RIVER RESEARCH AND APPLICATIONS

River Res. Applic. **18**: 507–531 (2002)

CONTROLS ON THE SIZE AND OCCURRENCE OF POOLS IN COARSE-GRAINED FOREST RIVERS

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ABSTRACT

Controls on pool formation are examined in gravel- and cobble-bed rivers in forest mountain drainage basins of northern California, southern Oregon, and southeastern Alaska. We demonstrate that the majority of pools at our study sites are formed by flow obstructions and that pool geometry and frequency largely depend on obstruction characteristics (size, type, and frequency). However, the effectiveness of obstructions to induce scour also depends on channel characteristics, such as channel gradient, width:depth ratio, relative submergence (ratio of flow depth to grain size), and the calibre and rate of bed material supply. Moreover, different reach-scale channel types impose different characteristic physical processes and boundary conditions that further control the occurrence of pools within a catchment. Our findings indicate that effective management of pools and associated aquatic habitat requires consideration of a variety of factors, each of which may be more or less important depending on channel type and location within a catchment. Consequently, strategies for managing pools that are based solely on single-factor, regional target values (e.g. a certain number of wood pieces or pools per stream length) are likely to be ineffective because they do not account for the variety of local and catchment controls on pool scour and, therefore, may be of limited value for proactive management of complex ecosystems. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: pool scour; flow obstructions; wood debris; forest channels; resource management; mountain drainage basins

INTRODUCTION

Pools are important components of physical habitat in lotic ecosystems, both for vertebrates (Bisson *et al*., 1982; Sullivan, 1986; Lonzarich and Quinn, 1995; Montgomery *et al*., 1999) and invertebrates (Huryn and Wallace, 1987; Wallace *et al*., 1995). Besides offering preferred habitat for some aquatic species, pools contribute to hydraulic complexity (habitat diversity) by providing end-member flow conditions of high depth and low velocity, particularly during low flow. Pool frequency and geometry (depth, surface area, and volume) can be used to evaluate and monitor channel condition (MacDonald *et al*., 1991; WFPB, 1993; FPC, 1996), and regional target values of pool attributes are widely used in channel assessment (USDA and USDI, 1994; USDA, 1995; NMFS, 1996). However, many factors can influence pool dimensions and frequency, including sediment load (Lisle, 1982; Madej and Ozaki, 1996), wood debris and other flow obstructions (e.g. Keller and Swanson, 1979; Lisle, 1986b; Montgomery *et al*., 1995), and channel geometry and bed material size (Montgomery and Buffington, 1997). A variety of land management activities can influence any number of these factors (McIntosh *et al*., 1994). As a result, interpreting cause-and-effect relationships for changes in pool size and frequency and choosing effective strategies to protect and restore pools can be problematic.

Pools occur in a variety of channel types including steep step–pool reaches and gentler pool–riffle and dune–ripple channels (Montgomery and Buffington, 1997). Although both pool morphology and the mechanisms of pool formation are quite variable, the requirements for pool formation in alluvial channels are similar: pools represent zones of local bed scour caused by convergent flow and macroturbulence capable

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Received 15 May 2001
Revised 24 January 2002
Accepted 1 February 2002

of mobilizing the bed surface material and transporting sediment away from that location faster than it is supplied. As scour proceeds, the scouring mechanism weakens until equilibrium is established between sediment entering and exiting the pool. In pool–riffle channels not greatly influenced by obstructions, scour commonly alternates with deposition downstream at wavelengths of several channel widths, thereby forming bar–pool sequences. Pools and bars are parts of the same macrobedform, and bars commonly form the control sections that pond pools. Therefore, factors that inhibit bar formation are likely to also inhibit pools.

Our purpose in writing this paper is to identify factors affecting pools in coarse-grained rivers (gravel-, cobble-, and boulder-bed channels). Our motive is to help managers interpret variations in pool dimensions and frequency within and among streams and to identify opportunities and limitations for maintaining pool habitat. We focus on mountainous, forested catchments with drainage areas typically less than 100 km^2 and containing channels that are small enough that land management could be expected to influence pools. In such channels, pools are commonly formed by scour around obstructions and bedrock-reinforced bends (Lisle, 1986b; Montgomery *et al.*, 1995). Our thesis is that both channel geometry and bed material load influence the effectiveness of obstructions to induce scour of pools. Some factors, such as channel gradient and the exposure and irregularity of bedrock that forms obstructions, are geologically imposed conditions that are relatively insensitive to catchment disturbances that occur over short time scales. Other factors, such as wood debris loading, sediment supply, and stream bank stability, can be influenced by land use activities that (1) alter routing of catchment products (water, sediment, wood debris), (2) change riparian vegetation, or (3) cause mechanical disturbance of the channel bed or banks, such as stream-bank trampling by livestock.

We examine relationships between pool characteristics (geometry and frequency) and controlling factors, including: the type, size, and frequency of obstructions; stream gradient and channel geometry; relative submergence (ratio of bankfull flow depth to median particle size, d_{BF}/D_{50}); and the rate and calibre of bed material supply. We present new data, but to be more comprehensive, we also review previous research and make some speculative arguments based on known channel processes and incomplete information. We compare the influence of factors affecting pool scour in different channel types. We also relate the occurrence of pools to reach-scale channel morphology and examine the physical controls on these morphologies. Finally, we discuss implications for management strategies.

STUDY SITES AND METHODS

Study reaches are in northern California, southern Oregon, and southeastern Alaska, and include gravel- and cobble-bed channels with drainage areas ranging from 1.1 to 520 km^2. Site characteristics and methods for measuring channel slope, surface grain size, and channel geometry are further described elsewhere (Lisle, 1986b; Marcotte, 1989; Lisle and Hilton, 1992, 1999; Woodsmith and Buffington, 1996; Buffington and Montgomery, 1999a). We present previously unpublished data for Hurdygurdy Creek, Indian Creek, and Thompson Creek, which drain parts of the Siskiyou Mountains in northern California. Techniques for measuring pool depth and volume are detailed by Hilton and Lisle (1993), and techniques for measuring obstructions are described by Lisle (1986b). Pool dimensions (maximum depth, d_{max}, surface area, and volume, V_{sp}) are residual values, that is, the downstream riffle crest defines their maximum elevation (Bathurst, 1981; Lisle, 1987). Scour depth (d_s) reported in the engineering literature is the maximum depth of scour below the original or ambient stream-bed elevation. We recognize that scour in natural channels may be truncated by resistant bed materials; nevertheless we assume that $d_{max} \sim d_s$ at least closely enough to make meaningful comparisons between measurements in natural pools and experimental values. Values of V_{sp} do not include volumes of fine sediment (sand and fine gravel) that are supply-dependent and tend to be scoured out of pools at high flow (Andrews, 1979; Lisle and Hilton, 1992, 1999), because they could confound relations between pool and obstruction dimensions. Fine-sediment volumes are measured with the procedure described by Hilton and Lisle (1993). Pool volumes were not measured at the Alaskan study sites.

Pools are topographic depressions; however, there is no widely accepted definition for the minimum size of a pool (Montgomery *et al.*, 1995). At our Alaska sites, we imposed minimum pool depth and width requirements that scaled with channel width. Topographic depressions were classified as pools if they were wider than one-tenth of the active channel width and if the elevation difference between the deepest point of the pool and the active channel margin was at least 5% of the active channel width (Woodsmith and Buffington, 1996). The California and Oregon studies tended to focus on the larger pools within a study reach (measurable pools were defined as having widths at least half the low flow channel width, and residual depths at least twice the water depth at the downstream riffle crest during low flow; Lisle, 1986b; Hilton and Lisle, 1993).

Pool volumes are scaled by channel dimensions in order to compare channels of different size: V_M* is the median value of V_{sp} for the reach divided by unit channel volume (the product of mean bankfull depth and the square of mean bankfull width: $d_{BF}W_{BF}^2$); total dimensionless pool volume (V_T*) is the total V_{sp} in a reach divided by the total channel volume ($d_{BF}W_{BF}L$, where L is reach length). V_M* is used to quantify the influence of reach-average dimensionless channel characteristics (slope, relative submergence, etc.) on pool scour, while V_T* is used to examine the aggregate influence of obstructions on pool scour within a reach. We also calculate a reach-mean standardized residual pool volume to compare pool volumes between different pool types. The standardized residual pool volume (V_Z) equals the value of V_{sp} for a pool minus the mean for all pools in the reach divided by the standard deviation.

Most of our reaches have incipient floodplain development; the elevation of this floodplain is taken as the bankfull elevation. In steeper channels, the average maximum active channel elevation is taken as the bankfull elevation.

To measure the total scour potential provided by the obstructions in a reach, we use total dimensionless obstruction area ($A_{OB}*$), defined as total vertical obstruction area within a reach (ΣBd_{OB}) divided by the bankfull longitudinal area ($d_{BF}L$). Obstruction width (B) is the average width of an obstruction below bankfull elevation projected onto the upstream cross-section (Lisle, 1986b). Average height of the obstruction (d_{OB}) is used here only for vertical obstructions (described below), and is measured from the channel bed up to the bankfull elevation. The ratio $V_T*/A_{OB}*$ is defined as obstruction effectiveness.

OBSTRUCTIONS AND POOL SCOUR

Obstruction Types and Scour Mechanisms

Various types of obstructions are responsible for forming many of the pools in gravel- and cobble-bed channels. We examine four types of natural obstructions and their associated scour mechanisms.

Vertical obstructions project steeply from the channel bottom and intersect the full depth of flow over some portion of the channel width. Based on analogy with engineering studies of scour around bridge abutments and piers, we divide vertical obstructions into two categories: lateral vertical obstructions (abutments) that project out from the channel bank, and isolated vertical obstructions (piers) that divide flow around them. Lateral obstructions (abutment-type) occur in natural channels as bank projections, bedrock outcrops, and debris jams that are sutured to one or both banks, while isolated vertical obstructions (pier-type) occur as rootwads, boulders, debris piles, and islands. The flow structure and resultant bed scour caused by vertical obstructions depends on the size of the obstruction, its shape (blunt versus streamlined), the angle of attack (direction that the flow impinges on the object), the surface roughness of the obstruction, and whether the obstruction is isolated (pier-type) or attached to the bank (abutment-type; Breusers *et al.*, 1977; Melville, 1992). For example, the proximity of abutment-type obstructions to the channel margin creates a near-bank eddy that damps the turbulence around the obstruction, reducing the extent of scour compared to that of isolated (pier-type) obstructions (Melville, 1997). Nevertheless, there are some basic similarities of flow and scour common to both types of vertical obstructions. For both abutment-type and pier-type obstructions, a vertical pressure gradient causes flow impinging against the upstream face of the obstruction to downwell, driving high-velocity water toward the bed upstream of the obstruction (Figure 1A). This downward flow, together with flow accelerating around the edges of the obstruction, initiates bed scour along its upstream edge. Flow separation upstream of the obstruction and over the lip of the scour hole creates a large-scale vortex close to the bed with a nearly horizontal axis wrapping around the upstream face of the obstruction (Figure 1A,B). In addition, wake vortices with vertical axes are shed from the downstream edges of the obstruction, circulating high-velocity flow behind the obstruction and out again. The vertical velocity gradient

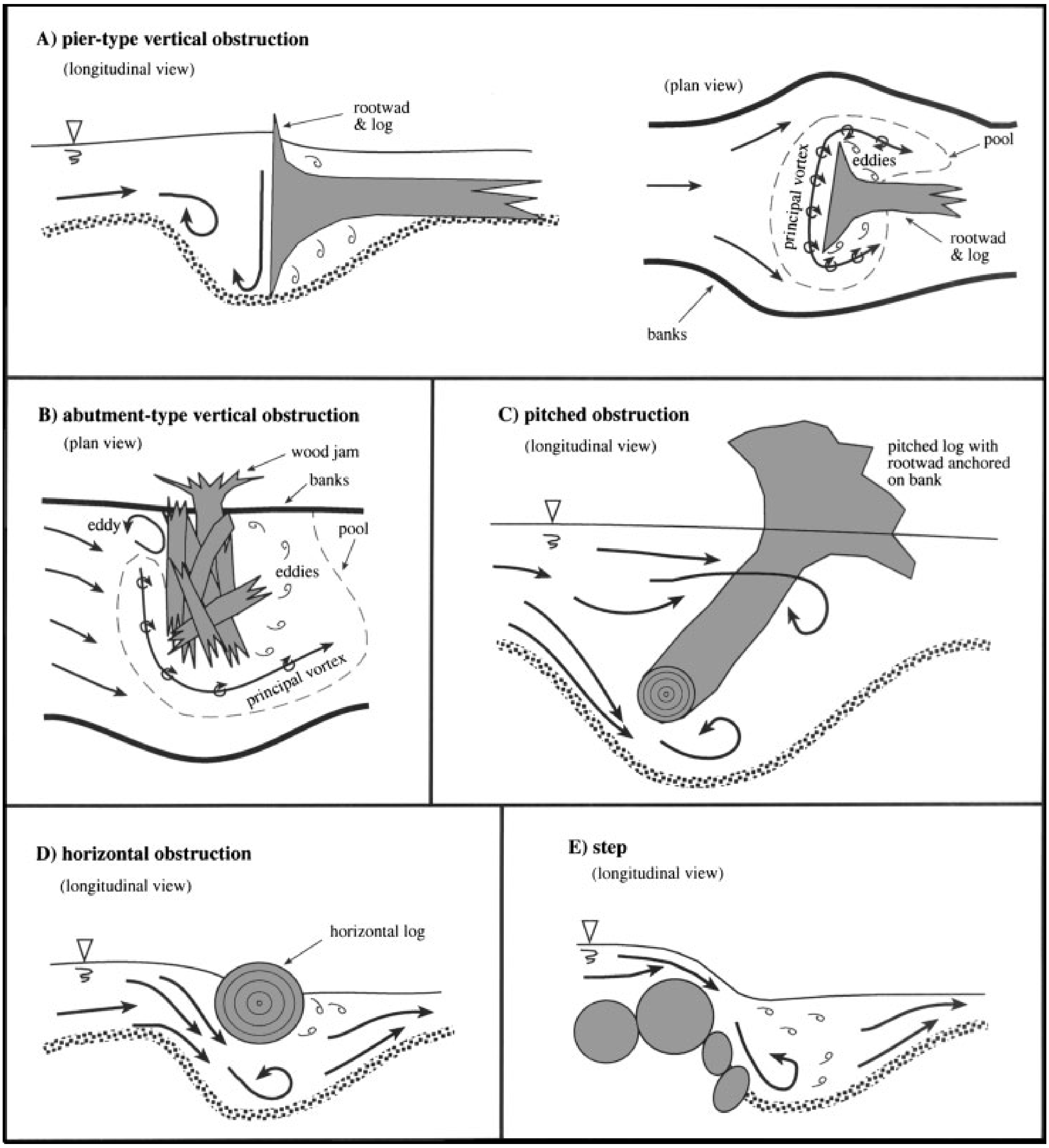

Figure 1. Flow structure and scour around each of the obstruction types examined in this study: (A) depth-spanning vertical pier-type obstruction; (B) depth-spanning vertical abutment-type obstruction; (C) pitched obstruction; (D) horizontal obstruction; (E) step

deflects the axes of the wake vortices from the vertical to the horizontal, producing another large-scale vortex opposite to the first. Together, these vortices scour the channel bed by advecting high-velocity flow downward and sweeping the bed surface of mobile sediment. Further details of the flow structure and scour around vertical obstructions are provided by Breusers *et al.* (1977), Melville and Raudkivi (1977), Melville (1997), and Thompson *et al.* (1998).

Pitched obstructions are typically logs that are canted at an angle to the water surface (Figure 1C). They may or may not span the full depth of flow and occupy some portion of the channel width. Like vertical obstructions they force local flow accelerations and shed turbulent wakes that scour the bed surface, but the flow structure around pitched obstructions is typically more complicated, with flow accelerating over, under, and around the obstruction. The magnitude and extent of scour due to pitched obstructions depends on opening ratio (flow-perpendicular width of an obstruction relative to channel width), log diameter, height above the bed, pitch from horizontal, and angle of attack (Cherry and Beschta, 1989).

Horizontal obstructions are typically logs that are fixed above the bed at a near-zero pitch and deflect flow downward against the bed (Figure 1D). Scour depends on local flow velocity (a function of flow constriction under the obstruction), angle of attack, diameter of the obstruction relative to flow depth, distance from the obstruction to the undisturbed bed, and turbulent vortices and bursts associated with the obstruction and its downstream wake (Beschta, 1983; Chiew, 1991). Horizontal obstructions differ from pitched obstructions by their predominantly downward advection of flow.

Steps formed by bedrock, boulders, or wood debris create low dams over which the flow spills, producing a converging jet that scours the bed below the step (Figure 1E; Chin, 1989). Scour is a function of jet energy (usually measured as the head drop or upstream water surface slope), unit discharge of the jet, size and sorting of the bed material, and flow depth. Scour is enhanced by dynamic pressure fluctuations, and secondary currents in the scour hole (Rajaratnam and Beltaos, 1977; Mason and Arumugam, 1985; Bormann and Julien, 1991).

When flow overtops horizontal obstructions, flow paths both under and over an obstruction are created and scour processes associated with both step and horizontal obstructions are present. These can interfere with one another, resulting in reduced scour or a reduction in the rate of increase in scour depth with increasing discharge. Laboratory studies indicate that scour depth is greatest for flow over steps, intermediate for flow under horizontal obstructions, and least for combined step and horizontal obstruction scour (Beschta, 1983; Uyumaz, 1988).

Each of the above obstruction types corresponds with standard pool morphologies recognized in channel unit classifications (e.g. Bisson *et al.*, 1982; Sullivan, 1986; Robison and Beschta, 1990; Church, 1992). Vertical obstructions typically form scour pools or eddy pools (both as defined by Sullivan, 1986), or if they span the entire channel width, a dammed pool may result (Sullivan, 1986). Pitched obstructions also typically form scour pools or eddy pools, while horizontal obstructions create underscour pools, and steps form plunge pools (step pools; Woodsmith and Buffington, 1996).

Large inventories of pools in gravel- and cobble-bed rivers of northern California and southeastern Alaska show that each of the above four obstruction types may form pools within a single reach, but typically the largest percentage of pools result from scour around near-vertical obstructions (Table I). Moreover, at our study sites most pools are formed by obstructions (rather than being self-formed) and a large proportion of the obstructions are created by wood debris, conditions that are commonly observed in forest channels (e.g. Zimmerman *et al.*, 1967; Keller and Swanson, 1979; Lisle, 1986b; Montgomery *et al.*, 1995).

Obstruction-forced pool scour

The basic mechanism of pool scour (flow convergence and turbulence) is common to all obstruction types. However, the orientation, structure, and strength of the scouring mechanisms differ with obstruction type. Consequently, there is no universal relationship between scour and obstruction dimensions. Rather, obstructions are scaled in different ways depending on obstruction type: vertical obstructions are measured by their flow-perpendicular width (Melville, 1997; Lisle, 1986b); pitched logs are measured by their opening ratio, diameter, angle of attack, height above the bed, and pitch (Cherry and Beschta, 1989); horizontal logs are measured by their diameter and height above the bed (Beschta, 1983); and steps are measured by the drop in water surface elevation created by the step (Abt *et al.*, 1984).

Scour caused by vertical obstructions

Much of our understanding of scour around vertical obstructions comes from research on bed scour at the base of bridge piers and abutments. The relationship between scour depth and the size of a vertical obstruction is regulated by flow depth, especially for vertical obstructions whose width is large relative to flow depth.

Table I. Channel characteristics

	Reach length (m)	Drainage area (km^2)	Slope	W_{BF} (m)	d_{BF} (m)	D_{50} (m)	Number of pools	Obstruction-formed pools (% of all pools)					
								Vertical	Pitched[a]	Horizontal	Step[b]	Wood	All obstructions
Northern California													
Jacoby	2600	36.3	0.0062	12.0	1.00	0.040	39	85	—	0	0	21	85
Hurdygurdy 1	4603	32.0	0.0148	38.4	1.59	0.128	90	81	—	0	2	8	83
Hurdygurdy 3	1491	—	0.0245	19.0	1.11	0.192	87	47	—	0	1	14	48
Thompson	278	27.0	0.0277	14.3	0.79	0.114	32	47	—	0	22	53	69
Indian	301	47.0	0.0405	8.1	0.75	0.153	65	38	—	0	9	29	47
Southeastern Alaska													
12 mi. 1	360	29.6	0.0021	23.34	1.05	0.0266	15	53	13	0	0	67	67
12 mi. 2	170	—	0.0028	22.47	1.10	0.0249	4	25	0	0	25	50	50
Maybeso 1	400	39.5	0.0095	22.31	1.24	0.0532	9	89	0	0	11	0	100
Maybeso 2	500	39.4	0.0065	29.12	1.10	0.0386	22	77	0	5	5	64	86
Maybeso 3	324	36.8	0.0024	27.07	1.11	0.0396	11	64	18	0	0	73	82
Maybeso 4	436	35.9	0.0036	24.48	1.12	0.0477	7	43	29	0	29	71	100
Cable	300	22.6	0.0017	16.89	0.96	0.0206	20	25	25	5	15	70	70
FUBAR 1	360	9.8	0.0106	17.84	0.66	0.0475	31	58	19	13	6	97	97
FUBAR 2	300	9.0	0.0127	16.32	0.85	0.0608	5	40	40	0	0	80	80
Indian	480	—	0.0122	24.60	1.32	0.0851	10	60	0	0	10	10	70
Muri	300	8.3	0.015	14.29	0.64	0.0535	8	38	13	13	13	75	75
Bambi	80	1.1	0.0102	4.60	0.32	0.0177	8	50	0	0	0	38	50
Hook	250	21.4	0.011	21.37	0.88	0.0319	42	36	17	24	19	93	95
Trap 1	165	10.2	0.0055	12.92	0.95	0.0178	43	40	16	21	7	58	84
Trap 2	220	10.1	0.0071	15.59	0.77	0.016	57	26	21	23	26	91	96
Trap 3	220	9.9	0.0093	11.84	0.66	0.0165	76	36	18	14	21	84	89
Trap 4	220	8.9	0.0088	9.67	0.76	0.0162	51	31	22	16	24	82	92
Trap 5	175	8.7	0.011	14.11	0.75	0.0212	35	37	9	20	26	80	91
Trap 6	200	8.3	0.012	15.76	0.78	0.0187	53	30	17	23	19	85	89
E Fk. Trap 2	172	5.8	0.0127	10.65	0.66	0.031	40	30	13	23	20	73	85
Fowler 1	225	20.9	0.0063	18.03	0.74	0.0185	25	24	4	36	16	76	80
Fowler 2	210	15.6	0.0054	11.46	0.83	0.0245	27	19	4	26	26	67	74
Fish 1	167	—	0.0267	19.18	1.33	0.0409	36	25	14	28	28	94	94
Fish 2	280	18.5	0.0224	12.88	0.60	0.0483	22	36	5	27	23	91	91
Greens	260	—	0.022	12.90	0.85	0.047	31	35	16	26	13	77	90
Weasel 1	161	7.7	0.0137	12.07	1.06	0.1012	16	31	19	25	19	63	94
Weasel 2	242	7.2	0.0025	15.10	1.01	0.0482	22	32	36	14	14	86	95

[a] Pitched obstructions were not inventoried at the California study sites.

[b] Wood steps only.

Obstruction width controls the width of the flow incorporated into the scouring flow structure, but the radius of the vertical flow structure is limited by flow depth. Therefore, engineers commonly scale scour depth (d_s) and obstruction width (B) by the depth of the approaching flow (h_0). Data from flume experiments on bridge abutments (Melville, 1992, 1997) show that for relatively small vertical obstructions ($B/h_0 < 1$), scour depth depends on obstruction width, and for large obstructions ($B/h_0 > 25$), scour depth depends on the approaching flow depth. In the intermediate range, scour depth depends on both obstruction width and approaching flow depth.

The relation between scour depth and obstruction width for 223 natural pools formed by vertical obstructions in gravel- and cobble-bed rivers is shown in Figure 2a. Our data fall almost entirely within Melville's intermediate range of obstruction sizes; therefore, we expect scour depth to vary with both obstruction size and

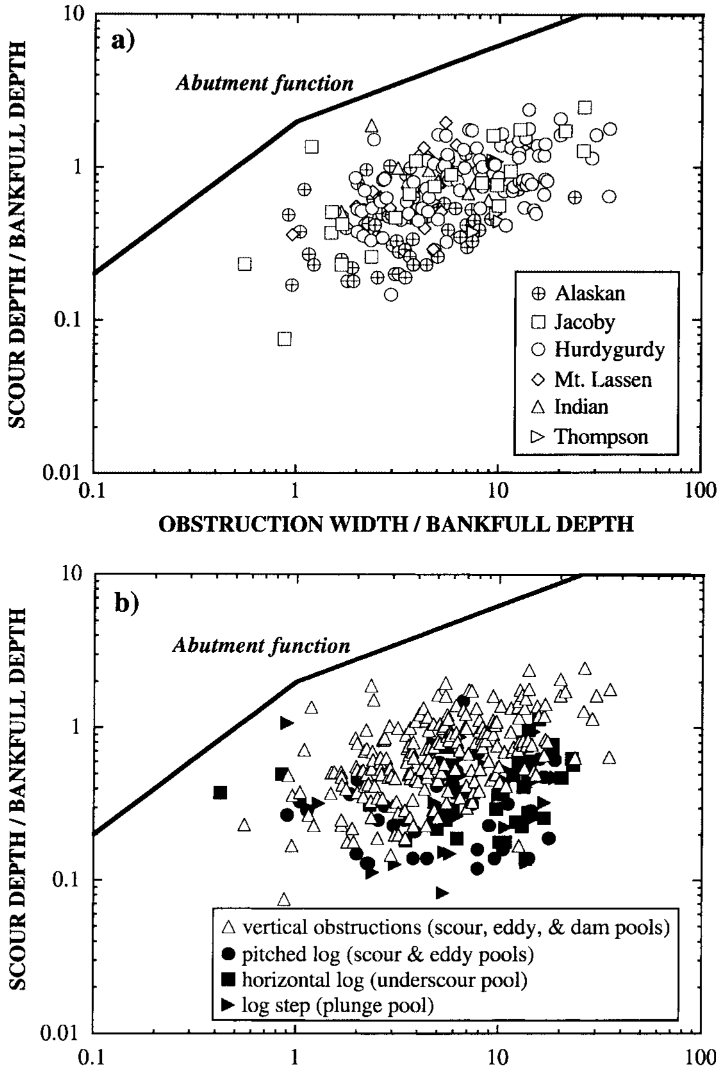

Figure 2. Relation between dimensionless obstruction width (B/d_{BF}) and dimensionless pool scour (d_s/d_{BF}). (a) vertical obstructions in northern California (mostly abutment-type obstructions) and southeastern Alaska (both pier- and abutment-type obstructions); (b) the former data compared to pitched, horizontal, and step obstructions in southeastern Alaska. The abutment function is for scour around a narrow, blunt-nosed, vertical abutment, with a 90° angle of attack and uniform-sized sediment at or above the threshold of motion (Melville, 1992, 1997). Inflections in the function correspond to transitions from small to intermediate obstructions and from intermediate to large obstructions

flow depth. Melville's function, which is an empirical upper limit for normalized flume data with uniform size sediment (see Figure 2 caption), plots approximately three to five times higher than the upper limit described by our data.

Frequently, natural pools are formed by a complex interaction of different obstruction types and scour mechanisms. To minimize this natural complexity and to isolate relationships between pool scour and obstruction dimensions, the data presented in Figure 2 are limited to pools formed by a single obstruction. These data represent a small proportion of the total number of pools inventoried at our Alaskan sites (21% of 876 pools sampled).

The large variability of scour at natural obstructions is probably due to variations in armouring, size and sorting of bed material, variable shapes and orientations of natural obstructions, and variable hydraulics of approaching flows. Nevertheless, the data from natural obstructions show a dependency of scour depth on obstruction width, which roughly conforms to experimental results (Figure 2a). In particular, the trend of the natural channel data has a slope (0.4) that is similar to that of the central portion of the Melville function (slope of 0.5).

The reduced magnitude of scour in natural channels can be attributed to several characteristics. (1) Natural channels typically contain numerous obstructions that can create significant form drag (Shields and Gippel, 1995; Manga and Kirchner, 2000; Buffington, 2001) and may cumulatively decrease approach velocities for downstream obstructions, thereby potentially reducing scour around them. (2) Natural obstructions also commonly have rough surfaces and complex forms that may impose greater frictional resistance and less scour compared to the smooth, simple obstructions used in the laboratory studies. (3) In contrast to Melville's normalized data, sediment sizes in natural channels are not uniform. Laboratory experiments demonstrate that obstruction-related scour depth decreases with poorer sediment sorting, as well as increasing sediment size (Melville, 1992, 1997). (4) The proportion of obstruction width responsible for flow disturbance and pool scour can vary in natural channels, making the effective width less than the total width of the obstruction (that which is plotted in Figure 2). For example, at our Alaskan sites we find that individual large obstructions can influence up to five different pools, with each pool associated with different portions of the obstruction. In this particular case, five different pools formed along the length of a large channel-spanning log and were not linked to one another (they did not share common heads or outlets). Use of the total obstruction width in cases such as this overestimates the effective width (that portion of the obstruction width actually responsible for the scour of a pool) and shifts the data in Figure 2 to the right, resulting in apparently less scour than observed for piers and abutments.

Comparison of scour caused by different obstruction types

Scour depth and surface area. Scour caused by vertical obstructions appears to be greater than that caused by other types of obstructions (Figure 2b). Vertical obstructions span the full flow depth (unlike the other obstruction types), and thus offer relatively larger obstruction areas and greater potential for flow disturbance and scour. We tested this hypothesis using ANOVA with the Tukey–Kramer multiple comparison procedure (Sokal and Rohlf, 1981). Data were transformed to $\log_{10}$ values to achieve normal, homoscedastic distributions.

Log_{10} mean dimensionless pool scour depth (d_s/d_{BF}) for vertical obstructions is significantly greater than that of all other obstruction types ($P < 0.001$), while there is no significant difference in $\log_{10}$ mean d_s/d_{BF} between the other obstruction types ($P > 0.10$). Following the same analysis procedures for the southeast Alaskan data, we find no significant difference in $\log_{10}$ mean dimensionless pool area (pool area divided by bankfull width squared) between the four obstruction types ($P = 0.68$). The latter analysis is restricted to the Alaskan data because pool surface area was not measured at the California and Oregon study sites.

Comparing scour between obstruction types is uncertain because the associated scour mechanisms and relevant obstruction characteristics differ. However, Beschta's (1983) experiments with horizontal obstructions provide information to draw a rough comparison between scour caused by horizontal obstructions versus that of vertical obstructions. In a narrow flume, he varied the discharge and the diameter and vertical position of horizontal circular cylinders ('logs') and observed depths of scour. Maximum scour depths of no greater than 1.5 times log diameter occurred when the flow just overtopped the log, regardless of log distance above the bed. Maximum scour depth achieved by horizontal obstructions in Beschta's experiments ($d_s/h_0 = 1.5$, where the water surface is at the top of the log) roughly corresponds to the maximum scour achieved by vertical obstructions at width-to-depth ratios (B/h_0) near 1 (Melville function, Figure 2a).

Pool volume. Of the four obstruction types examined, the scouring mechanisms of steps are most unique. However, we find no significant difference in pool volumes (V_{sp}) between step pools and bar pools that occur together in twenty study reaches in northern California and southern Oregon. In these study reaches, steps are formed by boulders or wood debris, while bar pools are part of bar–pool sequences and are most commonly formed at abutment-type obstructions or bends. The mean values of the standardized residual pool volumes ($\overline{V_Z}$) for each pool type for all channels indicated that step pools (−0.07) are smaller than bar pools (0.014) but the difference was not significant (one-tailed t-test, $P = 0.27$). Therefore, for this regional data set, pools formed below steps did not differ in volume from those formed at abutment-type obstructions, although, as stated above for our complete data set, we found dimensionless scour depth to be significantly greater for vertical obstructions.

Total dimensionless pool volume (V_T*) within a reach is positively related to the total dimensionless vertical obstruction area ($A_{OB}*$; Figure 3), further demonstrating the influence of obstructions on pool scour. These data show considerable scatter, probably reflecting differences in obstruction characteristics, channel geometry, slope, bed material size, and hydraulics of approaching flows. Similarly, other studies have found that the surface area of pools is directly related to wood debris volume (e.g. Bilby and Ward, 1989; Beechie and Sibley, 1997).

INFLUENCE OF CHANNEL MORPHOLOGY AND SEDIMENT LOAD

In addition to the effects of obstructions, pool scour is influenced by other channel characteristics and physical processes. For example, pool dimensions scale with drainage area (a surrogate for bankfull discharge; Figure 4), similar to well known hydraulic geometry relationships (Leopold *et al.*, 1964). Pool volume and unit channel volume ($d_{BF} W_{BF}^2$) increase at approximately the same rate with drainage area (Figure 4a), indicating that pools in small channels are not proportionally smaller or larger than pools in large channels. Similarly, pool scour depth and pool surface area increase with drainage area at rates comparable to those of bankfull depth and unit channel area (W_{BF}^2), respectively (Figure 4b).

Other channel characteristics that affect pool scour include gradient, width, depth, relative submergence, and the rate and calibre of sediment supply. These factors also influence reach-scale channel morphology which,

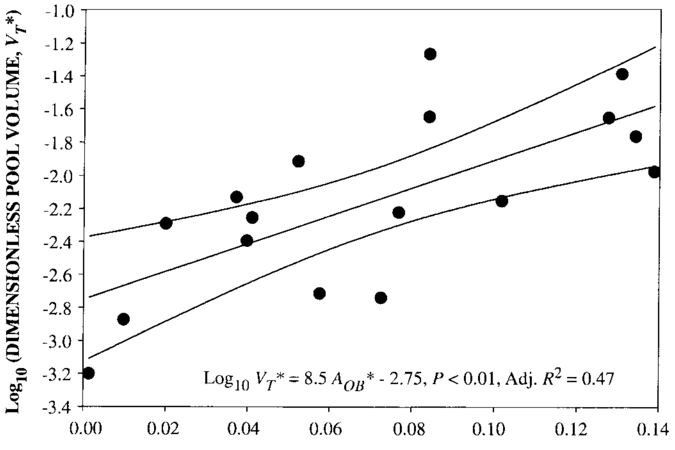

Figure 3. Total dimensionless pool volume (V_T*) as a function of total dimensionless vertical obstruction area ($A_{OB}*$) in reaches of Hurdygurdy, Indian, and Thompson creeks, northern California. Although both variables contain common terms (both are scaled by channel length and depth) there is a similar underlying relation between dimensional values of total obstruction area and total pool volume for these data. Log_{10} transformation yields constant variance and normal distribution of the dependent variable. 95% confidence-interval estimates are displayed

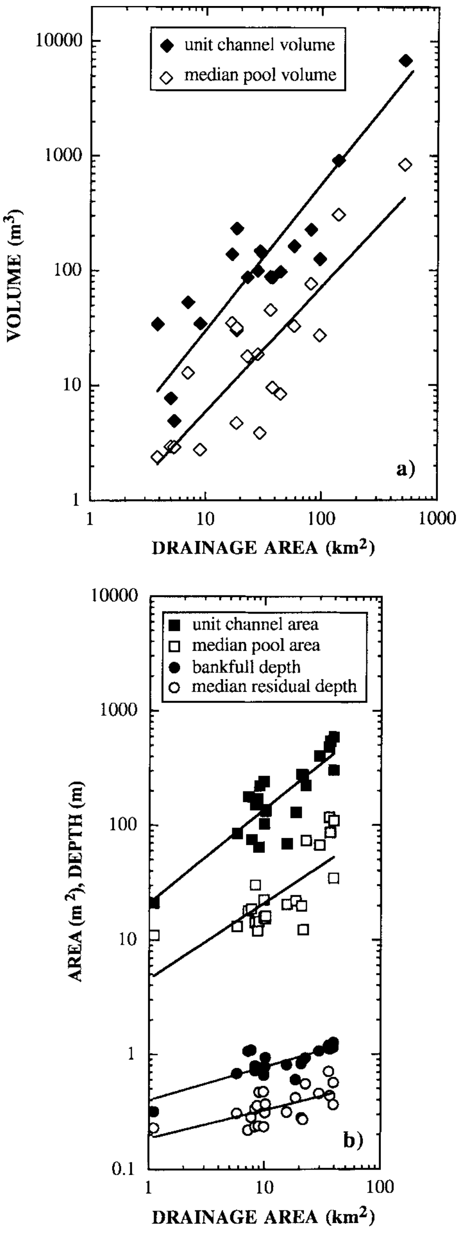

Figure 4. Pool and channel dimensions as a function of drainage area (a surrogate for bankfull discharge) for study reaches in (a) northern California and (b) southeastern Alaska. Unit channel volume in (a) is the product of bankfull depth and width squared ($d_{BF}W_{BF}^2$). Unit channel area in (b) is the bankfull width squared (W_{BF}^2)

in turn, imposes different characteristic physical processes and boundary conditions that further control the potential for pool scour. Here, we examine each of these factors.

Channel gradient and particle size

Steep channel gradients and associated coarse bed material apparently work together to diminish scour of pools at gradients greater than about 2%. Relative submergence (d_{BF}/D_{50}) is generally less for steeper channels. Therefore, steeper-gradient channels tend to have bed-surface particles that protrude further into the flow, inhibiting lateral flow oscillation and downstream patterns of flow convergence and divergence that are needed in the absence of obstructions to scour pools and deposit bars for a pool–riffle morphology. Greater particle protrusion also creates form drag that extracts fluid momentum and diminishes the boundary shear stress acting on the bed, decreasing the potential for bed load transport and pool scour (Andrews, 2000). Furthermore, as depth and maximum particle diameter converge, it becomes difficult to entrain and deposit one particle on top of another to form an incipient bar (Church and Jones, 1982). Church and Jones (1982) compute a corresponding lower limit of slope inhibiting bar formation at 2.5%, which approximately agrees with slope limits for bar formation identified in other studies (Kopaliani and Romashin, 1970; Kinoshita and Miwa, 1974; Florsheim, 1985).

Field and experimental data confirm that large particle size, relative to flow depth or obstruction width, inhibits scour. Experimental data show that greater median particle size decreases scour depth caused by vertical obstructions when the ratio of obstruction width to particle size is less than 25 (Melville, 1997). At our northern California study sites, we found that vertical obstruction effectiveness ($V_T*/A_{OB}*$) increases with greater relative submergence over the range $5 < d_{BF}/D_{50} < 30$ (Figure 5).

Field evidence also indicates that pool depth and volume are diminished on steep slopes. At our northern California and southern Oregon study sites, we found that both median pool volume and the fraction of bar–pools generally decreased with greater channel slope (Figure 6). Median pool volume scaled by unit channel volume (V_M*) varied widely at low gradients ($S < 2\%$) but became limited to low values at greater slopes, such that the upper limit of V_M* values decreased with increasing slope. Similarly, Wohl *et al.* (1993) found a downstream increase in the ratio of pool depth to riffle depth as slope decreases and discharge increases. Although pool volume is inversely related to channel slope, it is the bed material size and its covariance with slope that probably controls pool scour (Wohl *et al.*, 1993). Finally, bar–pool formation may be suppressed in steep channels because they are prone to convey debris flows that obliterate bar–pool sequences. The probability of debris-flow runout decreases downstream as stream gradient decreases below approximately 5% (Ikeya, 1981; Benda and Cundy, 1990).

Sediment load

The effectiveness of pool scouring mechanisms can be inhibited by large inputs of sediment, and mediated by the calibre of the input. The volume of sediment scoured from a pool is a dynamic balance between sediment entering a pool from upstream and the strength of the scouring flow structure to transport sediment through the pool. Transport capacity in the pool is modulated by both input rate and particle size of introduced sediment.

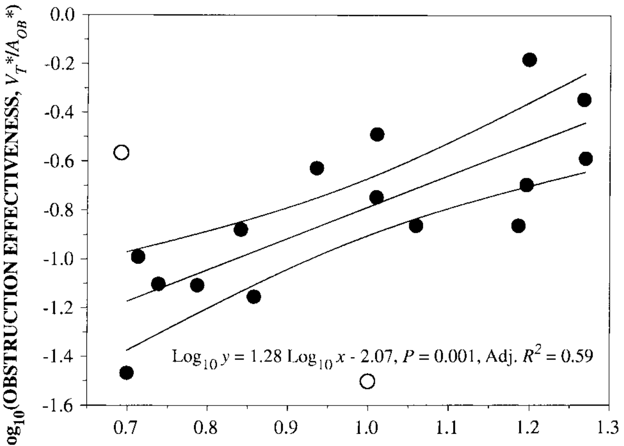

Figure 5. Relation between vertical obstruction effectiveness ($V_T*/A_{OB}*$) and relative submergence (d_{BF}/D_{50}) for study reaches of Hurdygurdy, Indian, and Thompson creeks, northern California. Logarithmic transformations accomplish constant variance and normal distribution of data. Two outliers (open circles) are not included in the regression because of excessive influence, based on a *t*-test of Studentized residuals

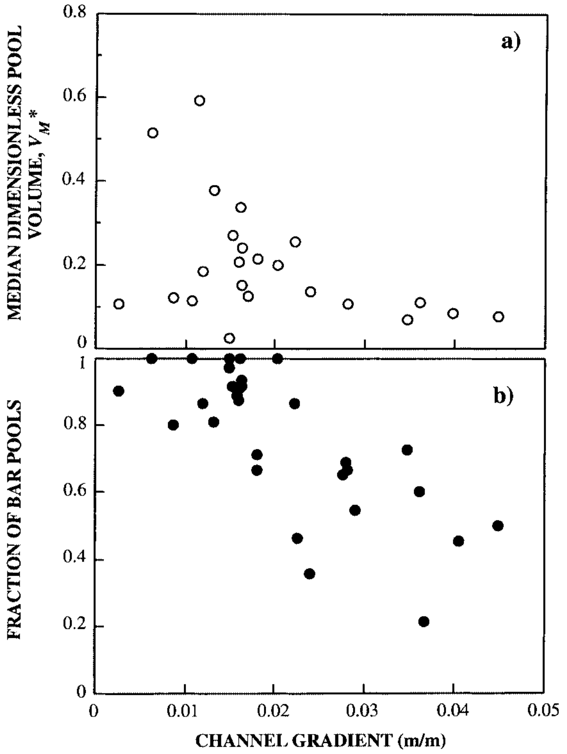

Figure 6. Relations between channel gradient and (a) median dimensionless pool volume (V_M*) and (b) fraction of bar pools for northern California and southern Oregon channels

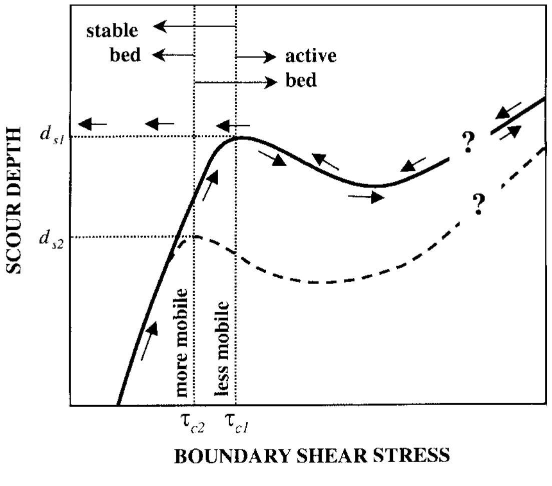

Figure 7. Conceptual model of scour depth around a newly placed obstruction as a function of boundary shear stress. Two cases are presented, one with a more mobile bed and lower entrainment threshold than the other ($\tau_{c2} < \tau_{c1}$). Maximum scour depth (d_s) is established at τ_c (the entrainment threshold for the upstream bed) and remains as flow decreases and transport ceases

The progression of scour and deposition around obstructions during various phases of sediment entrainment and transport can be illustrated by a conceptual model of scour that has been observed around modelled bridge piers in experimental channels (Chabert and Engeldinger, 1956; Raudkivi, 1990; Melville, 1997; Figure 7). Consider the progression of scour around a new obstruction placed in a channel as flow increases. Flow accelerations around the obstruction and turbulent eddies cast from it cause combined boundary shear stresses and lift forces in the vicinity of the obstruction to be greater than those upstream. As stage increases, local boundary shear stress around the obstruction exceeds the threshold for sediment transport, thereby inducing scour, while upstream stresses remain less than critical for sediment transport. As stage continues to rise, scour around the obstruction increases rapidly because sediment is transported out of the scour hole by the strengthening scouring mechanisms and no sediment enters the hole from upstream (rising limb of Figure 7; stresses less than critical for the upstream bed). Size-selective transport and associated bed degradation may enhance scour depths; however, selective transport may also armour the pool, making it more resistant to further scour. At steady flow, scour is limited by the decrease in local boundary shear stress in the pool as it deepens; continuity requires that the velocity and water-surface slope decrease across the pool as it deepens at steady flow, resulting in a decrease in boundary shear stress. Scour also may be limited by the adverse exit slope of the pool and the shear stress required to transport bed load up this slope and out of the pool. However, once sediment transport is initiated upstream and sediment enters the pool (τ_c in Figure 7), the equilibrium scour depth is less likely to continue to increase with increasing reach-average shear stress. Instead, scour depth may increase or decrease depending on variations in sediment transport to and from the pool.

To use this model to understand the influence of sediment supply on scour depth, it is instructive to make the simplifying assumptions that a definite entrainment threshold exists above which bed load transport is related to reach-averaged boundary shear stress by a constant function, and that equilibrium scour depth is maintained dynamically beyond the entrainment threshold. If so, regardless of variations in equilibrium scour depth beyond general entrainment ($\tau > \tau_c$ in Figure 7), the scour depth observed after the peak event (d_s in Figure 7) will be that achieved when the average shear stress decreases to the entrainment threshold of the upstream bed material (τ_c). Therefore, a decrease in the entrainment threshold ($\tau_{c2} < \tau_{c1}$) should result in a decrease in observed scour depth ($d_{s2} < d_{s1}$), because the equilibrium scour depth would be achieved at a shear stress when the scouring mechanism is weakened. The above argument assumes identical thresholds for sediment entrainment and distrainment (grain stopping). However, distrainment thresholds are typically less than entrainment values (Reid *et al.*, 1985). Consequently on the falling limb of the hydrograph, sediment transport and pool filling may continue to occur at shear stress considerably less than the critical value for incipient motion.

Changes in the supply and calibre of the sediment load can affect the entrainment threshold, and thereby affect scour depth according to this model. An increase in supply of bed material without a change in sediment calibre can decrease armouring and increase bed mobility (Dietrich *et al.*, 1989; Buffington and Montgomery, 1999b), leading to smaller scour depths according to the above model (Raudkivi, 1990). Limited field observations support this hypothesis; decreases in pool depth have been observed in natural channels with increased inputs of mixed bed load that result in greater bed load transport rates at lower flows (Lisle, 1982).

On the other hand, sediment starvation also may reduce pool volume. Bars form the structure of alluvially formed pools, and reduced sediment supply can reduce bar amplitude. In steep channels that have transport capacities greater than sediment supply, the occurrence of alluvium in which pools are scoured may depend on how recent are debris flow inputs (Benda, 1990) or channel-spanning log jams that form large sediment dams (Montgomery *et al.*, 1996a). Pool geometry in these channels may be limited by the thickness of deposited alluvium (i.e. depth to bedrock).

A decrease in sediment calibre without a change in input rate may also lower the entrainment threshold and fill pools. This effect has not been clearly documented except where inputs of fine bed material (commonly sand and fine gravel) are selectively transported and then deposited in pools at stages below the entrainment threshold of coarser bed material (Platts *et al.*, 1989; Lisle and Hilton, 1992, 1999). Two entrainment thresholds apparently regulate the residual volume of scour between peak flows: the higher threshold of the gravel armour controlling scour into the gravel bed material, and the lower threshold of fine material controlling scour into the fine layer covering the gravel (Jackson and Beschta, 1982). However, fine bed material may also affect the higher threshold as well, because increases of sand in a gravel–sand bed mixture can increase the mobility of the bed as a whole (Ikeda and Iseya, 1987; Whiting *et al.*, 1988; Wilcock *et al.*, 1999).

Inputs of selectively transported, relatively fine bed load apparently have modest effects on pool volume. The fraction of residual pool volume filled with fine sediment ($V*$) increases in lithologies that produce abundant fines as erosional products, but values of $V*$ greater than 0.4 are exceptional (Lisle and Hilton, 1999).

The conditions under which coarse inputs affect pool volume and frequency are poorly understood and may depend on local conditions (i.e. channel type and associated physical processes, geomorphic history, etc.). On the one hand, inputs of coarse material from debris flows and landslides can accumulate in pools and reduce pool volume, or they may increase form drag and diminish boundary shear stresses, thereby reducing scour potential. Moreover, large inputs of coarse material can lead to structural changes of the channel, such as channel widening, braiding, and aggradation, which are commonly associated with substantial reductions in pool volume and frequency (Lisle, 1982; McIntosh *et al.*, 1994). On the other hand, coarser material may increase the entrainment threshold of the channel, thereby enhancing obstruction-related scour (Figure 7; Raudkivi, 1990), or it may force local convective accelerations and turbulence that initiate or enhance pool scour.

In self-formed alluvial channels, hydraulic roughness provided by the amplitude and wavelength of bed forms (and thus pool geometry and frequency) may adjust toward an equilibrium between rates of sediment supply and bed load transport, thereby creating a stable channel morphology (Montgomery and Buffington, 1997). In a flume study of bed morphology and sediment transport in step–pool channels, Whittaker and Davies (1982) forced the locations of steps, but allowed pool scour to adjust to imposed water and sediment inputs. They found that pools were deepest for low equilibrium transport rates, but progressively filled as sediment supply was increased. Pool filling smoothed the bed and reduced the hydraulic roughness of the channel, increasing both the flow velocity and bed load transport rate, thereby providing a mechanism for equilibrating rates of sediment supply and bed load transport and creating a stable channel morphology. Similar changes in bed topography and channel roughness have been observed in natural gravel-bed rivers in response to episodic inputs of coarse sediment (Madej, 2001).

Channel widening

Channel widening is generally compensated by a decrease in depth at a given discharge, and given the dependency of local scour depth on ambient depth, a reduction in pool dimensions can be expected. Grazing exclosure experiments provide some of the clearest examples of the effect of changes in width and depth on pool dimensions because there are minimal differences in streamflow and sediment load between treatment and control reaches. Excluding grazing animals decreases channel width consistently and substantially, particularly in channels transporting enough fine sediment to rebuild banks (McDowell and Magilligan, 1997). In eight channels in eastern Oregon, bankfull width decreased 13–38% in six exclosures; one of the exceptional cases could be explained by the effects of beaver dams (McDowell and Magilligan, 1997). Low-flow depth increased 9–24% in six channels, pool area increased 6–88% in seven channels, and maximum pool depth increased 6–23% in six channels. In summary, post-grazing recovery of channel width is most often accompanied by increases in water depth, pool area, and pool depth (McDowell and Magilligan, 1997). Reduced bank strength from grazing may cause sections of bank to fail that would otherwise enhance scour by presenting resistant bank projections or sharp bends. Furthermore, failed and trampled banks may create a hummocky bank topography that generates form drag, thereby decreasing bed stresses and further reducing the potential for scour.

Reach-scale channel morphology

The foregoing channel characteristics (gradient, particle size, width, depth) are mutually adjusted for imposed conditions of valley slope, channel confinement, hydraulic discharge, sediment supply, and riparian vegetation and manifest common reach-scale channel morphologies or types (Rosgen, 1994; Montgomery and Buffington, 1997). For example, field data from a variety of rivers in western North America and Europe demonstrate that channel morphology varies systematically with channel slope, relative submergence, and width:depth ratio (Figure 8). Each channel type shows distinct, but overlapping, distributions of these factors (Figure 9). In addition to differences in channel gradient, grain size, and channel geometry, each channel type

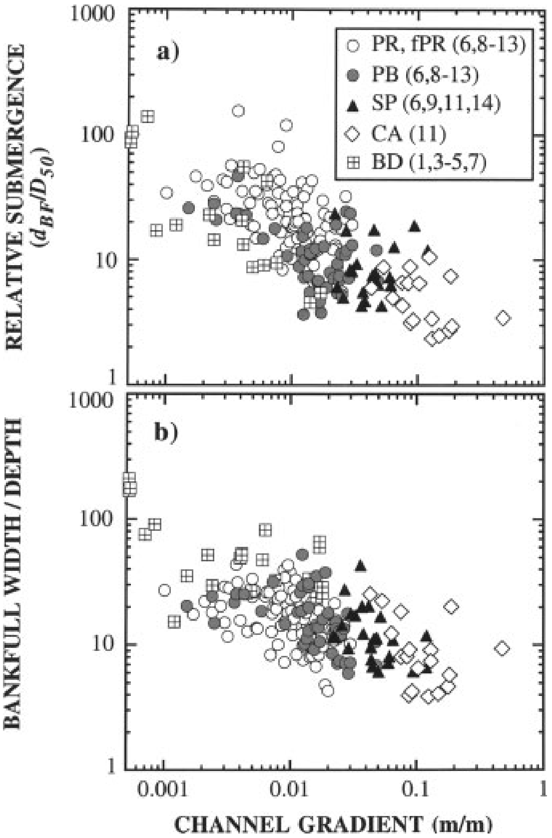

Figure 8. Slope versus (a) relative submergence and (b) width:depth ratio for pool–riffle (both self-formed (PR) and obstruction-forced (fPR)), plane-bed (PB), step–pool (SP), cascade (CA), and braided (BD) channel morphologies. Numbers in parentheses indicate data sources: 1, Leopold and Wolman (1957) (mean annual discharge); 2, Fahnestock (1963); 3, Emmett (1972); 4, Burrows *et al.* (1981); 5, Prestegaard (1983); 6, Florsheim (1985); 7, Ashworth and Ferguson (1989); 8, Buffington and Montgomery (unpublished data); 9, Montgomery *et al.* (1995); 10, Montgomery *et al.* (1996b); 11, Montgomery and Buffington (1997); 12, Buffington and Montgomery (1999a); 13, Montgomery *et al.* (1999); and 14, Traylor and Wohl (2000)

Table II. Relative influence of factors affecting pool scour

Channel type[a]	Supply of wood and other obstructions	Coarse sediment inputs	Fine sediment inputs	Bank disturbance, channel widening
Cascade (A:2-3)	low	low	low	low
Step–pool (A/G:2-3)	moderate	low	low	low
Plane-bed (B:3-4)	high	moderate	low	moderate
Pool–riffle (C/E/F:3-5)	high	high	moderate	high
Braided (D:3-5)	moderate	moderate	low	moderate

[a] Rosgen (1994) channel types that commonly correspond with those of Montgomery and Buffington (1997) are given in parentheses.

exhibits different characteristic physical processes (Montgomery and Buffington, 1997). Consequently, each channel type has different tendencies to form pools, and channel disturbances have various influences on pools depending on channel morphology. Here, we compare relative effects of (1) flow obstructions, (2) inputs of coarse and fine sediment, and (3) bank disturbance on the formation and scour of pools in different channel types (Table II).

Cascade channels are typically headwater channels in mountainous areas and generally have the steepest slopes and lowest relative submergence for alluvial channels. For this data set, cascade channels occur on

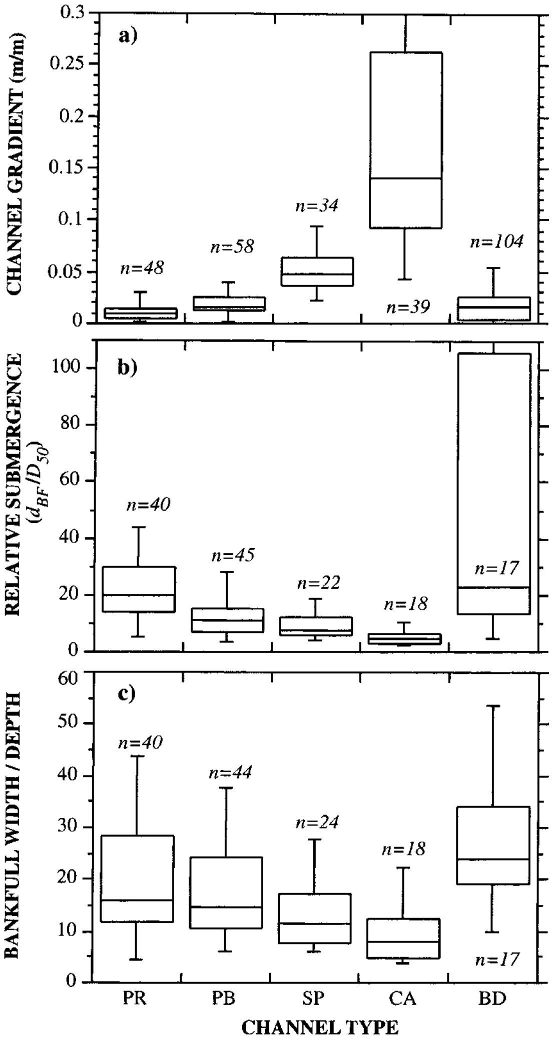

Figure 9. Distributions of channel slope, relative submergence, and width:depth ratio for data of Figure 8. Additional data from Fahnestock (1963) are also included here for gradients of braided channels. The line within each box is the median value of the distribution, box ends are the inner and outer quartiles, and whiskers are the inner and outer tenths; n is the number of observations

slopes >4% with maximum values of d_{BF}/D_{50} near 10 (Figures 8 and 9). Cascade channels are frequently confined by valley walls, with little to no floodplain, and are high-energy channels directly coupled to hillslopes. High densities of relatively immobile, boulder-sized clasts and significant particle form drag prohibit extensive pool scour in these channels; however small pools may occur locally below irregularly spaced boulder steps that span a portion of the channel width. Large bed material, resistant channel boundaries, and high transport capacities for cobble- to sand-sized bedload make cascade channels resilient to disturbance. Consequently, flow obstructions, sediment inputs, and bank disturbance have little effect on pools, if they exist.

Step–pool channels also typically occur high in the channel network at slopes of 2–9% or more and $d_{BF}/D_{50} < 20$ (Figures 8 and 9). Like cascade channels, they are commonly confined by valley walls and have high transport capacities. Step–pool morphology is characterized by periodic ribs of large clasts or logs that form step obstructions, creating a drop in water surface elevation and a vertical jet, which scours pools by turbulent, tumbling flow (Chin, 1989). The spacing and height of steps is believed to be adjusted so as to offer maximum hydraulic roughness and a stable bed configuration (Whittaker and Jaeggi, 1982; Abrahams *et al.*, 1995; Wohl *et al.*, 1997). Low relative submergence, which creates near-critical flow conditions, also is conducive to step–pool formation (Grant, 1997). Step–pool channels are susceptible to remoulding by debris flows; however, mobilized boulders quickly reorganize into steps and re-establish plunge pools (Sawada *et al.*, 1983). Following initial pool scour and selective transport, the remaining bed material is coarse enough to resist scour. Because of high transport capacities, all but the coarsest sediment inputs are likely to be routed quickly, and any resulting pool filling is likely to be short-lived (Schmidt and Ergenzinger, 1992). Because of channel confinement and resistant, bouldery banks, most channel disturbances are unlikely to cause significant channel widening and consequent changes in pool geometry.

Log steps are common in step–pool channels because they are usually small enough to retain wood (Wohl *et al.*, 1997). Loss of wood debris could result in loss of log steps or conversion to boulder steps (Heede, 1985). We hypothesize that pools are slightly more affected by disturbance in step–pool channels than in cascade channels, because large wood can form new steps and enhance others formed by large bed particles.

Plane-bed channels most commonly occur midway through the channel network at moderate slopes of 1–4% (Figures 8 and 9). They may or may not be confined by valley walls and have correspondingly variable floodplain widths. Low to moderate relative submergence (Figures 8 and 9) promotes development of plane-bed channels by inhibiting lateral flow oscillations that would otherwise create a pool–riffle morphology. Consequently, plane-bed channels generally lack pools and bars, except where locally forced by flow obstructions. Forced pools in plane-bed channels may be more sensitive to sediment inputs and bank disturbance than step–pool channels, but only moderately so. Bedload, especially fine material, is likely to be routed rapidly through these moderate-gradient channels. However, the steeper slopes generally characteristic of plane-bed channels (Figure 9) make them more susceptible than self-formed pool–riffle channels to passage of debris flows, which could fill pools and either add or remove pool-forming obstructions.

Pool–riffle channels occur low in the river network at slopes less than about 2–3% and typically have higher relative submergence than do plane-bed channels (Figure 9), which is consistent with our earlier argument that high relative submergence enhances pool development. Pool–riffle channels are characterized by a downstream oscillating pattern of flow that scours pools and deposits bars on alternating sides of the channel. Pool–riffle channels are commonly unconfined by valley walls and have floodplains that can buffer the channel from direct hillslope inputs and provide room to form meanders. Because of their low gradients, pool–riffle channels are likely to store sediment, and so would be sensitive to large sediment inputs, especially of coarse material. Alluvial banks are sensitive to trampling and loss of vegetation, and resulting erosion and channel widening could decrease pool volume or, in extreme cases, lead to channel braiding and development of a bar–riffle morphology with few pools.

Although, pools and bars are likely to form naturally in pool–riffle channels in the absence of extrinsic obstructions, obstructions may enhance pool frequency and volume and add complexity to pool habitats. Wood debris and other obstructions can create a forced pool–riffle morphology in channels that otherwise would have either a self-formed pool–riffle morphology or a plane-bed morphology (Montgomery *et al.*, 1995).

Braided channels occur across a broad range of slopes, and tend to have low relative submergence for a given channel gradient (Figure 8). Braided channels may be composed predominantly of bar and riffle morphology with few pools, or they may have a multiple-row, bar–pool topography. Width:depth ratios in braided channels are typically large (Figures 8 and 9), which may encourage lateral flow oscillation and development of a multiple-row, bar–pool or bar–riffle morphology, despite values of relative submergence generally less than or equal to those of plane-bed channels at comparable slopes (Figure 8). Periodic convergence of distributary channels in braided rivers can locally concentrate flow and may promote pool scour. As with pool–riffle channels, wood debris can enhance pool formation, but obstructions are less effective because of the limiting effect of ambient depth on obstruction-related scour. Consequently, flow convergence of distributary channels is responsible for relatively more pools. Large sediment inputs tend to increase braiding (Ashmore, 1991; Germanoski and Schumm, 1993) and form smaller, if more numerous, pools. Bank destabilization and consequent channel widening also may increase braiding (Millar, 2000).

POOL FREQUENCY AND AREA

In the absence of major obstructions, mean pool-to-pool spacing in alternate-bar channels is typically five to seven channel widths (Leopold *et al.*, 1964; Keller and Melhorn, 1978), but can be as low as three channel widths (Carling and Orr, 2000). However, the number of pools within a reach is often related to the frequency of obstructions that facilitate pool development (Montgomery *et al.*, 1995; Thompson, 2001). In forest, gravel-bed channels, high frequencies of wood debris can drive reach-averaged pool spacing to less than one channel width per pool (Figure 10). In contrast, pool spacing at low wood frequencies (<0.2 pieces per metre) depends less on obstructions and more on channel type and associated physical conditions. At low wood loading, plane-bed channels typically have higher pool spacings than pool–riffle channels (Figure 10), which is consistent with the low pool-forming tendencies of plane-bed channels, as described earlier.

The inverse relation between mean pool spacing and wood frequency is similar across different physiographic regions of northwestern North America (Figure 10). Nevertheless, values of mean pool spacing are quite variable for a given wood frequency. This variability likely reflects site-specific differences in scour potential caused by differences in channel characteristics outlined previously and varying size definitions of pools and wood debris. Despite differences in channel characteristics and how pools and wood debris are defined by different investigators, pool spacings of much less than five to seven channel widths, as expected in steams without obstructions, are commonly reported for pool–riffle channels in forested basins of western North American (Hogan, 1986; Nakamura and Swanson, 1993).

As the number of pools per reach increases with greater wood loading (Figure 10), the total pool area also increases (Figure 11), indicating that more wood obstructions create more pool scour and a greater total area of pools, rather than simply subdividing existing pool area.

DISCUSSION AND CONCLUSIONS: IMPLICATIONS FOR MANAGERS

To maintain and manage aquatic habitat provided by pools it is necessary to understand controls on pool formation and the relative importance of all factors that affect pools in each channel. Our examination of the relative influence of factors controlling pool formation in coarse-grained forest rivers indicates that the size, frequency, and type of obstruction exert the primary controls on pool geometry and frequency. However, the

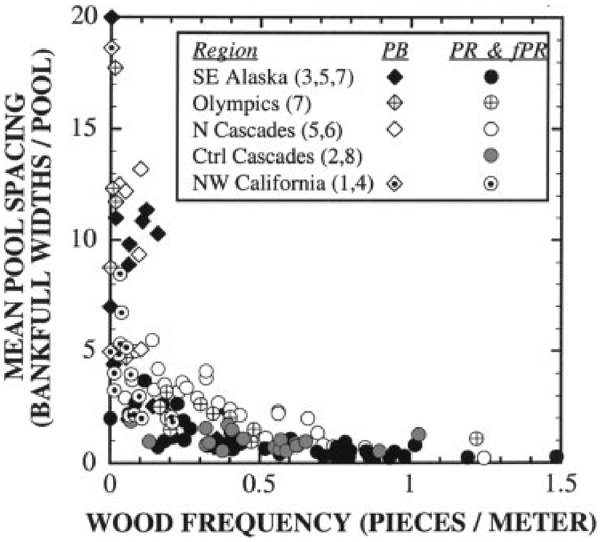

Figure 10. Pool spacing versus wood debris frequency for plane-bed and pool–riffle channels (both self-formed and wood-forced). Numbers in parentheses indicate data sources: 1, Florsheim (1985); 2, Bilby and Ward (1989) (slopes <2%); 3, Buffington and Montgomery (unpublished data); 4, Keller *et al.* (1995); 5, Montgomery *et al.* (1995); 6, Beechie and Sibley (1997) (slopes <2%); 7, Buffington and Montgomery (1999a); 8, Turaski (2000)

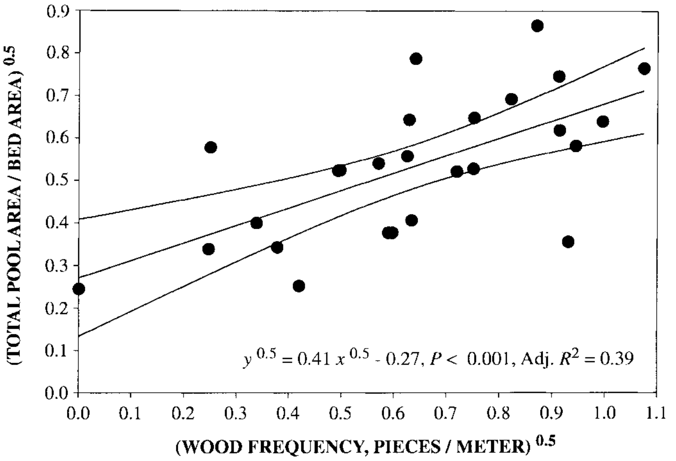

Figure 11. Ratio of total pool area to total bed area (proportion of channel area in pools) versus wood debris frequency for southeast Alaskan channels. Square root transformations yield constant variance and normal distribution of the variables. 95% confidence-interval estimates are displayed

effectiveness of obstructions to scour pools can be strongly influenced by the volume and calibre of sediment supply and by the channel type and associated physical processes and boundary conditions, including gradient and width of the channel, relative submergence, and width:depth ratio. Therefore, assessment of aquatic habitat should include not only information on pool size and frequency, but other channel characteristics as well; in particular, those that affect obstruction frequency and effectiveness.

Engineered scouring structures

The importance of obstructions for pool formation suggests that pool volume and frequency can be effectively increased by adding obstructions to channels where pool habitat is limited and where channel processes and boundary conditions are conducive to pool formation. However, our data also indicate that there are limitations to pool volumes obtained by adding structures. Large obstructions are required to create a major pool, and empirically derived relations between obstruction size and associated scour overestimate scour depth in natural channels (Figure 2). For example, to scour a pool whose maximum residual scour depth is equal to bankfull depth requires a vertical obstruction that extends above bankfull elevation and is as wide as approximately five bankfull depths (Figure 2). Engineered structures of this size can be quite expensive, particularly if a large number are desired and if the study site is in a remote location. Moreover, critical reviews of habitat enhancement projects that have employed engineered structures indicate a mixture of successes and failures (Reeves *et al.*, 1991), and in some cases ancillary disturbance of the channel during restoration has negatively impacted riverine ecosystems (Beschta *et al.*, 1994).

Wood debris

An alternative strategy to engineered structures would be to maintain a natural supply of obstructions (such as wood debris). Wood debris commonly forms the most abundant pool-scouring agents, especially in channels that are associated with riparian forests in late seral stages. Furthermore, a naturally functioning ecosystem, containing natural inputs of wood debris, is more likely to be biologically productive and diverse than one in which isolated stream improvements have been made to mitigate one of many disturbances within a given landscape (NRC, 1992). However, the size and stability of pools formed by wood debris is strongly dependent on wood size. As discussed above, large individual wood pieces or jams are required to scour major pools (Figure 2), and the stability of wood-scoured pools depends on wood piece size relative to channel size (Abbe, 2000; Braudrick and Grant, 2000).

Wood debris can also influence larger-scale physical processes that indirectly influence pools, such as channel meandering, avulsion, braiding, and changes in channel slope, width, and depth (e.g. Zimmerman *et al.*, 1967; Keller and Swanson, 1979; Hogan, 1986; Nakamura and Swanson, 1993; Piégay and Gurnell, 1997).

Large wood jams can have significant and long-lasting impacts on channel morphology (Hogan *et al.*, 1998). In steep, relatively narrow streams, channel-spanning wood jams can force alluvial reaches and aquatic habitat in channels that otherwise would be bedrock (Swanson *et al.*, 1976; Montgomery *et al.*, 1996a). In lower-gradient alluvial valleys, wood jams may influence rates and patterns of channel migration across alluvial valleys, control the development of side channels and forested islands, affect the frequency and magnitude of valley-floor flooding and wetland development, and influence the structure and composition of valley-floor forest patches (Bryant, 1980; Fetherston *et al.*, 1995; Abbe and Montgomery, 1996). Wood jams in lower-gradient channels also commonly scour pools that have larger and more variable depths than either free-formed pools or those formed by other obstructions (Abbe and Montgomery, 1996).

Land use activities can change the amount and character of wood debris supplied to a river, thereby potentially altering channel processes, morphology, and aquatic habitat (Lisle, 1986a; Bisson *et al.*, 1987; Murphy and Koski, 1989; Bilby and Ward, 1991; Beechie *et al.*, 2000). Channels flowing through forests in late seral stages typically have higher wood loadings that create a larger number and variety of pools, a greater spatial variability of flow depth and velocity, bed and bank topography, and bed-surface grain size, and a greater diversity of aquatic habitats than stream reaches intensely affected by timber harvesting (e.g. Woodsmith and Buffington, 1996; Hogan *et al.*, 1998; Buffington and Montgomery, 1999a). Land management practices that reduce in-channel wood and deforest riparian zones simplify channel hydraulics, bed and bank morphology, and aquatic habitat (e.g. Hicks *et al.*, 1991; Ralph *et al.*, 1994). Finally, loss of in-channel wood and riparian forests reduces hydraulic roughness of both the channel and floodplain and may result in more frequent bed load transport, higher rates of bank erosion, and increased potential for channel change in response to a given discharge event.

Relation between pools and channel morphology

An understanding of the relation between pools and larger-scale channel characteristics is essential for effective river management, including the maintenance and monitoring of pools and related channel features. As discussed earlier, the relative and absolute strength of factors influencing pool formation vary strongly between channels of different morphologies. Table II summarizes some of these salient differences. Because step–pool channels are relatively insensitive to all but the severest disturbances (e.g. debris flows), monitoring pools in these channels would probably yield little useful information for land managers. The supply of pool-forming obstructions in plane-bed channels is essential for maintaining pools, and indicates that the frequency and supply of large obstructions and associated pools are important monitoring targets. Because of the dominating influence of obstructions and a high transport capacity in plane-bed channels, sediment-sensitive pool parameters, such as residual volume and $V*$ (Lisle and Hilton, 1999), would probably show only modest and short-term response to moderate sediment inputs. Maintaining stream habitat in pool–riffle channels will require (1) preserving obstructions that enhance the volume, frequency and diversity of pools and (2) controlling factors that influence obstruction effectiveness, such as bank integrity and sediment supply. Monitoring pools and obstructions as part of an interdisciplinary linkage between watershed and riparian processes and aquatic habitat could provide useful information for adaptive management in these channels (Everest *et al.*, 1987).

Considering the variety of factors influencing pool geometry and frequency, even under undisturbed conditions, the use of standardized regional target values of pool parameters as measures of channel condition or habitat integrity requires careful evaluation. If a lack of pools is believed to be limiting populations of aquatic organisms in potentially complex lotic ecosystems, then all factors influencing pool formation warrant consideration, at both reach and watershed scales. Emerging critical factors, such as the supply of sediment or wood debris, can then become the basis for evaluating management practices potentially affecting pools and for developing adaptive management strategies. For example, if depleted wood debris is the critical factor, then measuring present and potential supplies of wood debris may be the most effective way to monitor conditions for maintaining pool habitat, rather than measuring pools themselves.

Consideration of all factors influencing pool formation may increase opportunities for proactive, rather than reactive, management. For example, by the time pool monitoring indicates reduced pool habitat was caused by depleted wood debris, it would be difficult to significantly reverse the trend within a scale of decades. In contrast, if an analysis of local factors that strongly influence pools indicates that pools are especially dependent on the supply of wood debris, measures such as setting aside wide buffer strips can be taken to protect the supply of wood debris likely to someday enter the channel. Such measures could be logically justified before pool habitats were lost. Identification of other controlling factors, such as sediment supply or mechanical damage to stream banks, might suggest different monitoring and management strategies. Moreover, channel type, associated physical processes, and relative influences of factors that affect pool scour also should be considered (Table II). For example, in a high-gradient channel with a natural absence of obstructions, low pool volume may be a natural condition, which would require extraordinary measures to 'improve'. Locations within a catchment where pools are likely to occur and where management efforts might be best focused can be determined from association of pools with specific reach-level morphologies which are, in turn, functions of channel slope, relative submergence, and width:depth ratio (Figure 8).

Finally, standardized regional targets may not encourage an interdisciplinary and adaptive management outlook. Pools are only one aspect of habitat complexity (end members of water depth and low velocity). Aspects of pools other than simple, easily quantifiable pool dimensions may also be important to lotic ecosystems. The factors that naturally favour pool formation, such as an adequate supply of wood debris, may best preserve overall habitat complexity.

ACKNOWLEDGMENTS

Financial support for J.M.B. was provided in part by the USDA Forest Service (cooperative agreement PNW 94-0617) and the National Research Council (USGS Research Associateship). Data collection in northern California was aided by S. Bowman, S. Garinger, C. Haluzak, M. Hansler, M. Manning, B. McGoldrick, M. Napolitano, R. Noyes, P. Phillips, A. Rohn, D. Sutherland, and S. Tordoff; and in southeast Alaska by J. Guldman, T. Henwood, S. Highland, K. Hocker, L. Morris, K. Schneider, E. Soderstrom, J. Teal, C. Veryzer, and D. Veryzer. Critical reviews by Alan Barta, Stephen Lancaster, Jack Lewis, Mary Ann Madej, and Doug Thompson improved earlier versions of the manuscript.

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