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Effects of coarse woody debris and its removal on a channel affected by the 1980 eruption of Mount St. Helens, Washington

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Abstract. During the May 18, 1980, eruption of Mount St. Helens, Washington, a pyroclastic surge introduced large volumes of coarse woody debris (CWD) and fine grained sediment to Clearwater Creek, approximately 15 km northeast of the summit. Effects of controlled CWD removal on sediment storage, substrate, and pool frequency and volume were measured in four reaches, each with three 200-m segments, from 1982 to 1990. In each reach the upstream segment served as a control with no debris removal, and CWD was totally and selectively removed from the other two segments. Unique among similar experiments are the large size and volume of CWD and the large inputs of fine grained sediment. Except for segments of two reaches that received debris torrents, the Clearwater channel thalweg scoured until 1985. In three reaches, total debris removal caused additional scour and coarsening of the bed surface compared to segments with no or partial debris removal. Pools contracted from 1982 to 1985 and expanded afterward, especially in control segments. Total debris removal apparently caused pools to become shallower and, in segments of low sinuosity, decreased the frequency of major pools. Habitat complexity decreased after total debris removal, as indicated by a decrease in the standard deviation of residual depth and an increase in the size of substrate patches.

Introduction

Coarse woody debris (CWD) whose diameter (>10 cm) and length equal substantial fractions of water depth and channel width can have profound effects on channel morphology, flow, and sediment transport in forest stream channels [*Swanson et al.,* 1976; *Keller and Swanson,* 1979; *Mosley,* 1981; *Lisle,* 1986a; *Nakamura and Swanson,* 1993]. Forest, fisheries, and waterway managers are commonly concerned about CWD in streams because land use practices and natural disturbances such as fire, wind storms, floods, and mass movement commonly cause great and long-lasting changes in the volume and distribution of CWD in watersheds [*Bisson et al.,* 1987; *Sedell et al.,* 1988].

From an ecological standpoint, CWD can add considerable heterogeneity to physical habitats and store nutrients for food webs of aquatic and riparian ecosystems [*Harmon et al.,* 1986; *Bisson et al.,* 1987; *Sedell et al.,* 1988]. I define habitat heterogeneity here as the spatial variability of physical factors and combinations of factors that are available to an organism or community of organisms. *Jungwirth et al.,* [1993] quantify habitat heterogeneity in a stream by the variance of thalweg depth and show highly significant correlations with the number and diversity of fish species. The contribution of CWD to habitat complexity has not been quantified, however.

Although the morphological effects of individual pieces can be related to their size, shape, orientation, and position [*Keller and Swanson,* 1979; *Beschta,*1983], *the* myriad of combinations of CWD and channel characteristics and overlapping influences of individual elements are apt to defeat attempts to evaluate or predict the effect of adding or removing CWD. Many of the effects of CWD on channel processes can be counteractive, depending on the density, size, and orientation of debris; characteristics of the channel; and the scale at which CWD effects are observed. For example, flow concentration around CWD elements can locally scour the bed, but the overall greater flow resistance in channels with CWD can also promote deposition over a wider area.

Experimental manipulation of CWD in natural channels is a feasible approach to evaluating effects of populations of CWD elements and predicting channel response to changes in CWD. Assuming that the range of characteristics of individual pieces and conglomerations of CWD is represented in experimental reaches, the problem becomes focused on how CWD of different sizes and volumes affects channels of different characteristics and conditions. Results of previous debris removal experiments in a variety of channels [*Beschta,*1979*; Bilby,*1984*; Heede,* 1985; *Lisle,* 1986a; *Smith et al.,* 1993a, b] have not been altogether consistent, particularly for effects on pools, and not all combinations of characteristics of CWD and associated changes in water discharge and sediment supply have been investigated. An important missing combination has been where large volumes of CWD and sediment have been introduced together.

The eruption of Mount St. Helens, Washington, on May 18, 1980, created a grand natural experiment on the effects of CWD on geomorphic processes. Early in the eruption, a pyroclastic surge blew down large conifers in a rugged terrane of over 500 km^2 (Figure 1) and, along with associated and later tephra deposition, introduced large volumes of fine sand and coarser pumice and minor volumes of gravel to hillslopes and stream channels [*Lehre et al.,* 1983; Smith, 1987; *Meyer and Martinson*, 1989]. Many low-order channels were initially inundated by sandy deposits of debris flows and hyperconcentrated flows. In the following one to two wet seasons after the eruption, large volumes of predominantly fine sediment (fine gravel, sand, and finer material) were eroded from hillslopes and low-order channels and transported to major rivers, al-

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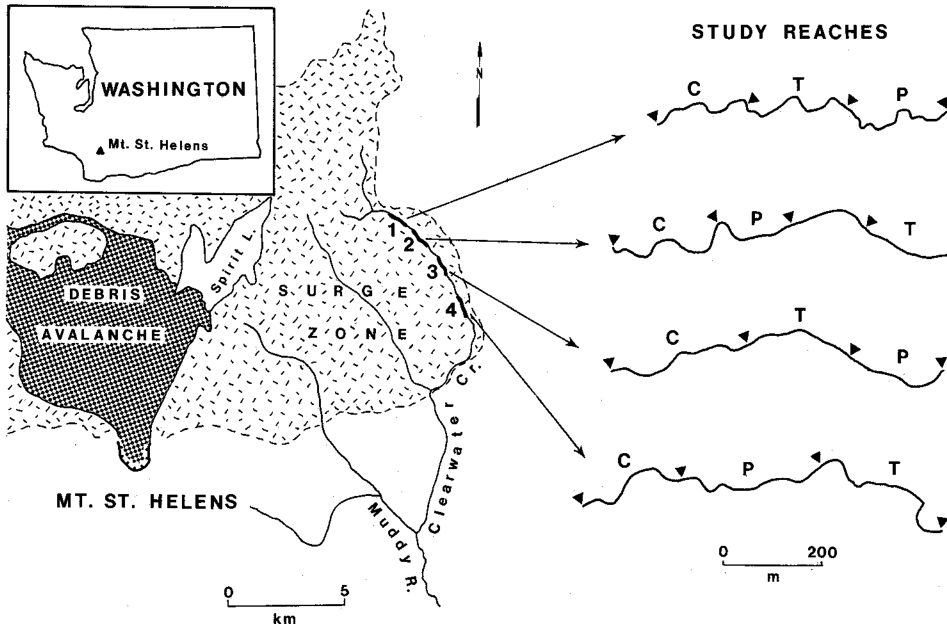

Figure 1. Clearwater Creek and the study reaches. Segments are denoted by "C" for control, "P" for partial removal, and "T" for total removal.

though important volumes were stored for longer periods around CWD and in low-gradient reaches in tributaries [*Lehre et al*., 1983*; Smith*, 1987*; Meyer and Martinson,* 1989]. Since 1982, accelerated shallow landsliding has introduced coarser sediment to channels along steep hillslopes [*Meyer and Martinson*, 1989].

Land management agencies were concerned about the effects of large inputs of CWD on channel stability, salmonid habitat, and storage of fine-grained sediment. Large concentrations of sand and finer material can greatly affect fish and benthic invertebrates that inhabit gravel bed streams [*Cordone and Kelley*, 1961*; Hicks et al.,* 1991].

The motive for the research reported herein was to increase basic knowledge of the physical role of CWD in stream channels and its ecological consequences and to provide information to improve riparian management strategies. I describe physical responses to experimental CWD removal from four reaches of a stream channel in the blowdown area over the first decade after the eruption of Mount St. Helens. I report changes in bed elevation, channel morphology, pool depth and frequency, and bed particle size and briefly discuss consequences to the physical habitats of stream organisms. Two features make this study unique among debris removal experiments: The first is the great size and volume of CWD. In many reaches, nearly all large trees, many of which had diameters greater than 1 m and lengths greater than 60 m, were toppled directly into the channel. The second is the great volume of fine-grained sediment. For example, 2400 t km^{-2} were delivered to Clearwater Creek from one tributary in the first year after the eruption [*Smith*, 1987].

Study Site

Clearwater Creek lies approximately 15 km northeast of Mount St. Helens and just within the area affected by the May 18, 1980, pyroclastic surge (Figure 1). Its valley has a broad bottom and steep side slopes and, since Pleistocene glaciation, has been partly filled by alluvial fans that originate in steep tributaries. The surge toppled streamside trees generally across the channel from river-right to left (southeast to northwest) (Figure 2). However, intervening peaks along the western valley rim shielded some of the valley from the direct force of the surge and locally channeled the surge downvalley and upvalley. As a result, the pattern of blown down trees was complex, and trees along some channel reaches were killed but left standing. *Hawkins and Sedell* [1990] describe ecological effects of the 1980 eruption on Clearwater Creek.

Four reaches of Clearwater Creek, each containing three segments of 200 m or longer, were chosen for experimentation (Figure 1). All reaches have predominantly single-thread, sinuous channels with alluvial beds and banks. Mean bank-full channel width for each reach ranges from 15 to 25 m, bank-full depth averages about 1 m, and channel gradient ranges from 0.0047 (reach 3) to 0.0088 (reach 4) (Table 1). Since the eruption, riffles have been paved with gravel and cobbles, but many lower gradient areas have remained covered with sand, pumice, and fine-to-medium gravel.

Methods

In each study reach the upstream segment served as a con trol where no CWD was removed, and different portions of CWD were removed from two downstream segments. All CWD was removed from the "total removal" segment; all recoverable merchantable CWD (pieces that were not embedded in the channel and had diameters greater than about 0.3 m and lengths greater than about 3 m) was removed from the "partial removal" segment. Partial removal was meant to replicate current practices of salvaging merchantable timber from extensive blowdowns in riparian areas. We measured CWD volumes within the active channel in summer 1982 (before debris was removed during the following fall) and again in 1990. Reappearing debris was removed from "total removal" segments of reaches 1-3 in summer 1984. We first measured

reach 4 in September 1984, soon after CWD was removed and before any major channel response. More CWD was removed from reach 4 in 1985.

My coworkers and I surveyed cross sections and longitudinal thalweg profiles of the bed and water surface in each reach annually from 1982 to 1987 and in 1990 to document erosion and aggradation of the channel and to measure changes in channel morphology. We also established some cross sections in reaches 1 and 4 in summer 1981, before this study began. In each reach we established some cross sections in local debris free zones in order to measure channel response to changing sediment loads without the confounding influences of CWD. In all reaches these cross sections showed the same patterns of erosion and aggradation as corresponding longitudinal pro files, and so will not be presented.

In all years but 1982 we recorded lengths of the thalweg covered by fine bed load material consisting of sand and fine, pumiceous gravel (mostly produced by the 1980 eruption), which I refer to hereafter as "fine sediment." The remainder of the bed surface was coarser nonpumiceous gravel (mostly present before the 1980 eruption).

Table 1. Drainage Areas and Mean Hydraulic Variables of the Four Experimental Reaches of Clearwater Creek

	Drainage Area, km^2	Channel Gradient	Bank-Full Width, m	Bank-Full Depth, m
Reach 1	9.3	0.0085	14.6	0.97
Reach 2	9.7	0.0073	17.7	1.02
Reach 3	21.5	0.0047	18.6	1.14
Reach 4	32.7	0.0088	25.2	1.16

Results

Coarse Woody Debris Volume

Coarse woody debris was abundant in Clearwater Creek after the 1980 eruption. The volume of CWD per channel area before experimental removal in 1982 ranged from 280 to 650 m^3 ha^{-1}, which is within the higher range of values reported for other stream channels of similar width in old growth, Dou glas fir dominated forests in the Oregon Cascades (Table 2). Volumes in the control segments of reaches 3 and 4 (950-990 m^3 ha^{-1}) exceeded this range in 1990 when CWD was remea sured.

Volumes of CWD changed widely in many reaches between 1982 or 1984 (before debris removal) and 1990. Total removal of CWD resulted in very low volumes (2–95 m^3 ha^{-1}), which included pieces that were too deeply buried to remove. CWD volumes in control segments showed no change (reach 2), a threefold increase (reach 3), and a 45% decrease (reach 1) due to a debris torrent, which will be described later. In partial removal segments, CWD volumes actually increased to values that were approximately 40% greater in 1990 (420–730 m^3 ha^{-1}) than before removal (340-480 m^3 ha^{-1}). Large varia tions in CWD in control segments and increases in partial

Table 2. - Volumes of Coarse Woody Debris

	Coarse Woody Debris Volume per Channel Area, m^3 ha^{-1}	
	1982 (Preremoval)	1990 (Postremoval)
Clearwater Creek		
Reach 1		
Control	400	220
Total removal	290	2
Partial removal	480	730
Reach 2		
Control	650	660
Total removal	320	30
Partial removal	380	520
Reach 3		
Control	320	950
Total removal	280	95
Partial removal	340	420
Reach 4		
Control	…	990
Total removal	…	28
Partial removal	…	480

	Coarse Woody Debris Volume, m^3 ha^{-1}
West Slope Cascades, Oregon [a]	
Channel width 10-15 m (n = 3)	570-700
Channel width 15-20 m (n = 3)	150-880
Channel width >20 m (n = 2)	60-230

[a]Channels in old growth Douglas fir forests, west slope Cascade Range, Oregon [*Harmon et al.,* 1986].

removal segments are likely due to large introductions from standing dead trees falling into the channel, exhumation of buried debris by channel scour, and transport during high flow.

Aggradation and Erosion of Channels

As in similar channels affected by the surge [*Lehre et al.,* 1983; *Lisle et al.,* 1983; *Meyer and Martinson,* 1989], the supply of fine sediment in Clearwater Creek declined in the first decade after the eruption. I visited reach 4 in the summers of 1980 and 1981 and reach 1 in 1981, before the experiment began. I observed sandy material aggrading the channel during the first months after the eruption and being partially flushed during the following wet seasons, exposing a coarse pavement particularly over riffles. During moderate discharges in June 1982, sand and fine pumiceous gravel covered most of the bed and moved as dunes. When I observed the channel at lower flows in later years, there was no bed load transport, and more coarse gravel was exposed on riffles.

Although we applied uniform treatment prescriptions to each set of segments, they responded differently because of variations in channel size and form, initial eruption effects, and subsequent geomorphic processes. These variations are described below.

Reach 1. The pyroclastic surge toppled all large trees along the channel. In 1981, incision into thick deposits and discontinuous paving of the streambed indicated that much of the postetuption sediment delivered to the channel had been redistributed or eroded from the reach during the following year. Cross sections surveyed in the control segment in 1981 and 1982 showed local scour or fill of as much as several decimeters but no overall trends (F. Swanson et al., unpublished data, 1983). I observed transport of sandy bed load. during low flow (0.4 m^3 s^{-1}) as late as August 1981, but by the beginning of the experiment in summer 1982, low-flow transport had ceased, and cobbles were exposed on bars and riffles and in deeply scoured thalwegs of pools, particularly around CWD. CWD was distributed haphazardly as it fell into the channel. Deep local scour and deposition were commonly associated with large pieces or agglomerations that deflected a large portion of the flow. In some cases, CWD appeared to control the positions of bars and pools.

In the first year following debris removal (1983), all segments scoured slightly (Figure 3). During the subsequent winter (1983-1984) a debris torrent bearing large volumes of sediment and CWD inundated the upstream (control) segment and resulted in the following sequence of changes:

1. A matrix of CWD apparently formed the front of the flow and stopped 160 m downstream from the beginning of the

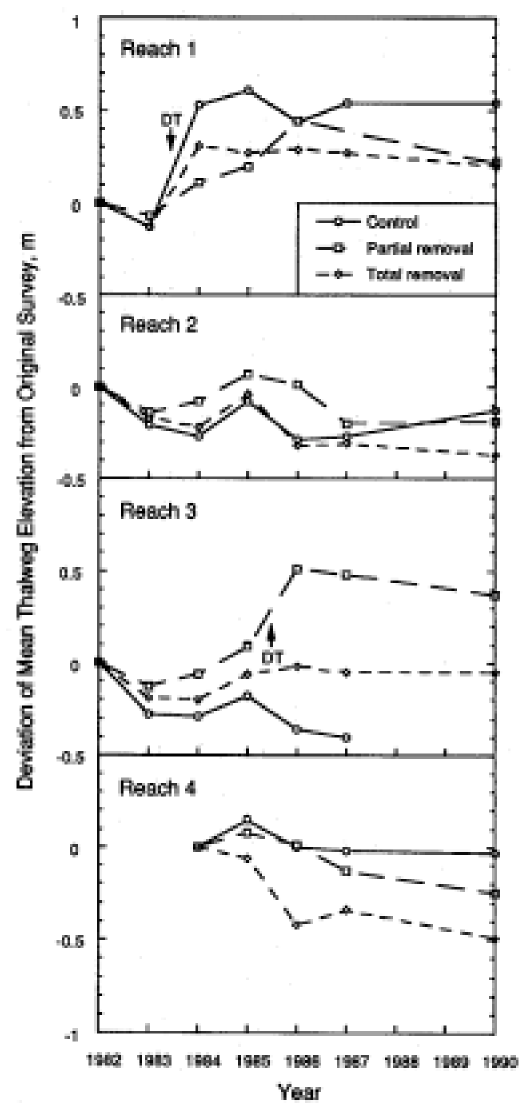

Figure 3. Changes in mean thalweg elevation. "DT" marks occurrence of debris torrents in the control segment of reach 1 and at the bottom of the partial removal segment of reach 3. Debris was removed after measurements in 1982.

control segment, where it formed a 3-m-high debris jam and a major step in the channel profile. The torrent reduced CWD volume in the channel upstream of the jam.

2. Relatively well sorted medium-to-coarse gravel and sand were deposited during the final phase of the torrent, mostly in the control segment upstream of the terminus. Here, CWD was rearranged, and the channel course was altered. Large bars were deposited as high as the former floodplain.

3. These gravelly deposits were soon incised, and smaller bars formed within the incised channel before our visit in summer 1984.

4. Bed elevations remained approximately 0.5 m higher than the original throughout the remainder of the study, apparently because of damming by the debris jam. In 1985, willows became established in narrow corridors along the active bed margin about 0.3 m above the low-flow water surface. Willows grew largest around CWD and were absent on gently sloping bar surfaces.

Although most of the gravelly sediment that passed through the debris torrent terminus was deposited within the control segment, some was deposited as far as 400 m downstream of the terminus. With reduced CWD and increased gravelly sediment in the treatment segments, a pronounced sequence of bars and pools formed in preexisting meanders. From 1984 to 1990, bank-full channel width increased by 2 m, on average, but changes in channel morphology and bed elevation were minor.

Because the control segment was altered by the torrent more than the treatment reaches, and partial removal had little apparent effect on channel morphology and bed material in all reaches, I use the partial removal segment of reach 1 as the control in some evaluations of effects of total removal.

Reach 2. Reach 2 was somewhat sheltered from the blast, and more trees were left standing than along reach 1. Nevertheless, CWD was abundant in the channel and included many small limbs. Recent sandy alluvium was deposited as high as 0.5 m above bank-full elevation. Reach 2 was less sinuous than reach 1, and bars in reach 2 were poorly defined.

All segments eroded at the beginning of the experiment, aggraded in 1985, and then eroded again (Figure 3). The total removal section showed net aggradation of 0.5 m by 1990. In the control and partial removal segments, abundant CWD maintained frequent steps in the profile and may have impeded formation of well-defined bars. By 1990 the bed consisted of patches of sand and fine, pumiceous gravel and weakly formed pavements of coarser gravel. Willows grew thickly in narrow corridors near low-flow channel margins. Cross sections not influenced by CWD showed no change in channel width from 1982 to 1990.

Reach 3. Reach 3 resembled reach 2. The slightly sinuous channel contained frequent CWD that was positioned as it had fallen into the channel. Scour around CWD extended no more than several stem diameters longitudinally, and only jams were large enough to form major pools that spanned most of the channel. The bed was similarly fine-grained. Bars formed in bends and behind CWD in the control segment, and lower alternate bars formed in segments with CWD removed.

All segments eroded initially, but a backwater imposed by a debris torrent dam complicated the response to debris removal. The control segment eroded approximately 0.4 m from 1982 to 1987 (Figure 3). The debris torrent entered the downstream end of the reach (partial removal segment) from a right bank tributary during the rainy season of 1985-1986 and created a bouldery deposit that elevated the local base level approximately 1.5 m. A wedge of fine-grained sediment was deposited upstream through the partial removal segment and halfway into the total removal segment. As a result the partial removal segment aggraded 0.4 m in 1986, and subsequently degraded by 0.1 m; the total removal segment aggraded slightly in 1987 and remained stable thereafter. As in reach 2, none of the cross sections showed widening unless they were influenced by the wedge of sediment.

Reach 4. Compared to the upstream reaches, reach 4 was wide and steep (Table 1) and contained large bars and bends. Reach 4 was shielded from the direct force of the surge, and most riparian trees were killed but not immediately toppled. Nevertheless, CWD was plentiful in the channel, and a greater fraction accumulated in jams than in the reaches upstream. CWD influenced thalweg courses, caused local scour and deposition, and created temporary diversions that promoted braid ing in some sections. However, most steps in the profile were created by cobbly riffles. Fine sediment was not as pervasive in reach 4 as in study reaches upstream. Although pools were partly filled with fine sediment throughout the experiment, cobbly pavements were widespread.

We did not survey treated segments until 1984, just before CWD was first removed, but had surveyed a reach that included part of the control segment in 1980 and 1981. Six cross sections in this reach, including two in the control segment, showed minor erosion from 1980 to 1984 (T. Lisle, unpublished data, 1984).

CWD was removed from both treated segments in 1984, and more was removed from the total removal segment in 1985. The control segment showed no significant change from 1984 to 1990, while the partial removal segment eroded 0.2 m and the total removal segment eroded 0.5 m (Figure 3). After CWD was removed from the total removal segment, channel bends replaced a complex series of scour holes, sandy deposits, and distributary channels that were created by CWD. Point bars were formed, outside banks eroded, and large pools scoured along the outside bank of bends. Willows became established near the low-flow channel margins.

In summary, control segments that were unaffected by debris torrents indicated background channel erosion of approximately 0.3 m by 1985 and relative stability afterward. Changes in channel morphology and channel width were minor except in reach 1, which was aggraded and widened by a debris torrent. Total removal of CWD apparently caused additional thalweg erosion of 0.3 to 0.5 m.

Bed-Surface Particle Size

The percent of the thalweg bed surface covered with fine sediment (sand and fine pumiceous gravel) showed wide annual variations (Figure 4). Reach 4, which had a high gradient considering its downstreammost position (Table 1), contained the smallest overall percentage of fine sediment. Percentages in control segments, which represent background conditions, fluctuated widely and inconsistently.

Reaches 2 and 4, which did not receive debris torrents, provided the best case histories of the effects of CWD and its removal on fine sediment abundance. Fine sediment coverage in the total removal segments (as well as the partial removal segment of reach 4) decreased after about 1985 and remained relatively low afterward.

Debris torrents affected fine sediment abundance in reaches 1 and 3. The torrent entering reach 1 in winter 1983-1984 apparently coarsened the bed surface upstream of its terminus

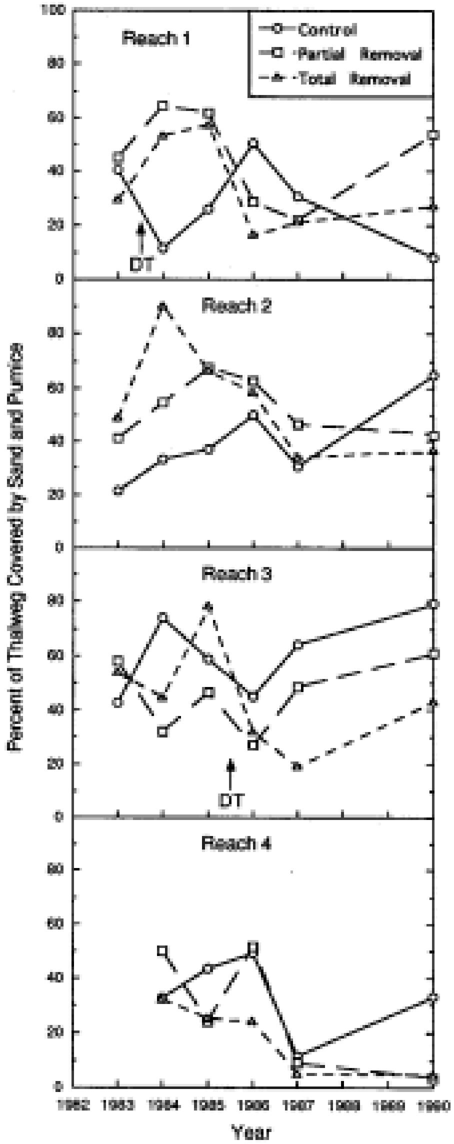

Figure 4. Changes in the percent of the thalweg bed surface covered with sand and pumice. "DT" marks occurrence of debris torrents in the control segment of reach 1 and at the bottom of the partial removal segment of reach 3.

in the control segment, but more fine sediment was deposited in the treated segments downstream. In 1985 and 1986, fine sediment accumulated in the control segment, now depleted of much of its CWD, and was scoured from the treated segments, particularly the total removal segment. Fine sediment in the control segment decreased in subsequent years. In reach 3, damming of the downstream end by a debris torrent in winter 1985-1986 induced fine sediment deposition the following year in the partial removal segment just upstream. The depositional wedge may have induced bed surface fining in the total removal segment as well.

Considering all of the reaches together and taking into account the effects of debris torrents, I conclude that total removal of CWD caused increased erosion of mobile sand and pumice from the bed surface and exposure of approximately 40% more of the coarse, preeruption substrate. However, the lack of pretreatment data in reaches 1, 2, and 3 obscures the effects of treatment.

Pools

I evaluated changes in the frequency, length, and depth of channel depressions (pools and smaller scour holes) from measurements of residual depth taken every meter along the longitudinal thalweg profiles. Residual depth is the difference in elevation between a point in the channel and the highest thalweg elevation downstream, provided it is higher than the point [*Bathurst,* 1981; *Lisle,* 1986a]. Otherwise, residual depth is zero. In a pool-riffle sequence, for example, residual depth in a pool is the depth below the elevation of the downstream riffle crest.

I suspected CWD to affect channel depressions differently at different scales, because any piece of CWD near the bed tends to deflect the flow and create some depression, while major pools are commonly associated with larger features such as channel bends. Consequently, I measured the frequency of two classes of depression: (1) major pools, in which maximum residual thalweg depth [$(d_r)_{max}$.] is greater than 0.5 m (about one half of bank-full depth) and (2) all pools and scour holes, in which $(d_r)_{max}$. > 0.1 m. From field observations I chose this criterion to distinguish major pools, whose formative hydraulic conditions affect the entire width of the active streambed, from smaller pools or scour holes [*Lisle,* 1986b]. The classification of major pools seems to be consistent with previous studies. Major pool spacing averaged 4.2 (s.d. = 3.0) times the mean channel width of each segment, which is not substantially different from the mean value (5.2) for a variety of natural pool-riffle channels [*Keller and Melhorn,* 1978]. When I counted all pools and scour holes, average pool spacing decreased to 1.1 channel widths (s.d. = 0.24).

Changes in pool frequency showed few strong trends. In many segments, including control segments, major pool frequency was lowest, and the frequency of all pools and scour holes was highest, between 1983 and 1986 (Figures 5a and 5b). This finding suggests that during this period some major pools were filled enough to become classified in the shallower category but did not disappear altogether. By the end of measurements, major pool frequency again equaled maximum values in control segments of reaches 1, 2, and 4. It remained low in total removal segments of reaches 2 and 3, which can be distinguished from the other total removal segments in having lower sinuosity and fewer bends (Figure 1). Sinuosities of total removal segments of reaches 1-4 are 1.22, 1.04, 1.02, and 1.27, respectively. I will discuss the role of sinuosity in pool formation later.

Total pool length, defined as the percent thalweg length with $(d_r)_{max}$ > 0.1 m, declined in nearly all segments from 1982 to 1985, then increased in control and partial removal segments and remained low in most total removal segments (Figure 6). Pool length in the reach 1 total removal segment increased moderately, however, after 1985.

Debris removal apparently resulted in a decrease in pool depth (Figure 7), which I quantified by $(d_r)_{90}$, the residual thalweg depth greater than that for 90% of the profile. As $(d_r)_{90}$ is computed from the entire profile, it is a function of both the depth and the frequency of pools, but as the deepest 10% it is a measure of the deepest areas of major pools. Most segments showed a decrease in $(d_r)_{90}$ to a minimum value in 1985 and an increase afterward. With the exception of reach 1, values of $(d_r)_{90}$ in total removal segments were reduced rela-

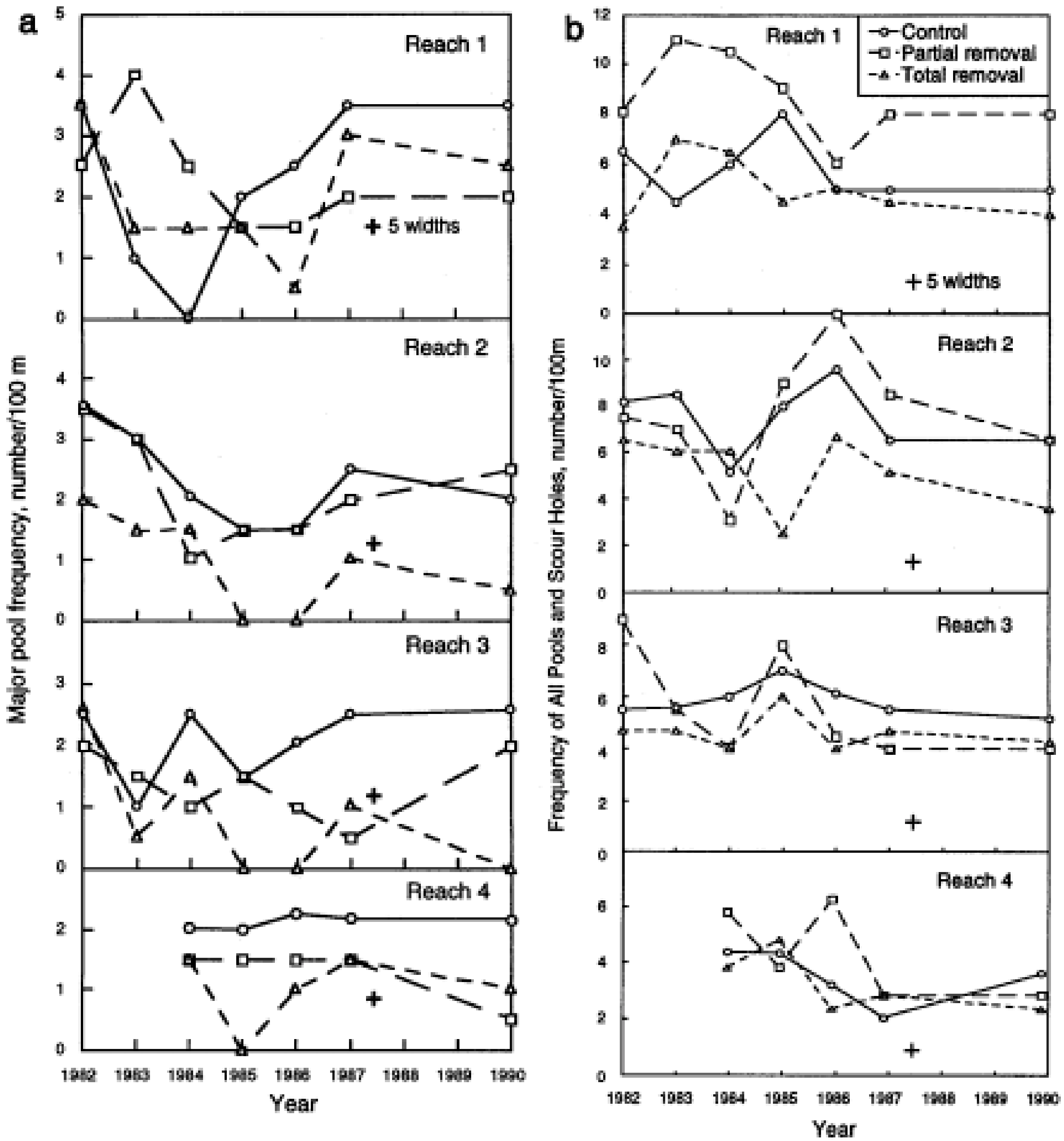

Figure 5. Changes in the frequency of (a) Major pools [$(d_r)_{max}$> one-half bank-full depth] and (b) All pools and scour holes [$(d_r)_{max}$ > 0.1 m]. The plus sign indicates a pool spacing of 5 times the mean channel width of each reach.

tive to preremoval values and were smaller than those for control segments by the end of the experiment.

In summary, although pool dimensions and frequency commonly decreased after CWD removal, changes in pools were often associated with other factors. For example, major pool frequency, total length, and depth decreased in many control segments between 1982 and 1985 and increased afterward. Also, only the less sinuous total removal segments showed a loss in major pool frequency, and the frequency of all pools showed no important changes in any reach. Pools ultimately shallowed, however, in all total removal segments and remained deep in control segments. I infer that the removal of CWD from pools eliminated obstacles that generated scouring flow structures. This caused the volume, if not the number, of scoured areas to decline.

Habitat Complexity

I evaluated habitat complexity from the irregularity of thalweg profiles, the variation of residual depth over different lengths of channel, and the size of substrate patches. Evidence for debris removal decreasing habitat complexity was strongest in the total removal segments of reaches 2 and 3. In the control segment of reach 2, for example, the amplitude and frequency of thalweg irregularity in 1990 (after the channels had readjusted to removal of CWD) were as great as or greater than those in 1982 (Figure 8). Profile irregularity declined in the

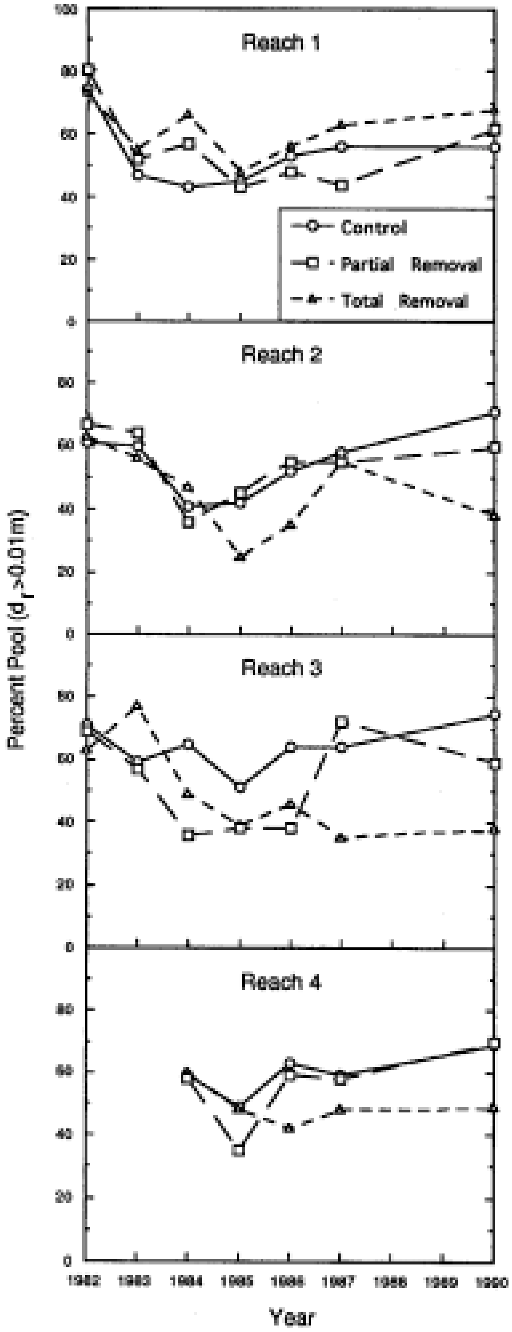

Figure 6. Changes in the percent of channel length in pools ($d_r > 0.1$ m).

total removal segments of reaches 2 and 3 (Figure 9), and moreover, most of the local variation in depth and bed gradient was preserved near residual CWD. Irregularity was maintained in the more sinuous total removal segments of reaches 1 and 4.

I used the spatial variance of residual thalweg depth as one parameter of habitat complexity. I measured thalweg bed elevations every 2 m down the control and total removal segments of each reach for before debris removal (1982 or 1984) and 1990. I then computed the standard deviation of residual depth over two scales of channel in each segment: (1) the standard deviation of depths in the entire segment (σ_{d_r})*;* and (2) the mean standard deviation of residual depth measured within all 10-m lengths of channel (($\bar{\sigma}_{d_r}$)$_{10}$). I intended σ_{d_r} to quantify the range of depths available in each segment, regardless of lengths of channel over which different variations may occur. I intended ($\bar{\sigma}_{d_r}$)$_{10}$ to quantify the range of depths available in a channel length that is typical of home ranges of salmonids [*Bachman,* 1984; *Hesthagen,* 1990; *Bridcut and Giller,* 1993].

Variations in σ_{d_r} and ($\bar{\sigma}_{d_r}$)$_{10}$(Table 3) are consistent with qualitative differences in plotted profiles (Figures 8 and 9). In control segments, both, σ_{d_r} and ($\bar{\sigma}_{d_r}$)$_{10}$ increased or decreased no more than about 20% from the beginning to the end of the study period. In total removal segments, σ_{d_r} decreased 40% and 62% in reaches 2 and 3 but changed little in reaches 1 and 4. Values of ($\bar{\sigma}_{d_r}$)$_{10}$ were roughly one half those of σ_{d_r} in all segments. In total removal segments the largest decreases in ($\bar{\sigma}_{d_r}$)$_{10}$ occurred also in reaches 2 (58%) and 3 (64%); $\bar{\sigma}_{d_r}$)$_{10}$

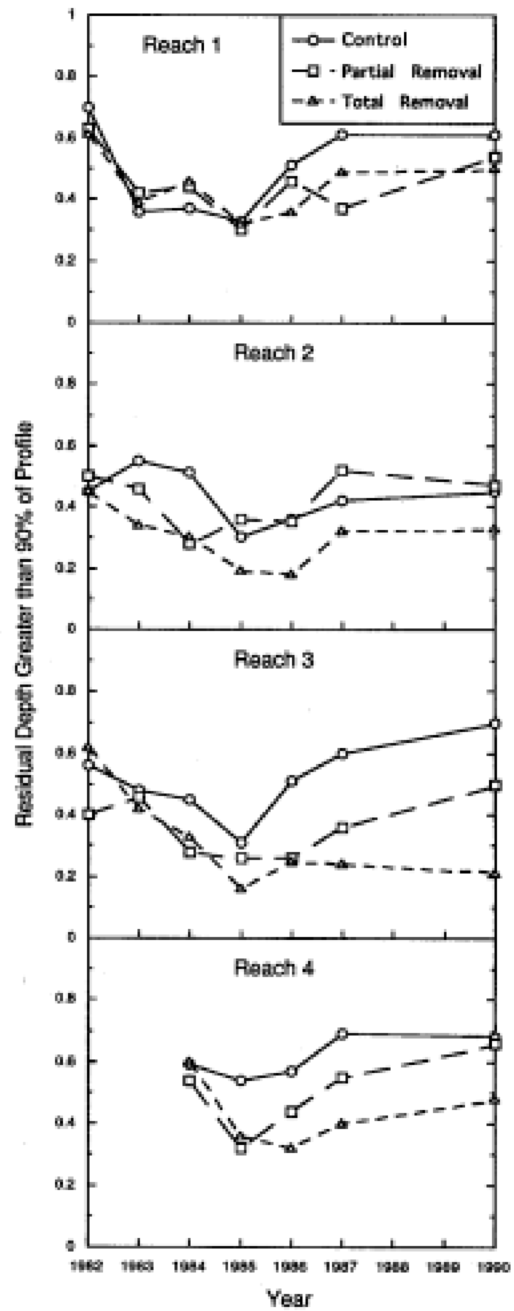

Figure 7. Changes in residual thalweg depth deeper than 90% of the channel profile.

decreased 36% in reach 4 and remained constant in reach 1. Substituting the partial removal segment of reach 1 for the control segment in order to negate the effect of the debris torrent does not change the conclusion that total debris removal had little effect on the variance of residual depth. Taken together, these measures quantify some important losses in habitat complexity in two, if not three, of the segments where CWD was removed.

Another measure of habitat complexity is the size of patches of bed material, stratified here as either fine sediment or non-pumiceous gravel. I assume that patchiness (many small patches) characterizes complex habitats. Field observations indicated that CWD in the channel increased the patchiness of bed material. Although CWD promoted deposition of fine sediment, flow that was diverted around and under debris locally swept fine sediment from the bed surface. Riffles, where invertebrate production is commonly greatest, were winnowed of fine sediment regardless of the abundance of CWD in a segment.

The size of patches of fine bed material or gravel was reduced by debris removal, although the lack of data in 1982 prevented a direct evaluation of treatment effects (Table 3). Along with the decrease in total length of fine-sediment patches (Figure 4), this suggests that gravel patches in total removal segments expanded as fine patches were lost. In 1990 the average length of individual patches measured along the thalweg (L_P) in control and total removal segments ranged from 9 to 84 m. The ratio of L_P (total removal) to L_P (control) ranged from 2.1 to 3.7. I infer that the large value for L_P in the reach 1 control segment (37 m) was due to CWD displacement and gravel deposition by the debris torrent. If I use the partial removal segment of reach 1 as the control, the ratio of L_P (total removal) to L_P (control) increases to 8.9.

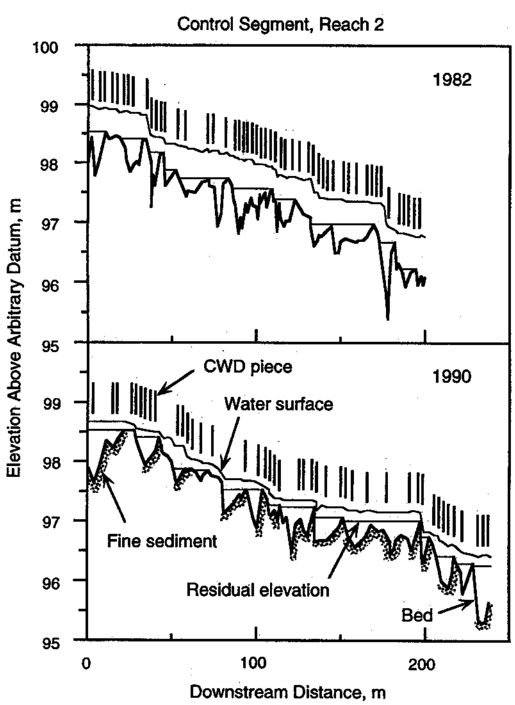

Figure 8. Longitudinal profiles of thalweg bed, water surface, and residual elevations of the control segment of reach 2 in 1982 (before CWD removal) and 1990. Substrate was not recorded in 1982.

Discussion

Comparisons With Other Experiments

Six other CWD removal experiments in forestland streams in western North America offer comparisons with results from Clearwater Creek (Table 4). Lengths of treated reaches in these experiments are sufficient to evaluate resulting channel erosion and aggradation and changes in substrate particle size; four are long enough to evaluate changes in pools, considering that pool frequency in pool-riffle channels commonly averages about 5-7 channel widths. Before CWD removal, all reaches contained high volumes of CWD that were coarse enough or clumped into large enough jams to profoundly affect pool locations and dimensions. All channels have gravel beds with differing sediment loads and size distributions. Clearwater Creek is unique in having a large supply of sand and fine gravel. (The large supply for Mill Creek is mostly stored in debris jams in the treated reach.) Despite differences in sediment, channel responses in Clearwater Creek were similar to those observed in other experiments.

In most experiments, CWD removal has led to modest erosion and an overall coarsening of the bed surface. I infer that CWD removal constitutes a loss in large roughness elements, resulting in an increase in boundary shear stress available for sediment transport, winnowing of mobile sediment from the bed surface, and overall coarsening.

Pools have usually become shallower, but pool frequency is commonly unaffected in channels where pronounced bars form, commonly in association with frequent bends and high sinuosity. In Clearwater Creek, for example, major pool frequency was maintained better after debris removal in the reaches (1 and 4) with the greatest sinuosity and most pronounced bar formation. In three other experiments, pool frequency was maintained as bars were formed, and sinuosity is reported as relatively high in two of these (Bambi and Larry Damm Creeks [*Smith et al.,* 1993a; A. MacDonald, personal communication, 1989, Seattle, Washington]). In Bambi Creek, bar formation actually resulted in net filling of the bed [*Smith et al.,* 1993a].

Pools are commonly associated with bars; thus pool frequency could be maintained by (1) hydraulic/sedimentologic conditions that induce bars and pools to form independently of channel planform and/or (2) large structural elements other than CWD, such as bends or large obstructions, that can force bars and pools to form under a wide range of hydraulic/sedimentologic conditions. The influence of hydraulic/sedimentologic conditions is not clearly evident from the comparison of experimental results. Depending on channel width and bed material size (data not available from some of these studies), channels with gradients from about 0.001 to 0.02 tend to form bar-pool bed topography inherently [*Ikeda,* 1975; *Jaeggi,*1984; *Florsheim,* 1985; *Montgomery et al.,* 1992]. We can expect pool frequency to be maintained in channels with gradients in this range. However, pools were lost from two segments of Clearwater Creek, whose slopes (0.0052) are within the bar-forming range. On the other hand, frequent pools were maintained after debris removal from West Willow Creek, whose slope (0.067) corresponds to a range in which step-pools form [*Grant et al.,* 1990; *Montgomery et al.,* 1992].

I suggest that pool-forming structural elements other than CWD have preserved the existence, if not the depth, of many of the pools in these experiments after debris removal. Bends, outcrops, rooted bank projections, and other obstructions besides CWD are common in many natural channels and can

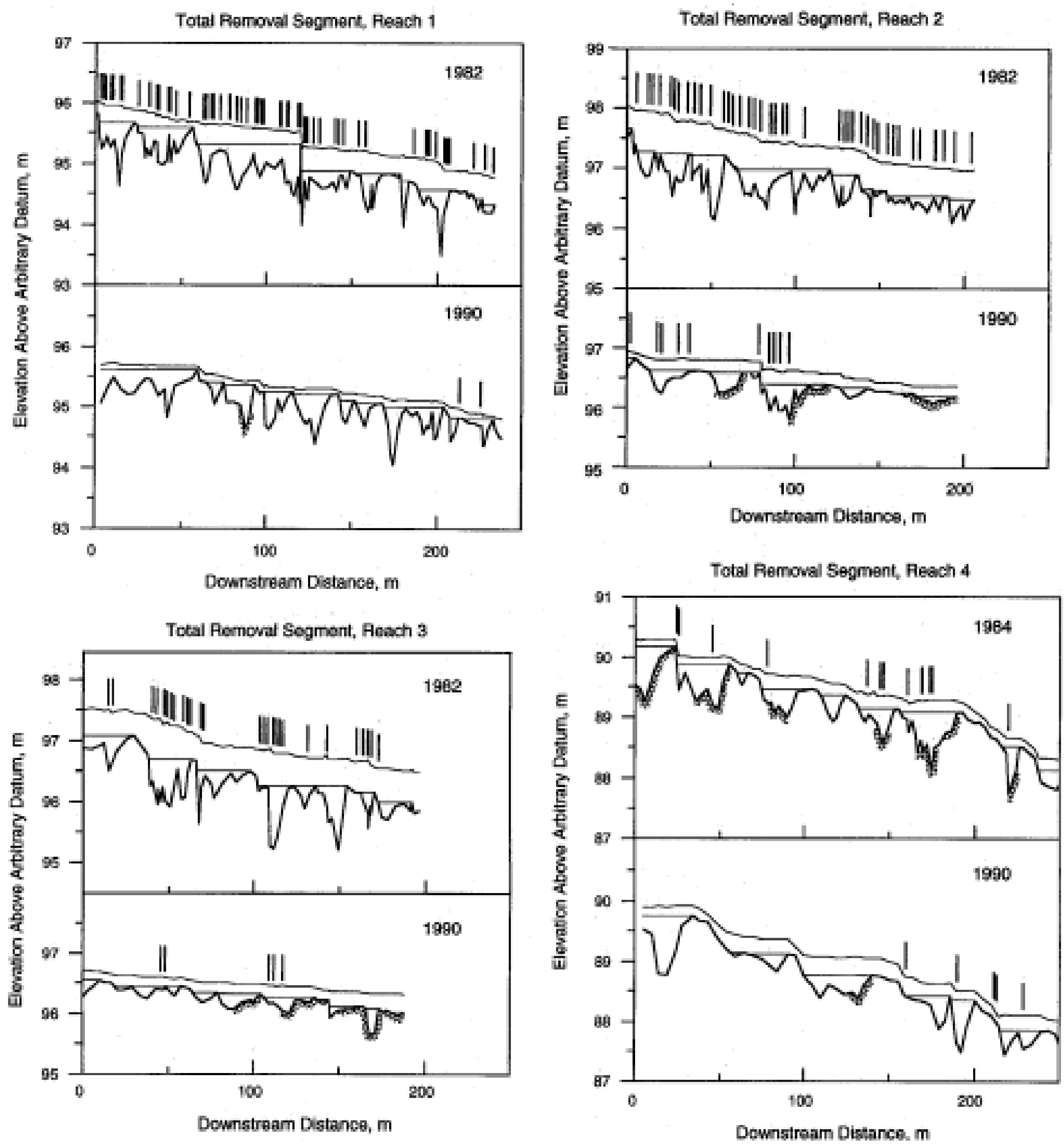

Figure 9. Longitudinal profiles of thalweg bed, water surface, and residual elevations of the total removal segments before CWD removal and in 1990 (with the exception of reach 4, where some debris had been removed in 1984 but no high flows had occurred to alter the channel). Substrate was not recorded in 1982.

govern bar-pool morphology by inducing large-scale scour and deposition [*Lisle,* 1986b].

Management Implications

A common management response to extensive blowdowns and tree mortality in riparian zones has been to quickly remove most of the merchantable timber. Most merchantable timber was removed from the affected hillslopes and channels around Mount St. Helens from 1981 to 1984. The rationalization for removal from channels was to recover economic value of the timber and to accelerate flushing of fine-grained volcanic sediments, which are commonly considered to be detrimental to fish habitat. Goals in situations elsewhere have included flood control, fish passage, navigation, and channel stability. However, even if extensive CWD removal helps significantly to achieve these goals, long-term effects on aquatic habitat are often poorly understood.

Effects of removing CWD from Clearwater Creek and other channels with large inputs of sediment and CWD can be evaluated by weighing the benefits of speeding the flushing of sediment from the channel against the loss of habitat structure before the recovering riparian forest can replace CWD. Large inputs of sediment can be deleterious to many life stages of stream-dwelling salmonids [*Cordone and Kelley*, 1961; *Hicks et al.,* 1991]. The record of thalweg elevations in Clearwater Creek indicated that sediment supply was high until about

Table 3. Variability of Residual Thalweg Depth Before CWD Removal and in 1990

		(σ_{d_r})		$(\bar{\sigma}_{d_r})_{10}$		
Reach	Segment	Preremoval	1990	Preremoval	1990	$\bar{L}_P$ for 1990
1	control	0.27	0.30	0.15	0.13	37
1	partial removal	0.22	0.22	0.14	0.11	8.9
1	total removal	0.23	0.19	0.13	0.13	79
2	control	0.20	0.19	0.14	0.11	8.8
2	total removal	0.20	0.12	0.12	0.05	33
3	control	0.20	0.28	0.13	0.17	15
3	total removal	0.24	0.09	0.14	0.05	31
4	control	0.25	0.26	0.12	0.11	26
4	total removal	0.24	0.23	0.11	0.07	84

Parameters are as follows: σ_{d_r} , standard deviation of residual depth; $(\bar{\sigma}_{d_r})_{10}$ mean standard deviation of residual depth over 10-m lengths of channel; $\bar{L}_P$, mean lengths of thalweg substrate patches. Values are in meters.

1985. During this period, pools in all segments contracted, presumably because high sediment concentrations, active bars, and smaller bed forms diminished the effectiveness of scouring processes. After 1985, pools expanded and deepened. Insofar as CWD removal hastened the flushing of sediment, it benefited pool enlargement. However, the period of high sediment supply was much shorter than the several decades of expected residence of CWD contributed by the eruption and shorter still than the period required for new trees of this size to grow and fall into the channel. Hastening sediment flushing would not significantly improve pool habitat over the long term. Conversely, removal of CWD would eliminate a long-term primary agent of pool maintenance and habitat complexity.

Total CWD removal caused the area of streambed covered with fine sediment to decrease, but some favorable habitat conditions for salmonids and other aquatic species were maintained in control segments, where fine sediment was relatively abundant. Here, gravelly patches were created on riffles and in areas where CWD concentrated flow, causing fine sediment to be entrained and carried away. Fine sediment abundance varied inconsistently in control segments, but the supply of fine sediment in mobile storage areas in the channel as a whole appeared to decline. This was indicated by lower thalweg elevations and cessation of low-flow bed load transport within a few years after the eruption. The added roughness of CWD tended to increase flood stages and may have helped to transfer fine sediment from channels to floodplains [*Lisle et al.*, 1983].

Effects of selective removal of CWD, which replicated commercial salvage by attempting to minimize disturbance of the channel, could not be detected with the methods used and the length of the study. Two questions remain concerning selective removal: (1) How was habitat complexity affected in areas outside of the thalweg, where measurements were not fo cused? (2) How would reducing the long-term supply of CWD affect the channels in the future? These questions will require finer-scale measurements and longer periods of study.

Conclusions

1. Segments of Clearwater Creek that were not affected by debris torrents degraded within 5 years after the eruption of Mount St. Helens, which introduced large volumes of fine sediment and CWD, but stream banks were not significantly affected. Total removal of CWD increased erosion of fine sediment from gravel beds.

Table 4. Results of CWD Removal Experiments and Characteristics of Experimental Channels

Stream	Reach Length[a] (Channel Widths)	Channel Gradient	Sediment Supply: Size	Sediment Supply: Volume[b]	Effects of LWD Removal: Scour/Fill[c]	Substrate Size	Pool Depth	Pool Frequency	Bars[d]
Clearwater Creek									
Reach 1	17	0.0053	sand	high	+0.20	no change	no change	no change	high
Reach 2	11	0.0052	sand	high	-0.38	coarser	shallower	small decrease	low
Reach 3	11	0.0052	sand	high	-0.03	coarser	shallower	decrease	low
Reach 4	10	0.0082	sand	high	-0.50	coarser	shallower	no change	high
Bambi Creek	18	0.008	gravel/sand	moderate	+0.12	...	no change	no change	high
Larry Damm Creek	7.1	0.014	sand/gravel	…	no change	coarser	shallower	no change	high
Mill Creek	4.3	0.07	gravel/sand	high	–0.90	coarser	...	…	…
Prince of Wales Island	74	0.021	gravel/sand	low	scour	coarser	shallower	no change	…
Salmon Creek	52	0.015	gravel/sand	…	-0.13	?	shallower	decrease	…
West Willow Creek	227	0.067	gravel	…	-0.1	?	…	no change	high

References: Bambi, *Smith et al.*, [1993a]; Larry Damm, *MacDonald and Keller*, 1987; Mill, *Beschta* [1979]; Prince of Wales Island, *Lisle* [1986a]; Salmon, *Bilby* [1984]; West Willow, *Heede* [1985]

[a]Length of channel where CWD was totally removed.

[b]Relative volume of mobile sediment stored in the channel before LWD removal.

[c]Change in mean bed elevation (in meters); scour is negative.

[d]High, pronounced bars formed after debris removal; low, low bars formed.

2. Pools contracted in all reaches during the first few years of the study and expanded to original depths and frequencies in control reaches thereafter. Although total CWD removal did not affect the frequency of all pools and scour holes, it decreased pool depth, total length of pools, and frequency of major pools in two to three of four reaches. Channel sinuosity helped to maintain pools in the remaining total removal segments.

3. Habitat complexity, as measured by irregularities in the thalweg profile, variance of depth at scales important to salmonids, and patchiness of substrate, was maintained in control segments but lost from segments from which nearly all CWD had been removed. These results reaffirm the important role of CWD in channel processes that diversify a variety of natural rivers. Additionally, they indicate that during large-scale, severe disturbances, CWD can diversify hydraulic forces and maintain structural complexity, thereby counteracting the tendency for large sediment inputs to inundate and simplify aquatic ecosystems.

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