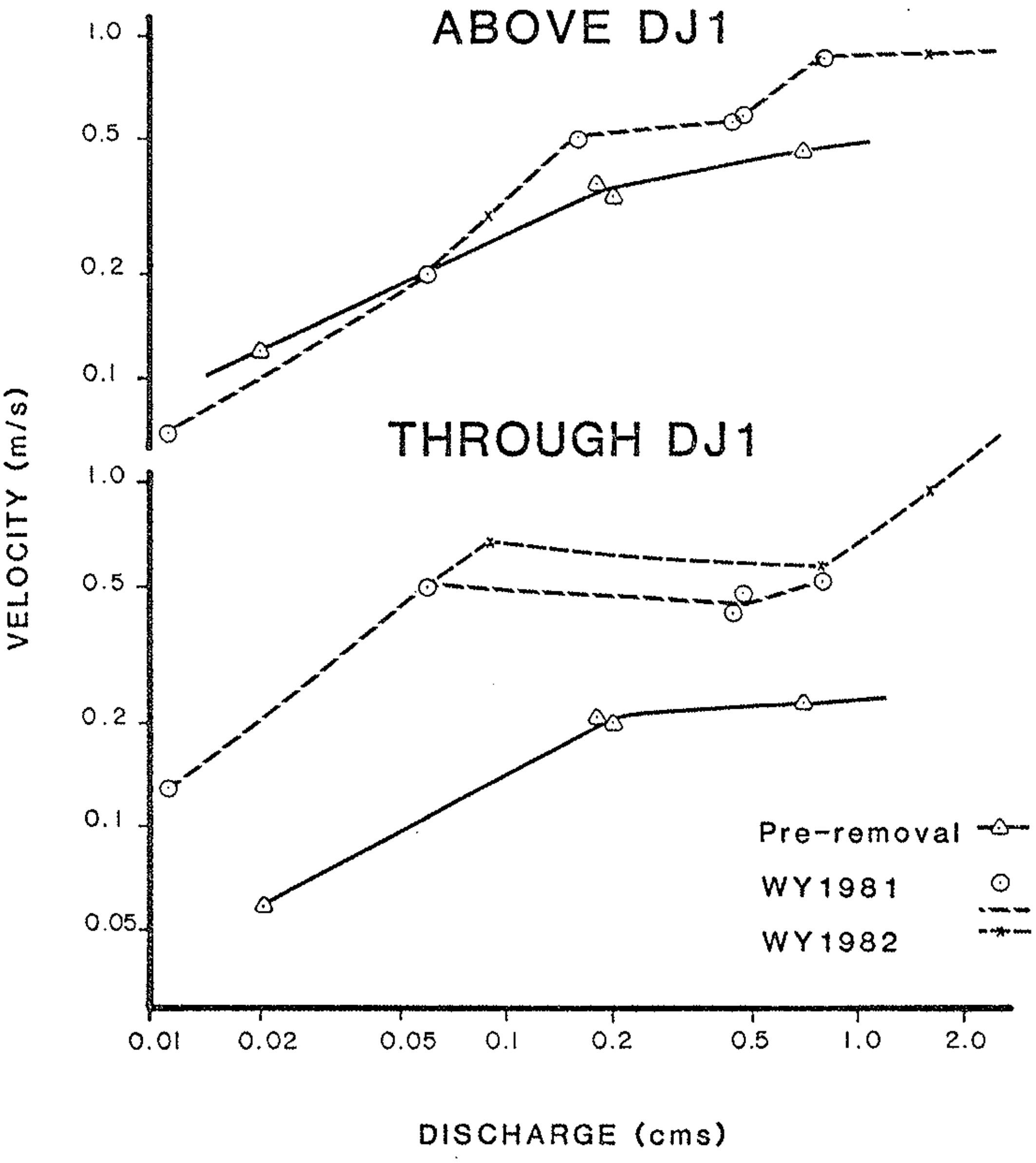

Figure 10: Mean reach velocity vs. discharge for reach above and through debris jam 1, Larry Damm Creek, before and after debris removal.

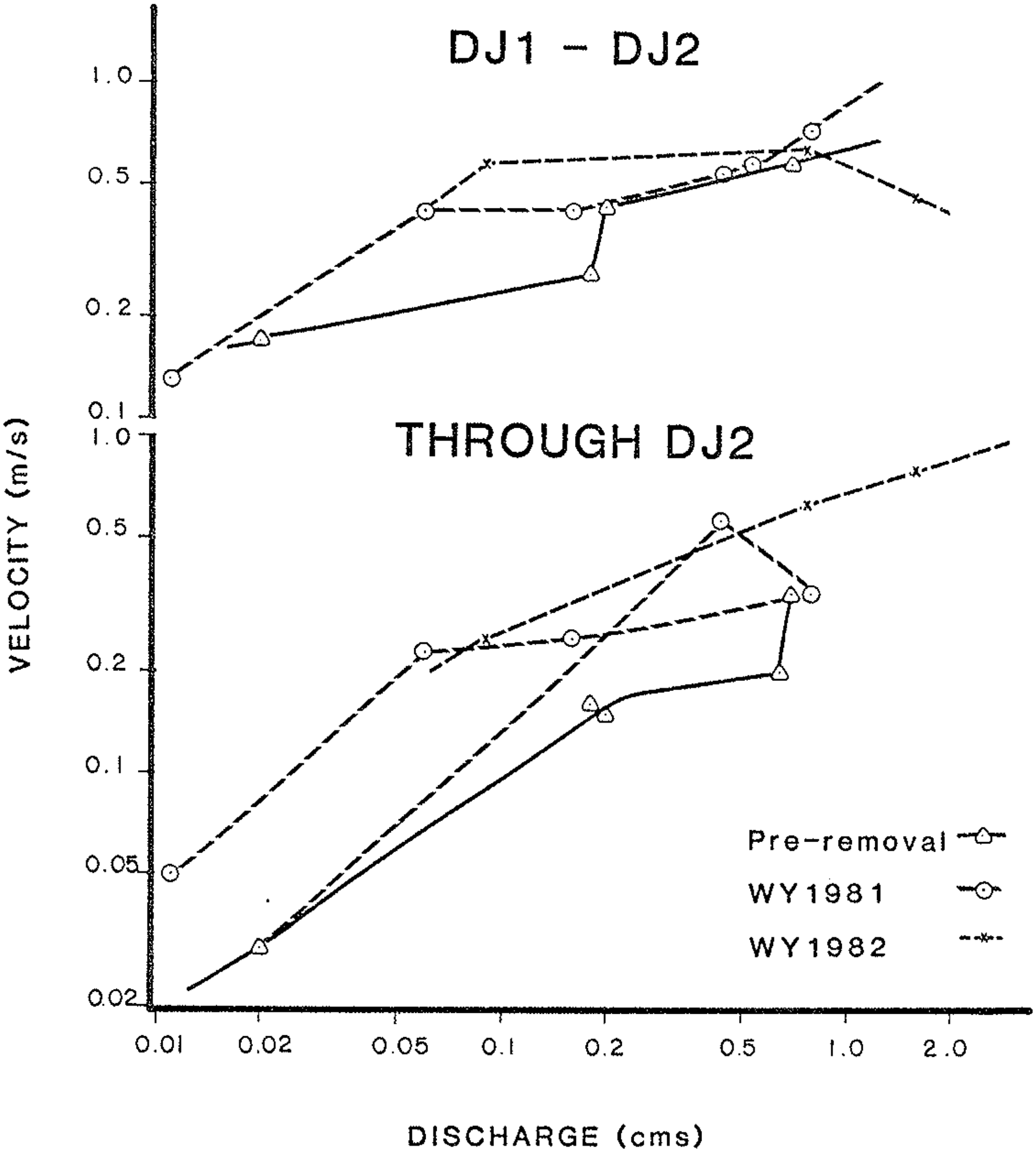

Figure 11: Mean reach velocity vs. discharge for reach above and through debris jam 2, Larry Damm Creek, before and after debris removal.

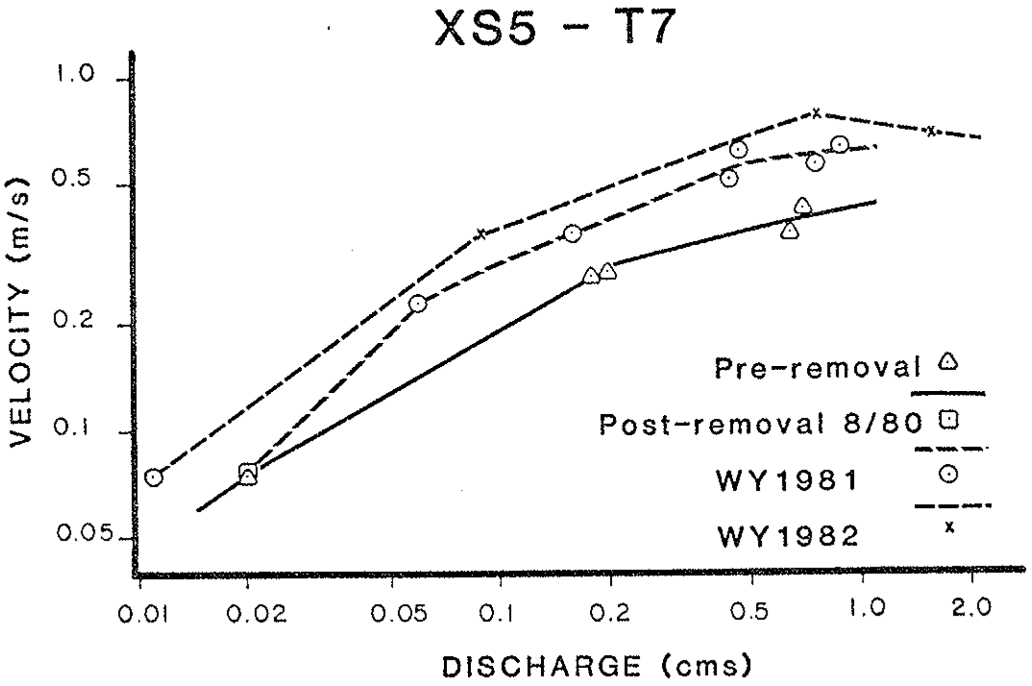

Figure 12: Mean reach velocity vs. discharge, head of "Pull" reach through debris jam 2, Larry Damm Creek, before and after debris removal.

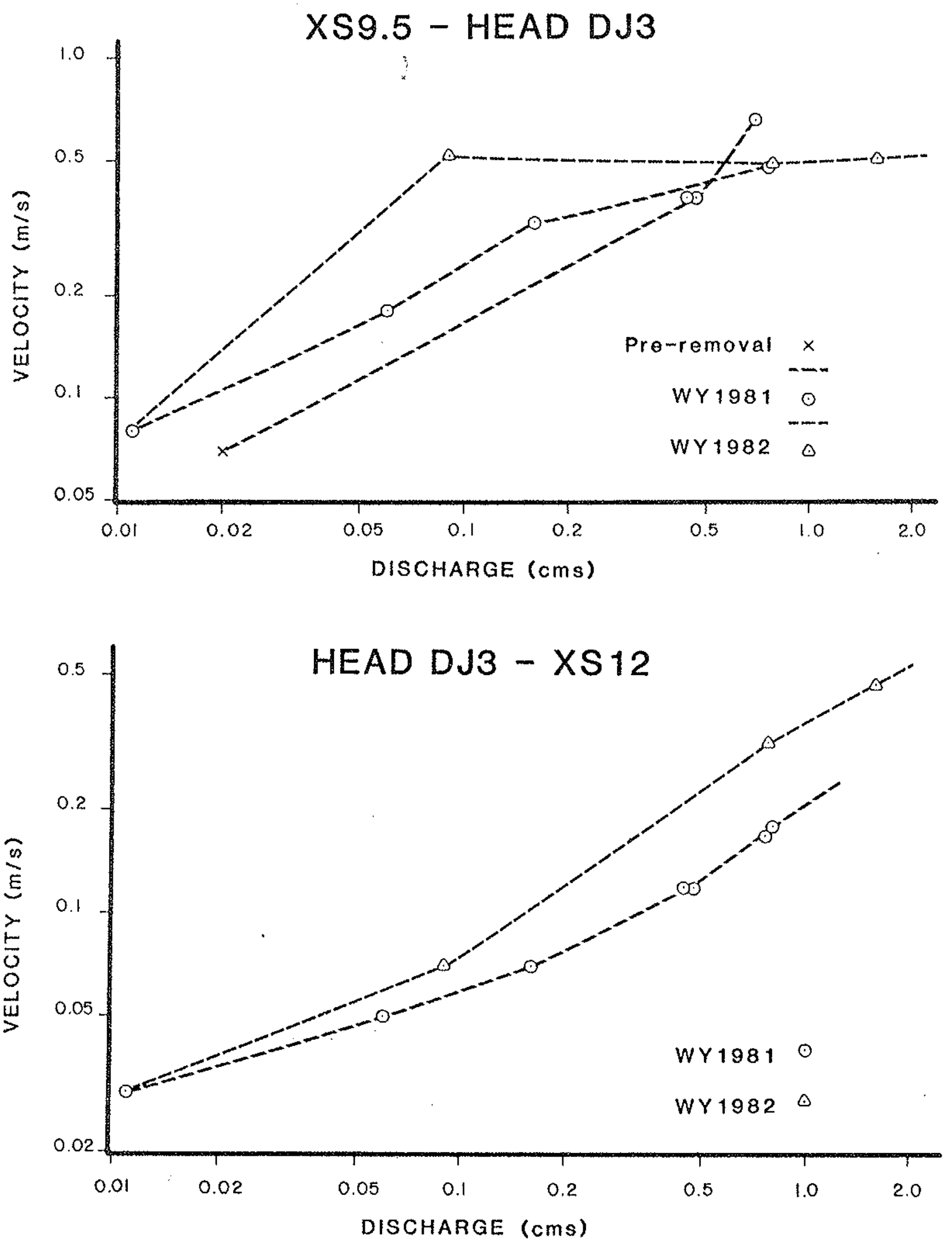

Figure 13: Mean reach velocity vs. discharge for reach above and through debris jam 3, Larry Damm Creek.

(<1 to 40 percent of bankfull; figures 10 to 12). As seen on figure 12, comparing travel times from the head of the pull reach at XS5 to a location immediately downstream of the former location of DJ2, continued adjustment of the channel morphology favors higher velocities through this reach.

Unfortunately, a wider range of sampled discharges was not possible, particularly prior to debris removal, owing to the short duration of flows greater than 50 percent of bankfull. Instead, travel times for the reach above (figure 13a) and through (figure 13b) the next debris jam downstream (DJ3) were determined during the winters of 1981 and 1982, over the same discharge range as that used in the "pull" reach. It is important to note here the effect of aggradation, seen in figure 7, on the flow velocity. Velocities above this lower debris jam decreased from 1981 to 1982 as the channel area inundated at a given discharge increased due to channel widening. At the same time, flow velocity through the jam increased as more porous levels in the jam were reached owing to increased channel bed height upstream. This suggests that flow impedence by debris jams varies markedly from jam to jam, as well as at a specific jam with variations in discharge or upstream channel configuration.

Implications for Management of Large In-channel Organic

Debris

Large organic debris is increasingly recognized as an integral part of fluvial systems in forested watersheds. In terms of enhancing anadromous fish habitat, we have shown that debris provides cover for juveniles directly, as well as indirectly in the form of extensive debris-created pools. In steep stream channels, debris jams also provide variability in flow velocity and depth at flood discharges, a requirement for over-winter habitat (Rieser and Bjornn, 1979). Habitat enhancement projects currently undertaken in the Pacific northwest, including northwestern California, (Reeves and Roelofs, 1982), are attempting to mimic organic steps with wood and rock wiers. Finally, within limits, the sediment storage capacity of debris jams allows buffering of locally high sediment input. Because organic debris jams are often considered barriers to anadromous fish migration, management efforts have been directed towards their removal.

Our work suggests that, while debris removal may indeed be a reasonable management alternative in certain situations, it should be addressed on a case-by-case basis with careful consideration of the "costs" in mind. These costs, byond those incurred in the physical act of debris removal, stem from likely downstream aggradation and loss of habitat at the jam site, as sediment ponded behind the jam is eroded. Potential mass wasting of oversteepened stream banks in the vicininty of the former jam site would aggravate this. Material removed will be transported downstream until a suitable deposition site(s) is reached, probably behind another jam. This is suggested by the current high rate of sediment delivery to the main stem of Redwood Creek by many tributary channels, which currently store an average of less than 40 years of average annual bedload yield, and by Marston´s findings in New Zealand, discussed earlier. Our study supports this as well: the high stream power over a simple organic step with a filled storage compartment indicates a high potential rate of sediment transport if sediment is available, and substantial downstream aggradation was observed following the debris removal experiment on Larry Damm Creek. The cost of debris removal is particularly high if good quality anadromous fish habitat exists below the dam being removed, and/or the potential for high quality habitat above the jam is low. This is often the case in high gradient stream channels, where downstream siltation has the added impact of clogging spawning gravels, and debris removal eliminates large areas of pool habitat around the former jam site.

The quesstion of the optimum level of debris loading is more difficult to judge. Tally (1980) observed that in Little Lost Man Creek, the effect of one log, comprising 60 percent of the debris loading in the reach, when set in the channel subperpendicular to flow, was no greater than that of smaller logs siminlarly oriented. Spacing of debris steps and jams, to the extent that it controls pool-to-pool spacing and the amount of pool area, appears more important. Fisheries literature contains no good data on the optimum ratio of riffle to pool area, or spawninig + feeding to rearing/cover habitat. It seems most appropriate, therefore, to take a clue from the natural environment and suggest that pool producing accumulations spaced 3 to 6 channel widths apart are within an optimum range.

This level of debris loading, (in terms of spacing, if not volume), may be greatly exceeded in streams draining logged watersheds, and many of the jams may be blocking access for formerly or potentially high quality anadromous fish habitat. In these cases, the danger of downstream aggradation is also particularly high due to the larger amounts of sediment stored by the jam. Partial, rather than complete removal of log jams has been suggested by Hall and Baker (1982) as an alternative for large jams. This has the effect of decreasing barrier height and the potential for catastrophic failure of the jam, while limiting the amount of sediment released. Debris can also be used to direct flow away from unstable banks; partial removal of Humboldt crossings (logs set into the stream channel and used as bridges during yarding of timber) has been used in Redwood National Park to decrease channel widening at the jam for the express purpose of decreasing sediment production in channels unused by fish. The presence of only a few logs longer than bankfull width are required to stabilize debris accumulations (Lienkaemper and Swanson, 1980). Organic debris in forested streams is ubiquitous, and the management guidelines outlined abeove attempt to work with the natural fluvial system, which necessarily includes large organic debris.

References Cited

Bagnold, R.A., 1977, Bed load transport by natural rivers: Water Resources Research, 13: 303-312.

Bilby, R.E., and Likens, G.E., 1980, Importance of organic debris dams in the structure and function of stream ecosystems: Ecology, 61: 1107-1113.

Bryant, M.D., 1980, Evolution of large, organic debris after timber harvest: Maybeso Creek, 1949-1978: U.S.D.A. Forest Service General Technical Report PNW-101, 30 p.

Bull, W.B., 1979, Threshold of critical stream power: Geological Society of America Bulletin, Part I, 90: 453-464.

Calkins, D., and Dunne, T., 1970, A salt tracing method for measuring channel velocities in small mountain streams: Journal of Hydrology 11: 379-392.

Church, M., and Kellerhals, R., 1970, Stream gauging techniques for remote areas using portable equipment: Inland Waters Branch, Canadian Department of Energy, Mines and Resources, Technical Report 25, 89 p.

Dietrich, W.E., Smith, J.D., and Dunne, T., 1979, Flow and sediment tansport in a sand-bedded meander:

Journal of Geology, 87: 305-315.

Geiger, A.F., 1965, Developing sediment storage requirements for upstream retarding reservoir: Proceedings, Federal Interagency Sedimentation Conference, U S.D.A. Miscellaneous Publication 970, p. 881-905.

Hall, J.D., and Baker, C.O., 1982, Rehabilitating and enhancing stream habitat: 1. Review and Evaluation: U.S.D.A. Forest Service General Technical Report PNW-138, 29 p.

Heede, B.H., 1972, Flow and channel characteristics of two high mountain streams: U.S.D.A. Foerst Service General Technical Report RM-96, 12 p.

Heede, B.F., 1981, Dynamics of selected mountain streams in the western United States of America: Zeitschrift fur Geomorphologie N.F., 25: 17-32.

Herd, D.G., 1978, Intracontinental plate boundary east of Cape Mendocino, California: Geology, 6: 721-725.

Iwatsubo, R., Nolan, K.M., Harden, D.R., and Glysson, G.D., 1976, Redwood National Park Studies Data Release Number 2, Redwood Creek, Humboldt County, and Mill Creek, Del Norte, County, California: April 11, 1974 to September 30, 1975: U.S.G.S. Open File Report 76-678, 247 p.

Janda, R.J., and Nolan, K.M., 1979, Stream sediment discharge in northwestern California: in, A field trip to observe natural and management related erosion in Franciscan Terrane of northern California: Geological Society of America Cordilleran Section, Ch. IV, 27 p.

Lienkaemper, G.W., and Swanson, F.J., 1980, Changes in large organic debris in forested streams of western Oregon: Geological Society of America Abstracts with Programs, 12: 116.

Keller, E.A., and Swanson, F.J., 1979, Effects of large organic material on channel form and fluvial processes; Earth Surface Processes, 4: 361-380.

Keller, E.A., and Tally, T., 1979, Effects of large organic debris on channel form and fluvial processes in the coastal redwood environment: in, D.D. Rhodes and G.P. Williams, (eds.), Adjustments of the Fluvial System: Tenth Annual Geomorphology Symposium, Binghampton, New York, Kendall Hunt Publishing, Dubuque, Iowa, p. 361-380.

Keller, E.A., MacDonald, A., and Tally, T., 1982, Streams in the coastal redwood environment: the role of large organic debris: in, R.N. Coats, (ed.), Proceedings, Watershed Rehabilitation in Redwood National Park and Other Pacific Coastal Areas, August 24-28, 1981: Center for Natural Resource Studies of JMI, Inc., and the National Park Service, p. 161-176.

Keller, E.A., Tally, T., Macdonald, A., and Merritt, N.J., (in preparation), Effects of large organic debris on channel morphology and sediment storage in selected tributaries of Redwood Creek: *in*, K.M. Nolan, D.C. Marron, and H.M. Kelsey, (eds.), Redwood Creek: U.S.G.S. Professional Paper.

Kelsey, H.M., 1982, Structure and tectonics of Plio-Pleistocene sediments exposed within and adjacent to Prairie Creek State Park, Humboldt County, north coastal Cailfornia: *in*, D.R. Harden, D.C. Marron, and A. MacDonald, (convenors), Late Cenozoic History and Forest Geomorphology of Humboldt County, California, 1982 Pacific Cell Friends of the Pleistocene Field Trip, p. 130-149.

Lisle, T.E., and Kelsey, H.M., 1982, Effects of large roughness elements on thalweg course and pool spacing: *in*, L.B. Leopold, (ed.), American Geomorphological Field Group Field Trip Guidebook, 1982 Conference, Pinedale, Wyoming, p. 134-135.

Marston, R.A., 1982, The geomorphic significance of log steps in forest streams: Annals, American Association of Geographers, *72*: 99-108.

Megahan, W.F., and Nowlin, R.A., 1976, Sediment storage in channels draining small forested watersheds in the mountains of central Idaho: Proceedings, Third Federal Interagency Sedimentation Conference, Denver, Colorado.

Mosley, M.P., 1981, The influence of organic debris on channel morphology and bedload transport in a New Zealand forest stream: Earth Surface Processes and Landforms, 6: 571-579.

Pitlick, J., 1982, Organic debris in tributary stream channels of the Redwood Creek basin, in, R.N. Coats, (ed.), Proceedings, Watershed Rehabilitation in Redwood National Park and Other Pacific Coastal Areas, August 24-28, 1981: Center for Natural Resource Studies of JMI, Inc., and the National Park Service, p. 177-190.

Prestegaard, K.L., 1983, Variables influencing water-surface slopes in gravel-bed streams: Geological Society of America Bulletin, 94: 673-678.

Reeves, G.H., and Roelofs, T.D., 1982, Rehabilitation and enhancing stream habitat: 2. Field applications: U.S.D.A. Forest Service General Technical Report PNW-140, 38 p.

Rieser, D.W., and Bjornn, T.C., 1979, Habitat requirements of anadromous salmonids: U.S.D.A. Forest Service

General Technical Report PNW-96, 54 p. Swanson, F.J. and Lienkaemper, G.W., 1978, Physical consequences of large organic debris in Pacific Northwest streams: U.S.D.A. Forest Service General Technical Report PNW-69, 12 p.

Swanson, F.J., Lienkaemper, G.W., and Sedell, J.R., 1976, History, physical effects and management implications of large organic debris in western Oregon streams: U.S.D.A. Forest Service General Technical Report PNW-56, 15 p.

Tally, T., 1980, The effects of geology and large organic debris on stream channel morphology and processes for streams flowing through old-growth redwood forests in northwestern California: unpublished PhD. dissertation, University of California, Santa Barbara, 273 p.

Tally, T., MacDonald, A., and Keller, E.A., 1980, The effects of large organic debris on sediment routing in redwood forest streams: Geological Society of America Abstracts with Programs, 12: 155.