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Effects of experimental removal of woody debris on the channel morphology of a forest, gravel-bed stream

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Abstract

Experimental removal of woody debris from a small, gravel-bed stream in a forested basin resulted in dramatic redistribution of bed sediment and changes in bed topography. Removal of debris changed the primary flow path, thereby altering the size and location of bars and pools and causing local bank erosion and channel widening. Marked bed adjustments occurred almost immediately following experimental treatment in May 1987 and continued through to the end of the study period in 1991. Increased bed material mobility was attributable to destabilization of sediment storage sites by removal of debris buttresses, elimination of low-energy, backwater environments related to debris, and an inferred increase in boundary shear stress resulting from the removal of debris-related flow resistance. In contrast to these changes, which favored sediment mobilization, deposition was favored by the elimination of debris-related scouring turbulence and by increased flow resistance from a developing sequence of alternate bars.

A more regularly spaced sequence of alternate bars replaced the pretreatment bar sequence, whose location, size, and shape had been strongly influenced by large woody debris as well as by bank projections and channel curvature. Following initial readjustment of the stream bed during the first posttreatment year, loss of scouring turbulence and increased flow resistance from alternate bars resulted in deposition of approximately 44 m^3 of sediment within the 96 m study reach. The loss of 5.2 m^3 to bank erosion left a net increase in sediment storage of 39 m^3. Mean spacing of thalweg cross-overs and pools did not change measurably following debris removal, although variability of spacing between thalweg cross-overs tended to decrease with time as the location of bars stabilized. No consistent pattern of change in mean residual depth of pools or in distribution of depths occurred within the first 4 years following debris removal.

Introduction

In forest streams large woody debris (LWD) has an important effect on

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hydraulics, sediment routing, and channel morphology (Swanson et al., 1976; Keller and Swanson, 1979). Obstruction-related pools are the rule rather than the exception in forest streams (Lisle, 1986a; Robison and Beschta, 1990), therefore characteristics of channel morphology and sediment routing may differ substantially from streams in other environments. Effects of LWD occur randomly in space, owing to randomly occurring processes of delivery from the adjacent riparian zone, such as wind throw, stem breakage, and bank erosion. Beaver activity accounts for additional input of debris (Bryant, 1984). Mass soil movements deliver debris from upland areas (Sidle and Swanston, 1982).

In channels not strongly influenced by LWD, bank projections, or other large obstructions, bars and pools have been found to develop at a mean spacing of 5–7 channel widths (Leopold et al., 1964; Keller, 1972; Richards, 1976). In forest streams, however, pools have been found to be more closely spaced than in non-forest areas (Keller et al., 1981; Hogan, 1986; Robison and Beschta, 1990). In forest streams, in-channel obstructions such as LWD can modify streamflow to create strong turbulence that scours the gravel stream bed despite subcritical average conditions (Beschta, 1983; Smith, 1990). Stationary obstructions thereby stabilize pool and gravel bar locations (Lisle, 1986a).

Hogan (1987) found that in forest streams in the Queen Charlotte Islands, British Columbia, sediment storage sites were larger but less frequent in channels where LWD had been redistributed by logging or debris flows. This difference was largely attributable to the tendency for LWD to be oriented parallel to the banks in disturbed channels, thereby storing less sediment except at infrequent, very large sites (Hogan, 1987).

Large woody debris constitutes an important element of hydraulic resistance in forest streams, the effectiveness of which varies with debris size and spacing (Swanson and Lienkaemper, 1978; Richards, 1982). By analogy with other components of total roughness, including grains on the bed, bed topography, banks, and planform geometry (Parker and Peterson, 1980), we infer that elimination of LWD can increase the component of boundary shear stress affecting grains on the bed. Such an increase may cause adjustments in bedload transport, bed slope, grain-size distribution, or bar–pool topography (Dietrich and Whiting, 1989).

Although much is known in an observational and qualitative sense about the geomorphic function of woody debris, previous research has included only a few experimental studies designed to quantify its influence on channel morphology. Beschta (1979) reported scour of more than 5000 m^3 of stored sediment along a 250 m reach the first winter following debris removal from an Oregon Coast Range stream. Debris removal also increased turbidity and suspended sediment transport (Beschta, 1979). Removal of LWD from a first-order stream in the White Mountains of Arizona eliminated local base levels imposed by log steps and caused increased sediment delivery by bank erosion (Heede, 1985). Formation of new gravel bars at the sites of removed steps replaced lost debris-related resistance (Heede, 1985).

Lisle (1986b) reported that in southeast Alaska, greater debris loading in logged sites than in forested streams resulted in greater total residual pool length (Bathurst, 1981) and greater length of channel with large residual pool depth. MacDonald and Keller (1987) reported scour of stored sediment, alteration of local hydraulics, changes in bed surface texture, and changes in the distribution of pools following removal of two LWD jams from Larry Damm Creek, northwest California. A point bar developed, becoming the dominant sediment storage site following debris removal (MacDonald and Keller, 1987).

Effects of LWD on channel morphology and sediment routing contribute in major ways to the formation and quality of habitat for aquatic organisms, including economically important salmonid species and lower levels of the lotic food chain (Cummins, 1974; Sedell et al., 1982; Bisson et al., 1987).

In the present paper, we report changes in channel morphology resulting from experimental debris removal. The goals of this study are to quantify the function of debris with respect to channel morphology and to study potential effects of land-management-related disturbance of the naturally occurring distribution of woody debris in streams.

Study area

The study stream is Bambi Creek, a second-order (Strahler, 1957, based on 1:63 360 scale topographic maps), gravel-bed stream located on Chichagof Island, southeast Alaska (Fig. 1). The study reach is located approximately 500 m upstream of the confluence with third-order Trap Creek. Elevation of the catchment ranges from 8 to 614 m. The drainage area, above the sampling site, is 155 ha. The stream drains the western portion of a Pleistocene glacial cirque. The bedrock is composed of granitics, Silurian graywacke and argillite, and Devonian limestone (Lanphere et al., 1965). Soils are largely spodosols with organic horizons commonly 20 cm deep. Numerous bogs (muskegs) at lower elevations may moderate peak runoff, although this has not been demonstrated. The study basin is undisturbed by land management. Vegetation is predominantly Sitka spruce (*Picea sitchensis*)–western hemlock (*Tsuga heterophylla*) old-growth forest.

The climate is typical of coastal southeast Alaska with cool summers, high

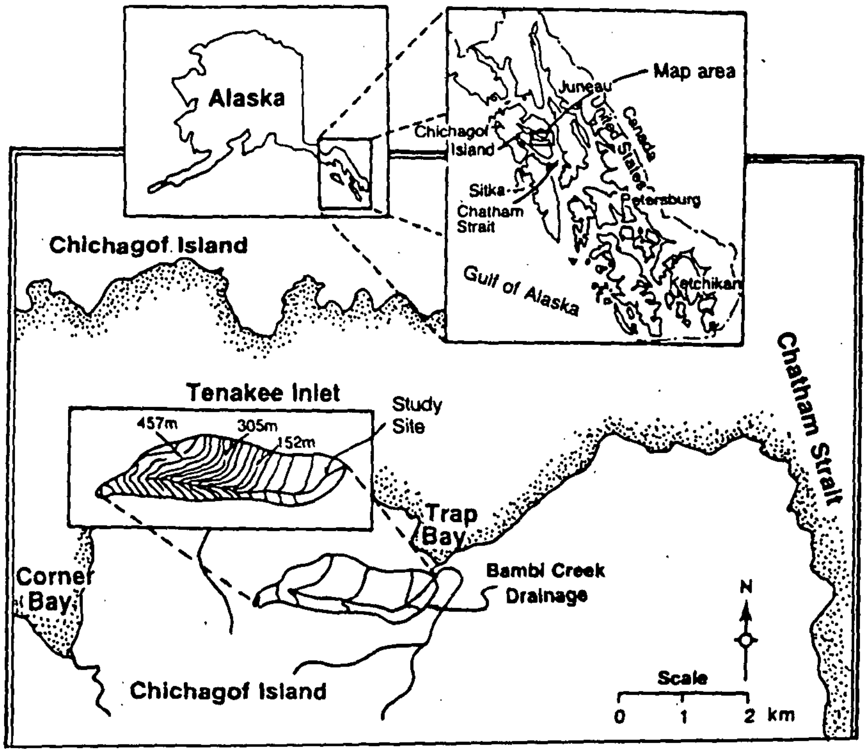

Fig. 1. Study area in southeast Alaska, USA (from Campbell and Sidle, 1985).

rainfall during fall and early winter, intermittent snow pack at low elevations during winter and early spring, and moderate rainfall with occasional snow in the spring. Mean annual precipitation at sea level is 1670 mm based on data from a station at sea level in nearby Tenakee Springs.

The length of the study reach was 95.7 m (25 channel widths). Bankfull discharge was 1.7 m^3 s^{-1}. The average gradient of the bed along the thalweg was 0.010 prior to treatment and 0.008 in 1991, 4 years after debris removal. The average width of the bed was 3.9 m prior to treatment and 4.0 m in 1991. The average bankfull depth was 0.41 m before treatment and 0.32 m in 1991. Discharge, at which bedload transport was great enough to be readily measured using a Helley–Smith sampler with sample time less than 5 min, was 0.25 m^3 s^{-1} (Sidle, 1988). The median grain size (D50) of the stream bed pavement was 28 mm, and D50 of the subpavement was 9 mm (Campbell and Sidle, 1985). The particle-size distribution of the stream bed is given by Campbell and Sidle (1985). The channel banks were composed of alluvium and soil and were commonly defended by roots and LWD.

Prior to experimental manipulation, debris formed a series of log steps and plunge pools, creating high-energy, turbulent sites as well as low-energy sites characterized by sediment storage and quiet-water habitat. Woody debris loading in the study reach was typical of forested areas in the region, consisting of a wide range of piece sizes, shapes, and orientations. The dry weight of small organic detritus from riparian vegetation, collected during a 26 month period in 0.5 m^2 litter traps, was 0.42 kg m^{-2} $year^{-1}$ (Sidle, 1986).

Campbell and Sidle (1985) and Sidle (1988) reported multiyear, seasonal, and within-storm patterns of bedload transport and changes in channel morphology related to bedload transport in Bambi Creek prior to experimental debris removal. Removal of woody debris discussed herein resulted in a fourfold increase (from 0.017 to 0.063 kg m^{-1} s^{-1}) in bedload transport rate at bankfull discharge based on a comparison of the 1987 bedload rating curve to that for 1980–1986 (Smith et al., 1993). An increased transport rate persisted for all 12 storm flows during the first storm season (September–November 1987) following debris removal (Smith et al., 1993).

Methods

All woody debris larger than 1 cm diameter as well as accumulations of smaller debris were removed during May 1987 from the bankfull channel in the study reach to an elevation well above bankfull height. Debris lying outside the banks was also removed if it was attached to in-channel debris. All removal work was done by hand in order to minimize disturbance of the bed. Larger pieces were cut in place to facilitate removal. Initial surveys of the channel were done immediately after removal, insuring that measured changes were the result of fluvial processes rather than treatment disturbance. Debris embedded in channel banks was cut flush with the bank to insure that resistance to bank erosion was not affected by removal (Smith et al., 1993).

Changes in channel morphology resulting from debris removal were quantified by repeat surveys of an array of 84 cross-sections spaced, on average, 1.14 m apart (Fig. 2). Cross-sectional profiles were surveyed with an engineering level and stadia rod immediately following debris removal, after each large storm in 1987, and one or more times a year through 1991. Elevations were measured to the nearest 0.005 m at points of topographic change on the bed, an average interval of approximately 20 cm. Only those surveys showing important change in channel morphology are reported herein. Change in stored sediment volume (scour or fill) between survey dates was calculated using a computer program developed by Noel and Sidle (1989), modified to calculate volumetric change over a continuous reach surveyed at several closely spaced cross-sections. The volume of sediment stored in the reach prior to manipulation was taken as the datum

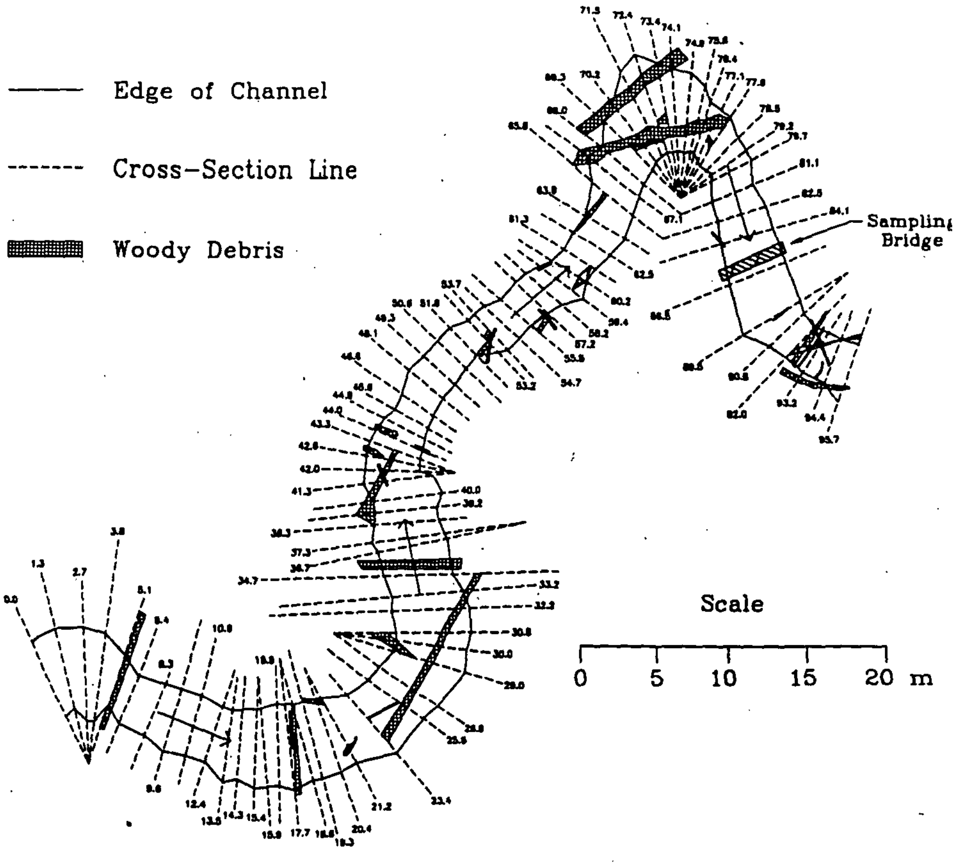

Fig. 2. Study site. Arrows indicate direction of flow. Cross-sections are labeled according to distance along the channel center line from the upstream edge of the study reach.

for these calculations. In order to monitor changes in sediment storage in an area of the mainstem unaffected by debris removal, an array of ten (monitoring) cross-sections was established 26–40 m upstream of the upstream end of the study reach. These were surveyed during each of the surveys of the study reach.

Discharge was calculated from stage height based on rating curves developed at a sediment sampling bridge and at a continuous stage recorder located near cross-section 94.4 (Fig. 2). Stage–discharge relationships were established only for flows less than bankfull, but were extrapolated to provide rough estimates of larger discharges. Stage was measured throughout autumn 1987 and, owing to winter freezing, mostly during the non-winter months of succeeding years. Use of the terms left and right herein assumes a downstream-looking perspective.

Results and discussion

Debris volume

The volume of woody debris larger than 1 cm diameter removed from the study reach was 1.63 m^3 per 100 m^2 of bankfull channel area. Large woody debris (greater than 10 cm diameter and greater than 100 cm length) comprised 93% of this volume. No LWD was delivered to the study reach during the study period (1987–1991), either directly from the adjacent riparian zone or from upstream. Removal of LWD eliminated most sites where smaller debris could be trapped and retained, therefore smaller debris entering from the adjacent forest or from upstream tended to be quickly transported through the reach (Gillilan, 1990).

Discharge record

The partial discharge record for the study period demonstrated that many of the largest peak flows occurred during autumn (Fig. 3). However, large, winter-time peaks in the 1990 and 1991 hydrographs indicated that some large flows during winter months may not have been recorded during other years (Fig. 3). The period of study included several flows exceeding bankfull discharge (1.7 m^3 s^{-1}) and one very large flow in 1990 roughly estimated at 12 m^3 s^{-1} (Fig. 3), coinciding with very large flows in other streams in the region (US Geological Survey, Water Resources Division, data on file at Juneau, Alaska). Following completion of debris removal in May 1987 and prior to the beginning of operation of the continuous stage recorder on 18 September (day 261), 1987 (Fig. 3), general discharge patterns in Bambi Creek were known from local weather conditions and frequent site visits. No large flows occurred during this period.

Stream bed adjustment to debris removal

At many locations where LWD had been an important stabilizing factor, major changes in bed morphology occurred almost immediately following debris removal, despite the absence of large storms. Elsewhere, changes in bed and bank morphology resulted from redistribution of sediment by subsequent storm flows. Debris orientation and position affected sediment storage. Debris oriented parallel to the general flow direction tended to store less sediment than pieces oriented across the channel. Debris suspended above bankfull flow had relatively little effect on the bed or on sediment storage.

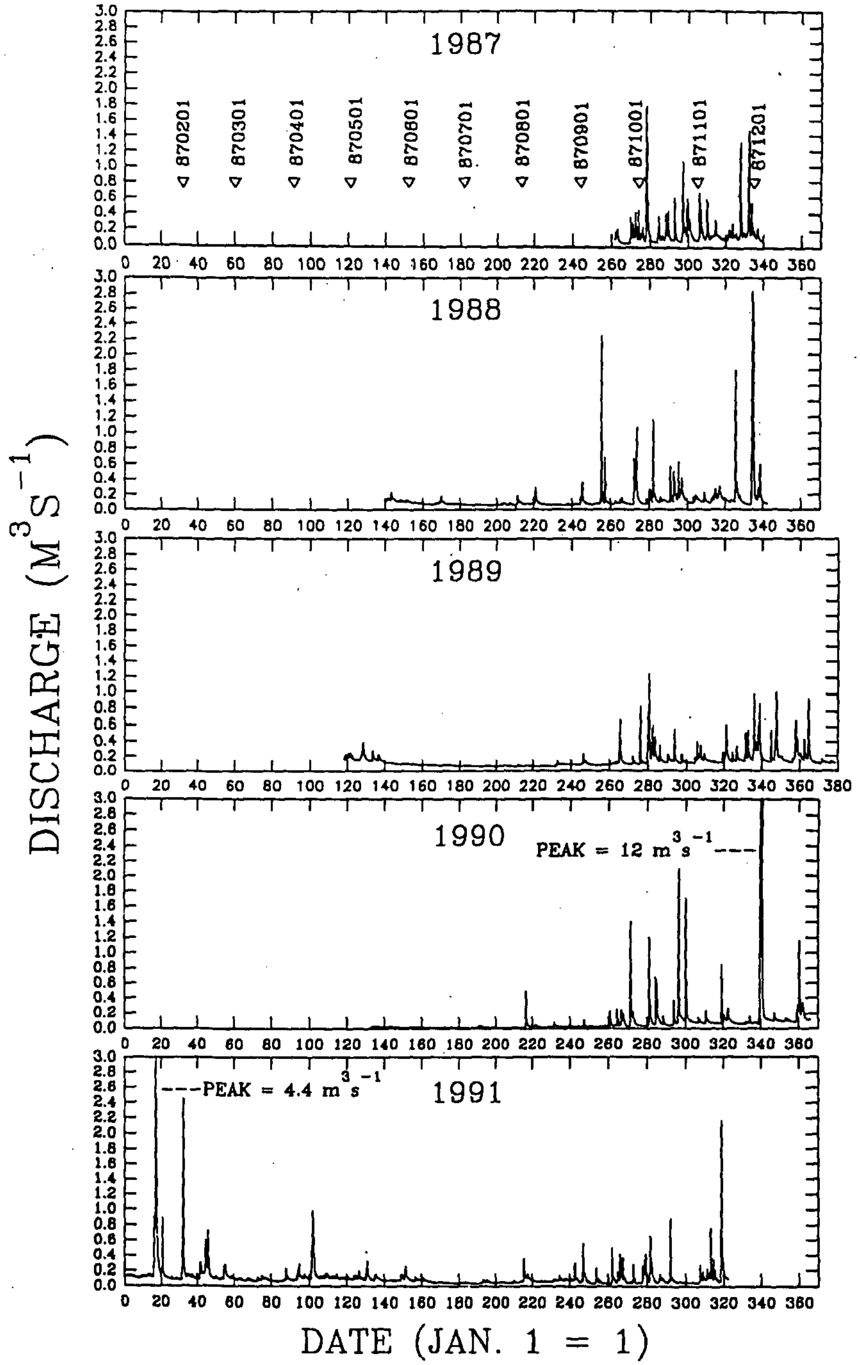

Fig. 3. Partial discharge record for Bambi Creek, based on stage height–discharge rating curves established for flows as large as bankfull discharge (1.7 $m^3 s^{-1}$). Larger discharges are estimated based on extrapolation of these curves.

Following removal of debris at A (Fig. 4), an upstream, previously buttressed sediment storage site was scoured somewhat by low flows and markedly by a series of large storms in autumn 1987 (870623 and 871203 surveys at 2.7 m in Fig. 5 (dates are given as year–month–day)). A point bar attached to the right-hand side (looking downstream) developed after the 880512 survey. In 1991 this bar generally exceeded the pretreatment bed elevation (910516 survey at 2.7 m in Fig. 5).

This scenario of immediate scour followed by fill exceeding the pretreatment bed elevation also occurred downstream of debris piece A at cross-section 6.4 and at 16.9 m following removal of debris at B (Fig. 4). At 16.9 m a point bar developed on the left-hand side following large flows in 1987, forcing flow to the right and relocating the thalweg (871203 survey at 16.9 m in Fig. 5). Later flows deposited sediment across the entire cross-section and enlarged the left-hand side point bar, leading to scour of the opposite bank (910516 survey at 16.9 m in Fig. 5).

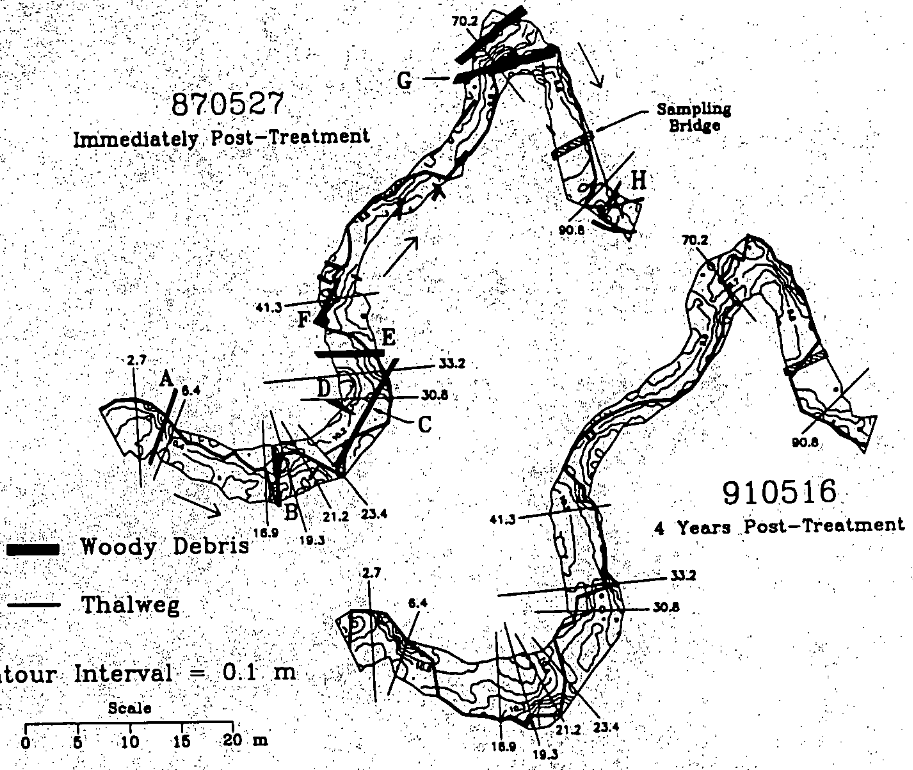

Fig. 4. Study site immediately following debris removal (870527) and at the completion of the study period (910516). Selected cross-sections are shown for reference and are labeled according to distance along the channel center line from the upstream edge of the study reach. Arrows indicate direction of flow. Dates are given as year–month–day (yymmdd).

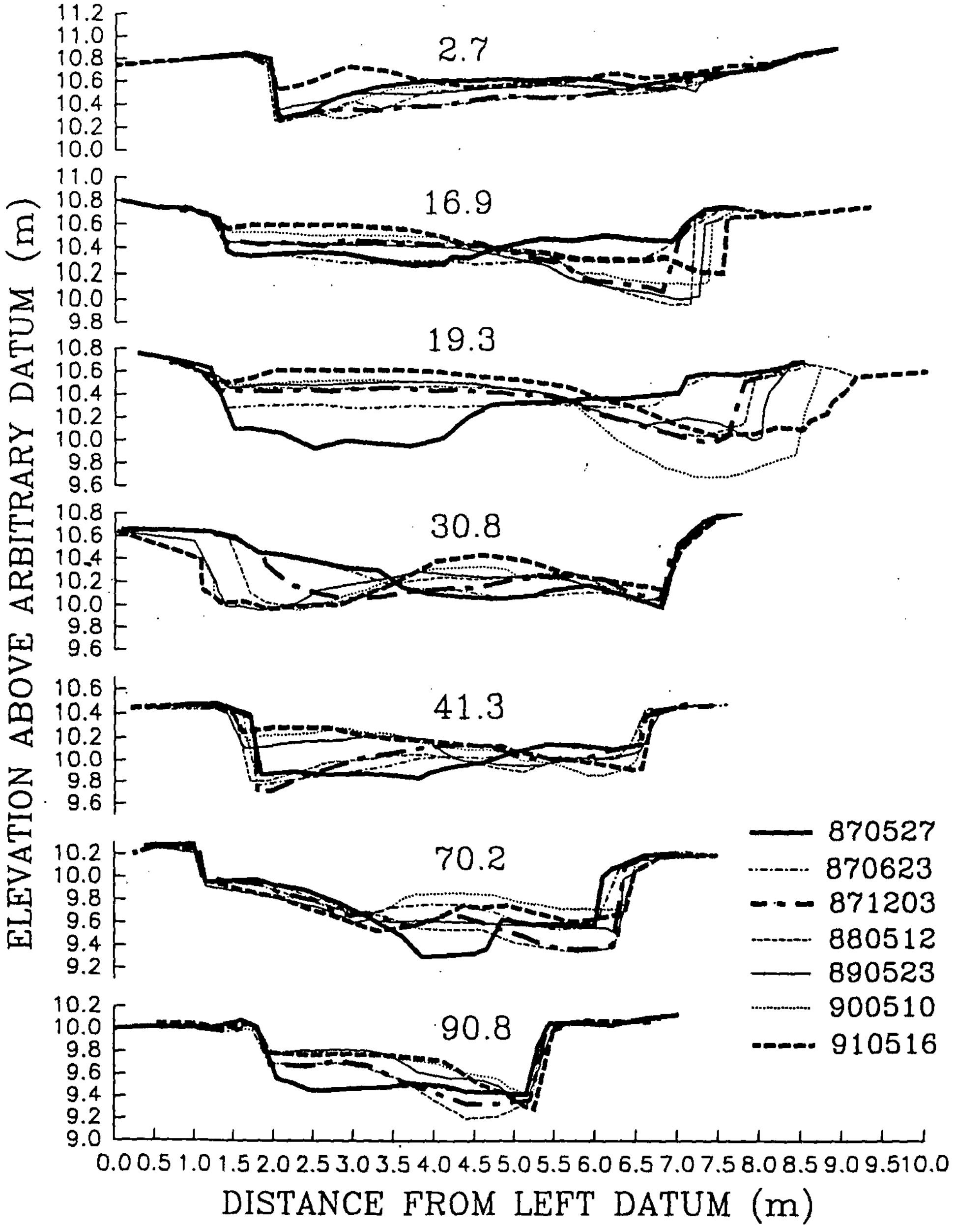

Fig. 5. Cross-sectional surveys within the study reach. Perspective is looking downstream. Labels indicate distance along the channel center line from the upstream edge of the study reach.

Removal of debris at B resulted in dramatic shifts in the location of thalweg cross-overs that had been spatially fixed by the debris (Fig. 4) and caused rapid filling of a downstream, debris-related scour pool (870623 survey at 19.3 m in Fig. 5). Development and growth of a left-hand side point bar forced the thalweg to the right (Fig. 4), causing marked bank erosion and channel widening (surveys at 19.3 m in Fig. 5). The right-hand side scoured dramatically in 1990, leading to collapse of the right bank and filling of the thalweg in 1991 (surveys at 19.3 m in Fig. 5). Following debris removal, flow was deflected at 21.2 m by a debris-defended bank projection on the right-hand side, leading to bisection of a large, left-hand side point bar and creation of a thalweg cross-over (Fig. 4).

The large log at C, oriented nearly parallel to streamflow (Fig. 4), only slightly influenced sediment storage, therefore its removal resulted in only minor initial bed adjustments. However, by December 1987, bar development on the right-hand side was evident, and redirected flow scoured sediment previously stored in the lee of debris on the left side at D (Fig. 4, 871203 survey at 30.8 m in Fig. 5). This trend continued through 1991, resulting in right-hand side bar development, substantial erosion of the left bank, and channel widening (Fig. 4, surveys at 30.8 m in Fig. 5).

Removal of the channel-spanning log at E (Fig. 4) had little effect on the upstream bed morphology owing to its suspension above the bed. Downstream, however, the thalweg was no longer deflected toward the left-hand side debris at F, consequently high flows in 1987 scoured the right-hand side, and enlarged a left-hand side alternate bar (Fig. 4).

Removal of debris at F (Fig. 4) resulted in erosion of a right-hand side bar and development of a midchannel bar at 41.3 m beginning with larger storms in 1987 (871203 survey at 41.3 m in Fig. 5). Deposition, particularly after 1988, enlarged this bar, attaching it to the left bank (surveys at 41.3 m in Fig. 5). The portion of channel between 45 and 65 m had the least LWD (Figs. 2 and 4), and underwent relatively little change in sediment storage through 1988. Later the area steadily aggraded.

Prior to debris removal, plunging flow over the large log at G scoured a pool, thereby anchoring the location of the thalweg near the inside of the meander bend (Fig. 4). Debris removal resulted initially in filling of this pool and development of a new thalweg on the right-hand side (870623 survey at 70.2 m in Fig. 5). Subsequent growth of a right-hand side point bar, particularly in 1990, forced the thalweg back to the left (surveys at 70.2 m in Fig. 5).

Removal of several pieces of debris at H (Fig. 4) had minor initial effects on the channel at 90.8 m, owing to suspension of debris above the bed. However, beginning with the 871203 survey and continuing through 910516, a left-hand side point bar developed, deflecting flow that scoured the right-hand side bed and bank (surveys at 90.8 m in Fig. 5).

Effects on sediment storage

Large woody debris is commonly believed to promote sediment storage (Megahan and Nowlin, 1976; Swanson et al., 1976). However, hydraulic conditions created by LWD in Bambi Creek affected sediment storage in complex ways. Prior to experimental treatment, debris-related eddies and other backwater areas provided storage sites. Additional storage was provided by LWD buttresses. Removal of debris eliminated these low-energy depositional sites and buttresses, resulting in a net, cumulative decrease in sediment storage through the 880512 survey (Fig. 6). This is consistent with an increase in measured bedload transport during autumn 1987 (Smith et al., 1993).

Other effects of LWD discouraged sediment storage. Flow convergence and scouring turbulence at LWD obstructions strongly altered interactions of flow and sediment transport relative to conditions described by Nelson and Smith

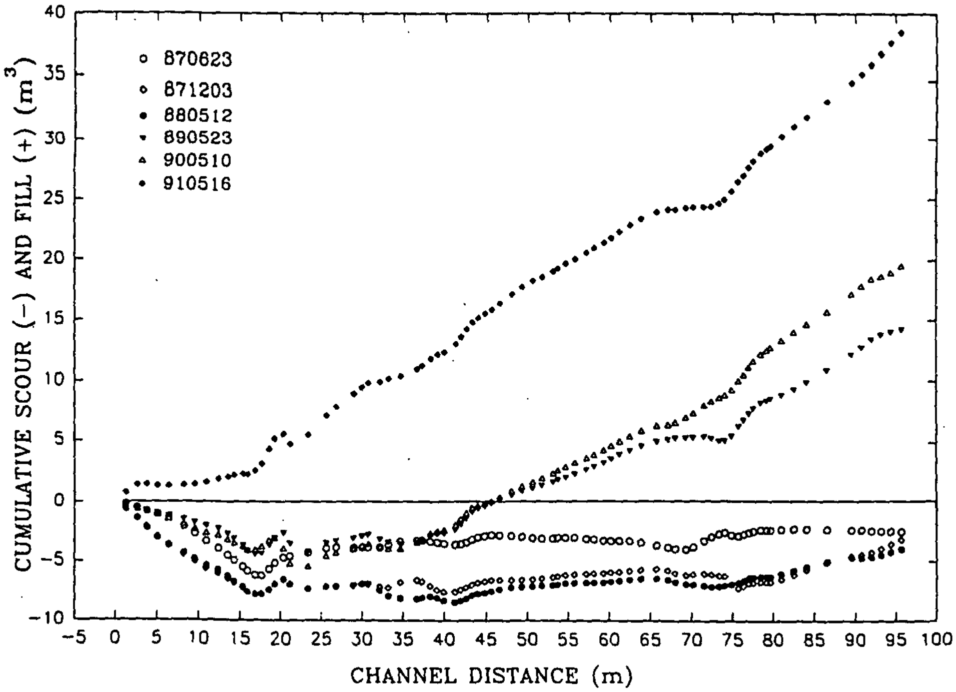

Fig. 6. Cumulative net change in sediment storage relative to the 870527 survey (datum) for selected surveys. Positive and negative slopes indicate local fill and scour, respectively, relative to the 870527 survey.

(1989) for unobstructed flow in alluvial channels. Prior to removal, LWD strongly influenced location, form and size of bars and location of the thalweg, particularly at locations B, C, F, and G (Fig. 4). Bars were present, but commonly, flow deflected by LWD disrupted bar development by scouring or terminating bars prematurely, and bar location was fixed by the presence of LWD. Scour by debris-related turbulence has been addressed in studies by Beschta (1983) and Smith (1990). Beschta (1983) found that the interaction of flow with woody debris created turbulence that can scour the bed despite subcritical average shear stress. Smith (1990) found that turbulence in a debris-related scour pool maintained bedload transport, despite deposition at other locations in the channel.

Adjustments of channel morphology to debris removal included development of a regularly spaced sequence of alternate (Ikeda, 1984) bars (Fig. 4). Bars attached to convex banks, particularly bars centered at about 18 and 78 m (Figs. 2 and 4) are more properly termed point bars (Church and Jones, 1982). Similar sequences are common in streams without the dominant influence of large, in-channel obstructions such as LWD (Leopold et al., 1964; Church and Jones, 1982; Ikeda, 1984), implying that alternate bar development in Bambi Creek was an adjustment to the absence of LWD obstructions.

The study reach clearly aggraded with time following debris removal. During the study period, 44 m^3 of sediment were deposited within the 1987 channel margins. Bank erosion removed 5.2 m^3, leaving a net increase of 39 m^3 (Fig. 6). Changes in sediment storage were not uniformly distributed (Fig. 6). The upstream portion of the study reach, to about 17 m, strongly scoured following treatment (Fig. 6), owing to destabilization of bed material previously buttressed by debris at A (Fig. 4), development of two thalweg cross-overs, and scour of the right-hand side bed and bank between about 10 and 17 m (Fig. 4). Magnitude of scour in this area, relative to the 870527 survey, decreased with time, changing to fill by 1991 (Fig. 6). Fill of scour pools associated with debris at B (Fig. 4) locally reversed the trend of scour between about 17 and 20 m, although net, cumulative change in volume of sediment stored remained negative at this location until 1991 (Figs. 4 and 6). The development of right-hand side point bars resulted in rapid rates of fill between about 42 and 45 m and between about 75 and 80 m (Figs. 4 and 6).

Sediment delivery to the upstream channel was not measured, and delivery by episodic processes such as snow avalanches may have affected channel response to debris removal. No evidence of recent mass movement events was noted during frequent aerial inspections of the basin throughout the study period. Repeat surveys of an array of ten monitoring cross-sections in an upstream, mainstem reach unaffected by debris removal indicated no significant changes in sediment storage until an increase during the May 1990–May 1991 period (Fig. 7).

An inspection of the mainstem channel and tributaries upstream of the study reach in 1992 revealed recent deposits of sand- to cobble-sized, angular sediment in one first-order tributary, which joined Bambi Creek approximately 500 m upstream of the upstream end of the study reach. A source of this sediment was a 3–4 m high, headward-eroding knickpoint approximately 200 m upstream of the tributary mouth. Neither cause, nor rate of retreat, of the knickpoint were known. Similar sediment noted upstream of the knickpoint may have been delivered by snow avalanches.

The apparent increase in sediment delivery between the 1990 and 1991 surveys may have contributed to the marked increase in sediment storage in the study reach during this same interval (Fig. 6). However, the trend toward increased storage in the study reach was already well established in 1989 and 1990 while deposition at the upstream control site was negligible (Fig. 7). Regardless of changes in sediment delivery, LWD was clearly not required to maximize the volume of sediment stored in the study reach. Indeed, LWD may have limited sediment storage by inhibiting bar development and creating local sites of turbulent scour.

Development of bar–pool sequences in the absence of woody debris cannot

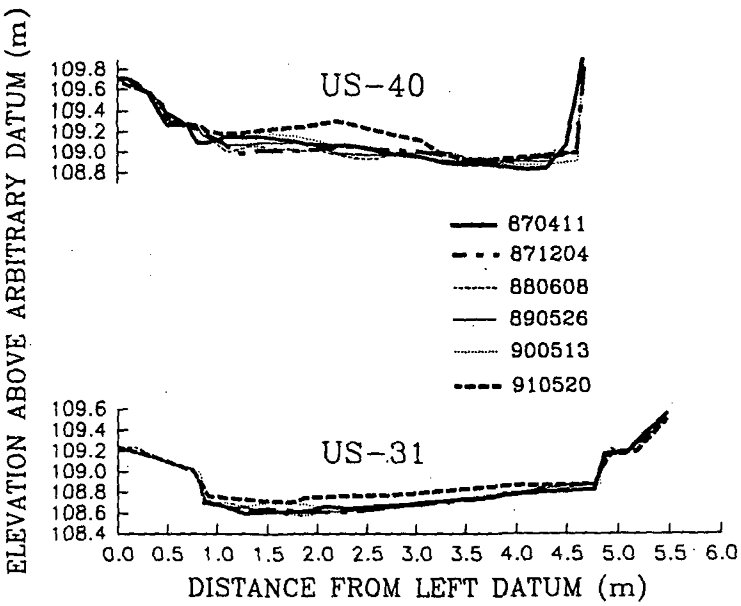

Fig. 7. Cross-sectional surveys 40 m and 31 m, respectively, upstream of the upstream end of the study reach. The vertical scale range is the same as in Fig. 5. Elevations are relative to an arbitrary datum having no relationship to that used in Fig. 5.

be expected to occur in all streams. The development of alternate bars is a function of stream width, depth, slope, grain size, and extent of armoring (Jaeggi, 1984). The effects of debris on bar development will, therefore, depend upon these variables, perhaps most importantly slope. In high-gradient channels, bar development will be limited by shallow depth and high shear stress (Church and Jones, 1982; Ikeda, 1984). In such cases, buttressing provided by LWD is more likely to promote sediment storage. The upper limits of slope for bar formation are commonly in the range 0.025–0.08, depending upon relative roughness and the value of critical shear stress; a value near 0.05 is often used (Church and Jones, 1982). In a study of bar formation in gravel-bed streams in northwest California, Florsheim (1985) found that at gradients greater than 0.02 bars only occurred downstream of in-channel obstructions. Similarly, effectiveness of randomly located bank projections at stabilizing bar and pool locations will depend upon projection size (Lisle, 1986a).

Effects on the flow path

In unobstructed flow in gravel-bed streams, the thalweg commonly flows across alternate bars from one side of the channel to the other at regular intervals, each cross-over being associated with one bar and one pool (Leopold et al., 1964; Ikeda, 1984). In Bambi Creek, debris removal changed deflection of the thalweg, and the thalweg location became largely determined by the pattern of bar development and by deflections of flow at channel banks (Fig. 4). Change between years in mean spacing between thalweg cross-overs was much smaller than standard deviations, indicating no statistical difference (Fig. 8). Small sample size precluded testing of this inference. Variability of spacing tended to decrease following an initial period of adjustment (Fig. 8).

Overall mean spacing for the five May surveys was 3.2 channel widths, using the reach-averaged width (3.9 m) (Fig. 8). Spacing differed before and after treatment from the commonly cited interval of 5–7 channel widths for alternate bar–pool sequences (Leopold et al., 1964; Keller, 1972). We attribute this difference following debris removal to the initiation of cross-overs by deflection of the thalweg at resistant bank projections, a common occurrence in forest streams. Such a deflection occurred at cross-section 21.2, initiating a thalweg cross-over (910516 survey, Fig. 4). The location of the cross-over at cross-section 33.2 was anchored by a right-hand side scour pool at a debris-defended bank projection (910516 survey, Fig. 4). This debris was incorporated into, and flush with, the bank. It was not removed during treatment in order to leave banks in the undisturbed condition. Resistant, non-alluvial portions of bank clearly affected the response of Bambi Creek

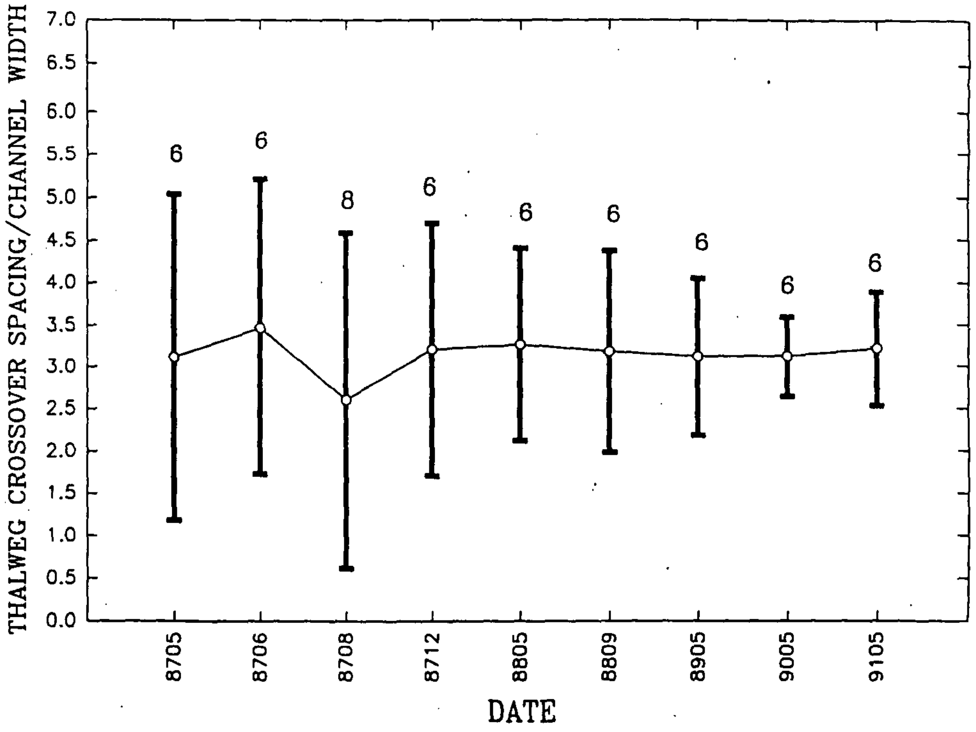

Fig. 8. Mean spacing between thalweg cross-overs normalized by the mean bed width. The number of cross-overs is given. Error bars indicate + and − one standard deviation.

to debris removal by deflecting flow and resisting erosion. Erodible, alluvial banks presumably would have resulted in increased distances between thalweg cross-overs.

Total area of undercut banks varied during the study period, because some banks were buried, then re-excavated during channel adjustments. Net change was a reduction from 46 to 36 m^2 due to the erosion of banks by deflected flow, the collapse of banks, and aggradation of alternate bars.

Spacing of pools

Clearly the number of pools counted in a reach depends on how pools are defined. Herein we arbitrarily define pools as topographic low areas in the stream bed having a residual depth (Bathurst, 1981) of 0.1 m or greater. Several adjacent low points in the bed are grouped into a single pool if their depth at a theoretical zero discharge (Bathurst, 1981) is controlled by a single downstream pool edge.

In streams where in-channel obstructions do not dominate, alternate bars

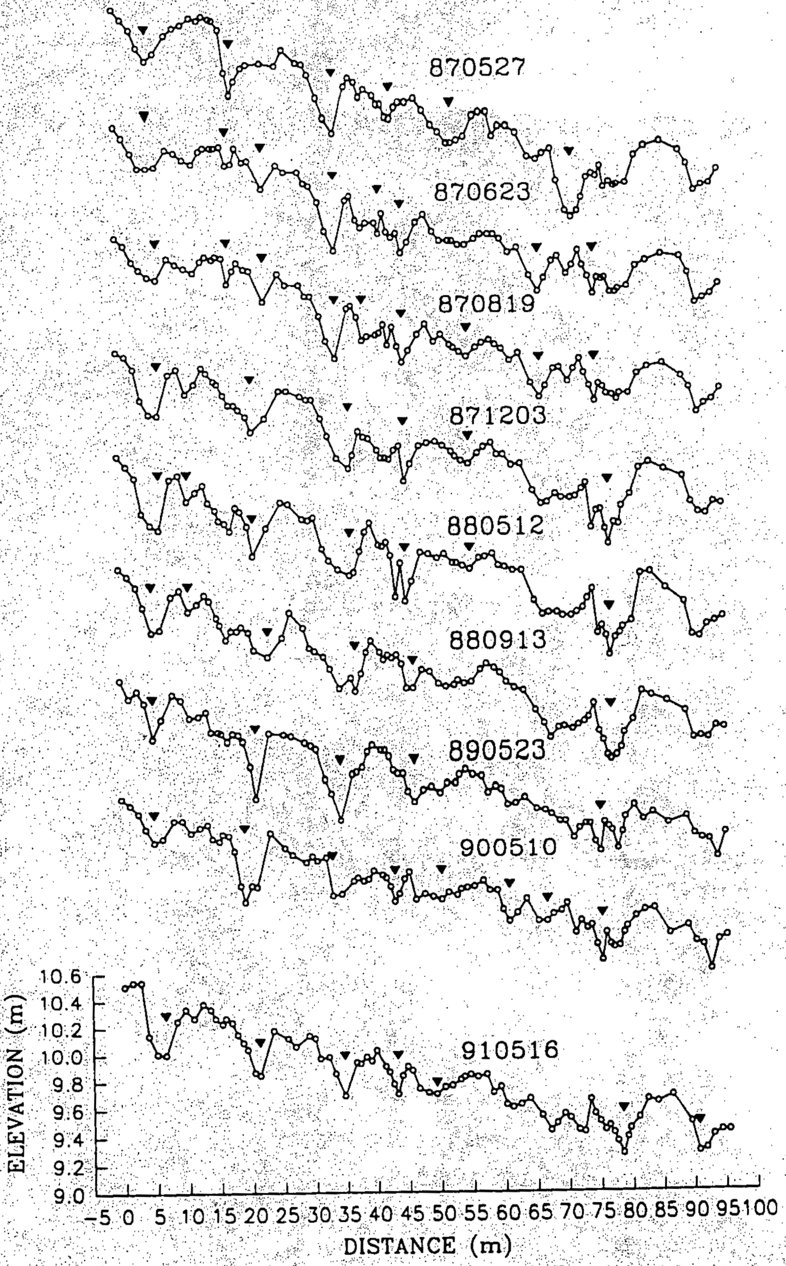

Fig. 9. Longitudinal profile for each survey, showing thalweg elevations along the channel center line from the upstream edge of the study reach. The center line distance was chosen, rather than the thalweg distance, to eliminate the effects of variation in thalweg length on the apparent location of pools. Pools having a residual depth of 0.1 m or more are indicated with a triangle.

and associated pools commonly migrate downstream if slopes are less than about 0.02 (Lewin, 1976; Leopold, 1982; Lisle et al., 1991). However, in forest streams, pools and bars are commonly stabilized by in-channel obstructions, including LWD and bedrock outcrops as well as at channel bends (Lisle, 1986a). The results of our study confirm that pool and bar locations can be anchored by non-erodible bank projections, even in the absence of in-channel LWD (Fig. 9). Following debris removal persistent pool locations occurred between 5 and 7 m, 19 and 25 m, 33 and 37 m, 43 and 47 m, and 76 and 78 m (Fig. 9). All of these pools were attributable to scour at high discharge by flow encountering a resistant bank projection along the outside bank of a channel curve (Fig. 2). Clearly these made up the majority of pools, exceeding those not related to flow obstructions.

Longitudinal profiles along the thalweg illustrate the complexity and dynamic character of the stream bed (Fig. 9). Debris removal did not cause any measurable change in either mean pool spacing or variability of spacing (Fig. 10) despite more regular spacing of thalweg cross-overs (Fig. 8). Mean spacing of pools varied from 2.6 to 4.5 channel widths for the five May surveys; overall mean was 3.4 channel widths (Fig. 10), considering only

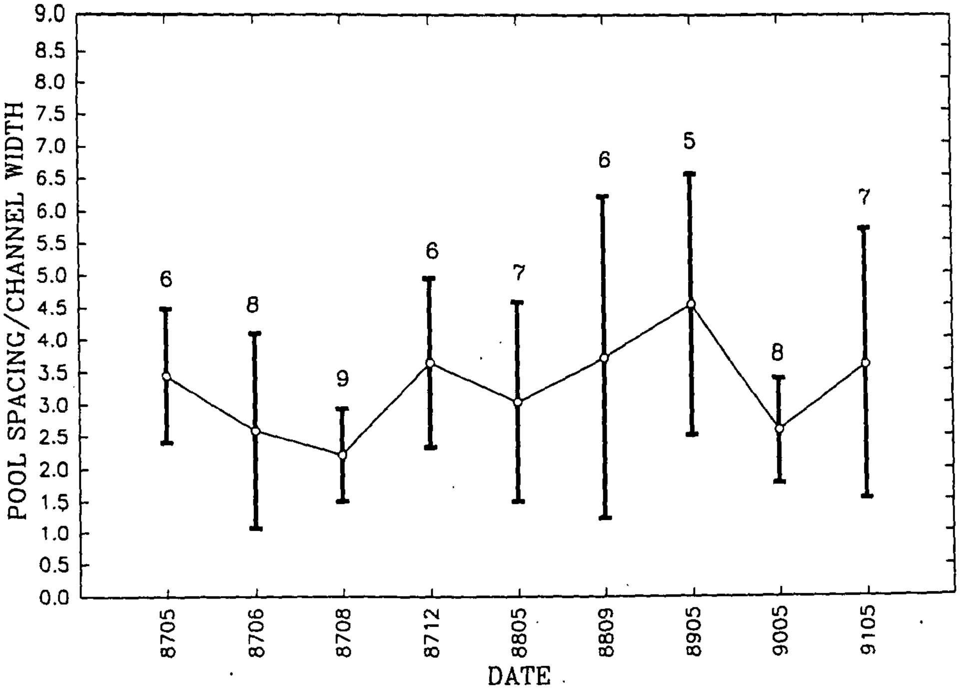

Fig. 10. Pool spacing normalized by the mean bed width for each survey. The number of pools is given. Error bars indicate + and - one standard deviation.

pools along the thalweg. Pools formed by scour at obstructions away from the thalweg are common in forest streams, further reducing pool spacing. This was not an important factor in Bambi Creek, because the narrow channel width promoted deflection of the thalweg into scour pools. Commonly the number of pools exceeded the number of cross-overs, owing to predictable formation of pools downstream of cross-overs as well as scour of pools at resistant bank projections. However, for the 890523 survey a pool did not form at every cross-over, and the number of cross-overs exceeded the number of pools (Figs. 8 and 10).

The spacing of pools in Bambi Creek was consistent with that found in other forest streams. Keller et al. (1981) report pool spacings varying from 1.8 to 6.6 channel widths in 14 forest stream reaches with varying management histories in northwest California. In five forest streams with variable management histories in the Queen Charlotte Islands, British Columbia, pool spacing varied from 1.7 to 3.5 channel widths (Hogan, 1986). Robison and Beschta (1990) found no evidence of consistent pool spacing, owing to the influence of randomly located LWD pieces, in 1530 m of Trap Creek, a pristine, gravel-bed stream in southeast Alaska.

Depth of pools

Following debris removal, the development of a regularly spaced bar–pool sequence provided alternating shallow and deep areas in the channel. These pools and, more importantly, those scoured at high discharge at resistant bank projections replaced, in a general sense, the number and depth of pools previously created by LWD (Fig. 11). Mean residual depth of pools was variable over time, but did not change measurably as a result of debris removal (Fig. 11). The distribution of residual pool depths was also variable, and was not measurably affected by debris removal (Fig. 12). The 1990 survey had an unusually large number of shallow pools (Fig. 12). This may have been caused by reduced scour of pools at high discharge, owing to a lack of large storms the previous year (Fig. 3).

Beginning with the 890523 survey and continuing throughout the study period, there was a net, cumulative increase in sediment storage in the study reach relative to the pretreatment condition (Fig. 6). The number and depth of pools were similar before and after debris removal, therefore increase in sediment storage was attributable to development and growth of the sequence of alternate bars rather than filling of pools.

Lisle (1986b) compared residual depths, measured at regular intervals, along streams that were undisturbed, logged, or logged then cleared of LWD on Prince of Wales Island, southeast Alaska. This differs from residual

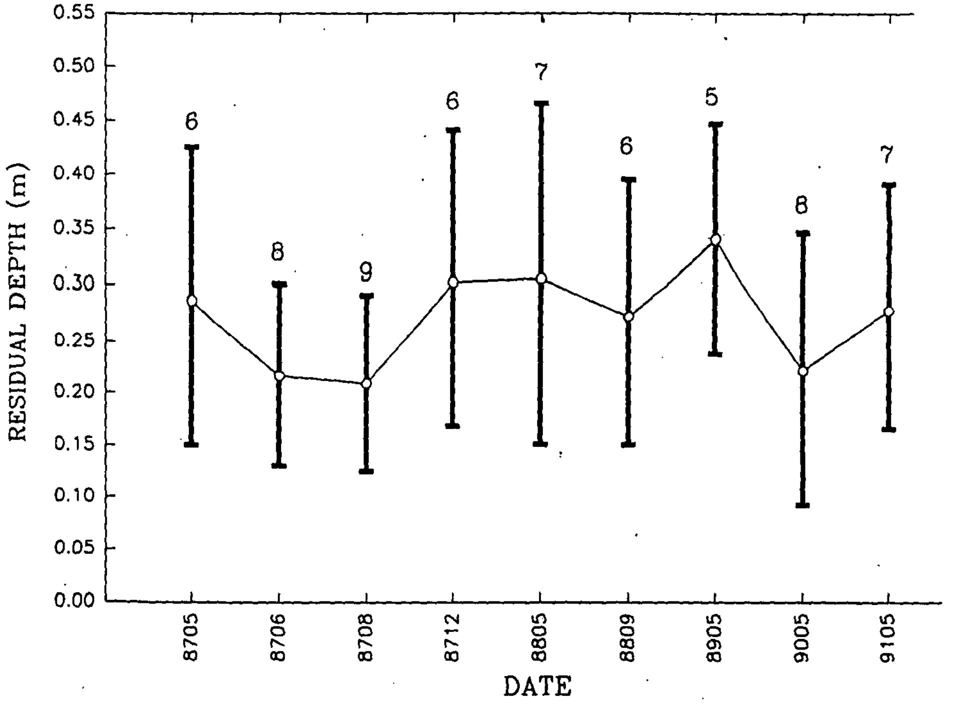

Fig. 11. Mean residual depth of pools along the thalweg for each survey. Only pools with a residual de
greater than 0.1 m are included. This restriction affects year-to-year variation in the number of po
included (shown) (see Fig. 8). Error bars indicate + and − one standard deviation.

depth measurements taken in individual pools only as was done in our stud
Lisle (1986b) found that the distributions of residual depth in streams th
were both logged and cleared of LWD did not differ significantly from tho
of streams logged but uncleared, owing to a large variation between channel
This unexpected result was attributed to retention of some debris accumu
lations following treatment, exhumation by flow of other debris from th
stream bed, and recruitment of debris from upstream (Lisle, 1986b). Non
of these factors were important at the Bambi Creek site.

Summary and conclusions

The results of this study indicate that major reductions in woody debri
loading in forest streams can result in important adjustments of channe
morphology, including local scour, deposition, bar development, ban
erosion, and channel widening. Destabilization of bed material resulte
from removal of debris buttresses, elimination of debris-related, low-energy
backwater sites where sediment was stored, and an inferred, short-ter

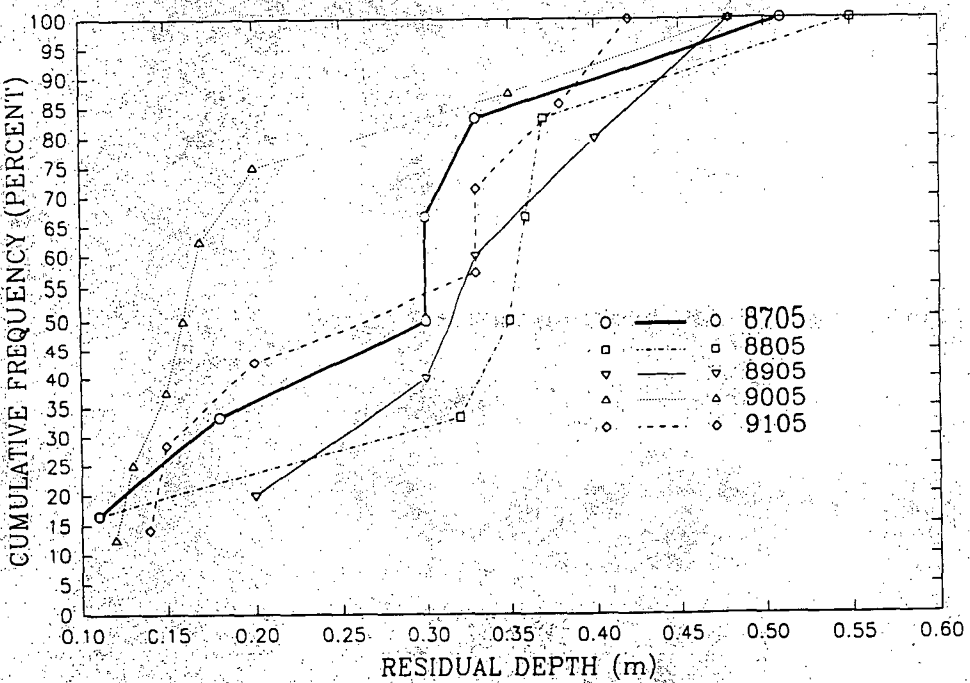

Fig. 12. The distribution of residual depths for the five May surveys. The vertical axis can be interpreted as the percentage of pools with a residual depth less than or equal to the corresponding depth on the horizontal axis.

increase in boundary shear stress. Although we did not measure shear stress, an inferred increase resulting from removal of the LWD component of total resistance is reasonable and can be expected to persist until debris is replaced by similar obstructions or until flows adjust the slope of the bed, bed surface grain-size distribution, or bar–pool topography (Dietrich and Whiting, 1989). The complexity of morphologic response found here suggests that detailed studies in a controlled laboratory setting are needed to improve our ability to quantify and predict the interactive adjustments of slope, grain size, bed topography, and sediment transport in response to reductions in LWD loading.

Sediment-routing models should not assume that LWD increases sediment storage. In Bambi Creek responses to debris removal that favored sediment mobilization, were counteracted by effects that promoted sediment deposition and storage, including the loss of LWD-related scouring turbulence and increased hydraulic resistance from developing alternate bars. Following initial readjustment of the stream bed during the first posttreatment year, this loss of turbulence and increased bar resistance resulted in the deposition of approximately 44 m^3 of sediment within the pretreatment channel. Bank erosion removed 5 m^3, leaving a net fill of 39 m^3 within the 96 m reach (Fig. 6), an average fill of approximately 0.1 m thickness if distributed over the entire channel bed. An apparent increase in sediment delivery from an upstream tributary may have accounted for a portion of the increase in sediment storage, particularly during the 1990–1991 interval. Regardless of changes in sediment delivery, increased sediment storage following debris removal indicated that LWD may have limited storage by altering bar development, and creating local sites of turbulent scour.

Woody debris greatly influenced the location of the thalweg and thalweg cross-overs. Following debris removal, the thalweg location was largely determined by the recently developed alternate bar sequence and location of resistant bank projections, which deflected flow and anchored the location of most pools. Elsewhere the stream bed remained dynamic, and the number and location of a few pools varied between surveys. Spacing of thalweg cross-overs averaged 3.2 channel widths, less than the commonly cited interval of 5–7 widths (Leopold et al., 1964), owing to deflection of the thalweg by resistant bank projections. Variability of spacing tended to decrease with time as the location of alternate bars stabilized. Treatment-related changes in the thalweg path commonly resulted in scour of the bed and erosion of the impacted bank, increasing sediment delivery to the channel.

Removal of debris did not result in any apparent change in mean spacing of pools, variability of pool spacing, mean residual pool depth, or distribution of depths. Despite this lack of change, profound alteration of pool and bar morphology occurred locally. This response was strongly affected by the random placement and characteristics of LWD prior to removal, because in the undisturbed condition the thalweg path, location of cross-overs and pools, and characteristics of pools were strongly influenced by large debris (Fig. 4). Other forest streams may have been differently affected by debris removal depending upon pretreatment volume and characteristics of LWD.

Implications for forest management and aquatic habitat

The results of this study indicate that forest land management practices that affect the long-term delivery and distribution of woody debris in stream channels will affect channel morphology. Current land management practices in southeast Alaska rarely include the removal of naturally occurring woody debris from other than low-order, tributary channels. However, the size of streams requiring special riparian zone management and the extent and nature of downstream impacts of management of headwater channels is controversial. Management impacts ranging from alteration of the riparian forest adjacent to large-order streams to removal of streamside forest adjacent to small, tributary streams will affect the timing of input, characteristics, and volume of material delivered to channels, cumulatively changing woody debris loading over time.

Partial or complete cutting of riparian forests will normally contribute high loadings of woody debris (e.g. unmerchantable limbs and trees) into streams during the harvest operation (Lisle, 1986b). Periods between harvesting operations will have reduced recruitment rates of LWD, because fewer or no sizable trees are left standing in the riparian zone that could later enter the channel during episodic, wind, or flood events. In contrast, when unharvested buffer strips of appropriate size are left along streams, the recruitment regime will be dictated more by the occurrence of large storms, high winds, upslope landslides, and insect outbreaks. Assuming that the stabilities of these riparian buffers are similar to the undisturbed forest, they function to insure a greater, and generally more continual, supply of LWD compared with the harvested scenario where inputs consist largely of smaller, less stable residues. In a similar fashion, the cutting of riparian forests along small, tributary streams may reduce long-term delivery of woody debris from upstream sources to downstream channels.

In this study, debris removal clearly affected quality of aquatic habitat by scour and redistribution of bed and bank material and by reduction of woody debris cover, undercut bank habitat, and number and size of low-energy refuges. The development of an alternate bar–pool sequence and scour at resistant bank projections replaced debris-related pools with pools of similar mean residual depth, depth distribution, and spacing. However, limitations of non-obstruction-related pools in terms of habitat include lack of cover formerly provided by LWD and reduced hydraulic complexity. Pools created by woody debris commonly provide a wide variety of hydraulic environments ranging from zones of scouring turbulence to low-velocity, backwater areas (Beschta, 1983; Lisle, 1986a; Sullivan, 1986; Smith, 1990). This complexity satisfies a variety of aquatic habitat requirements through a wide range of discharge.

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