Geomorphic Processes and Aquatic Habitat in the Redwood Creek Basin, Northwestern California

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U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454

This volume is published as chapters A through V. These chapters are not available separately. Chapter titles are listed in the volume table of contents

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1995

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, *Secretary*

U.S. GEOLOGICAL SURVEY

Gordon P. Eaton, *Director*

Library of Congress Cataloging in Publication Data

Geomorphic processes and aquatic habitat in the Redwood Creek Basin, northwestern California.
(U.S. Geological Survey professional paper ; 1454)
Bibliography: p.
Supt. of Docs, no.: I 19.16:1454
1. Geomorphology—California—Redwood Creek Watershed. 2. Slopes (Physical geography)—California—Redwood Creek Watershed. 3. Redwood Creek (Calif.)—Channel. 4. Stream ecology—California—Redwood Creek Watershed. I. Nolan, K.M. (Kenneth Michael), 1949- . II. Kelsey, H.M. III. Marron, D.C. IV. Series: Geological Survey professional paper ; 1454.
GB565.C2G46 1990 551.4'09794 86-600236

For sale by U.S. Geological Survey, Information Services
Box 25286, Federal Center, Denver, CO 80225

Effects of Large Organic Debris on Channel Morphology and Sediment Storage in Selected Tributaries of Redwood Creek, Northwestern California

By EDWARD A. KELLER, ANNE MACDONALD, TAZ TALLY, *and* NANCY J. MERRIT

GEOMORPHIC PROCESSES AND AQUATIC HABITAT IN THE REDWOOD CREEK BASIN, NORTHWESTERN CALIFORNIA

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1454-P

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BY EDWARD A. KELLER,[1] ANNE MACDONALD,[2] TAZ TALLY,[1] AND NANCY J. MERRIT[1]

ABSTRACT

Large organic debris (stems greater than 100 mm in diameter) exerts a major control on channel form and process, and thus on anadromous fish habitat, in streams draining coastal redwood forests. Total debris loading for a particular channel reach represents the relation between rates of debris entering and leaving the reach and is primarily a function of the following interrelated variables: number and size of trees in the vicinity of the channel, rate of decomposition, geology, valley-side slope, landslide activity, channel width, discharge, and upstream drainage area. Approximately two-thirds of the variability of the debris loading in old-growth forests may be explained by variability of the number of mature redwood trees per hectare within 50 m of the channel. Generally, there is an inverse relationship between debris loading and upstream drainage area, but in some instances third-order reaches may have a higher loading than adjacent second- or fourth-order reaches.

Effects of large organic debris on channel morphology and sediment storage tend to be complex for several reasons. First, large organic debris may reside in the stream channel for centuries and is a permanent part of the fluvial system. Minimum residence times for more than 30 individual pieces of large organic debris have been determined by dendrochronology, and about half of these exceed 100 years, with the oldest exceeding 200 years. Second, large organic debris exerts considerable control over channel morphology, particularly in the development of pools. In headwater regions of drainage basins, nearly all the pools may be either directly formed by, or significantly influenced by, large organic debris. As the size of stream increases, the percentage of pools formed by large organic debris decreases, but debris still may significantly influence the morphology of the pool environment. Third, large organic debris produces numerous sediment storage sites, supporting a sediment buffer system that modulates the routing of sediment through the fluvial system. A volume of sediment equivalent to approximately 100 to 150 years of average annual bedload is stored in debris-related sites along Little Lost Man Creek, and a volume equivalent to about 50 to 100 years of average annual bedload is available for future storage. Finally, large organic debris in steep streams significantly concentrates potential energy expenditure over short reaches where accumulations of debris exist. In headward reaches of drainage basins, approximately 30 to 60 percent of the total decrease in elevation of the channel may be associated with large organic debris. Thus, energy is dissipated at these locations, where it might otherwise cut a more deeply incised channel with unstable and eroding banks.

The study of large organic debris in streams is pertinent to two interrelated management problems brought about by road building and timber harvesting in northwestern California: (1) reduction of sediment pollution and (2) restoration and enhancement of anadromous fish habitat. In the management of streams to maximize production of anadromous fish in the coastal redwood environment, the role of large organic debris should be considered. Large organic debris in unusually large amounts may block fish migration and cause adverse channel erosion. However, within limits, large organic debris is necessary for streams to sustain healthy populations of anadromous fish; its presence provides habitat diversity, sites for organic nutrient processing, and a modulated release of sediment to trunk streams. Therefore, managers of stream-clearing operations must carefully weigh the benefits of locally stabilizing streambanks, opening up anadromous fish habitat, or marketing merchantable timber against the potential dangers of losing hydrologic variability and mobilizing large quantities of sediment stored in conjunction with large organic debris.

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INTRODUCTION

The primary purpose of this paper is to discuss relations between in-channel large organic debris (logs, stems, limbs, and rootwads greater than 100 mm in diameter) on the one hand and channel morphology, sediment storage, and formation and maintenance of anadromous fish habitat on the other. A secondary purpose is to discuss briefly the implications of these relations for management of streams to improve anadromous fish habitat.

Large organic debris in the active stream channel has a major control on channel form and process (Swanson and Lienkaemper, 1978; Keller and Swanson, 1979;

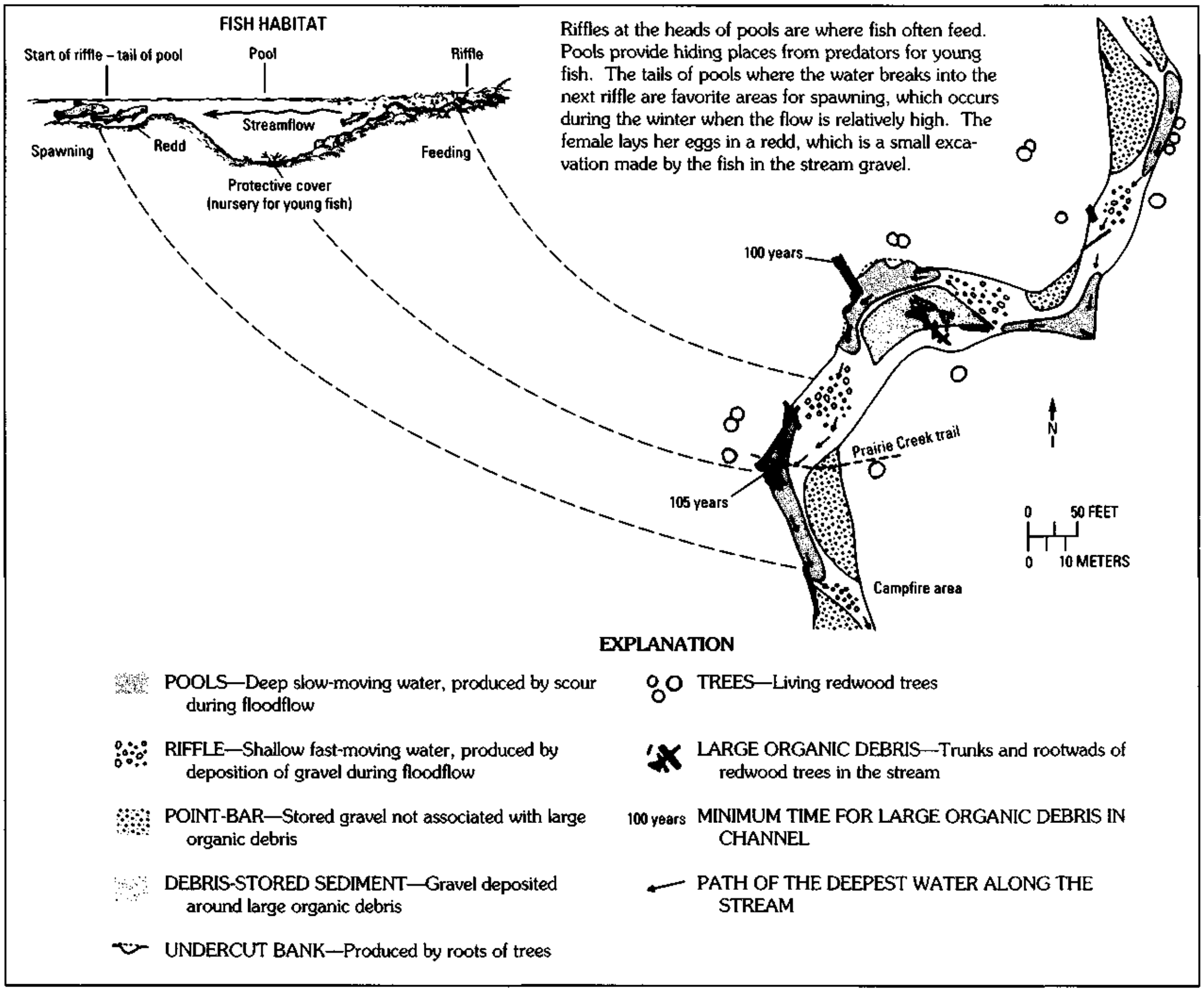

FIGURE 1.—Generalized relation between the various morphologic features of the stream channel and anadromous fish habitat.

Keller and Tally, 1979). Such debris may reside in the stream channel for centuries, providing a large roughness element that serves to fix the position of the thalweg and the spacing of large pools (Lisle and Kelsey, 1982). Large organic debris also facilitates storage of much bedload material and provides a natural buffer to modulate downstream discharge of sediment (Tally and others, 1980; Mosley, 1981). In steep headwater reaches of streams, a significant part of the decrease in channel elevation is locally concentrated at organic steps or other accumulations of large organic debris. Therefore, debris is pertinent to the solution of two interrelated management issues in northwestern California: restoration or enhancement of anadromous fish habitat and sediment pollution associated with timber harvesting or other land use change that directly or indirectly affects fish habitat. Decline in recent years of anadromous fish populations in streams of the north coast of California is well documented; many rivers and streams that once supported relatively large runs of salmon and steelhead trout now have significantly fewer fish (Denton, 1974). Causes for the decline in numbers of anadromous fish are multiple and complex, but many likely are related in part to habitat degradation caused by human uses of hillslopes (such as timber harvesting and urbanization) adjacent to stream channels and to in-stream modifications exacerbated by natural processes such as floods. The decline in noncommercial steelhead populations indicates that overfishing in the ocean is not the primary cause of the observed pattern.

Generalized habitat for anadromous fish is shown in figure 1; stream environments emphasized are pools and riffles. Pools and riffles are formed and maintained by a complex scour-fill sequence related to the morphology and hydraulics of the stream (Keller, 1971; Keller and Melhorn, 1973, 1978). Pools are topographic low areas produced by scour during relatively high channel-forming flows that occur every year or so. Riffles are topographic high areas produced by deposition during the same relatively high channel-forming flows. In gravel-bed streams, only the relatively fine sediment (sand-sized or finer) is transported at lower flows, and the pattern of transport is for fine sediment to be transported from riffles to pools. For gravel-bed streams that have little sand available for transport, movement of bedload may be confined entirely to channel-forming flow events, and pools may scour to bedrock and contain little if any bed material. Thus, for streams having available bed material ranging from gravel to sand and finer, pools tend to scour during relatively high flows and fill during lower flows, whereas riffles tend to fill during relatively high flows and may scour at lower flows.

Gravel-bed streams not affected by human activity often have little fine sediment, and so pools are areas of deep, slow-moving water during the summer low-flow times. Such pools provide good rearing habitat for many species and ages of juvenile anadromous fish. Land use changes such as those associated with timber harvesting and road building can adversely affect pool environments during the summer low-flow period, however, by filling pools with fine sediment. The filling results in degradation of nursery areas for anadromous fish, which remain in the stream for a year or so before migrating to the ocean. Therefore, an important limiting factor to fish production is the pool environment during summer (low-flow) months (Burns, 1971). Fine sediment that enters the stream channel also may fill the void spaces between gravel particles on riffles, prevent the aeration necessary to sustain fish eggs, and pose a physical barrier to emerging fry. Better understanding of channel morphology, sediment routing and storage, and effects of land use changes will facilitate improved management of anadromous fish habitat in streams of the coastal redwood environment.

ACKNOWLEDGMENTS

We gratefully acknowledge critical review by James C. Brice, Thomas E. Lisle, Richard A. Marston, and Fredrick J. Swanson. This work has been supported in part by the Water Resources Center, University of California at Davis grants WRR 588 and WRR 584, the U.S. Forest Service Redwood Sciences Laboratory, Prairie Creek Redwoods State Park, and Redwood National Park. Their help, and that of the following field assistants, is gratefully acknowledged: J. Levinson, S. Parkinson, 0. Maloney, M. Landon, F. Tramoni, J. Tilton, M. Thomas, L. Preston, J. Steude, K. John, L. Horowitz, and numerous winter 1980 enrollees of the California Conservation Corps, Del Norte Center.

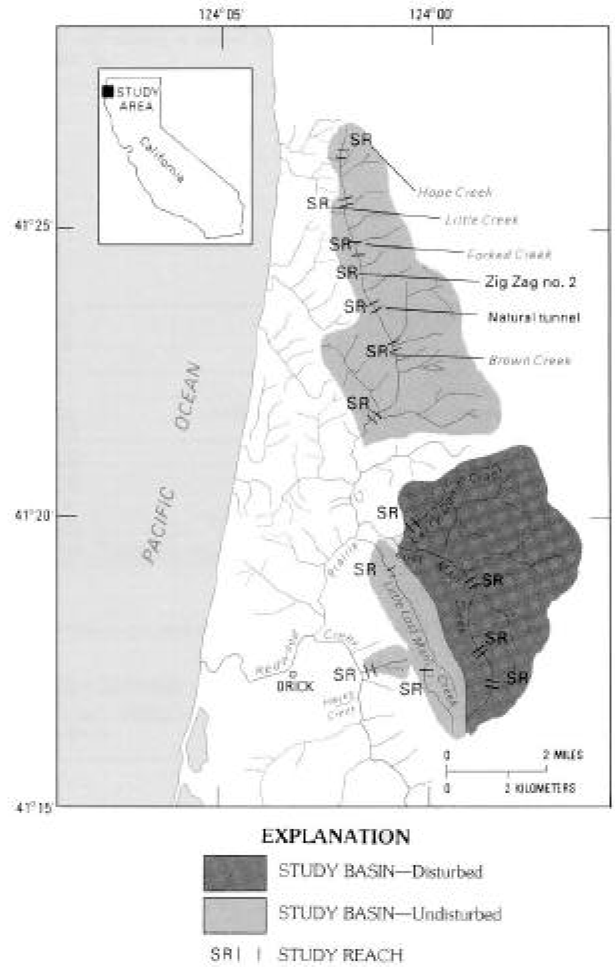

FIGURE 2.—Location of study reaches in the Redwood Creek drainage basin, northwestern California.

STUDY AREAS

The streams studied (with the exception of Caspar Creek, near Fort Bragg, Calif.) are located in the Redwood Creek drainage basin, near Orick, Calif, (fig. 2). Five streams were studied in detail, mostly during summer low-flow periods. Study reaches were chosen at locations that could be identified on topographic maps or aerial photographs, thus facilitating better measurement of drainage area and channel slope, as well as other properties. Research methods included measuring channel profiles and cross sections, sediment size distributions, and debris loading; estimating minimum residence time of large organic debris in the channels and estimating debris-stored sediment; and mapping.

Data summarizing the channel morphology of the stream reaches studied are shown in table 1. Three of the watersheds, Hayes Creek, Little Lost Man Creek, and

TABLE 1A.—*Morphologic data for undisturbed watersheds (tributaries to Redwood Creek) in northwestern California*

[Total percentages in stream environments may be less or greater than 100 percent due to overlaps such as pools that contain debris-stored sediment or to existence of other environments not listed]

Study reach	Hayes Creek	Little Lost Man Creek, Upper	Little Lost Man Creek, Lower	Prairie Creek, Hope Creek	Prairie Creek, Little Creek	Prairie Creek, Forked Creek	Prairie Creek	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	.12	.033	.048	.02	.014	.012	.009	.01	.01	.005
Debris loading (m^3/m^2)	.340	.283	.098	.436	.025	.026	.043	.212	.170	.039
Pool-to-pool spacing (in no. of channel widths)	2.4	[1]1.9	[1]1.8	[1]6.2	[1]4.7	2.6	6.6	2.7	6.0	4.0
Percent channel area in pool[2]	12	22	18	49	34	46	36	41	26	25
Percent channel area in riffle[2]	26	15	21	21	46	49	20	15	18	25
Percent channel in debris-stored sediment[2]	40	39	39	30	18	30	15	21	29	13
Percent channel area in undercut banks[2]	4	3	1	1	4	3	4	1	<1	1
Percent pool morphology influenced by debris[2].	83	100	90	86	71	87	50	80	67	50
Debris-controlled drop in elevation of the channel	38	59	30	43	27	34	8	<1	18	<1

[1] Spacing controlled by organic debris.
[2] At low flow.
[3] Ratio of cumulative loss of channel elevation associated with large organic debris to total fall of the stream reach.

TABLE 1*B*.—*Morphologic data for disturbed watersheds (tributaries to Redwood Creek) in northwestern California*

[Total percentages in stream environments may be less or greater than 100 percent due to overlaps such as pools that contain debris-stored sediment or to existence of other environments not listed]

Study Reach	North Fork Caspar Creek, Upper[1]	North Fork Caspar Creek, Lower[1]	Lost Man Creek, Upper	Lost Man Creek, Middle	Lost Man Creek, Lower	Larry Damm Creek
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 no. of channel widths)	[2]3.5	3.8	[2]4.1	[2]2.6	1.3	2.2
Percent channel area in pools[3].	24	36	33	43	14	27
Percent channel area riffles[3]	30	30	25	14	11	14
Percent channel in debris-stored sediment[3]	44	34	43	31	41	59
Percent channel in area undercut banks[3]	2	1	4	2	1	2
Percent pool morphology influenced by debris[3].	82	43	79	100	57	59
Debris-controlled drop in elevation of the channel (percent)[4]	57	37	69	33	30	17
Approximate period of timber harvest	1890's	1890's	Post-WWII-1960(?)	Post-WWII-1960(?)	Post-WWII-1968	1954-68

[1] Not in the Redwood Creek drainage basin.
[2] Spacing controlled by organic debris.
[3] At low flow.
[4] Ratio of cumulative loss of channel elevation associated with large organic debris to total fall of the stream reach.

Prairie Creek, are undisturbed; their basins are vegetated with old-growth redwood and associated flora. Both Lost Man Creek and Larry Damm watersheds have been disturbed. Approximately 87 percent of the 9-km^2 Lost Man Creek watershed above the gaging station was logged prior to 1968, and 15 percent was still highly disrupted as recently as 1976. The upper reaches of Larry Damm were logged from 1954 to 1968.

Prairie Creek is a relatively low-gradient, gravel-bed, meandering stream and, along most of the reaches studied, is entrenched as much as several meters into conglomerates and consolidated sands of the Prairie Creek Formation of Pliocene and (or) Pleistocene age. Some of entrenchment is hypothesized to be in response to recent and ongoing tectonic activity.

Little Lost Man and Lost Man Creeks are steep, gravel-bed tributaries of Prairie Creek. They both flow across steeply dipping sandstones, siltstones, shales, and conglomerates of the Franciscan assemblage of Late Jurassic and Cretaceous age (Harden and others, 1982). Local stream gradients of Little Lost Man Creek and, presumably, of Lost Man Creek are adjusted to the resistance of the various rock types (Tally, 1980).

Hayes Creek is a small, steep, gravel-bed tributary to Redwood Creek. The stream in the study reach flows over Franciscan sedimentary rocks, metapelites of the schist of Redwood Creek (schist), and the Grogan fault zone, which separates them.

Larry Damm Creek is a relatively low-gradient, sand and gravel-bed tributary to Lost Man Creek. The drainage basin is predominantly underlain by sands and gravels of the Prairie Creek Formation; Mesozoic Franciscan assemblage sandstones and shales are exposed in the lowermost portion of the basin.

FACTORS INFLUENCING LARGE ORGANIC DEBRIS LOADING

Debris loading, in cubic meters of large organic debris per square meter of active channel (m^3/m^2), is determined by measuring the length and diameter of all large organic debris having diameters greater than 100 mm. Redwood *(Sequoia sempervirens),* Douglas-fir *(Pseudotsuga menziesii),* Sitka spruce *(Picea sitchensis),* western hemlock *(Tsuga heterophylla),* big-leaf maple *(Acer macrophyllum),* and red alder *(Alnus oregonia)* are the main contributors of large organic debris to the streams of the coastal redwood forest. However, because redwood debris tend to be very large and resistant to decay, they usually dominate the total loading; a few large pieces may account for most of the debris loading in a particular reach. For example, 60 percent of the total loading along both the 200-m-long Zig-Zag no. 2 reach of Prairie Creek and the 400-m upper reach of Little Lost Man Creek consists of one redwood trunk in each reach. (See fig. 3 near *A-A'* and fig. 4 at DD6.)

Total debris loading in a particular channel reach is a function of the rate of debris entering and leaving that reach. Large organic debris may enter a channel by natural processes such as landslides, blowdown of whole trees or portions of trees, bank erosion, and flotation from upstream. Several of these processes often work in concert to deliver debris to a particular location in a stream channel, although the dominant process delivering debris to the channel often depends upon local geologic conditions. On steep sections of Little Lost Man Creek, for example, where the stream flows over resistant conglomerates and massive sandstone, the valley sides tend to be steep, and landslides commonly deliver large organic debris to the channel. Landslides adjacent to the banks of Hayes Creek also deliver considerable large organic debris to the channel. On the other hand, at locations where tributaries enter the stream, or along relatively low-gradient sections where streamside trees are rooted in thicker soils, blowdown and undercutting of the streambanks may deliver most of the material to the channel.

Large organic debris that are anchored in the stream or on the banks and extend out into the channel may be stable for decades. Such debris may be stabilized by having much of their mass resting outside of the channel or may become stabilized by partial burial in sediment within the channel. Debris also may be stabilized by being wedged between other debris, boulders, or other obstructions. Finally, debris may also be stabilized by the growth of "nursed trees" that send roots over the debris and into the soil, binding debris accumulations and substrate together.

Once debris collects in the channel, complex feedback mechanisms often influence additional debris input. For example, debris itself may increase bank erosion, which in turn may undermine additional trees that subsequently fall into the channel. Furthermore, large debris in the sediment storage sites produced by the debris may trap additional large organic debris delivered from upstream by flotation. Accumulation continues until the debris are removed by a combination of erosion, decay of supporting logs, or flotation during high flows. Debris thus released may move downstream to be incorporated in still other accumulations, again significantly affecting sediment routing and discharge patterns. Relations between these processes associated with organic debris in streams are shown on figure 5.

Debris loading in a particular reach under natural conditions is directly related to the availability of potential debris stored in living trees adjacent to the stream. Figure 6 shows that approximately 64 percent of the variability of large organic debris loading may be explained by the variability in the number of mature redwood trees per hectare within 50 m of the streambanks. The remaining 36 percent of the variability of large organic debris loading is presumably associated with local geologic and biogeographic conditions, such as those that differentiate the Prairie Creek and Little Lost Man Creek watersheds.

Debris loading values for Prairie Creek and Little Lost Man Creek range from about 0.02 to 0.44 m^3/m^2 and 0.1

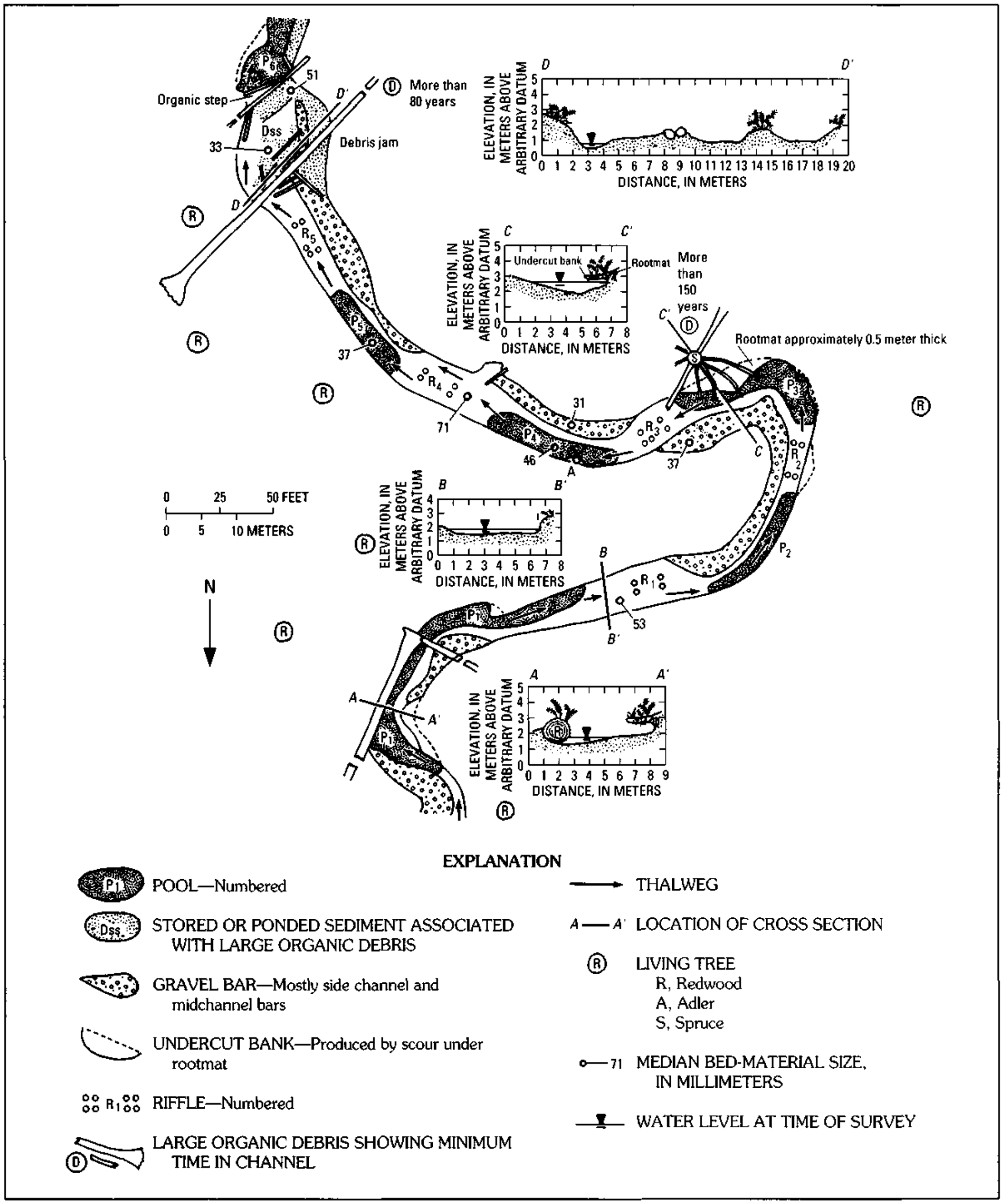

FIGURE 3.—Morphologic map of Zig Zag no. 2 reach, Prairie Creek. Reach location is shown in figure 2. Pool and riffle numbers correspond to those on the long profile shown in figure 19A

to 0.54 m^3/m^2, respectively. Examination of figure 6 shows that with one exception the debris loading in Prairie Creek is consistently less than that predicted by the regression line and that Little Lost Man Creek has debris loading that tends to be higher than would be predicted. The differences primarily reflect variable availability of debris near the channel and perhaps, to a lesser extent, differences between the ways in which large organic debris are delivered to the streams. Prairie Creek is a lower gradient meandering stream with a well-developed flood plain in some locations, and debris are introduced directly into the channel by tree fall and bank erosion. Little Lost Man Creek, on the other hand, is a small steep stream with little flood-plain develop-

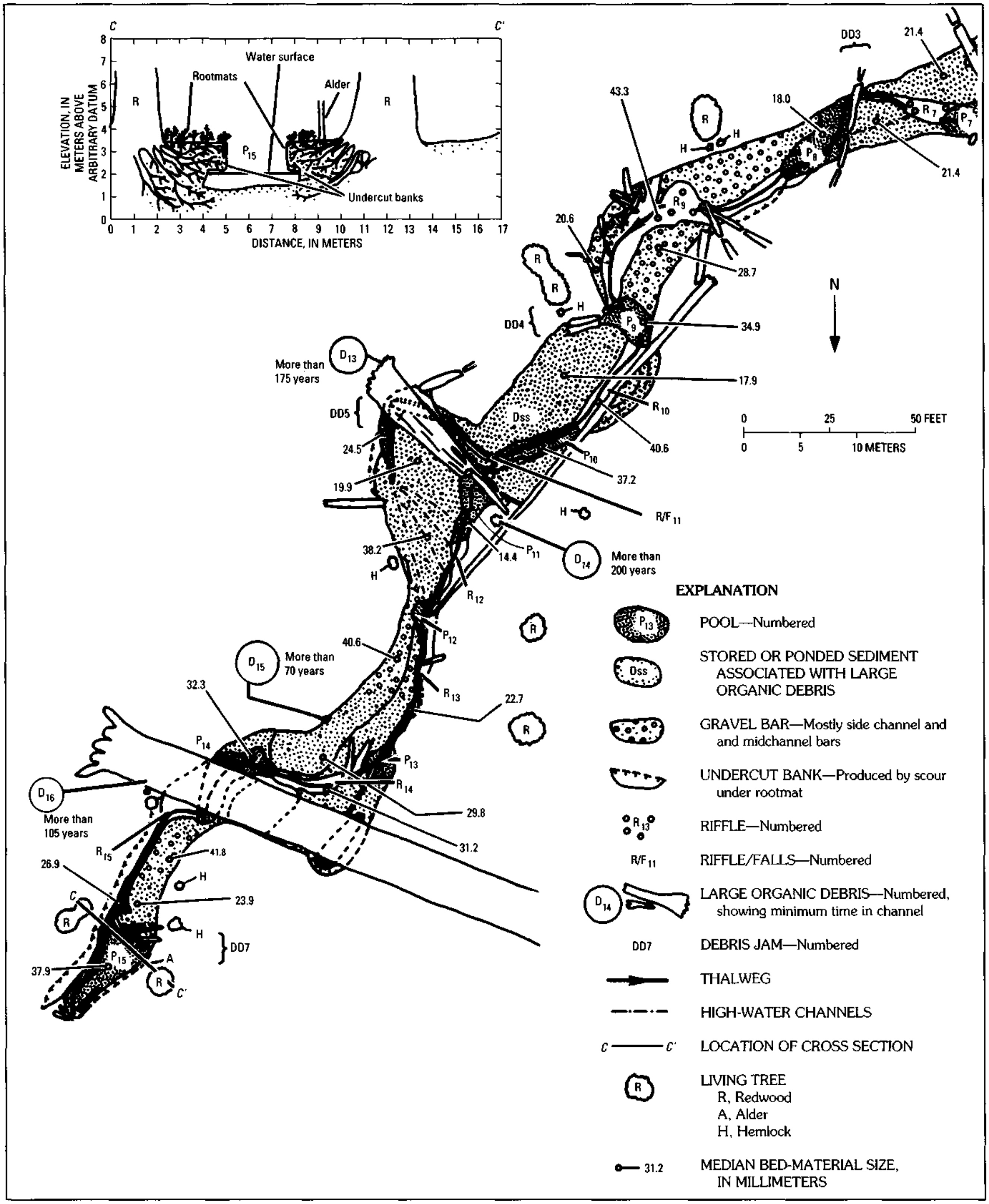

FIGURE 4.—Morphologic map of Little Lost Man Creek, upper reach (part), downstream extension of figure 7. Pool, riffle, and riffle/falls numbers correspond to the long profile shown in figure 16. Reach location is shown on figure 2.

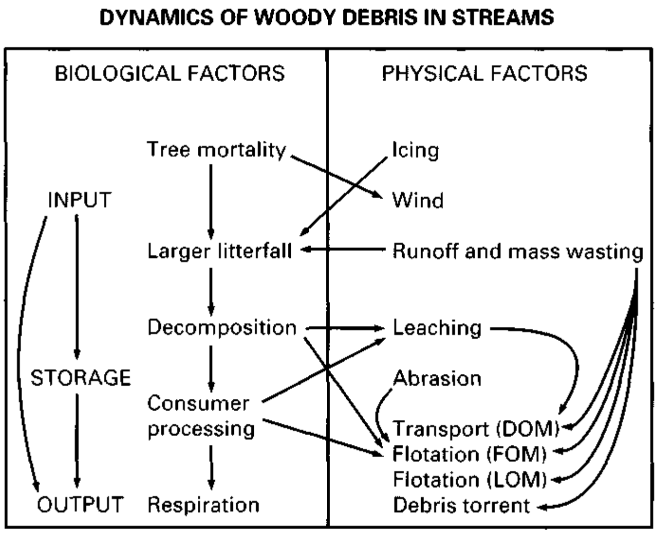

FIGURE 5.—Dynamics of woody debris in streams. DOM=dissolved organic matter; FOM=fine organic matter; LOM=large organic matter.

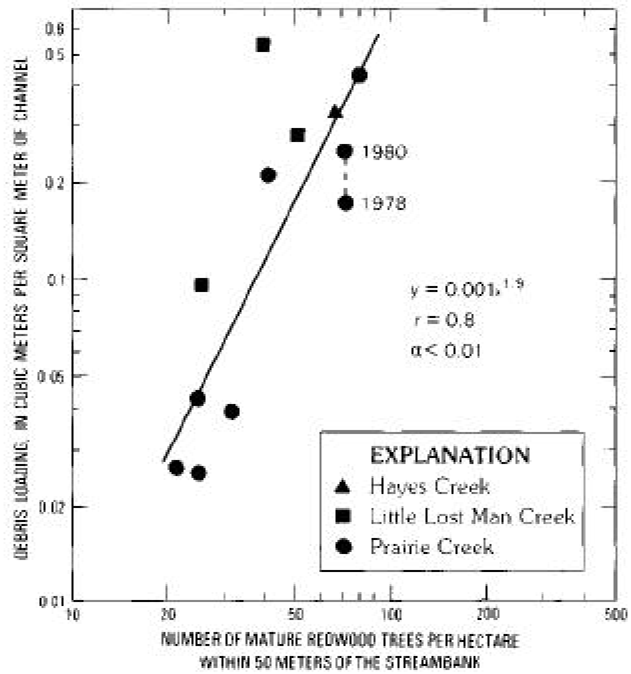

FIGURE 6. —Relation of debris loading to density of mature trees adjacent to the stream channel.

ment and relatively steep valley walls adjacent to the stream channel; mass wasting and other slope processes, as well as tree fall and bank erosion, are therefore important in transporting and concentrating large organic debris downslope to the stream channel.

Streams in the same drainage basin flowing through timber stands where trees are about the same size (other factors being similar) might be expected to have a debris loading that decreases as drainage basin area increases. This is because (1) tree density is partially related to topography (greater areal density on steeper slopes), (2) area of active channel increases downstream, and (3) flow in the upper reaches may not be sufficient to float large organic debris, whereas farther downstream there is sufficient stream power and water depth to move and sort debris into distinct debris accumulations or jams. Farther downstream even the largest debris may be floated away. The above relation between debris loading and drainage basin area is documented in streams that flow through Douglas-fir forests (Swanson and Lienkaemper, 1978) of the Pacific Northwest and in second-growth northern hardwood forests of New England (Bilby and Likens, 1980). Although redwood debris occur in a larger range of sizes, the same tendency can be observed: debris loading generally decreases in the downstream direction as channel width and drainage area increase (table 1). Debris accumulations in the lower reaches may be larger, however, more complex, and spaced farther apart than in the headwater areas. Some of these relations are shown diagrammatically on morphological maps for the upper reach of Little Lost Man Creek (figs. 4, 7) and lower reach (figs. 8, 9).

Debris loading in specific instances, over relatively short reaches, may deviate from the general relation with drainage basin area. For example, with the exception of the very headwaters of Prairie Creek, the Brown Creek reach has a debris loading higher than that found in either the upstream or downstream study reaches (see table 1). Examination of the Brown Creek reach suggests that there are several anomalies. A particularly significant anomaly may be the convex portion of the profile of Prairie Creek in the vicinity of the Brown Creek and Campground study reaches (fig. 10). The origin of the convex section of the profile is not known but may be related to the geology and, in particular, to recent tectonic uplift. Regardless of whether the entrenchment is due to recent tectonic activity, it influences debris loading by producing locally narrow valleys and steep valley sides adjacent to the channel, which can be seen in the cross-valley profile of the Brown Creek study reach (fig. 10). Figure 11 shows a morphologic map of part of that study reach. The relatively steep valley sides, more frequent entrance of tributary channels, and entrenchment into the Prairie Creek Formation increase the likelihood of large organic debris entering the stream channel. Tributary junctions are apparently significant because at these sites erosion acts along two adjacent banks, increasing the chances of a tree falling into the channel (Keller and Tally, 1979). Thus, the relatively

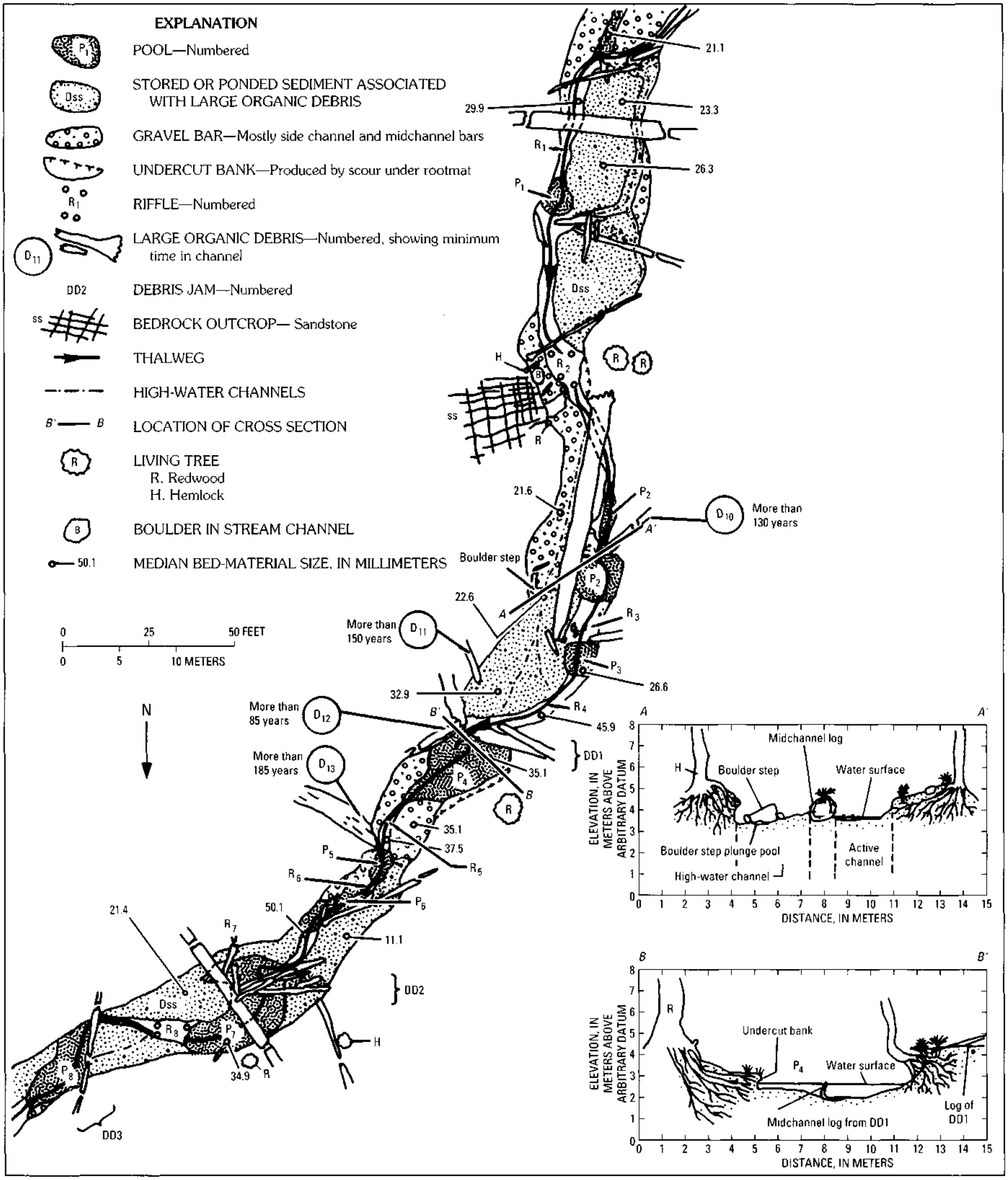

FIGURE 7.—Morphologic map of Little Lost Man Creek, upper reach (part). The downstream extension of this map is shown in figure 4. Pool and riffle numbers correspond to the long profile shown in figure 16.

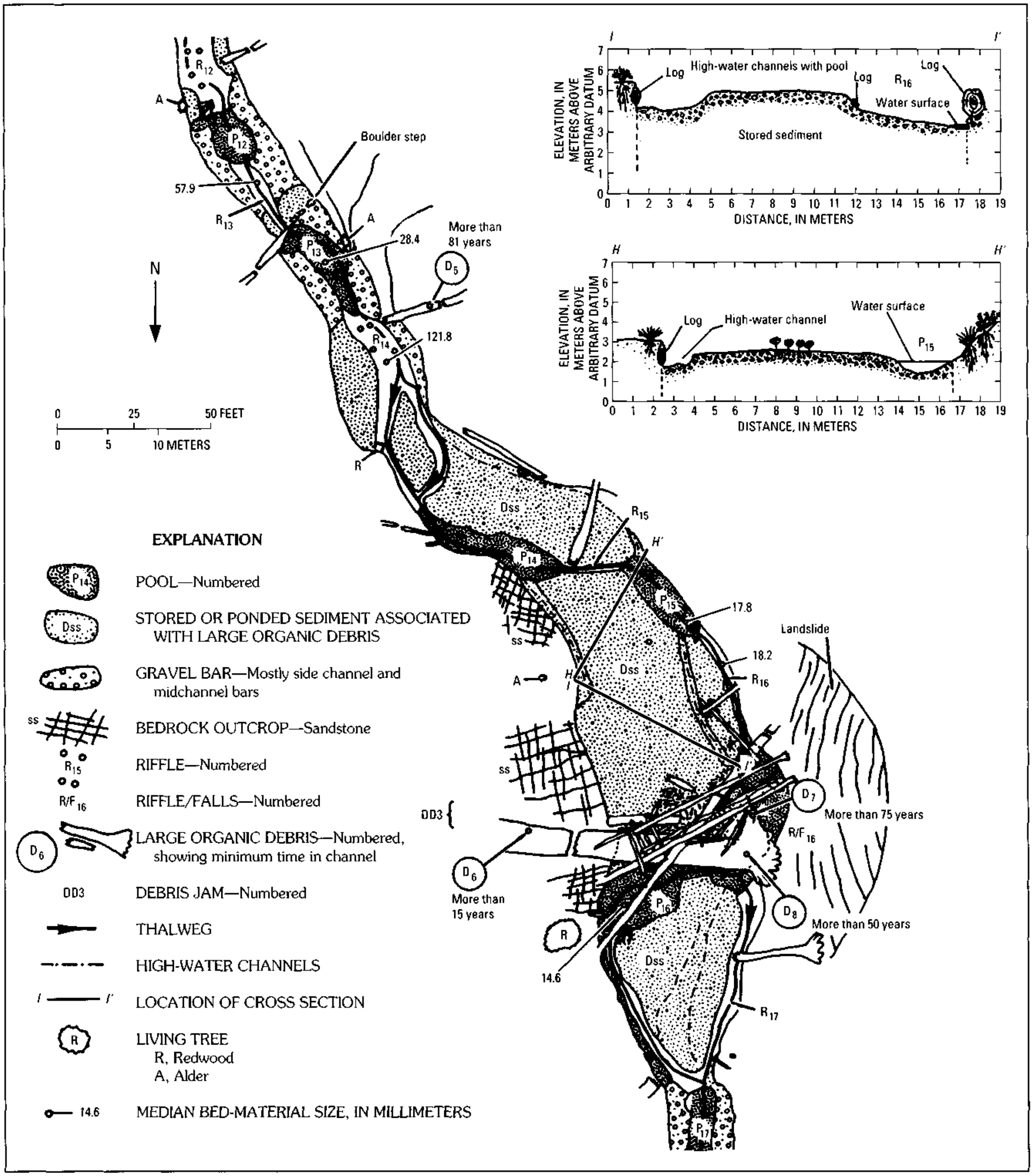

FIGURE 8.—Morphologic map of Little Lost Man Creek, lower reach. Location of reach is shown in figure 2. The corresponding long profile is shown in figure 17. The debris jam adjacent to the landslide has been in place for more than 75 years.

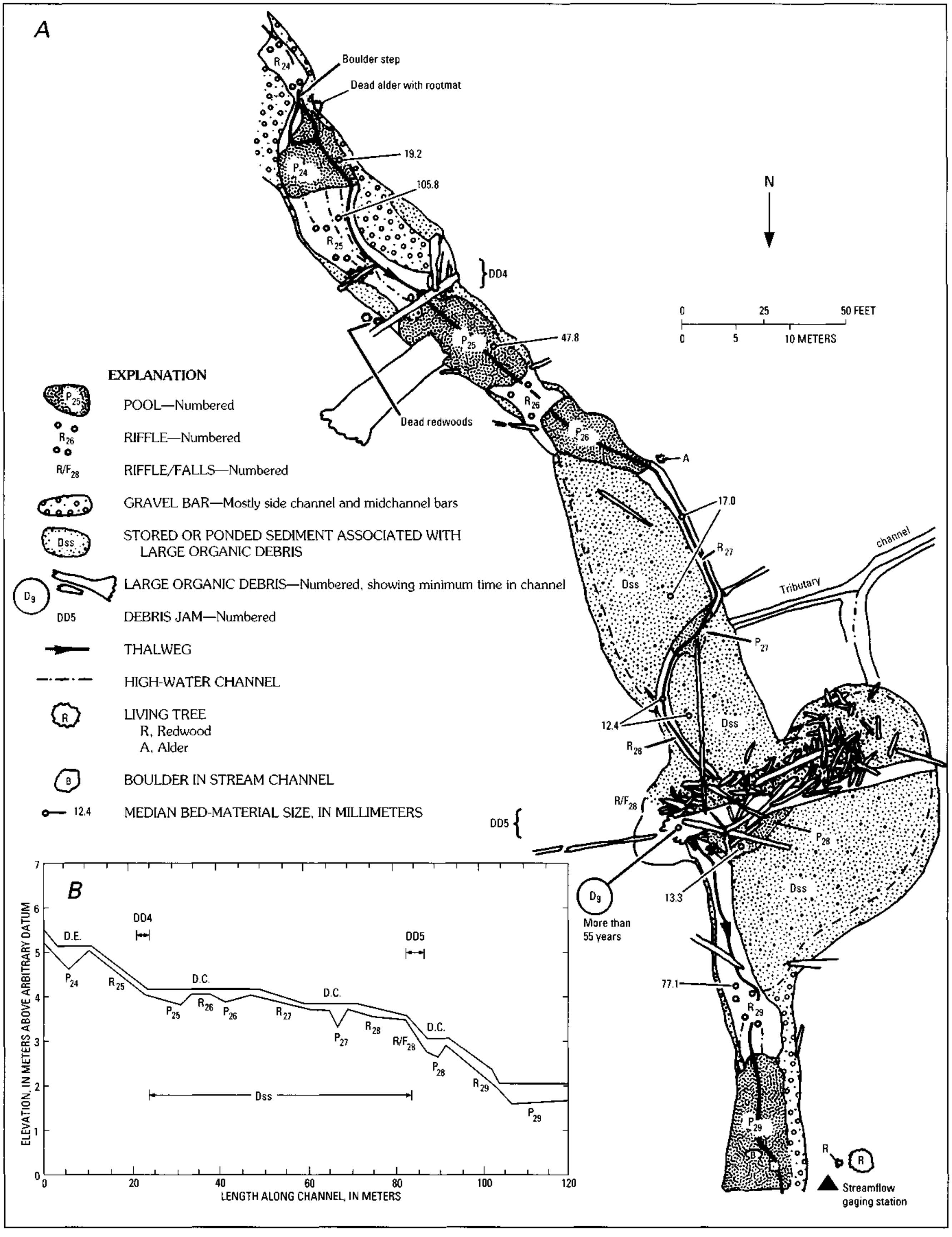

FIGURE 9. —*A*, Morphologic map and, *B*, Long profile of Little Lost Man Creek, lower reach (part), downstream from area shown in figure 8. Notice the marked channel widening associated with the debris dam and the finer particle size of the debris-stored sediment.

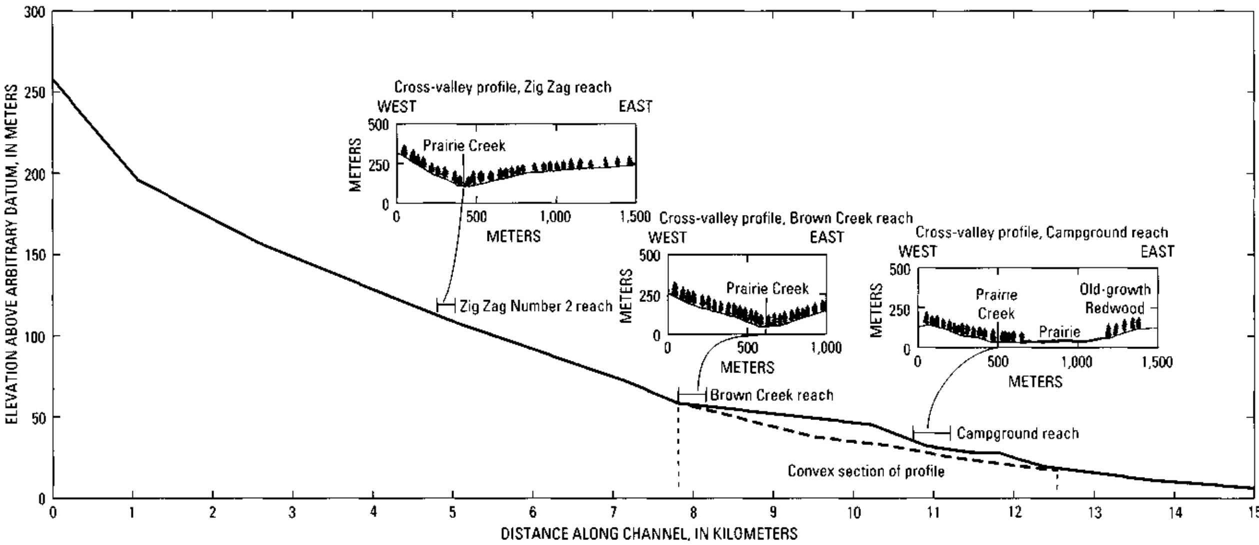

FIGURE 10. —Long profile of Prairie Creek showing the locations of study reaches discussed in this paper and cross-valley profiles at those reaches. Drawn from 7.5-minute topographic maps.

high debris loading at the Brown Creek reach is apparently directly related to both the number of redwood trees in the vicinity of the channel and local geomorphic conditions.

Marston (1982) reports that the frequency of log steps (not total debris loading) is greater for third-order streams than for second- or fourth-order streams. He believes that this situation results from the fact that the headward portions of streams may have V-shaped narrow valleys in which there is little likelihood of large organic debris actually falling in and blocking the active channel. Farther downstream in third-order streams, where valley sides are not as steep, it is more likely that debris actually reaches the channel; thus, there is a greater frequency of log steps. Certainly this hypothesis, although possibly reasonable for log steps, may not be generally true for total debris loading because often large organic debris in headwater reaches of streams do not form specific log steps, but rather the debris lie adjacent to the stream channel or extend only part way into the stream channel.

RESIDENCE TIME OF LARGE ORGANIC DEBRIS

Movement of large organic debris through the fluvial system is postulated to be primarily by flotation during high flows or perhaps, in very steep sections of some streams, by debris torrents (Swanson and Lienkaemper, 1978; Keller and Tally, 1979). Individual pieces of redwood debris in streams draining old-growth redwood forest (Prairie Creek, Hayes Creek, Little Lost Man Creek) may be very large, often several meters in diameter and several tens of meters long. Such large debris move only rarely and thus are semipermanent parts of the channel morphology. This conclusion was determined by examining trees such as hemlock, spruce, big-leaf maple, and redwood trees that grow on downed redwood trees. Coring of these trees provides a minimum time that the debris have been in the stream channel. Table 2 lists minimum residence times in Prairie Creek and Little Lost Man Creek for more than 30 pieces of debris. About half of these exceed 100 years, and the oldest exceeds 200 years, suggesting that large redwood debris may reside in the stream channel for at least several centuries.

CHANNEL MORPHOLOGY AND LARGE ORGANIC DEBRIS

Large organic debris in small- to intermediate-size forest streams significantly influences channel morphology. For example, a stream having an active channel width of several meters may have one entire bank, for a distance of several channel widths, completely formed and defended by a single downed redwood tree. (See fig. 3, *A-A'*.) The role of large organic debris is particularly significant in affecting channel width, depth, local slope, development of the long profile, and channel forms such as pools and riffles.

CHANNEL WIDTH

In many gravel-bed alluvial stream channels, the width of the active stream channel or bankfull channel

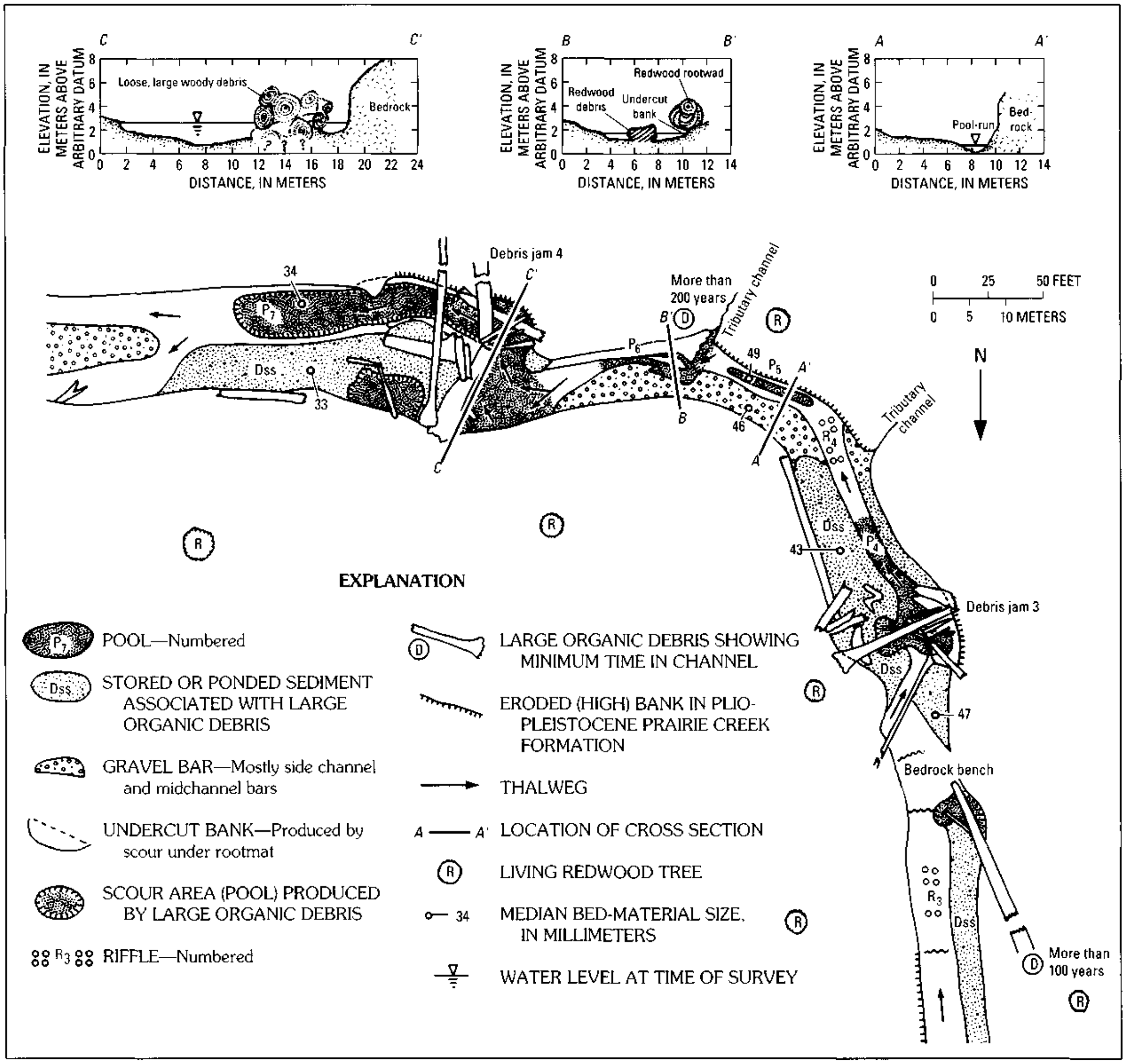

FIGURE 11. —Morphologic map of the Brown Creek reach of Prairie Creek (part). Reach location is shown in figure 2. Pool and riffle numbers correspond to those on the long profile shown in figure 19*B*.

width is relatively easy to measure, particularly at riffles where channel banks often are well defined. However, in many forested environments, large organic debris in the channel may make the definition of channel width difficult. The range of widths along a particular stream reach is often so variable that one or several measurements are nearly meaningless. The range of channel widths for selected study reaches of Little Lost Man Creek and Prairie Creek are shown on table 3, as are the mean widths of pools, riffles, and debris accumulations. To relate channel width to other variables such as upstream drainage area, we developed the "characteristic width," defined as the area of active channel in a reach divided by the channel length, as measured down the center line of the channel. Thus, the characteristic width is actually an average width over a reach. The length of reach measured is approximately 30 channel widths to ensure that several examples of various stream environments such as pools, riffles, and debris accumulations are included within the reach. As shown on table 3, the characteristic width is approximately the average width for pools and riffles (measured at their maximum width) but is quite different from the widths of debris accumulations. This disparity results because the channel width at a debris accumulation is often two or more times greater than the characteristic width of the channel. The characteristic width was measured at several locations in Prairie Creek, and the relation between width and drainage

TABLE 2.—*Minimum ages for large organic debris in the study reaches of Little Lost Man Creek and Prairie Creek*

[Study reaches are shown in figure 2]

Study reach	Tree type	Age (years)	Location[1]	Environment[2]
Little Lost Man Creek				
Upper	Hemlock	130	Not shown	Partial D.D./ B.D.Tr.
	....do....	130	Fig. 7; P 2	Partial D.D./ B.D.Tr.
	....do....	150	Fig. 7; R 4	B.D.Tr. on debris-stored sediment.
	....do....	85	Fig. 7; P 4	D.D.
	....do....	185	Fig. 7; P 5	Partial D.D./ B.D.Tr.
	....do....	175	Fig. 4; P 11	D.D.
	....do....	200	....do....	D.D.
	....do....	70	Fig. 4; P 13	M.C.B. behind D.D.
	....do....	105	Fig. 4; P 14	D.D.
Lower	Alder	60	Not shown	M.C.B. behind D.D.
	Redwood	75	....do....	Log over stream.
	....do....	220	....do....	B.D.Tr. downed trunk.
	....do....	100	....do....	D.D.
	....do....	80	....do....	Partial D.D.
	Alder	70	....do....	M.C.B.
	Sitka spruces	22	....do....	Partial D.D./ B.D.Tr.
	....do....	35	Fig. 8; R 14	B.D.Tr.
	....do....	115	Fig. 8; P 16	D.D.
	Redwood	75	....do....	D.D.
	....do....	50	....do....	D.D.
	Sitka	65	Not shown	D.D.
	....do....	40	....do....	B.D.Tr. downed trunk.
	Hemlock	20	....do....	B.D.Tr. downed trunk.
	Redwood	55	Fig. 9; P 28	D.D.
Prairie Creek				
Zig Zag no. 2 . . .	Sitka spruce	150	Fig. 3; P 3	B.D.Tr.
	Maple	80	Fig. 3; P 6	D.D.
Brown Creek . . .	Redwood	160	Not shown	D.D.
	Hemlock	100	....do....	D.D.
	....do....	100	Fig. 11	Partial D.D.
	Redwood	>200	Fig. 11; P 6	B.D.Tr. downed trunk.
Campground . . .	Redwood	50	Fig. 20; P 5	M.C.B. after D.D.
	....do....	100	....do....	Partial D.D.
	Hemlock	100	Fig. 20; P 6	B.D.Tr. with root mat.

[1] P=pool; R=riffle.
[2] Partial D.D.=debris dam blocking part of channel; B.D. Tr.= bank-defending tree; D.D.=debris dam blocking entire channel; M.C.B.=midchannel bar.

basin area is shown in figure 12. These data suggest that, in the upper part of the Prairie Creek drainage basin, the rate of change of characteristic width with drainage area is less than that farther downstream. This is consistent with observations by Zimmerman and others (1967) and probably reflects the importance of bank vegetation in

TABLE 3. —*Comparison of channel widths for pools, riffles, and debris accumulations for selected channel reaches*

Reach	Upstream drainage area (km^2)	Characteristic width[1] (m)	Mean pool width[2] (m)	Mean riffle width[2] (m)	Mean debris-jam width[2]	Range of widths (m)
Little Lost Man Creek						
Upper	3.5	6.4	7.1	6.6	8.1	2.4-15.6
Lower	9.1	9.6	10.8	11.4	17.2	2.0-24.0
Prairie Creek						
Zig Zag no. 2	8.2	6.7	7.3	5.6	15.0	3.0-15.0
Brown Creek	11.2	11.0	7.0	8.3	16.1	6.5-20.0
Campground	27.2(km^2)	18.5	20.1	16.0	25.5	10.0-31.0

[1] The characteristic (average) width is the area of the active channel in the study reach divided by the channel length.
[2] The mean widths of the pools, riffles, and debris jams are the average of the widths measured at the location of maximum width for each pool, riffle, or debris jam.

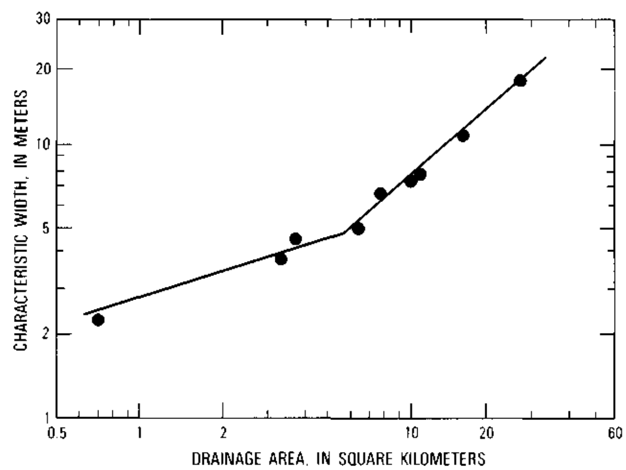

FIGURE 12. —Relation between characteristic channel width and drainage basin area for Prairie Creek.

stabilizing channel width in the upper part of the basin. However, as the drainage basin area increases, discharge and thus stream power also increase until a threshold is exceeded and the rate of change in channel width with increasing drainage area increases. In Prairie Creek the threshold may be at about 6 km^2 as suggested by the apparent change in slope on figure 12.

Channel width is often greatest at the site of debris dams because such dams often produce horizontal divergence of flow away from the center of the channel, causing deposition of a midchannel bar (stored sediment) upstream from the debris dam. The bar diverts the flow toward the sides of the channel, producing bank erosion and a locally wider channel. A plunge pool may form at the base of the debris dam as in P_{28} at debris dam no. 5 (DD5) on figure 9. Here a large redwood trunk has fallen across the channel, and the local stream width has been significantly increased. Debris that extend across part of the channel are common and may also affect channel width. Figure 13, for example, shows a short reach of Hayes Creek that has been highly modified by a large redwood stem that is subparallel to the channel.

CHANNEL SLOPE, DEPTH, AND THE LONG PROFILE

Channel slope and depth are related to the long channel profile and thus will be discussed together. Channel slope, one of the important dependent variables in the fluvial system, is a function of several independent variables including mean annual discharge of water and sediment, bedrock type, and recent tectonic activity. These factors, and others, interact to produce a long profile that is adjusted to produce a compromise between least work and equal work (Leopold and Langbein, 1962). The long profile and slope of a channel tend to adjust over a period of years (Mackin, 1948) and thus reflect relatively recent adjustment of the stream channel. Hack (1957) noted that channel slope is adjusted to bedrock resistance in such a way that the steepest reaches are underlain by the most resistant rock. Our discussion here will focus on effects of bedrock geology and large organic debris on profile development.

The effect of varying rock type on local channel slope was investigated along Little Lost Man Creek, where several sedimentary rock types crop out (Tally, 1980). The long profile, from headwaters to a point several kilometers downstream, where bordered by old-growth redwood forest, was surveyed with a hand level and tape during the summer of 1978. Figure 14 shows a 500-m segment of this survey. The profile clearly demonstrates an adjustment between geology and channel slope. The channel slope is steepest where the stream flows over conglomerate and massive sandstone, of intermediate value where flow is over thin-bedded sandstones, and relatively gentle when flow is over relatively nonresistant shales. A significant variable affecting channel slope is the percentage of massive sandstone; the correlation coefficient between the two for the entire profile (fig. 155) of Little Lost Man Creek is 0.81, significant at the 0.05 level. Thus, about 64 percent of the variability of channel slope may be explained by the variability of underlying rock type (Tally, 1980).

The long profile for Little Lost Man Creek, drawn from U.S. Geological Survey 7.5-minute topographic quadrangles, is shown on figure 15A; figure 15*B* shows much of the same profile as surveyed by hand level. The surveyed profile is approximately 10 percent longer for the same elevation change because it was measured along the thalweg rather than down the channel midline. Both profiles are convex, particularly in the central part. Convexity of a long profile may result from lithologic variability, tectonic uplift, or downstream decrease in discharge (Morisawa, 1968), and it is not an indicator of

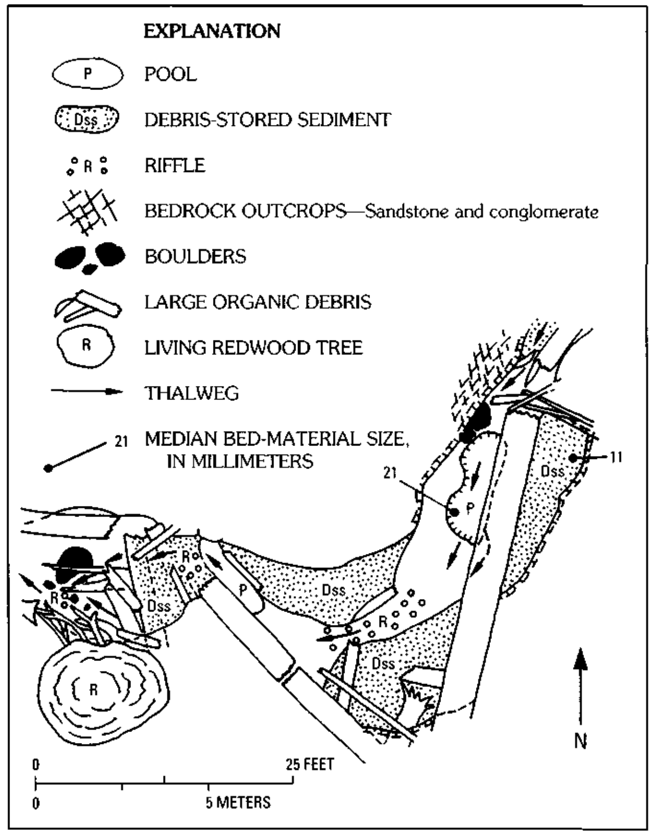

FIGURE 13.—Morphologic map of part of the Hayes Creek reach illustrating the potential stabilizing effect of large organic debris on channel banks.

stream equilibrium or disequilibrium. Discharge increases in the downstream direction in Little Lost Man Creek. While tectonic control is possible (especially because of the proximity of Little Lost Man Creek to northwest-trending shears along the plate boundary between the American plate and Humboldt plate as hypothesized by Herd (1978) and Dott (1979)), probably most of the convexity of the profile is due to lithologic control. As discussed above, there is good agreement between the resistance of the rock and the slope of the stream channel. In the central part of the basin, where the percentage of massive sandstone is relatively large, the convexity is the greatest (fig. 15).

On massive sandstone, which underlies approximately 43 percent of the surveyed channel, the average channel slope is 0.097 m/m, and 63 percent of the drop in elevation occurs. On thin-bedded sandstone, which underlies approximately 49 percent of the channel length, the average channel slope is 0.045, and 33 percent of the drop in elevation along the channel occurs. On shale, which underlies about 8 percent of the channel, the average slope is 0.029, and only about 4 percent of the drop in elevation occurs. These data are summarized in

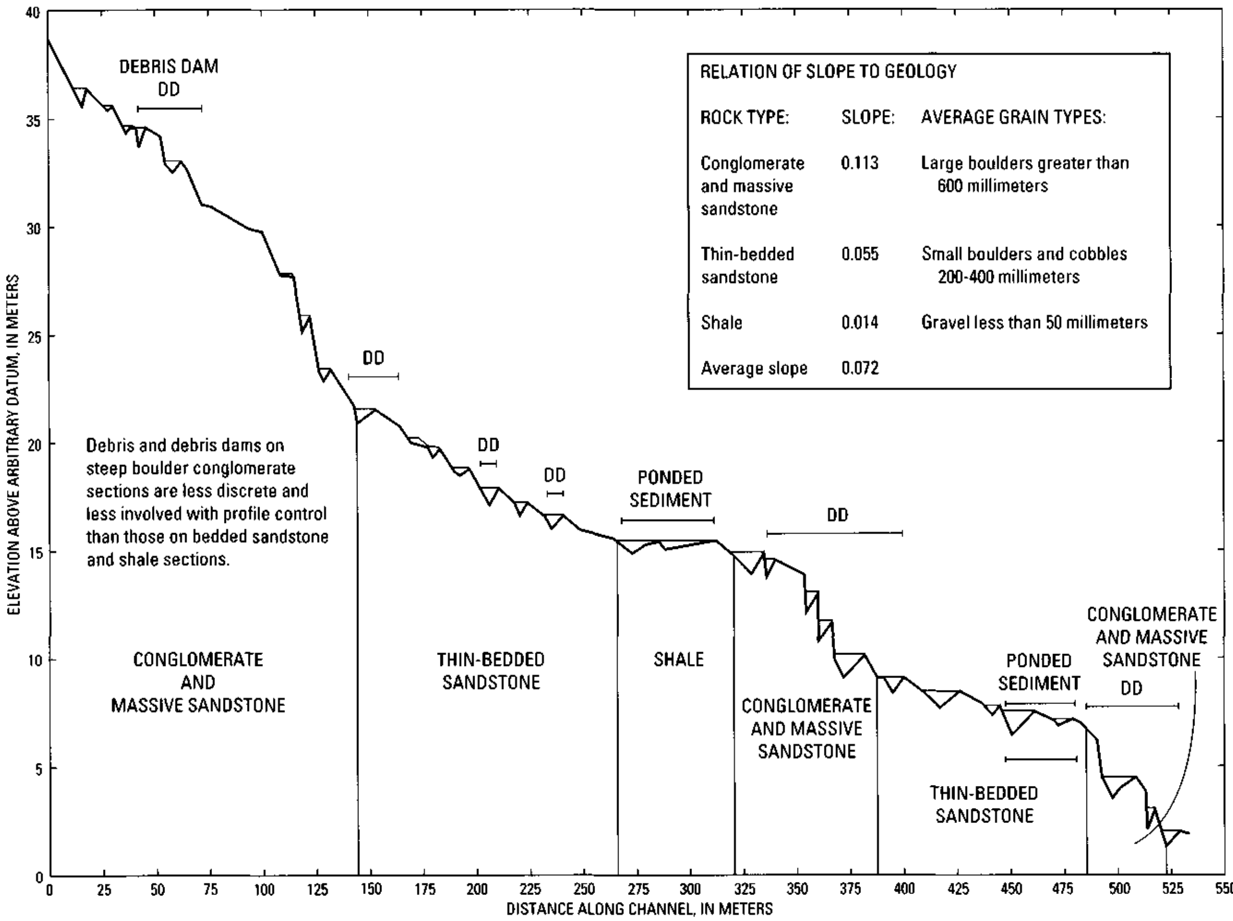

FIGURE 14.—Long profile of Little Lost Man Creek, upper reach, demonstrating adjustment of channel slope to the resistance of the underlying bedrock.

table 4 and further demonstrate the importance of lithologic control in influencing the convex profile of Little Lost Man Creek.

The average grain size of the bed material in the stream is also related to the bedrock type and channel slope (see fig. 14). The largest boulders are found in the steepest part of the channel where it is cut in massive sandstones and conglomerates. Smaller boulders and cobbles are associated with the thin-bedded sandstones and moderate channel slopes, and the smallest gravel is found at the gentler slopes on shale. This relation has been demonstrated in detail by Hack (1957) in his study of the long profiles of streams in Virginia and Maryland.

Effects of debris on the channel profile are shown also on figure 14. Notice that 59 percent of the decrease in elevation along the channel is associated with organic steps or debris dams. Furthermore, for some of the large accumulations there is extensive ponded or stored sediment upstream from the debris. However, in Little Lost Man Creek, it was also observed that debris dams on some of the steeper sections, where the channel is in

TABLE 4.—*Influence of rock type on channel slope, Little Lost Man Creek*

[From Tally, 1980]

Rock type	Length of channel controlled (m)	Percent length	Change in elevation of channel (m)	Percent change	Average slope
Massive sandstone	2,265	43	219.2	63	0.097
Thin-bedded sandstone	2,580	49	115.5	33	.045
Shale	445	8	13.3	4	.029
Total	5,290	100	348.0	100	0.066 (avg)

conglomerate, have less effect on the thalweg profile than do dams on the less resistant shale and sandstone. This situation occurs because bed material in the steeper reaches of Little Lost Man Creek often consists of very large boulders, and the large organic debris rest on these boulders, above the active stream channel.

Steep-gradient sections of Little Lost Man Creek and Hayes Creek often contain waterfalls interspersed with riffles. We have designated these sections as riffle/falls. Waterfalls over woody debris or rock outcrops often form pools.

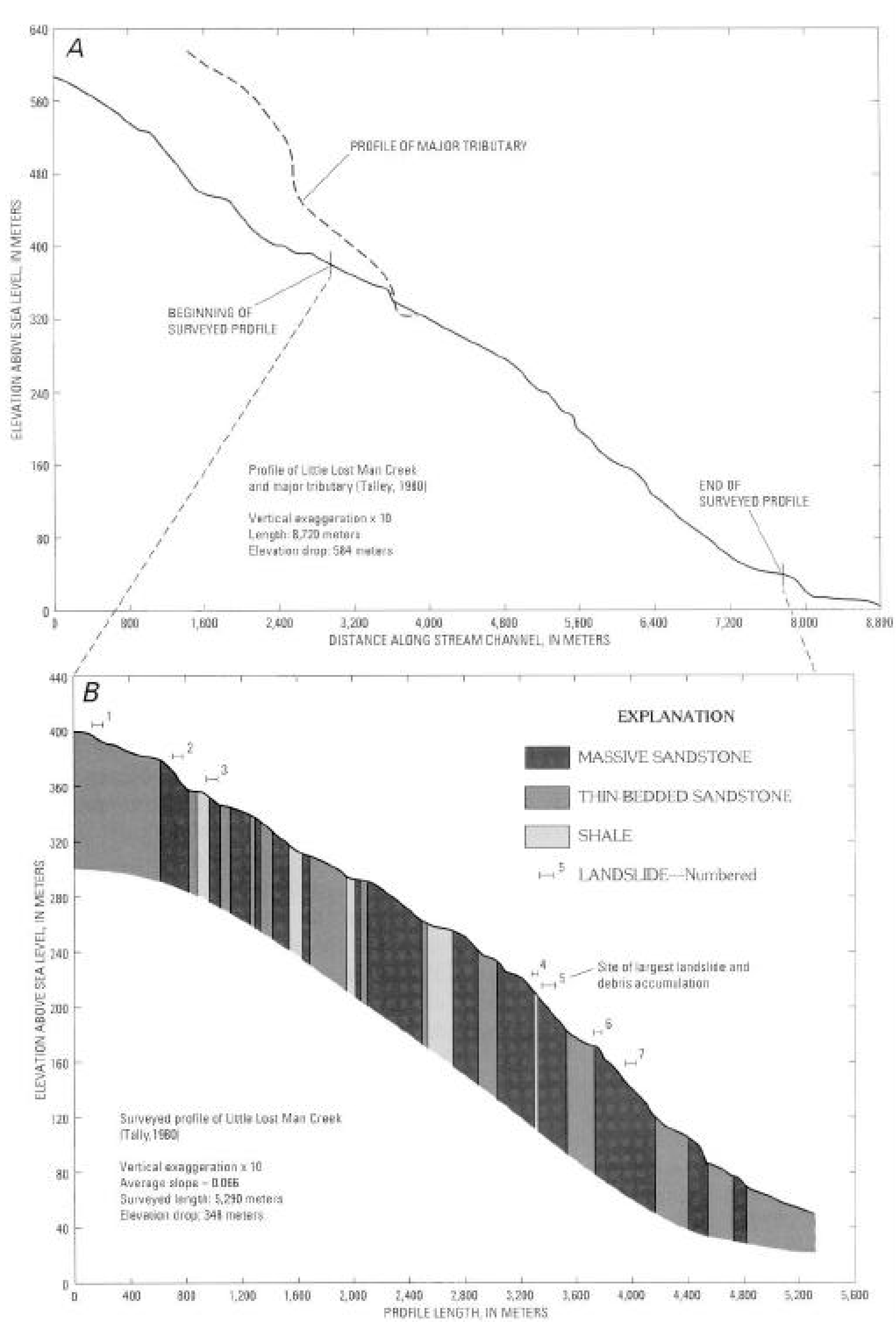

FIGURE 15.—A, Long profile of Little Lost Man Creek, drawn from 7.5-minute topographic maps. *B*, Surveyed profile of Little Lost Man Creek showing distribution of rock types along the channel.

Variations in channel depth were analyzed on detailed long profiles of the study reaches. In Little Lost Man Creek and Hayes Creek, the role of large organic debris in increasing the variability of channel depth is very pronounced. Figures 16, 17, and 18 show profiles for the upper and lower reaches of Little Lost Man Creek and

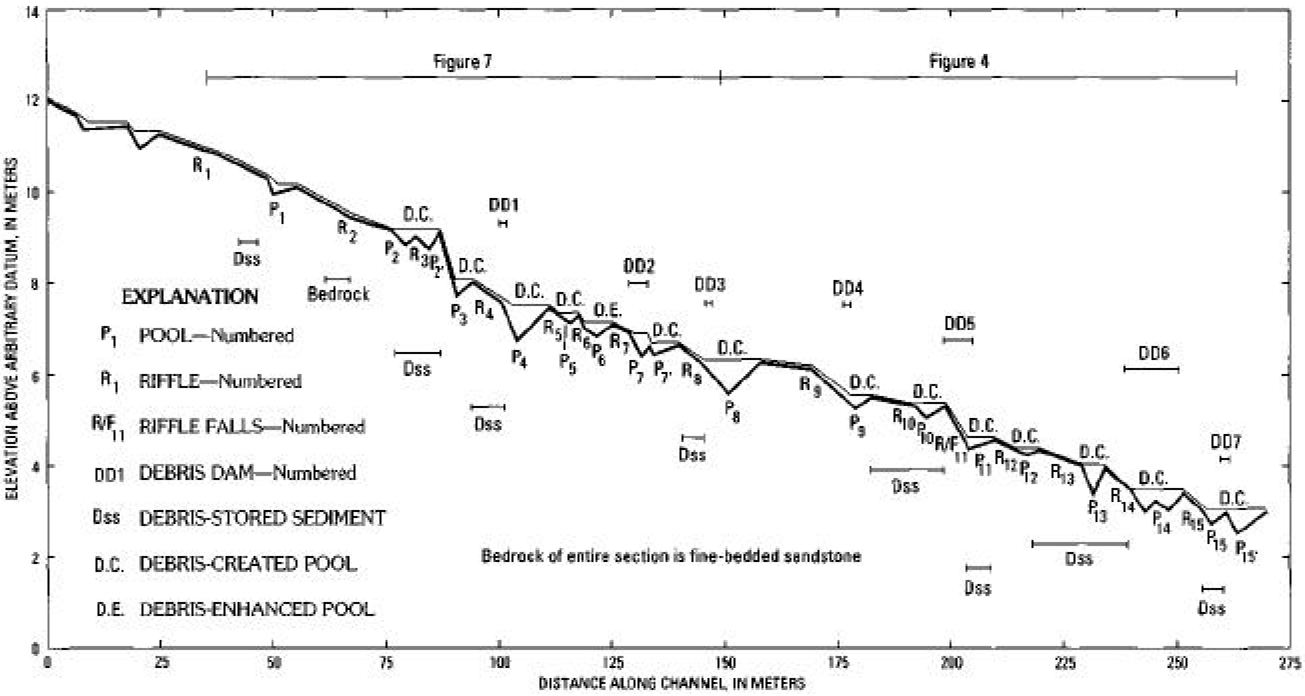

FIGURE 16.—Long profile of Little Lost Man Creek, upper reach. Corresponding morphologic maps are shown in figures 4 and 7.

the study reach for Hayes Creek and demonstrate some of the variability associated with large organic debris. In the upper reach of Little Lost Man Creek, debris are discrete and numerous, creating organic steps and a variety of channel depths (Keller and Tally, 1979). Similarly, the long profile for Hayes Creek (fig. 18) demonstrates the variability of depth produced by interactions among large organic debris, rock outcrops, and channel morphology. A series of organic steps produces a stream profile characterized by relatively long sections of stored sediment with relatively low gradient. These long sections alternate with short, steep cascades or falls spilling into a scour or plunge pools.

Large organic debris cause a less pronounced variation of water depth in Prairie Creek than in Little Lost Man Creek or Hayes Creek, because Prairie Creek has a lower gradient and tends to meander more. Pools and riffles are well developed, and in the lower reaches up to 50 percent of the pools form independently of large organic debris (see table 1). Profiles for three of the study reaches along Prairie Creek are shown on figure 19.

The stepped profile associated with large organic debris is important because loss of potential energy takes place at cascades or falls, thus reducing the energy available to erode the streambed and banks (Keller and Tally, 1979). Examination of table 1 reveals that a significant amount of the total decrease in elevation along a channel may be controlled by large organic debris, either in the form of organic steps or complex accumulations of stems and rootwads. Furthermore, this effect significantly decreases with decreasing channel slope in undisturbed reaches (rank-sum correlation r=0.81, significant at the 0.005 level) and also decreases as drainage basin area increases or along reaches where the channel is bordered by flats that reduce the input of large organic debris to the channel. For the steeper and smaller channels, the percent drop in elevation is approximately 30 to 60 percent. This drop is consistent with the results of Heede (1972), who concluded from studying small steep mountain streams that cumulative height of the steps in some cases nearly equals the total fall of the stream along a particular study reach. In contrast, Marston (1982) studied 163 km of streams in central Oregon and concluded that log steps accounted for only about 6 percent of the total decrease in elevation of the stream channels. Some of the discrepancy can be accounted for by the fact that Marston considered only log steps that completely block the stream channel, whereas Heede considered organic debris that were not fully incorporated into the channel but that were affecting flow and causing some storage of sediment. Furthermore, the average spacing of log steps in the streams that Marston studied was several hundred meters, compared to only a few meters in those studied by Heede. For the present study, the percentage of decrease in channel elevation associated with organic debris includes organic steps that block all or part of the stream and

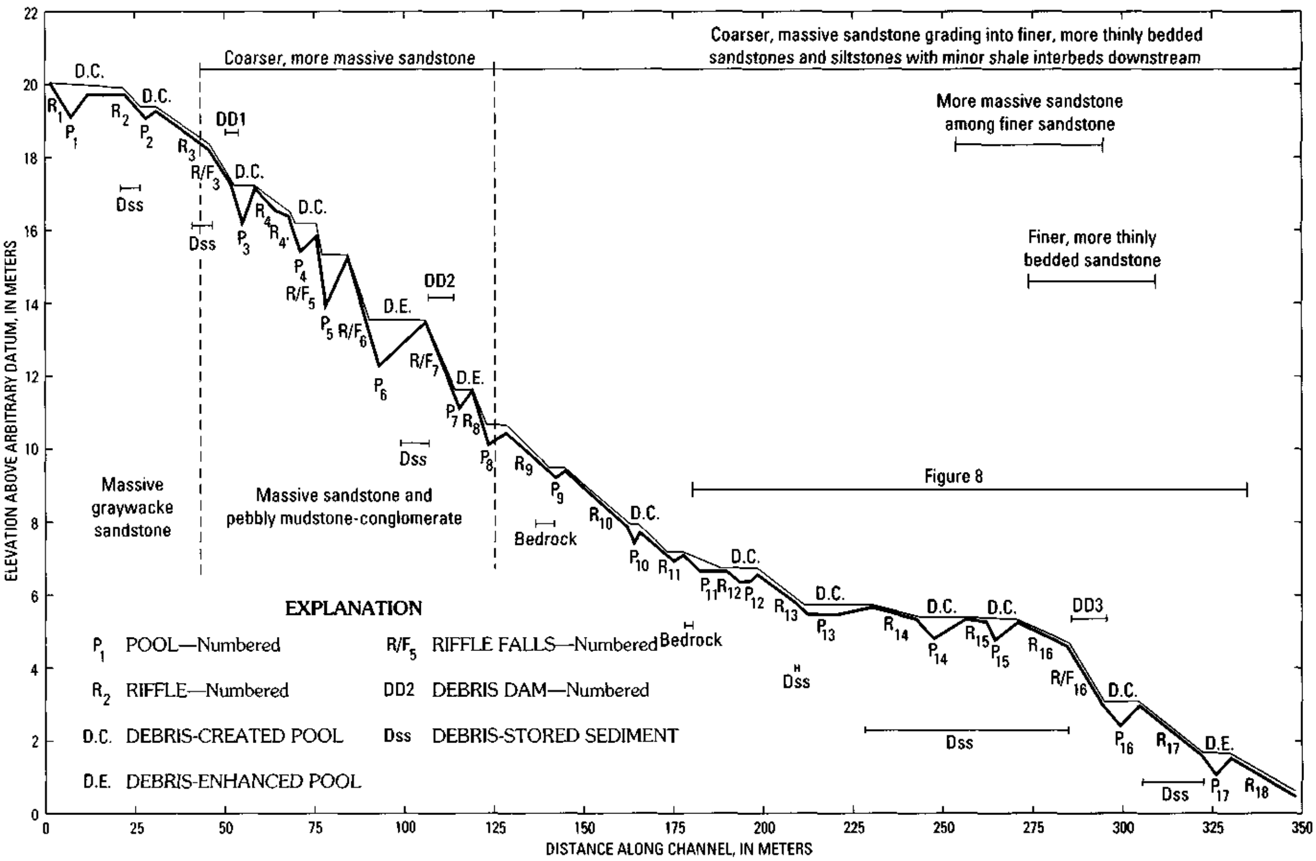

FIGURE 17. —Long profile of Little Lost Man Creek, lower reach (upper 60 percent of study reach). Corresponding morphologic map is shown in figure 8.

complex accumulations of debris that are associated with a drop in elevation of the streambed. Thus, the three studies are not directly comparable. Nevertheless, the conclusion remains that a significant amount of energy loss is associated with turbulent dissipation through debris jams and organic steps and that this energy might otherwise be dissipated in eroding channel bed and banks.

In Prairie Creek, the percentage of channel drop associated with large organic debris varies from less than 1 percent in the lower reaches to as much as 43 percent in the headwaters. Thus, as with debris loading, there is a general tendency for the percentage of decrease in elevation along a channel associated with large organic debris to decrease as the drainage basin area increases.

POOLS AND RIFFLES

Pools and riffles are major morphologic elements of streams that tend to be spaced at about five to seven channel widths along the length of the channel. However, if substantial inhomogeneity in bed or bank material is present to form large rough elements (obstacles to flow such as large boulders, bedrock outcrops, and large organic debris), then these may cause scour and thus control size, location, and spacing of pools (Lisle and Kelsey, 1982). Material scoured from the pools is deposited downstream in riffles and also in bars, which may or may not be stable.

Observations and measurements of channel morphology that forms during relatively high channel-forming flows were made during the summer low-flow periods. Thus we recognize that the distribution of pools, riffles, and other channel features observed during low flow are relics of the higher channel-forming discharges.

The effect of organic debris on pools is shown by the percent of pool morphology (area of active channel) influenced or enhanced by debris and by the pool-to-pool spacing, both of which vary strongly with slope in undisturbed reaches (table 1A). Rank-sum correlation of these values shows that the percent debris-influenced pool morphology increases with increasing channel slope (r=0.78, significant at the 0.008 level), while the pool-to-pool spacing increases with decreasing channel slope (r= -0.62, significant at the 0.06 level). In study reaches impacted by recent timber harvesting, similar but

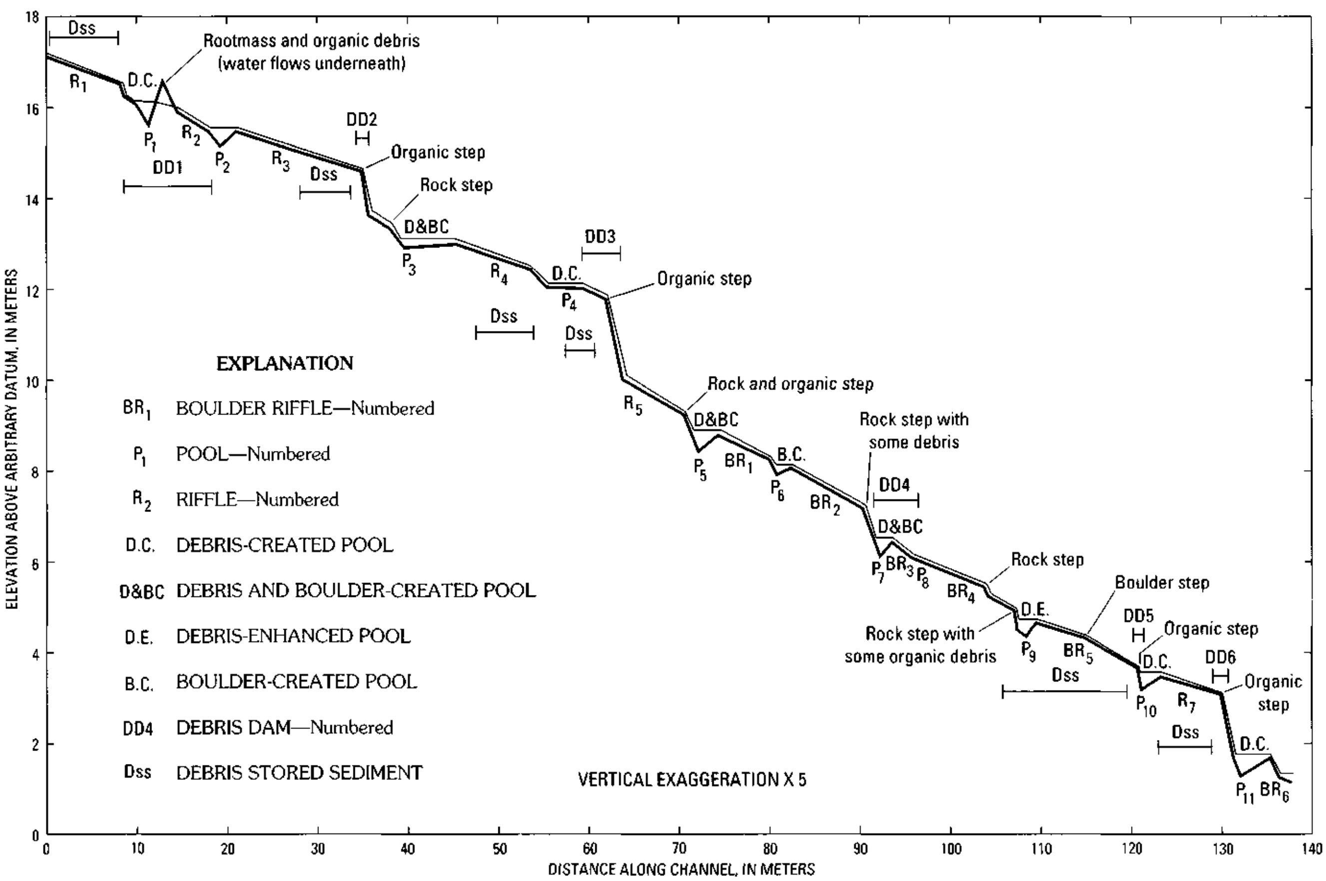

FIGURE 18. —Long profile of Hayes Creek.

weaker correlations are found among upstream channel area, the independent variable, and both debris-influenced pool morphology and pool-to-pool spacing.

In low-gradient streams such as Prairie Creek, pools may form by scour during relatively high channel-forming flows without the influence of large organic debris. Other pools in Prairie Creek are influenced or enhanced by large organic debris. Large organic debris may enhance a pool by forming a buttress along the outside bank and fixing the location of the pool for a long time. An example of such a pool is found along the Campground reach of Prairie Creek (see pool 6, fig. 20). The large rootwad on the right bank has been in that location for more than 100 years, and a very large pool has developed. This pool has water several meters deep during the summer and provides excellent habitat for juvenile anadromous fish. Other pools enhanced by large organic debris are shown on figure 11, which is a morphologic map of part of the Brown Creek reach of Prairie Creek. Pools 4, 6, and 7 are all enhanced by large organic debris. Notice that the log defending pool 6 has been in the stream channel for more than 200 years.

Farther upstream in the Brown Creek reach, there has been a significant change in the basic channel morphology. Figure 21 shows a sketch map of that section as it was in 1978 and changes that occurred in 1979 to produce the 1980 morphology. A large redwood tree on the left bank shown in the 1978 map fell into the stream channel in 1979, blocking the flow. The channel has been adjusting to the input of the new debris, and a period of a few years might be required before the channel returns to stable conditions. Interestingly, the addition of this one large redwood trunk to the stream has increased the debris loading in the Brown Creek reach by approximately 40 percent. (The new debris loading is not shown on table 1, which contains only data during the 1978 field season; we have not been able to remeasure the debris loading in all the stream reaches for comparative purposes.) The 1978 value of debris loading for the Brown Creek reach also was used in all the calculations and comparisons in this study. The addition of the new debris is mentioned because of its significance to the change in morphology of the stream channel.

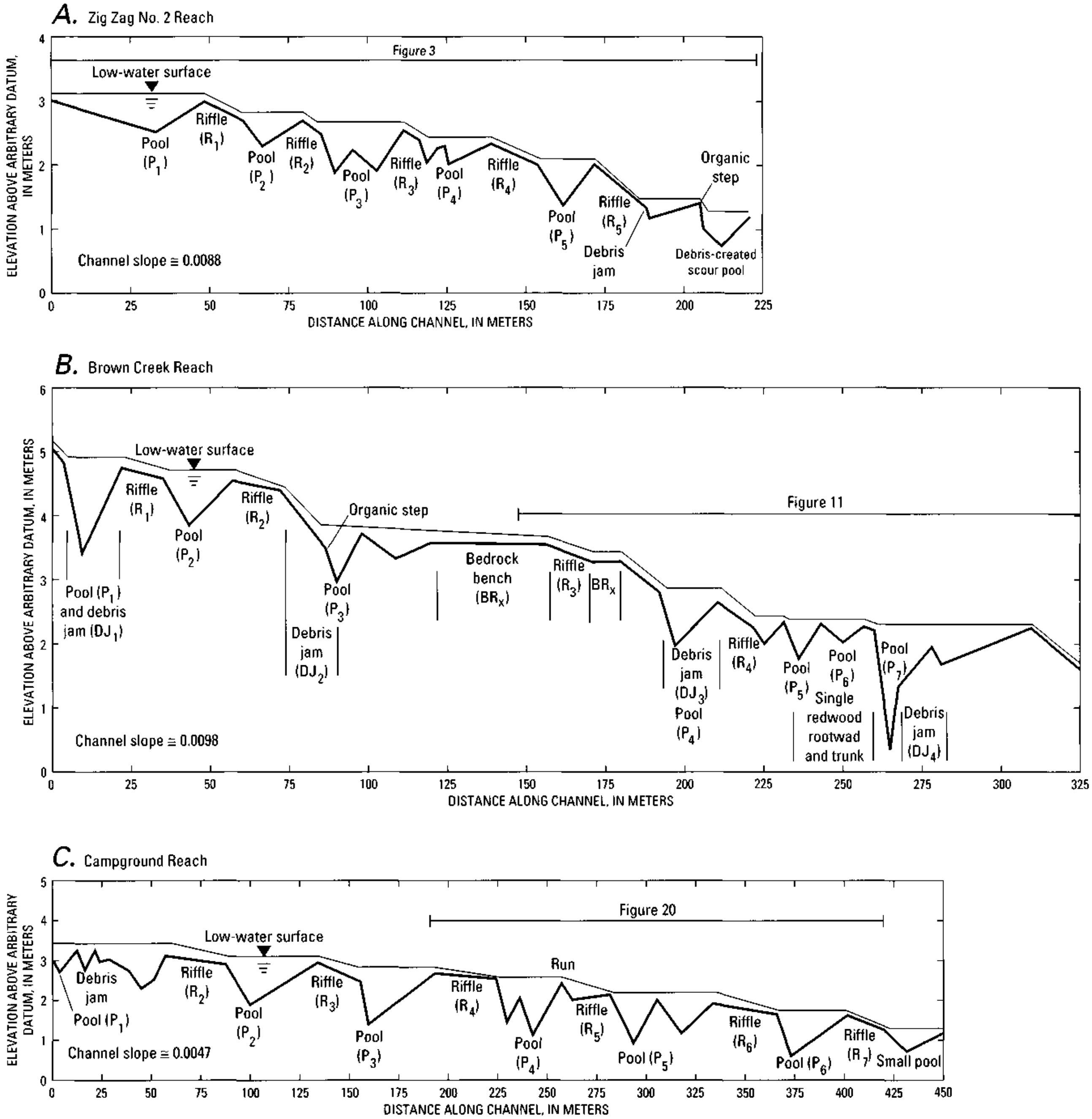

FIGURE 19.— Long profiles of selected reaches along Prairie Creek. *A*, Zig Zag no. 2 reach; *B*, Brown Creek reach; and *C*, Campground reach. Corresponding morphologic maps are shown in figures 3, 11, and 20.

In summary, nearly all the pools in the upper reaches of Prairie Creek are either produced directly by large organic debris or are influenced by it, and in the lower reaches 50 percent of the pools are influenced by large organic debris (table 1). Spacing of pools in Prairie Creek is more variable than in alluvial channels not influenced by debris owing to the influence of large organic debris. Pool spacing is generally two to six times the channel width in Prairie Creek compared to five to seven channel widths for gravel-bed streams in other environments (Leopold and others, 1964; Keller and Melhorn, 1973). Spacing of pools in the upper reaches of Prairie Creek is directly related to the spacing of large organic debris. Farther downstream near Campground reach, pools may form independent of large organic debris. That is, the pools begin to develop a scour-fill pattern similar to the general case of alluvial channels, which is different from the processes that form pools as a result of organic steps.

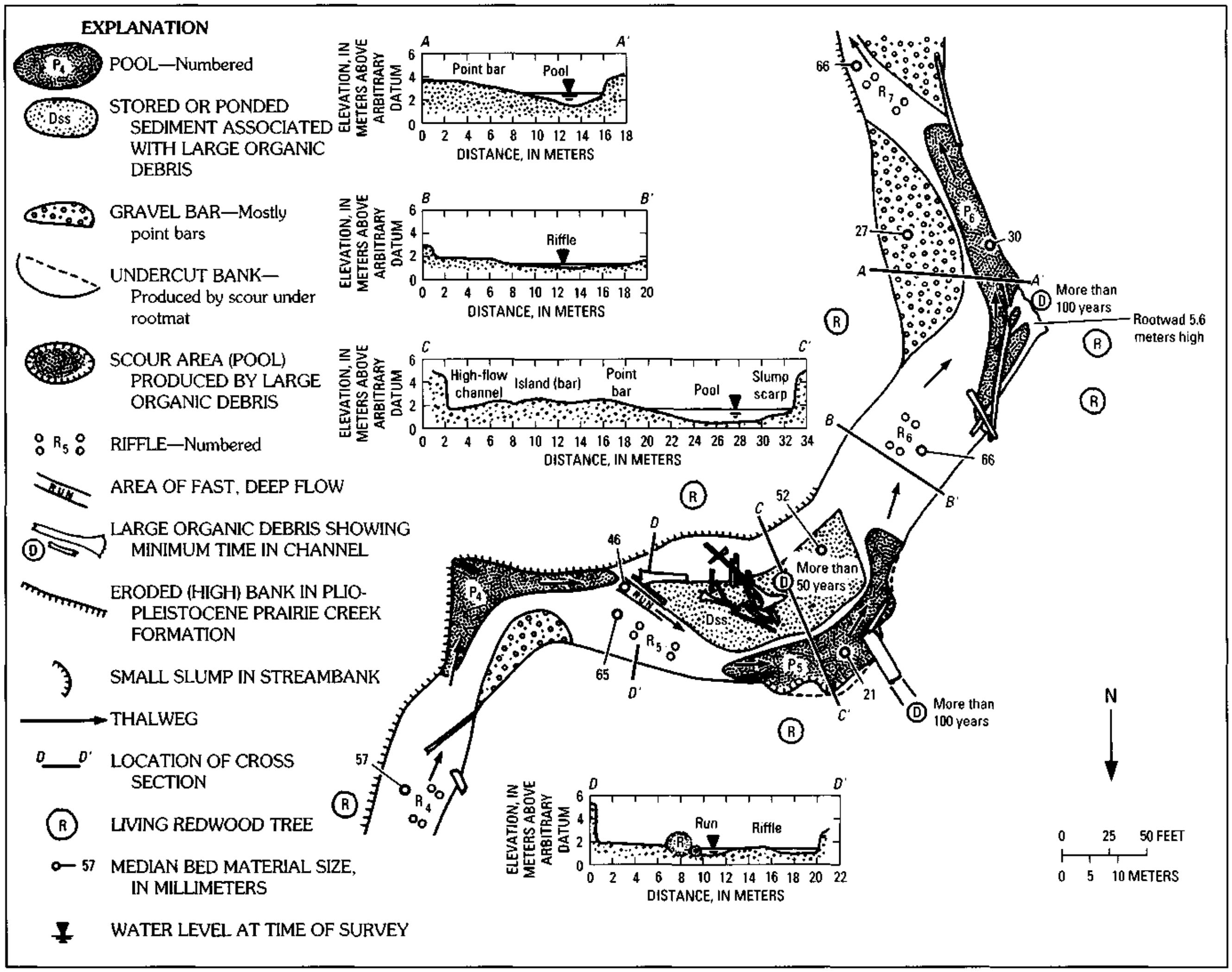

FIGURE 20.—Morphologic map of Prairie Creek, Campground reach (part), showing the pronounced effects of large organic debris on pool formation and the areal sorting of bed material, even at low levels of debris loading.

In Hayes Creek and Little Lost Man Creek, nearly all of the pools are either formed directly or significantly influenced by large organic debris. Most remaining pools are formed adjacent to bedrock outcrops or large boulders. Average spacing of pools in Little Lost Man Creek is about two times the channel width. This spacing of pools reflects spacing of large roughness elements and the fact that, in these small steep streams, organic steps are important in controlling local erosion and depositional patterns. Thus, the pool environment in Little Lost Man Creek and Hayes Creek, and the upper reaches of Prairie Creek, are characteristic of mountain streams described by Heede (1972, 1981), Swanson and Lienkaemper (1978), and Swanson (1981), whereas the pool environment in the lower part of Prairie Creek is more similar to that observed in meandering gravel-bed alluvial streams lacking significant large organic debris.

The pool environment is of particular importance to fish because the deep water, particularly in the summer, provides necessary cover and living space for young fish. Furthermore, pools that have undercut banks provide additional habitat. In Prairie Creek, some pools have undercut banks that extend several meters beneath root mats (see, for example, pool 3, fig. 3). The percent of the active channel area with undercut banks may be as high as 3 to 4 percent in some reaches of Prairie Creek, Hayes Creek, and Little Lost Man Creek (table 1). Actual percentage of channel area (at low flow) in pools varies from 12 percent in Hayes Creek to about 20 percent in Little Lost Man Creek and as high as about 50 percent in Prairie Creek. There is no clear relation between channel slope and the percentage of the active area in pool, but it is clear that, if large organic debris were not present in some of the steeper reaches, there would be considerably less pool environment.

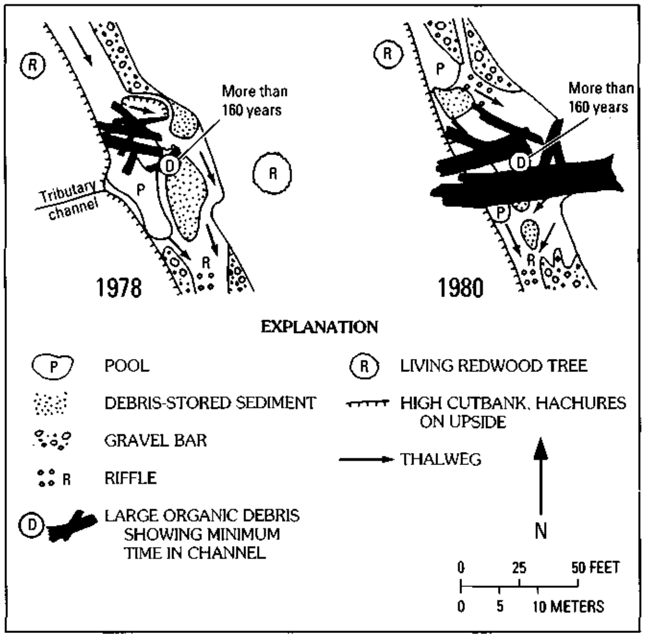

FIGURE 21.—Channel changes in part of the Brown Creek reach of Prairie Creek following the addition of a large redwood trunk.

Riffles are topographic high areas in the channel produced at channel-forming flows (bankfull flow and greater) by processes of deposition of relatively large bed material. Riffles are important to anadromous fish as spawning habitat. The intergranular flow of water is greatest at drops in the water surface profile as on riffles, providing oxygen-rich water to developing fish eggs buried in spawning gravel. In Hayes and Little Lost Man Creeks, the percentage of active channel at low flow covered by riffles varies from 15 to 26 percent. In Prairie Creek, the percentage of area covered by riffles varies from approximately 15 to almost 50 percent (table 1A).

LATERAL MIGRATION

In steep streams such as Hayes Creek and Little Lost Man Creek, there is little lateral migration of the stream channel owing to the very steep valley walls adjacent to the channel. On the other hand, one might expect that Prairie Creek, because it has a relatively low gradient with well-developed pools and riffles and numerous meander bends, would migrate laterally in its flood plain as do many meandering streams. This does not seem to be the case, however.

Lateral migration was studied by mapping the distribution of large living redwood trees near the channel. Estimates of the ages of these trees were determined by first counting the rings of large downed trees in the vicinity to determine a rough diameter-age relation for the local environment. This age relation was then used to date the living trees in the vicinity of the stream channel. The diameters and ages of three downed trees are 1.9 m, 568 years; 2.2 m, 898 years; and 2.8 m, 1,006 years. Therefore, it is conservatively estimated that living trees in the same environment with diameters of 3 to 5 m are at least 800 to 1,000 years old. Locations of these trees suggest that in several instances lateral migration of Prairie Creek has been less than one channel width in the last several hundred to 1,000 years. This apparent lateral stability does not mean that there is no change in the position of the channel with time. Meander cutoffs have occurred at some locations along Prairie Creek, but they appear to be fairly rare events. In several locations, abandoned channels were observed along Prairie Creek in areas of old-growth redwood. What may occur is that the stream periodically abandons one channel for another without a meander cutoff—that is, stream position may jump to an adjacent high water chute rather quickly, abandoning the old channel without lateral erosion. Debris jams have been shown to hasten such changes elsewhere (Keller and Swanson, 1979), and it is reasonable to assume that they could trigger sudden channel shifts in Prairie Creek as well. However, our work has not yet documented such occurrences. The strongest evidence for the lack of lateral migration is the redwood trees that grow in close proximity to the channel. When two large old-growth trees are located adjacent to both banks (see fig. 20 near sections *A-A'* and *C-C*"), then one may presume that the channel has been between the trees at least as long as the trees have been in their present location.

SEDIMENT STORAGE AND ROUTING: THE BUFFER SYSTEM

Large organic debris play a significant role in the routing and storage of sediment. Debris such as organic steps or more complex debris jams produce sediment storage compartments. Forested streams with a high debris loading may have many such compartments. Morphologic maps (figs. 3, 4, 7, 8, 9, 11, 13, and 20) show several examples of stored sediment found along Prairie Creek, Little Lost Man Creek, and Hayes Creek.

Newly formed organic steps and debris dams produce "open" sediment storage sites that collect sediment during high-flow events when bedload is transported. The storage site fills because the available stream power is less than the critical stream power necessary to transport the load at that location (fig. 22*A*). As the water flows over the organic step or accumulation, the available stream power exceeds the critical stream power, and so a plunge pool develops; immediately downstream, the available stream power may again be less than the

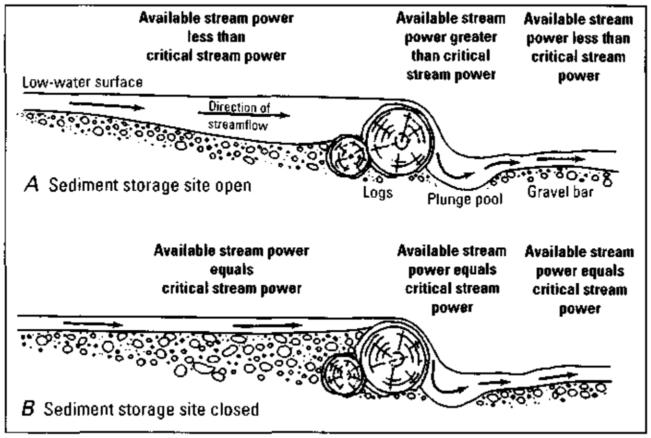

FIGURE 22.—Distribution of available (a) and critical (c) stream power over an organic step *(A)*. This distribution changes to allow substantial sediment transport over the step if the upstream storage compartment is filled *(B)*.

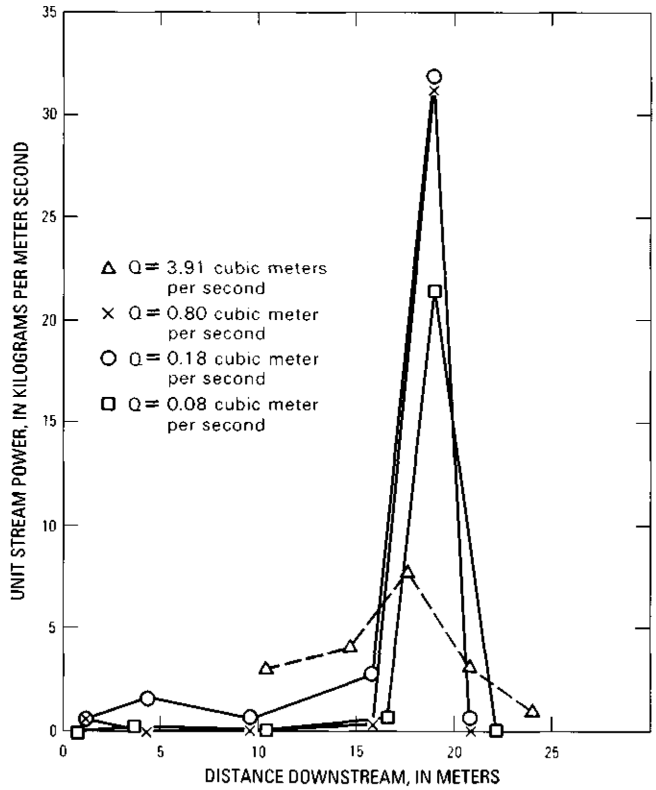

FIGURE 23.—Change in distribution of unit stream power with change in discharge over a simple organic step on Larry Damm Creek, which is 18.5 m below the head of the reach. Upstream storage compart ment is filled. Q, discharge.

critical amount, and a bar may form (fig. 22A). As the sediment storage site becomes filled, the available stream power eventually becomes equal to the critical stream power, and sediment is transported through the storage site without net deposition (fig. 22B). Thus equilibrium of action is reached, and sediment is pumped through the system. This explanation involves the utilization of the "threshold of critical power," which is based on the ratio of available to critical stream power (Bull, 1979).

The distribution of stream power over a single organic step with a filled upstream storage compartment is shown in figure 23. At the highest discharge measured in Larry Damm Creek, 95 percent of bankfull discharge, stream power was much more evenly distributed through the reach than at lower discharges, and predominantly sand-sized material was transported across the entire width of the active stream channel. The more evenly distributed stream power and pattern of sediment transport shown on figure 23 support the general model for a filled sediment storage site (fig. 22B).

Debris accumulations can reside in the channel for long periods of time, but they eventually do rot and wash out or else are removed by floods. New accumulations are periodically being formed, while others are maintained, and still others destroyed. Thus, the pattern of sediment transport through channels containing large organic debris may be complex and difficult to accurately determine (see Mosley, 1981).

An important generalization about debris-stored sediment is that the storage sites create a buffer system that modulates the movement of bed-material load through the fluvial system. As a result, the output of sediment from the watershed will be spread out over a relatively long period, even though the sediment may have been input during a short period of time. Because it will cause a lag time between input and output of sediment from the basin, the sediment buffer system has important ramifications for watersheds affected by land use changes that increase the sediment yield. If the buffer system is overwhelmed by sediment input and storage sites are filled, however, then sediment will be transported through the channel at higher rates than when the buffer system was operative.

That debris is effective in buffering high sediment input to the channel is suggested by examining the areal extent of debris-stored sediment in both disturbed and undisturbed basins. In undisturbed basins, the areal extent of debris-stored sediment increases with increase in reach slope (rank-sum correlation r=0.91, significant at the 0.0002 level). However, the mean area in debris-stored sediment is higher in channels draining disturbed basins than in those draining undisturbed basins (40 percent compared to 30 percent), suggesting that more of the potential storage is filled in basins affected by timber harvesting.

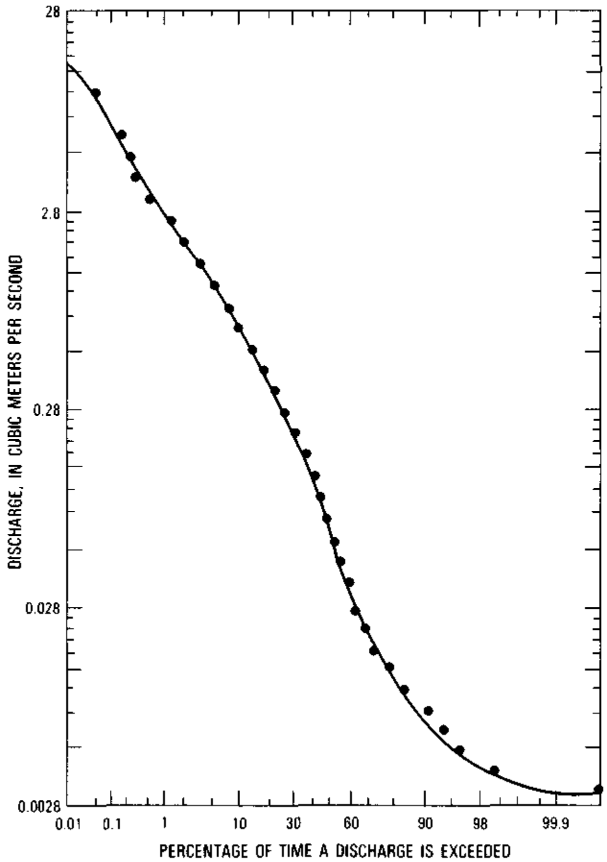

FIGURE 24.—Flow-duration curve for Little Lost Man Creek.

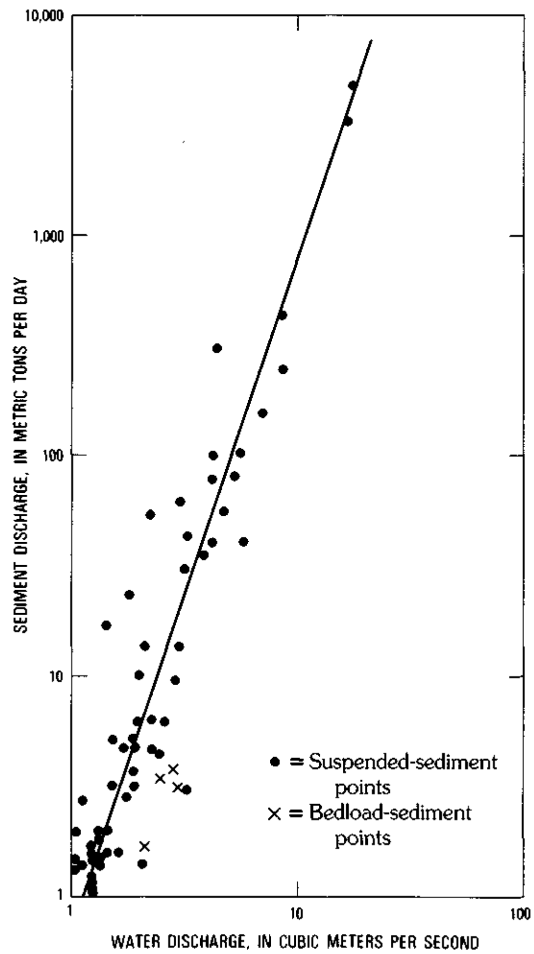

FIGURE 25.—Sediment-rating curve for Little Lost Man Creek.

The volume of the sediment buffer system for Little Lost Man Creek was evaluated by estimating the amount of debris-stored sediment in the stream channel and comparing this with the estimate of mean annual bedload transport (Tally, 1980). Several uncertainties are involved with the evaluation of the sediment buffer system, but estimates of volume are probably accurate within an order of magnitude. First, we assume that the amount of debris-stored sediment may be calculated from the observation that about 40 percent of the streambed is covered by debris-stored sediment to a depth of at least 0.35 m. This percentage for the areal extent of debris-stored sediment was observed on both study reaches on Little Lost Man Creek and for the study reach on Hayes Creek, all of which have channel slopes greater than 0.03 (see table 1). The estimate of average depth of debris-stored sediment is conservative, as many such accumulations are significantly thicker than 0.35 m, which is the depth of scour (in debris-stored sediment) observed by means of scour chains after winter storms (1978-79). A second assumption is that the annual bedload transport rate is about 25 percent of the annual rate of suspended load transported from the basin. Annual suspended sediment discharge for Little Lost Man Creek was computed by using the flow-duration curve (fig. 24) and sediment-rating curve (fig. 25), following the procedure outlined by Strand (1975). The average annual discharge of suspended sediment for water years 1975 to 1979 is approximately 50.2 (Mg/km^2)/yr, a value in close agreement with that of Nolan and Janda (1981), who determined that annual suspended sediment yield for Little Lost Man Creek was approximately 52 (Mg/km^2)/yr for water years 1973 to 1976. Only six measurements of bedload were made during the 5 years of available stream-gage data. The bedload yields range from 6 to 58 percent of the suspended load with an average of 25 percent. Thus, we assume that the bedload is approximately 25 percent of the suspended load, or approximately 13 (Mg/km^2)/yr. The unit weight of debris-stored sediment, which consists mostly of gravel and sand, is assumed to range from 1.36 to 2.00 Mg/m^3, values recommended by Geiger (1965) for these types of materials.

TABLE 5.—*Kruskal-Wallis one-way analysis of variance for pebble-count data from Little Lost Man Creek* [From Tally, 1980]

Environments tested Size fraction		*pHo* > chi-square	Ho[1]
Upper reach			
Pools, riffles, debris-stored sediment, bars . .	D_{10}	$p=0.28$	A
....Do....	D_{50}	$p<0.01$	R
....Do....	D_{90}	$p<0.002$	R
Lower reach			
Pools, riffles, debris-stored sediment.......	D_{10}	$p<0.01$	R
....Do....	D_{50}	$p<0.002$	R
....Do....	D_{90}	$p \ll 0.001$	R

[1]Ho=null hypothesis of no significant difference between the samples. A=accepted. R=rejected.

The average annual suspended sediment yield for Little Lost Man Creek drainage basin is about 450 Mg, and the bedload yield is about 25 percent of this, providing an annual bedload yield of approximately 113 Mg. The total available debris-related sediment volume in Little Lost Man Creek is estimated from field observation to be approximately 14,000 m^3 (19,000-28,000 Mg), and approximately 64 percent, or 8,960 m^3 (12,000-18,000 Mg), of this volume if presently full (Tally, 1980). Using the above assumptions, approximately 100 to 150 years of average bedload sediment yield is stored in debris-related sites along Little Lost Man Creek, and about 50 to 100 years of average bedload yield is available for future storage. Thus, if the storage system was filled to capacity, it would contain a volume equivalent to 150 to 250 years of average annual bedload. These estimations should not be interpreted to mean, however, that the sediment storage compartments associated with large organic debris effectively trap all of the bedload that moves into a particular reach.

Debris-stored sediment tends to be significantly finer than that found on riffles on Little Lost Man Creek. Tables 5 and 6 summarize the results from statistical analysis of pebble-count data for the upper and lower study reaches of Little Lost Man Creek (Tally, 1980). These data suggest that, for both the D_{50} and D_{90} particle sizes, there are significant differences between the materials found on riffles and those found associated with debris-stored sediment. Furthermore, the differences between the size of bed material in pools and in debris-stored sediment is generally not significant; this is expected, because both debris and pools tend to trap finer sediment during similar flow events. Because debris-stored sediment tends to be finer, it is transported more frequently in response to moderate flow. On the other hand, coarse material on riffles tends to armor the bed and is probably moved only during more extreme events. For example, the threshold for bedload transport of the D_{90} fraction of debris-stored sediment past the

TABLE 6.—*Mann-Whitney U-test for pebble counts from Little Lost Man Creek*
[From Tally, 1980]

Environment tested	Size fraction	*p*Ho will occur two-tailed	Ho[1]
Upper reach			
Riffles vs. pools	D_{50}	<0.10	A
Debris-stored sediment vs. pools	D_{50}	>>0.10	A
Bars vs. pools	D_{50}	>>0.10	A
Debris-stored sediment vs. riffles	D_{50}	=0.02	R
Bars vs. riffles	D_{50}	>0.10	A
Debris-stored sediment vs. bars	D_{50}	=0.328	A
Riffles vs. pools	D_{90}	>0.10	A
Debris-stored sediment vs. pools	D_{90}	<0.02	R
Bars vs. pools	D_{90}	<<0.05	R
Debris-stored sediment vs. riffles	D_{90}	<0.02	R
Bars vs. riffles	D_{90}	<<0.02	R
Debris-stored sediment vs. bars	D_{90}	=0.838	A
Lower reach			
Pools vs. riffles	D_{10}	<<0.02	R
Pools vs. debris-stored sediment.........	D_{10}	>>0.10	A
Debris-stored sediment vs. riffles	D_{10}	<0.05	R
Pools vs. riffles	D_{50}	<0.02	R
Pools vs. debris-stored sediment.........	D_{50}	>0.10	A
Debris-stored sediment vs. riffles	D_{50}	<<0.002	R
Pools vs. riffles	D_{90}	<0.02	R
Pools vs. debris-stored sediment.........	D_{90}	<<0.05	R
Debris-stored sediment vs. riffles	D_{90}	<0.002	R

[1] A=Accepted; R=rejected.
Ho=null hypothesis of no significant difference between two environments.
[2] D_{10}'s for Little Lost Man Creek, Upper, not tested, as no significant difference was found between environments under Kruskal-Wallis analysis. (See table 5.)

Little Lost Man Creek gaging station during the 1978 water year was 30 percent of bankfull discharge, a flow equaled or exceeded 3 percent of the time (Tally, 1980). When debris-stored sediment is mobilized, it probably moves from one storage site to another, as observed by Mosley (1981).

RELATION OF LARGE ORGANIC DEBRIS TO THE MANAGEMENT OF ANADROMOUS FISH HABITAT

In the management of streams to maximize production of anadromous fish in the coastal redwood environment, the role of large organic debris in the entire fluvial system should be considered. The recommendations that follow are based upon observations made in the Redwood Creek basin. Occasionally, large organic debris may block fish migration and cause adverse channel erosion. Such accumulations (especially when delivered to the stream channel in response to land use change) should be removed following the development of a specific plan for that site. However, within limits, large organic debris are necessary for a biologically productive stream environment (Swanson and others, 1976). Therefore, in clearing operations, the benefits of locally stabilizing stream-

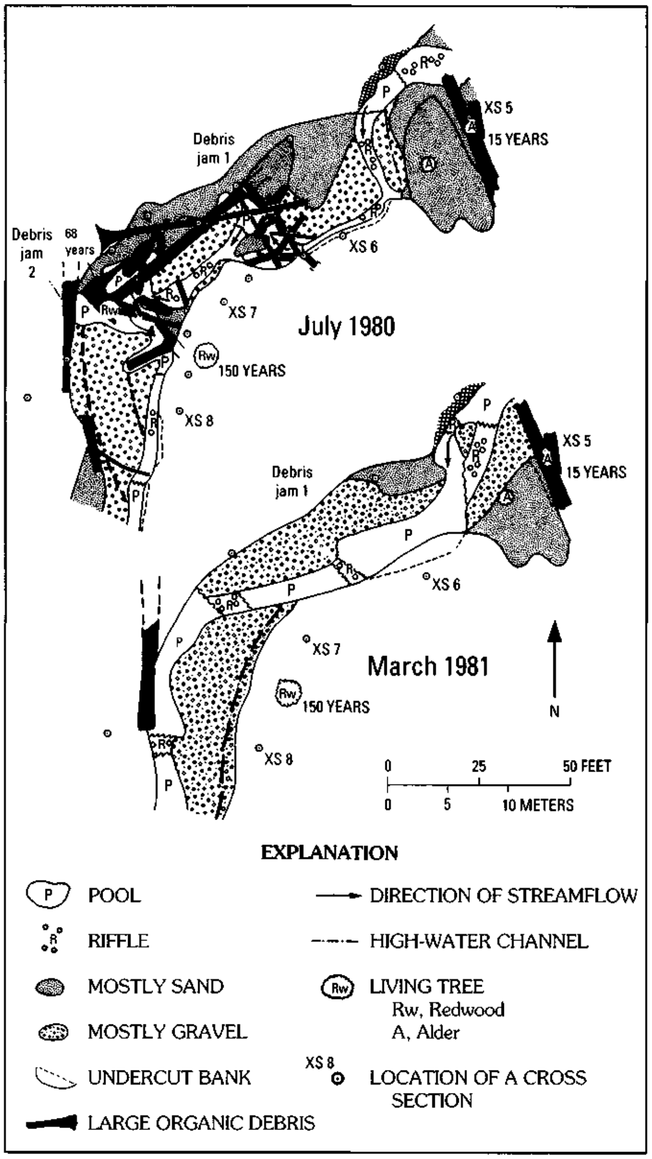

FIGURE 26.—Morphologic maps of the upstream portion of Larry Damm Creek before and after debris removal.

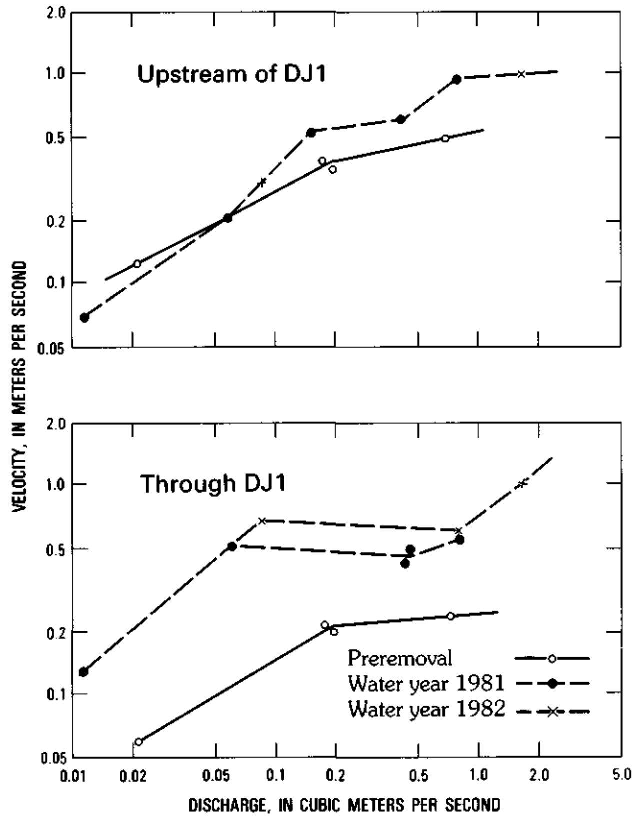

FIGURE 27. —Mean water velocity versus discharge for the reach above and through debris jam (DJ) no. 1, Larry Damm Creek, before and after debris removal. Maps of this reach are shown in figure 26.

banks, opening up anadromous fish habitat, or marketing merchantable timber must be considered in relation to the potential dangers of losing variability in habitat and mobilizing large quantities of bed material stored by large organic debris.

It is probably best to leave large organic debris that falls into the stream channel in watersheds having old-growth forest. Debris probably helps to create fish habitat by providing cover and also pool environments for juvenile anadromous fish. In addition, debris jams often create extensive backwaters at higher flows. Such low-energy habitat is necessary for overwinter survival of fish. An example of such habitat is shown in figure 26, maps of a portion of Larry Damm Creek. Although both debris jams shown on the maps create backwaters at high flows, the upstream jam (debris jam no. 1) created the larger and more persistent backwater. Mean water velocity both above and through the jam is shown in figure 27 for discharges ranging from less than 1 to 20 percent of bankfull. The jam significantly reduced water velocity from cross section no. 5 (XS5, fig. 26) through the debris jam at discharges greater than 5 percent of bankfull discharge. After the removal of all woody debris greater than 10 cm in diameter from the channel in this location, this backwater was no longer present.

Management of large organic debris in streams affected by timber harvesting should consider two potential problems: (1) loading of large organic debris after logging may increase due to the introduction of slash into the channel and (2) the long-term budget of large organic debris is changed when a forest is cut. Removal of large logs and slash introduced by logging may be necessary. Such removal should involve only logs derived from the logging; large organic debris present in the channel prior to logging and contributing to habitat should not be removed. Overzealous removal of large organic debris will result in unnecessary damage to the aquatic ecosystem. Mitigating the effects of changing the long-term large-organic-debris budget is difficult because the size of debris delivered to the channel from second-growth timber will be relatively small until about 100 years after logging ceases. Two aspects of large organic debris are pertinent to the budget problem: (1) it is the distribution of large organic debris rather than total debris loading that determines the quality of habitat and (2) large organic debris existing in the channel prior to logging may continue to reside there for several hundred years. Therefore, management plans for utilizing and enhancing "habitat-producing" large organic debris present in the channel prior to logging are advisable. By enhancement we mean increasing or decreasing the total large-organic-debris loading, or the spacing of debris, to maximize the quality and residence time of habitats such as pools produced by large organic debris. Such plans should strive to duplicate as much as possible natural occurrences in undisturbed basins. This "design-with-nature" approach recognizes that the natural fluvial system has evolved over hundreds and thousands of years in response to the presence of large organic debris. The more we learn about large organic debris, the more we recognize that it is intimately related to the fish habitat and thus to the production of anadromous fish. In many subtle ways the debris is interacting in positive ways to produce and maintain desired fish habitat. Therefore, a conservative practice concerning its removal should be adopted.

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