Geomorphic Effects Of Large Woody Debris In Streams

Richard D. Smith[1]

Abstract.--This paper reviews the geomorphic effects of in-channel obstructions, including large woody debris. It includes discussion of debris flows, debris removal, obstruction-pool interactions, obstruction-channel morphology interactions, mechanisms of pool scour, and scour in obstruction-related pools. Several questions are posed related to information needs required for widespread application of the turbulent scour model in forest streams.

INTRODUCTION

Some aspects of traditional geomorphic thinking need to be modified to fit the special case of forest streams, owing to their unique attributes including: 1) the presence of individual pieces and accumulations of large woody debris (LWD) in the channel, 2) windthrow of large trees along stream banks, and 3) debris flows rich in LWD. The location of debris and debris-related geomorphic features is determined by fluvial processes of bank erosion and transport from upstream sources as well as by several non-fluvial, random processes including windthrow and stem breakage. Beaver activity accounts for additional input (Bryant 1984). Mass soil movements deliver debris from upland areas (Swanson et al. 1976).

The purpose of this paper is not to provide a thorough review of the large body of literature addressing the role of woody debris is streams. Rather, it is to briefly acknowledge key contributions to our current understanding of the geomorphic effects of in-channel obstructions, including LWD, and to discuss recent advances, which commonly involve quantification of concepts presented in earlier literature. Summaries concentrating on the biological function of LWD in forest stream ecosystems include Harmon et al. (1986) and Bisson et al. (1987).

EARLY STUDIES

Early studies provided conceptual insights and initial quantification of the geomorphic function of LWD. Hack and Goodlet (1960) noted the ability of LWD accumulations to divert flood flow, leading to extreme incision into floodplain deposits. In small forest streams in New England, Zimmerman et al. (1967) documented channel meandering, avulsions, and changes in channel width, owing not to variation in upstream drainage area or discharge but to the influence of LWD. Zimmerman et al. (1967) stated, "Channel form, size, and location are greatly influenced by non-fluvial processes such as tree blowdown, damming by debris, and extension of roots."

Several important concepts were expressed in this early research including: 1) channel width was controlled, in large part, by LWD through windthrow of trees along the banks and flow deflection by tree stems or debris dams in the channel; 2) some LWD pieces defended the channel bed and banks from erosion, while other pieces enhanced erosion by deflecting and concentrating flow; 3) flow energy was dissipated by roughness provided by LWD; 4) LWD induced scouring turbulence, producing channel instability; and 5) LWD affected frequency and duration of overbank flow through effects on channel shape (Zimmerman et al. 1967).

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[1] USDA Forest Service, Pacific Northwest Research Station, Juneau, AK.

Effects of LWD on channel width in two small, forest streams in the Colorado Rocky Mountains resulted in a very weak dependence of width on upstream drainage area or discharge, contrary to the hydraulic geometry (Leopold and Maddock 1953) relationships of small, non-forest streams (Heede 1972). Expenditure of a large portion of the stream energy occurred over short distances at debris-defended steps in the stream profile, commonly creating a scour pool at the downstream edge of the step (Heede 1972).

In the western Cascades of Oregon, Swanson et al. (1976) noted the tendency of LWD to cause flow convergence, thus scouring mid-channel pools. Deflected flow also scoured pools against stream banks and created channel diversions. Broad, shallow pools tended to form upstream of debris accumulations (Swanson et al. 1976). Bank erosion by debris-deflected flow was an important source of sediment delivery to the channel (Swanson and Lienkaemper 1978).

LWD provides important buttressing of sediment storage sites, commonly accounting for the majority of sediment stored in a channel, which can exceed annual sediment yield by 10-fold or more in small, forest watersheds (Megahan and Nowlin 1976; Swanson et al. 1976; Keller and Swanson 1979). This storage capability is believed to slow the transport of sediment through the channel system (Swanson et al. 1976).

Swanson and Lienkaemper (1978) noted the scouring potential of mobile LWD pieces and accumulations. Debris jams can be transported hundreds of meters downstream during high flows, increasing the erosive consequences of floods and altering channel shape and distribution of alluvium (Swanson and Lienkaemper 1978; Keller and Swanson 1979).

Keller and Swanson (1979) distinguished the effects of LWD accumulations on low-gradient vs steep streams. In low-gradient streams debris jams diverted flow and altered flow hydraulics. This resulted in scour of the stream bed and banks, initiation of bar deposition downstream, and creation of upstream backwater effects leading to meander cutoffs. Debris also influenced the development of bars and channel braiding. In steep streams where development of bars, riffles, and floodplains was inhibited, debris jams provided important sediment storage sites and created plunge pools.

In a small, forest stream in New Zealand, variation in bedload transport rate was largely a function of sediment supply, which was strongly influenced by temporary base levels created by woody debris (Mosley 1981). Debris accounted for important quantities of sediment storage. Episodic releases of this sediment were caused by shifts in debris location.

DEBRIS FLOWS

Debris flows occur in both forested and non-forested channels, however the presence of LWD produces distinctive effects of these mass movements in forested areas. Swanston and Swanson (1976) found that occurrence of these flows depends on volume and stability of LWD in the channel as well as hillslope stability, channel slope, and peak discharge characteristics of the channel. Sudden breakup of large debris accumulations may trigger debris flows, and heavy loading of LWD may increase their erosive potential by enhancing scour of the channel bed and banks (Swanson et al. 1976). Conversely, entrained debris may reduce the travel distance of debris flows in forest channels, resulting in shorter, wider tracks than in non-forest areas (Swanson et al. 1976). Destructiveness appears to depend primarily on volume of the triggering landslide.

Debris flows can leave large, long-lived deposits at channel junctions, alluvial fans, and riparian areas (Benda 1985a, 1985b). These organic-rich deposits alter riparian vegetation and may persist as geomorphic features after stream channels recover from debris flows (Grant 1986). Kochel et al. (1987) observed flood-transported, large tree stems acting as dams confining stream flow and flood deposits such that the channel was aggraded above the surrounding flood plain. Subsequent channel diversion left pseudo terraces above the modern floodplain.

DEBRIS REMOVAL STUDIES

Attempts to further quantify the geomorphic effects of LWD and other in-channel obstructions included several studies investigating the effects of removal of debris. Beschta (1979) reported scour of more than 5,000 m3 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).

8 YD^3/LINEAR FOOT

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 through bank erosion (Heede 1985). Formation of new gravel bars at the sites of removed steps replaced lost debris-related hydraulic resistance. Heede (1985) interpreted development of these bars as an indication of increased bedload transport rate.

In southeast Alaska, Lisle (1986a) reported that greater debris loading in clear-cut streams relative to forested sites, owing to timber harvesting activity, resulted in greater total residual pool (Bathurst 1981) length and greater length of channel with residual pool depth providing high-quality salmonid habitat. Removal of debris from the clear-cut sites did not result in statistically significant differences in pool dimensions between treated and untreated sites, owing to large variation between channels (Lisle 1986a).

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 large woody debris jams from Larry Damm Creek, northwestern California. Pools were created or deepened at bends above and below the sites of debris removal. Size increase in these pools coincided with a decrease in size of numerous scour pools within the debris accumulations, where a point bar became the dominant sediment storage site.

In order to quantify the effects of LWD on bedload transport and channel morphology, Smith et al. (1993a) removed all woody debris larger than 1 cm diameter from a 100 m reach of Bambi Creek, a small, forest, gravel-bed stream in southeast Alaska. Debris removal resulted in a four-fold increase in inorganic bedload transport at bankfull discharge (Figure 1). This increase was statistically significantly at the 0.01 probability level. Despite early redistribution of the

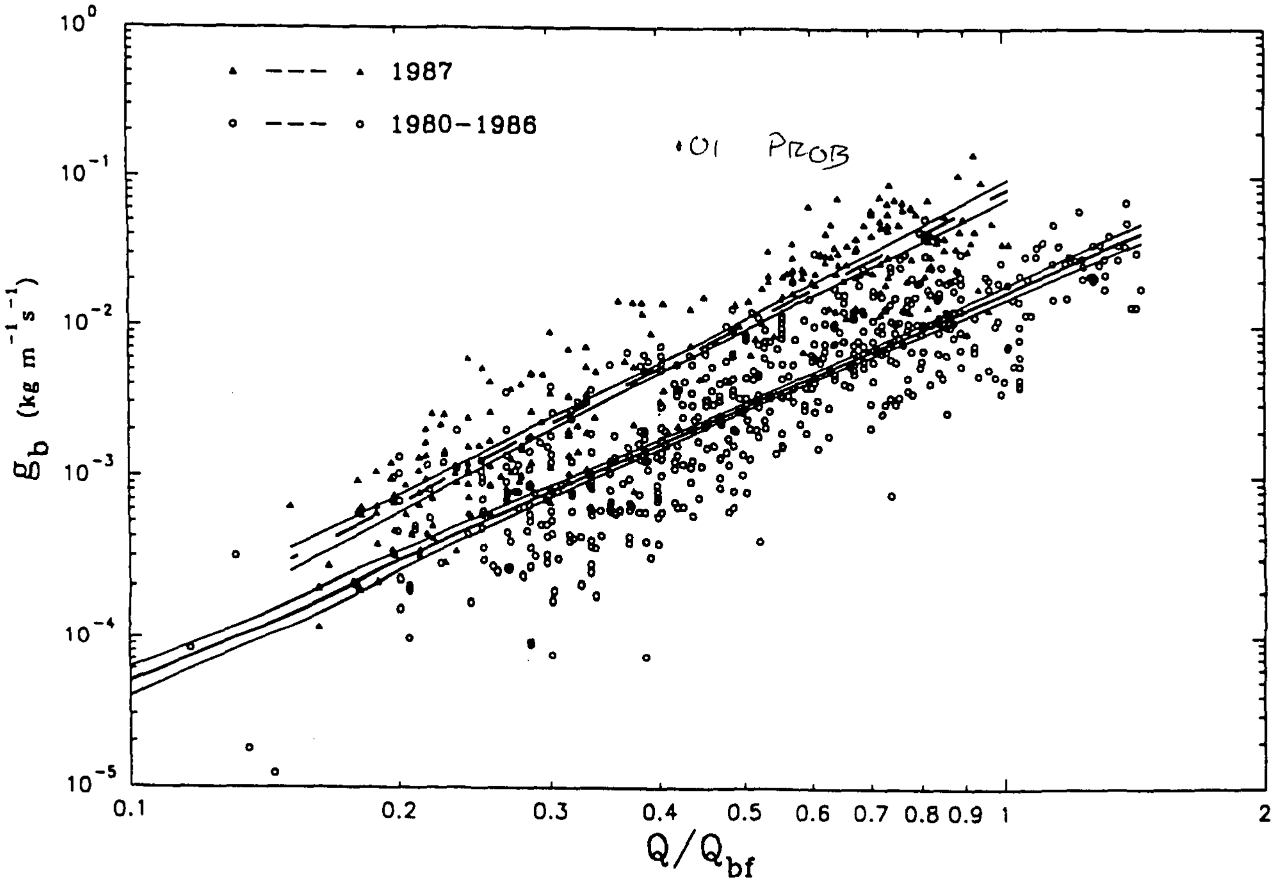

Figure 1. Bedload transport (gb) before (1980-1986) and after (1987) experimental removal of woody debris from Bambi Creek, southeast Alaska showing 95 percent confidence interval estimates. Q is water discharge. Qbf is bankfull discharge (1.7 m3s-1).

most easily-entrained sediment, increased bedload rates persisted throughout the first autumn storm season foll
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INPUT TO STREAM?

bankfull flow had relatively little effect on the bed or on sediment storage. Marked bed adjustments occurred almost immediately following experimental treatment and continue to the present as sediment is redistributed by storm flows. Adjustments of channel morphology included development of a semi-regular, alternate bar-pool sequence, (Ikeda 1984). Similar sequences are common in streams without the dominant influence of large, in-channel obstructions such as woody debris (Leopold et al. 1964; Church and Jones 1982; Ikeda 1984).

In unobstructed flow in gravel-bed streams, the thalweg commonly flows across alternate bars crossing from one side of the channel to the other at regular intervals, each crossover being associated with one bar and one pool (Leopold et al. 1964; Ikeda 1984). However, in undisturbed, forest streams the thalweg path, location of crossovers and pools, and characteristics of pools are strongly influenced by large debris. In Bambi Creek debris removal eliminated the influence of in-channel debris, and the location of the thalweg and thalweg crossovers became largely determined by the developing sequence of alternate bars and the random location of resistant bank projections (Smith et al. 1993b). Alteration of the flow path redirected flow, eroding banks and widening the channel. Area of undercut banks decreased following treatment, owing to bank collapse and aggradation of alternate bars.

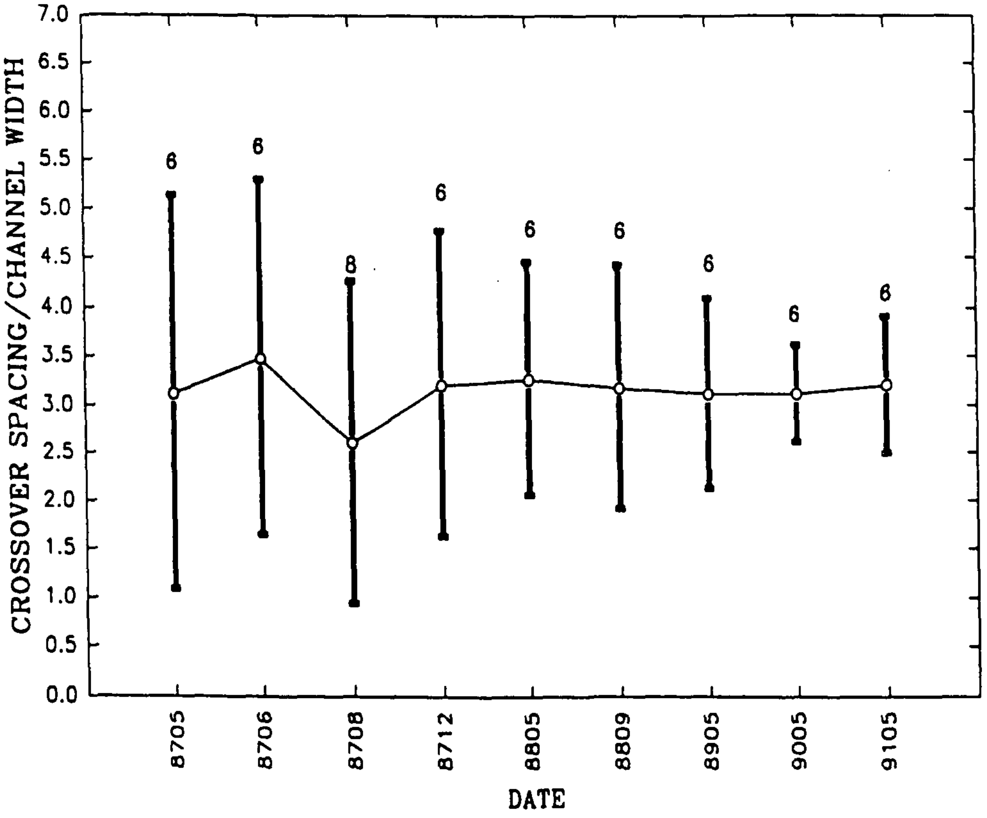


Figure 2. Mean spacing between alternate bars measured as the distance between thalweg crossovers normalized by the mean bed width for Bambi Creek, southeast Alaska. Number of crossovers is given as well as 95 percent confidence interval estimates. Dates are given as year-month (yymm).

Bar spacing, measured as the spacing between thalweg crossovers, fluctuated during the first few months after treatment, but changed very little after the 871203 survey (Figure 2) (Smith et al. 1993b). Variability of spacing tended to decrease following the initial period of adjustment (Figure 2). Bar spacing for the four years following treatment was not statistically different from that prior to debris removal as indicated by overlapping confidence interval estimates. Overall mean spacing for the five May surveys was 3.2 channel widths. Spacing differed before and after treatment from the commonly-cited interval of 5-7 channel widths (Leopold et al. 1964; Keller 1972; Richards 1976) for alternate bars. This difference was attributable to the initiation of crossovers by deflection of the thalweg at resistant bank projections, a common occurrence in forest streams.

In Bambi Creek mean pool spacing was different and more variable between surveys than crossover spacing (Figures 2 and 3), owing to the expected formation of pools downstream of crossovers as well as scour of pools at resistant bank projections (Smith et al. 1993b). 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 (Figure 3).

Debris removal did not cause consistent changes either in pool spacing or variability of spacing (Figure 3) despite more regular spacing of thalweg crossovers (Figure 2). Pool spacing was consistent with that in other forest streams, such as 1.8 to 6.6 widths for northwest California streams (Keller et al. 1981) and 1.7 to 3.5 widths for streams in the Queen Charlotte Islands, British Columbia (Hogan 1986).

In Bambi Creek the mean residual depth (Bathurst 1981) of pools was variable over time, but did not change in a consistent way as a result of debris removal (Figure 4; Smith et al. 1993b). Experimental treatment did not completely eliminate the effects of debris on channel morphology. Two of the deepest pools were formed where flow encountered debris-defended bank projections, creating bed and bank scouring turbulence.

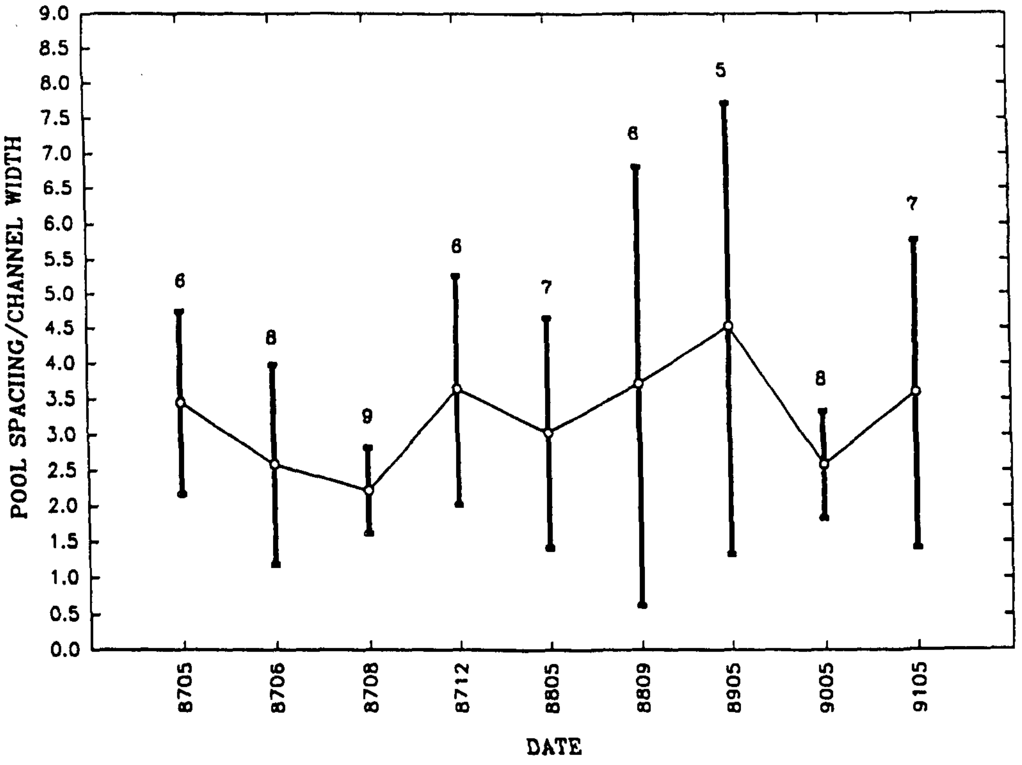
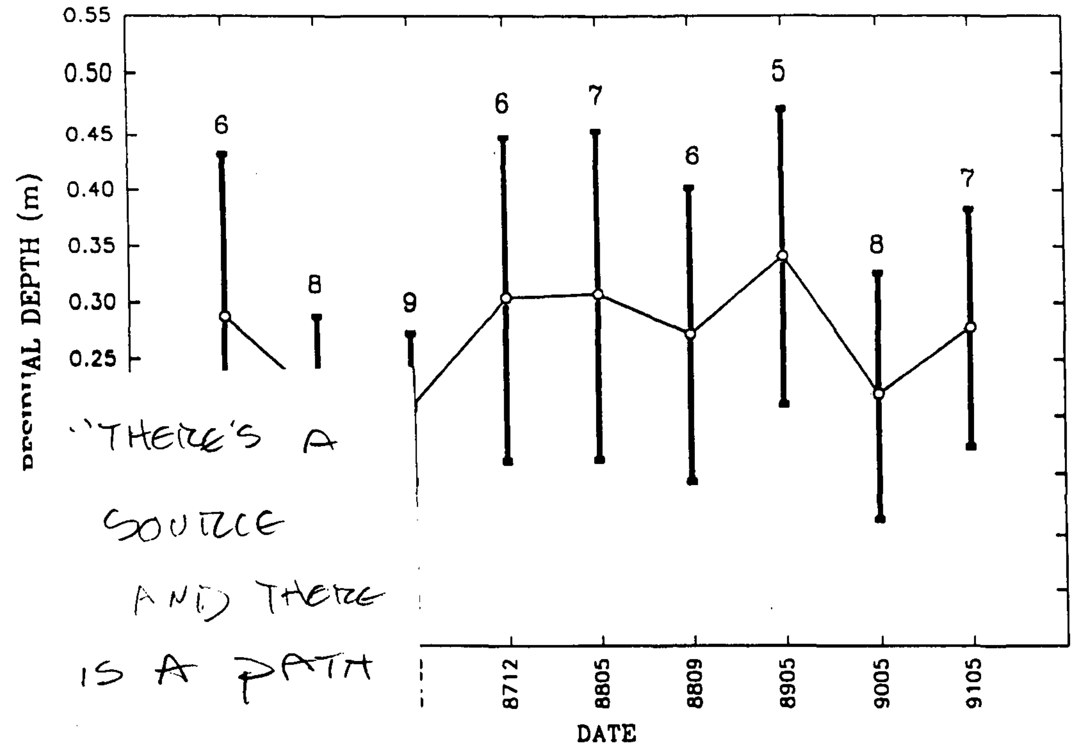


Figure 3. Pool spacing normalized by the mean bed width for each survey of Bambi Creek, southeast Alaska. Number of pools is given as well as 95 percent confidence interval estimates. Dates are given as year-month (yymm).



"THERE'S A
SOURCE
AND THERE
IS A PATH

Figure 4. Mean res **lweg for each survey of Bambi Creek, southeast Alaska. Number of pools**
is given as w **rval estimates. Only pools with residual depth greater than 0.1 m are**
included. Thi **ariation in the number of pools included. Dates are given as year-month**
(yymm).

In the Bambi Creek experiment, increased bedload transport and adjustments to the channel morphology, were attributable to: (1) elimination of woody debris buttressing of sediment storage sites in the channel bed and banks; (2) elimination of low-energy, backwater zones associated with woody debris; and (3) an inferred increase in boundary shear stress affecting grains on the stream bed resulting from removal of the woody debris component of flow resistance (Smith et al. 1993a, b).

Counteracting these factors favoring sediment mobilization was the loss of scouring turbulence created by interaction of the flow with LWD (Smith et al. 1993b). Following initial readjustment of the stream bed during the first post-treatment year, loss of debris-related turbulence resulted in increased sediment storage within the treated reach (Figure 5). This result was contrary to the common assumption that LWD promotes sediment storage (Megahan and Nowlin 1976; Swanson et al. 1976). Hogan (1987) found that in forest streams in the Queen Charlotte Islands, British Columbia, sediment storage sites were larger but less frequent in channels affected 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.

Increased sediment storage in Bambi Creek is plausible given a stream with sufficiently low gradient that alternate bars form. If LWD is added to such a channel, the resulting turbulence could be expected to cause net scour of bed material. In Bambi Creek, elimination of scouring turbulence allowed greater sediment storage than had been provided by debris buttressing and debris-related, low-energy microenvironments (Smith et al. 1993b). Conversely, at slopes greater than those at which bars form (commonly taken as 0.05 but varying with flow depth, grain size, and sediment fabric; Church and Jones 1982) large debris will likely promote sediment storage.

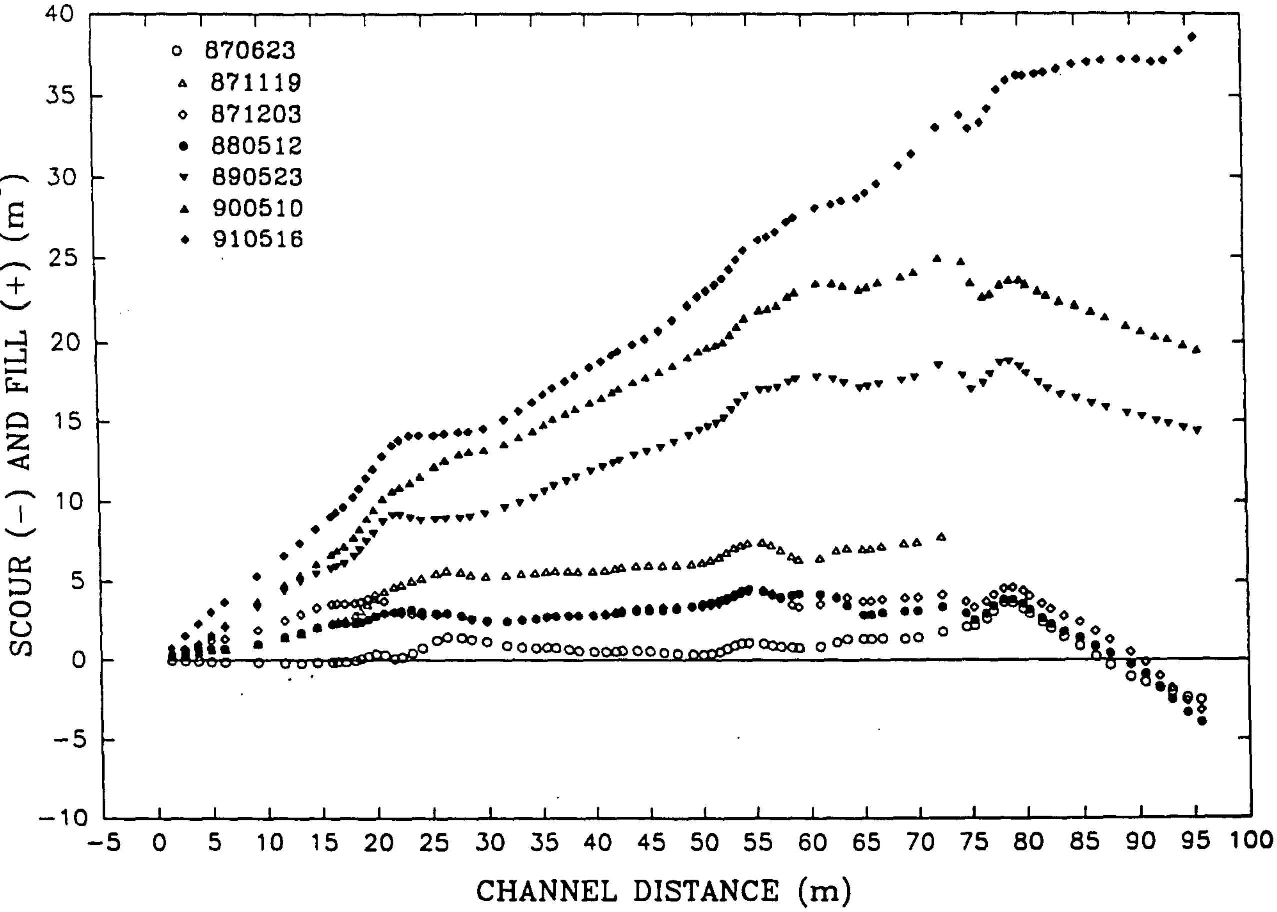


Figure 5. Cumulative change in sediment storage relative to the 870527 survey (datum) for Bambi Creek, southeast Alaska. 871119 was an incomplete survey. Dates are given as year-month-day (yymmdd).

Removal of debris did not result in any apparent change in bar or pool spacing, variability of pool spacing, residual pool depths, or distribution of depths (Smith et al. 1993b). These results were strongly affected by the random placement and characteristics of LWD prior to treatment. Other forest streams may have been more strongly affected depending on pre-treatment volume and characteristics of LWD. Furthermore, development of a bar-pool sequence in the absence of woody debris cannot be expected to occur in all streams. In high gradient channels where bar development is limited by shallow depth (Ikeda 1984), pool habitat may not be replaced by fluvial adjustment of the bed and banks.

OBSTRUCTION-POOL INTERACTIONS

Several recent studies have investigated interactions between large, in-channel obstructions and related pools and bed features. Sullivan (1986) investigated hydraulics and channel morphology in third- and forth-order forest, gravel-bed streams in western Washington. The characteristics of obstruction-created flow constrictions determined the hydraulic characteristics of associated pools, including the variation of velocity in the pool with discharge.

Lisle (1986b) noted that pools in obstruction-dominated streams were linked to obstruction location, and stationary obstructions tended to stabilize pool and gravel bar locations in a northwest California stream. The magnitude of channel constriction and obstruction orientation relative to the flow affected pool size and the stabilization of bars.

Cherry and Beschta (1989) conducted flume experiments investigating the characteristics of bed scour associated with obstructions. Position and orientation of obstructions and channel constriction created by the obstruction were found to affect pool depth, volume, and length of time required for scour.

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stable condition than in logged channels having fewer but larger storage sites generally upstream of debris jams. Smaller debris in logged streams led to formation of less stable debris jams. Reduced LWD loading in logged streams resulted in reduced variability of stream depth, channel width, and sediment texture (Hogan 1987).

Robison and Beschta (1990) evaluated interactions of LWD and channel morphology in a forest, gravel-bed stream in southeast Alaska. Time series analyses showed no periodicity of the longitudinal bed profile, indicating that spacing of pools was irregular and a function of the random spacing of LWD rather than a predictable function of channel size or discharge. Channel width and depth were both found to vary in an irregular way rather than to increase gradually along the channel.

In southwest Washington Bilby and Ward (1991) inventoried 70 stream reaches with variable management history. Compared to managed sites, old growth streams had more and larger LWD associated with a greater diversity of pool types and a greater percentage of plunge pools relative to scour pools.

Smith and Buffington (1992) measured characteristics of obstructions and related pools in several forested gravel-bed streams in southeast Alaska. Sites were approximately evenly distributed between pristine streams and streams clearly depleted of LWD either through forest management practices or experimentation. Multiple, rather than single, obstructions and associated pools tended to complicate relationships between pool and obstruction characteristics. A single obstruction, such as a large log, influenced the development of as many as five distinct pools. Conversely, as many as ten obstructions affected a single pool.

Preliminary results indicated that in pristine streams, where loading of LWD was generally greater, pools made up 48 percent of the wetted channel area (Smith and Buffington in press). In contrast, pools made up only 28 percent of disturbed streams. Scour around LWD obstructions created 80 percent and 46 percent of the pool area in pristine and disturbed streams respectively. In undisturbed streams single logs, rootwads, and debris clusters were by far the most common pool-creating types of obstructions. In disturbed channels non-debris obstructions, such as large boulders or resistant bank projections, played a greater role. However, LWD remained the most abundant type of obstruction. In these channels the few old-growth logs and stumps remaining after timber harvest played an important role in forming the larger, deeper, and more stable pools.

MECHANISMS OF POOL SCOUR

Several studies have investigated processes that maintain the morphology of pools not related to obstructions. The well-known shear stress (or velocity) reversal hypothesis attributes pool maintenance to a reversal in location of maximum boundary shear stress (or velocity) from riffles to pools as discharge increases to approximately bankfull (Leopold and Wolman 1960; Keller 1971). This results in scour and sediment transport through pools and deposition at riffles during high discharge. As discharge recedes, maximum shear stress is again present at riffles and fine sediment accumulates in the pools. The shear stress reversal model is consistent with the results of several studies (Leopold and Wolman 1960; Keller 1971; Lisle 1979; Sullivan 1986; Ashworth 1987; Dietrich and Whiting 1989).

Another approach to the problem of pool maintenance involves modeling the interactive adjustments of velocity, boundary shear stress, sediment transport, and water surface and bed topography in alluvial channels (Dietrich et al. 1979; Dietrich and Smith 1984; Dietrich and Whiting 1989; Nelson and Smith 1989a, 1989b). Studies of the more complex case of obstruction-related pools have not been done at this level of detail. In a gravel-bed stream in New Mexico, Dietrich and Whiting (1989) studied flow and sediment transport through a pool associated with a point bar in a meander bend, but unrelated to an obstruction. They found a reduction in cross-stream sediment delivery to the pool from the adjacent bar as increasing discharge reduced shoaling-induced cross-stream flow. The pool then scoured until the adjacent bar face became unstable, increasing sediment delivery to the pool, thereby maintaining an equilibrium pool depth. As discharge receded, shoaling-induced cross-stream flow increased bedload delivery from the bar to the pool, resulting in deposition in the pool until equilibrium was again achieved at lower flow. Shear stress reversal occurred as a result of the rapid increase in water surface slope at the pool during rising discharge (Dietrich and Whiting 1989).

SCOUR IN OBSTRUCTION-RELATED POOLS

Nearly all studies of the effects of LWD and other obstructions in forest streams observe that pools are commonly associated with in-channel obstructions. Indeed, obstruction-related pools are the rule rather than the exception in these small, gravel-bed streams (Keller and Tally 1979; Lisle 1986a; Robison and Beschta 1990). Mechanisms by which obstruction-related pools are formed and maintained are not necessarily the same as those for pools not related to obstructions. If hydraulic processes in these pools differ from those in non-obstructed flow, then patterns of channel morphology and routing of sediment in forest streams may differ substantially from streams in other environments.

Beschta (1983) conducted flume experiments investigating hydraulic conditions in obstruction-related pools. Obstructions created a wide variety of hydraulic environments ranging from zones of scouring turbulence to low-velocity, backwater areas. Pool depth and size were functions of complex interactions between obstruction diameter, obstruction position above the bed, and flume discharge. Flow underneath obstructions lying on the bed was an important scouring mechanism. For these cases, larger obstructions created deeper pools. For obstructions elevated above the bed, rate of increase in pool depth with discharge peaked when flow overtopped the obstruction.

Beschta (1983) reported that obstructions created zones of exceptionally high turbulence capable of scouring and removing gravel, even though temporal-mean, near-bed velocities indicated otherwise. This observation indicated that entrainment with rising discharge may be caused by an increase in obstruction-related turbulence rather than increased average shear stress; therefore the shear stress reversal mechanism may not be required to maintain pools formed by scour at obstructions.

Lisle (1986b) drew attention to the analogy of scouring, pool-forming processes associated with naturally-occurring obstructions to similar processes at bridge piers. This insight encouraged utilization of a very large quantity of laboratory research simulating fluvial scour around piers. In these studies, large-scale vortices were found to be the primary mechanism of local scour (Breusers et al. 1977). Downward flow in front of the pier induced a "horseshoe vortex" that wrapped around the pier near the bed (Tison 1961). Vortices with low-pressure centers were cast off from the pier, lifting mobile sediment from the bed with the generation of each vortex (Breusers et al. 1977).

Laursen (1962) described equilibrium scour conditions in pier-related scour holes as a balance of sediment discharge into and out of the scour hole. Increases in discharge resulted in increases in erosive force upstream of and in the scour hole, maintaining depth of scour. Bed material was mobilized by a combination of time-averaged boundary shear stress and turbulent agitation both ahead of the pier and in the lower portion of the scour hole (Melville 1975, 1984; Breusers et al. 1977; Melville and Sutherland 1988). Downward flow and vortices scoured pools at average shear stresses less than those required in the absence of obstructions (Tison 1961; Carstens 1966; Breusers et al. 1977). Bed scour near a pier was found to begin at velocities as low as 42 percent of the critical average velocity for material transport in the undisturbed part of the stream (Carstens 1966; Breusers et al. 1977).

Smith (1990) investigated hydraulic conditions in and around an obstruction-associated pool in a field setting by measuring boundary shear stress, scour and fill of the stream bed, bedload transport rate, and bedload grain-size distribution. Rate of increase with increasing discharge of the temporal-mean, near-bed velocity and boundary shear stress, computed from velocity, was statistically the same at the pool as at pool head and pool tail locations (Figure 6). There was no tendency for near-bed velocity or shear stress in the pool to exceed that at the pool head or tail for flows as large as 1.4 Qbf. In this respect, the pool clearly differed from pools not related to obstructions where the shear stress reversal model has been found to apply.

Scour and fill at this field site did not follow a systematic trend of pool filling at discharges below bankfull and scour at higher flows. Rather, scour and

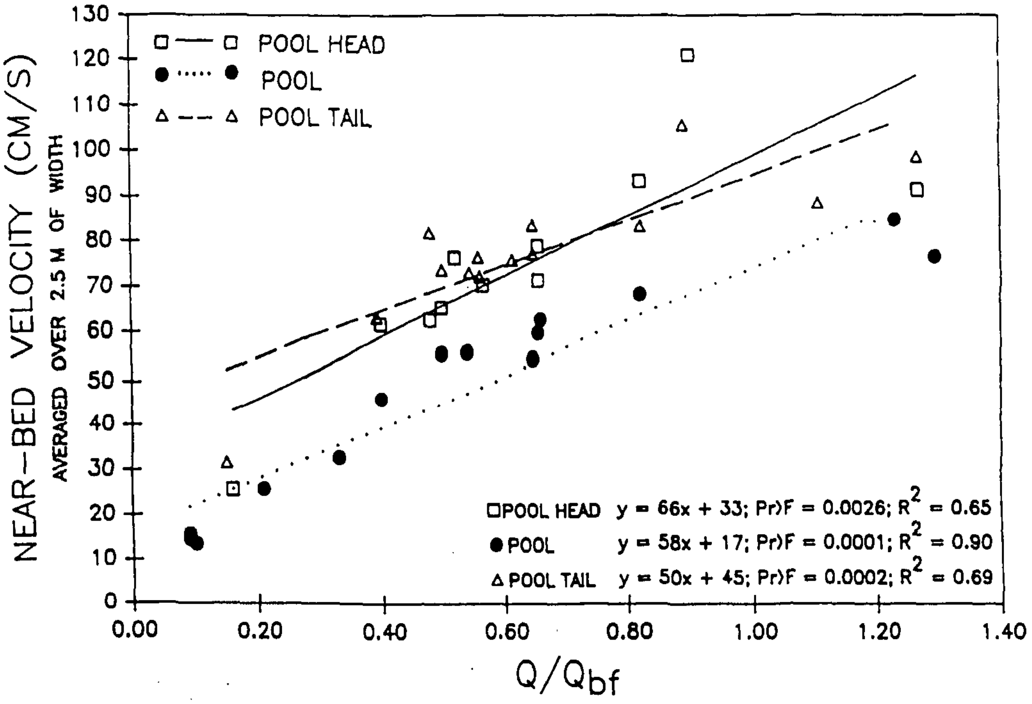

Figure 6. Variation in near-bed velocity with dimensionless discharge for Tom McDonald Creek, northwest California. Q is water discharge. Qbf is bankfull discharge (3.6 m3s-1).

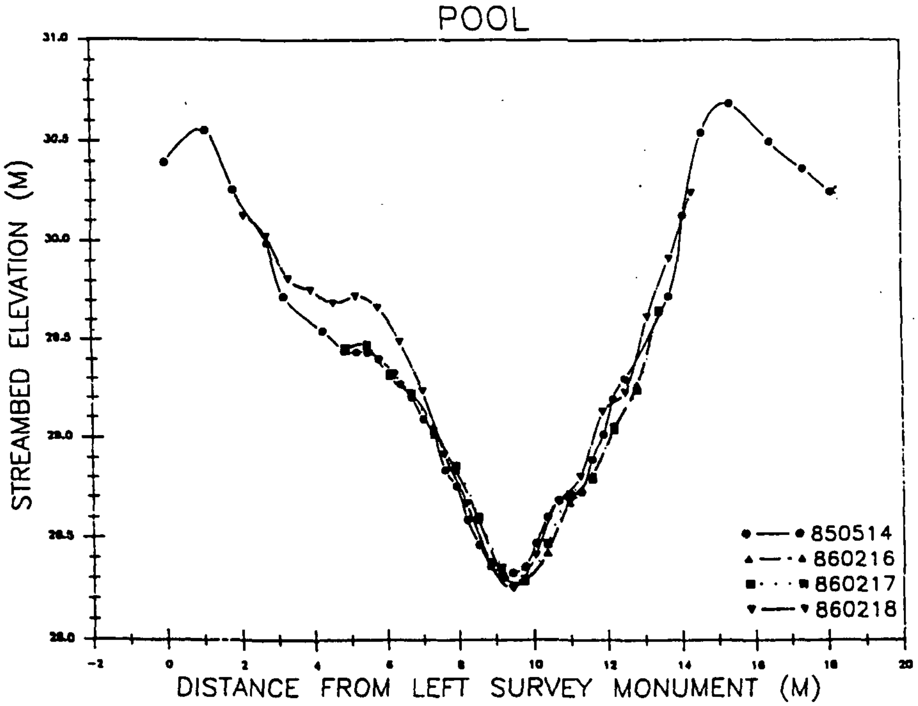

Figure 7. Cross-sectional soundings at Tom McDonald Creek, northwest California. Discharge at the time of the surveys ranged from less than 0.2 bankfull (850514) to greater than 3.5 bankfull (860217). Elevation is relative to an arbitrary datum. Dates are given as year-month-day (yymmdd).

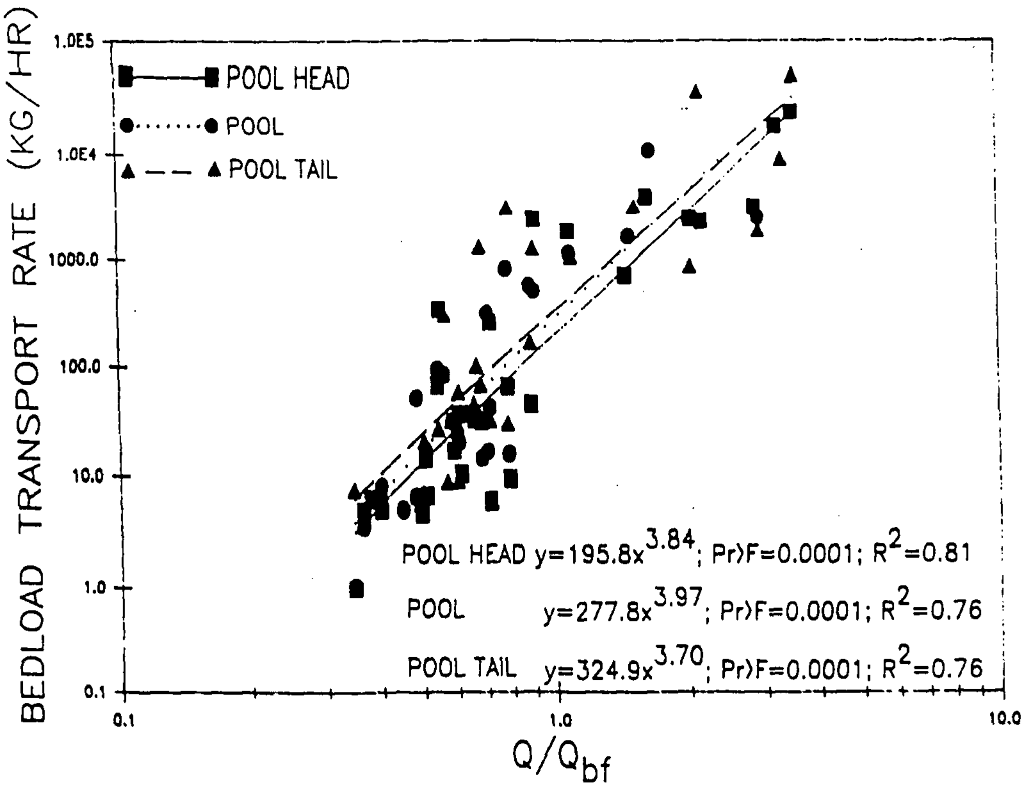

Figure 8. Variation in bedload transport with dimensionless discharge for Tom McDonald Creek, northwest California. Q is water discharge. Qbf is bankfull discharge (3.6 m3s-1).

fill occurred in response to inferred changes in sediment supply, throughout a wide range of discharge. Both scour and fill in the pool, calculated from soundings and from import and export of bedload, occurred well above and well below bankfull discharge in cycles varying in time from several minutes to several hours and on rising as well as falling hydrograph limbs. Scour pool morphology changed little in spite of large, sediment-transporting storms with an associated bedload flux much larger than the volume of the pool (Figure 7; Smith 1990).

No systematic spatial reversal of maximum bedload transport rate or of bedload competence with increasing discharge was observed, indicating that, through a wide range of discharge, total erosive force in the pool was similar to that at the pool head (upstream sediment supply section) and pool tail and that bedload was transported without discharge-dependent changes in pool storage (Smith 1990). The range in magnitude of bedload transport was similar, and Increase in bedload with discharge at the pool was not statistically different from increase at the pool head and pool tail (Figure 8). Competence was measured as the mean diameter of the five largest bedload clasts in each composite sample. Competence at the pool was not statistically different from that at the pool head or tail (Figure 9; Smith 1990).

Similarity of bedload transport rate and competence at the three cross-sections implied that total entrainment force at the pool was underestimated by time-averaged shear stress alone (Smith 1990). Therefore, mean stress in the pool must have been supplemented by additional tractive and lift forces resulting from instantaneous turbulent velocity fluctuations and vortices created by interaction of the flow with the LWD obstruction in a manner similar to flow around bridge piers. This combination of temporal mean shear stress and instantaneous turbulent forces created and maintained the pool at a site where a pool may not have formed in the absence of an obstruction. Smith (1990) summarized these hydraulic conditions as the conceptual "turbulent scour" model of pool maintenance. This model accounted for the observed balance, over time periods much shorter than the duration of individual storm hydrographs, of bedload import and export from the

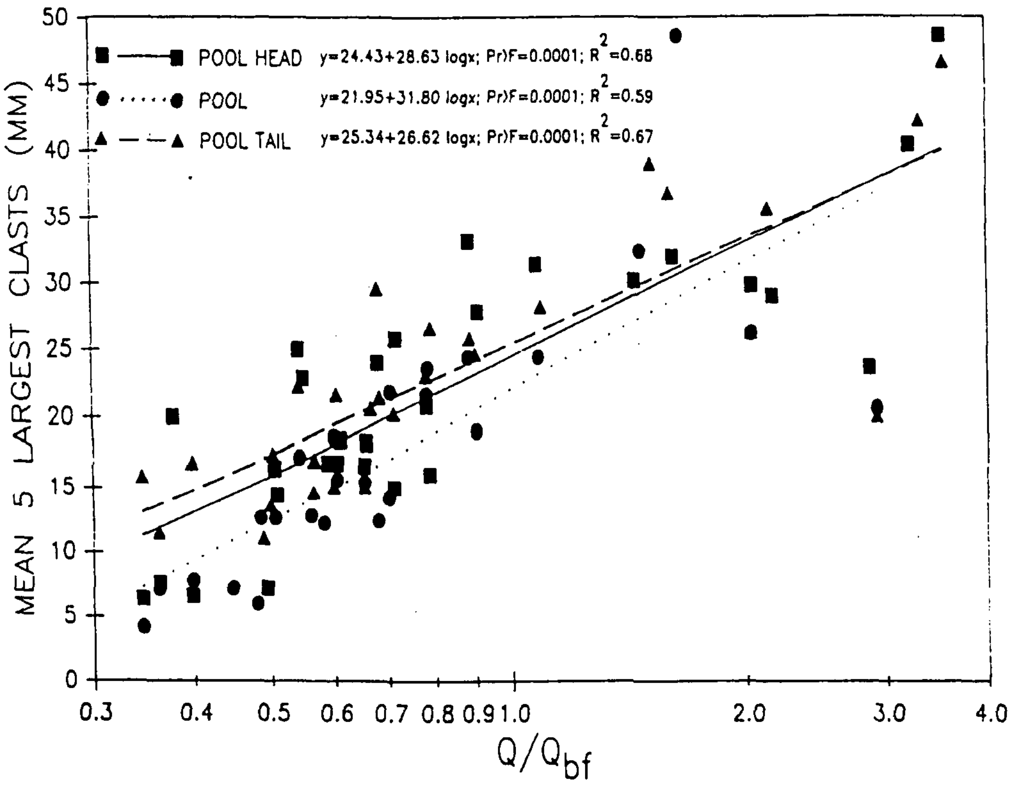

Figure 9. Variation in competence with dimensionless discharge for Tom McDonald Creek, northwest California. Competence was measured as the mean diameter of the five largest clasts in each composite bedload sample. Q is water discharge. Qbf is bankfull discharge (3.6 m3s-1).

pool, in response to apparent changes in sediment supply. This explained the approximately constant pool morphology despite bedload transport rates as large as 8300 kg hr-1m-1.

Application of the turbulent scour model to alluvial, gravel-bed streams in forested environments suggests that random input of LWD can be a dominant factor, perhaps as important as temporal-mean hydraulic variables and sediment grain-size characteristics, affecting local pool morphology and local bedload transport dynamics (Smith 1990). However, size and shape of LWD pieces and clusters in streams vary widely, as do geometric relationships of obstructions to scour pools. Extrapolation of results of this study to other obstruction-pool geometries is untested.

If the turbulent scour model describes a process widespread in forest streams, several related questions need to be addressed including; 1) In streams where LWD obstructions are common, is bedload transport initiated at lower shear stresses and, therefore, more frequently than in other streams?; 2) If transport rates are more dependent on sediment supply and less dependent on mean hydraulic variables, are commonly-used bedload transport equations likely to provide meaningful estimates?; 3) Does exogenous control of channel morphology and bedload transport, in the form of random input of LWD, decrease stability of channel morphology?; 4) Does it increase variability of bedload transport rates?; 5) Does cyclic scouring from obstruction-related pools contribute to commonly-observed pulses in bedload transport?; 6) What effect does the presence of LWD have on frequency, size, depth, and distribution of pools and gravel bars?; and 7) Are obstruction-related pools more likely to persist and recover quickly from high-magnitude sedimentation events, (i.e., do they decrease the sensitivity of streams to disturbance)? Understanding the answers to these questions and other geomorphic effects of LWD is vital to future management of forest lands, particularly with respect to understanding stream channel response to management impacts, assessment of stream sensitivity, prediction of cumulative watershed effects, and evaluating processes affecting aquatic habitat.

ACKNOWLEDGEMENTS

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Editors:

Dan Neary
USDA Forest Service
Rocky Mountain Forest
and Range Experiment Station
Flagstaff, New Mexico[1]

Kim C. Ross
USDA Forest Service
Tonto National Forest
Phoenix, Arizona

Sandra S. Coleman
University of Florida
Gainesville, Florida

---

[1] *Headquarters in Fort Collins, Colorado, in cooperation with Colorado State University.*

CONTENTS

(Continued)