3. Fluvial Processes in Puget Sound Rivers and the Pacific Northwest

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Abstract

The variability of topography, geology, climate, vegetation, and land use in the Pacific Northwest creates considerable spatial and temporal variability of fluvial processes and reach-scale channel type. Here we identify process domains of typical Pacific Northwest watersheds and examine local physiographic and geologic controls on channel processes and response potential in the Puget Sound region. We also review the influence of different channel types on opportunities and limitations for channel restoration. Finally, we develop regime diagrams that identify typical combinations of channel characteristics associated with different alluvial channel types. These diagrams can be used to set target values for creating or maintaining desired channel types and associated habitats or to assess the stable channel morphology for imposed watershed conditions. Regime diagrams that are based on explicit physical models also can be used to predict likely trends and magnitudes of channel response to natural or anthropogenic disturbances (such as restoration activities). Moreover, spatial linkages of processes and the potential for distal disturbances to propagate through channel networks means that local restoration efforts that do not address larger scale watershed processes and disturbances may be ineffective or costly to maintain.

Introduction

Millions of dollars are being spent in the United States on river and stream restoration projects. In the Columbia River basin alone, the Bonneville Power Administration spent an average of $44 million a year on habitat restoration projects and related research during the 5-year period from 1996-2000 (BPA 2001). Now, a comparably ambitious program for river restoration is developing in the Puget Sound region driven by concerns over salmon recovery under the Endangered Species Act. Despite the enormous capital investment in such efforts—and the legal and social mandates that underlie them—channel restoration efforts throughout the Pacific Northwest remain largely uncontrolled experiments with little pre-restoration analysis and even less post-restoration monitoring and assessment. Consequently, it is difficult to assess the success of these projects and to advance restoration practice in a systematic fashion.

Restoration projects focused on fish habitat can be traced back at least as far as the 1930s in the United States (Reeves et al. 1991). Critical reviews of habitat restoration projects report a mixed record of successes and failures (Frissell and Nawa 1992; Beschta et al. 1994), due in part to (1) incomplete understanding of fluvial processes, (2) project designs inappropriate for local channel processes, and (3) a focus on local conditions without consideration of the larger watershed context. The latter consideration is particularly important for restoration planning because river channels integrate watershed processes and translate natural and anthropogenic disturbances downslope through the landscape. For example, it would make little sense to "restore" an equilibrium channel form to a channel poised to receive an increased sediment load from an upslope legacy of past disturbance. Consequently, a holistic understanding of channel and watershed processes is needed for effective management and restoration of riverine ecosystems.

Preconceived notions of natural channel conditions underpin many river restoration efforts. The public frequently has an idyllic image of natural channels as tree-lined, meandering gravel-bed rivers with high quality, abundant aquatic and riparian habitat. While environmentally and esthetically desirable, that sort of channel can be supported only under very specific physical conditions, which may be of limited extent in a given watershed. This chapter examines controls on channel morphology and fluvial processes typical of Pacific Northwest watersheds and reviews the influences of different channel types on opportunities and limitations for channel restoration.

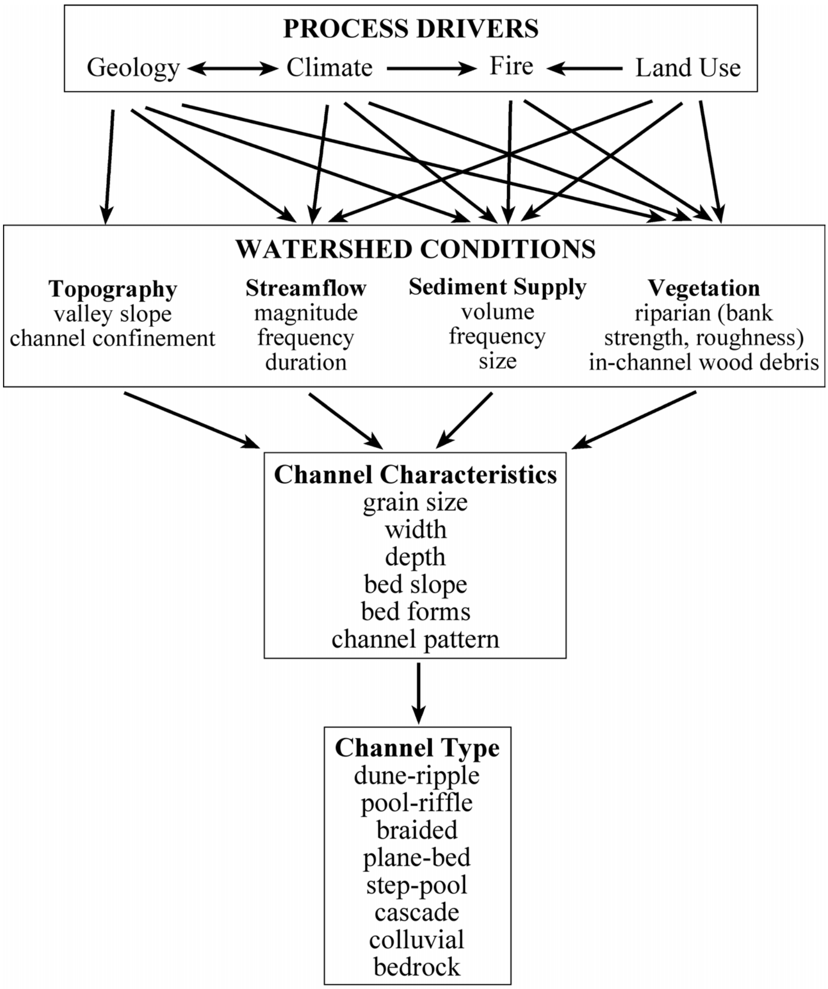


Figure 1. Controls on fluvial processes and channel morphology in Pacific Northwest watersheds. Arrows indicate interaction amongst different factors.

Controls on Channel Morphology

Physical processes within Pacific Northwest watersheds are driven by several primary factors: geology, climate, fire, and land use (Figure 1). These process drivers, in turn, impose a suite of watershed conditions on the fluvial system: topography, streamflow, sediment supply, and vegetation. The imposed watershed conditions influence channel characteristics: grain size, width, depth, bed slope, bed forms, and channel pattern. Mutual adjustment of channel characteristics for different combinations of imposed watershed conditions gives rise to different reach-scale channel types (or morphologies) that differ in habitat properties and resilience to disturbance. The sequential relationship between watershed conditions, channel characteristics, and channel type (Figure 1) has been recognized by many investigators (Mollard 1973; Schumm 1985; Kellerhals and Church 1989), but the role of differences in large-scale controls on channel conditions and response potential are not as widely recognized. In particular, the physiography and geologic history of a region may exert a dominant influence on channel processes and response potential (Chapter 2).

Physiography and Watershed Conditions

The Pacific Northwest contains several physiographic provinces (Figure 2) characterized by differences in process drivers and physical conditions. To-

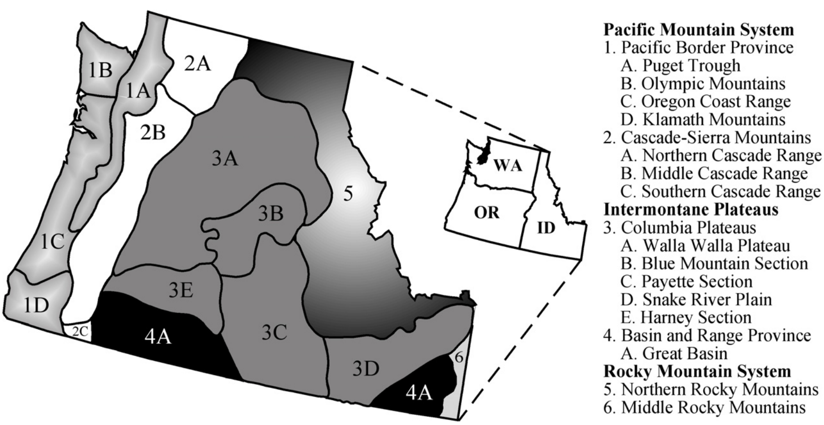


Figure 2. Physiography of the conterminous U.S. Pacific Northwest (after Powell [1896]). Fenneman's (1931) classification system is used to divide physiographic regions (bold items) into finer scale provinces (numbered items) and sections (lettered items).

pography in the Pacific Northwest varies from low-gradient glacial outwash plains of the Puget Lowland (north end of the Puget Trough) and basalt plateaus of the Columbia and Snake rivers to steep mountainous terrain of the Olympic Mountains, Cascade Range, and Northern Rocky Mountains. Rock types are equally diverse, including soft marine sediments, resistant basaltic lavas and metamorphic rocks, and granitic plutons that upon weathering produce large quantities of sand. Climate also varies from lush, coniferous rain forests on the western flanks of the Cascade Range to semi-arid, high elevation deserts east of the Cascades. Streamflow regimes range from the storm-driven winter flood regime west of the Cascade crest to the snowmelt-driven spring floods more typical east of the Cascade crest.

Even within the more restricted area of the Puget Sound, the diverse topography, geology, and glacial history of the region impart considerable spatial and temporal variability to fluvial processes through their influence on vegetation, sediment supply, and stream discharge (Chapter 2). The Puget Sound region can be subdivided into four physiographic sections: the northern and middle Cascade Ranges, the Olympic Mountains, and the Puget Lowland portion of the Puget Trough. The Cascade Ranges and Olympic Mountains, which together are defined here as the Puget Upland, are characterized by steep, mountainous terrain and rapid changes in slope over short length scales, giving rise to substantial spatial variability of channel morphology and fluvial processes within individual watersheds. In contrast, the Puget Lowland has relatively subdued topography in which local geology more strongly influences channel processes and response than do differences in slope. In mountain drainage basins of the Puget Sound region, and the Pacific Northwest in general, channel morphology typically ranges from steep, confined channels that are sediment-limited with boulder and bedrock beds (Figure 3a), to low-gradient alluvial channels that are typically unconfined and sediment-loaded, with sand and gravel beds (Figure 3b). The same suite of channel types occurs across both the Puget Lowland and Upland, but differences in watershed conditions and processes lead to very different conditions, dynamics, and responses between otherwise comparable channels. In particular, specific characteristics of Puget Lowland and Upland channels differ due to the huge supply of glacial sediment in the Puget Lowland and the inherited glacial lowland topography.

The range of channel morphologies found in Pacific Northwest landscapes can be related qualitatively to watershed conditions of streamflow, sediment supply, valley gradient, and channel confinement (Figure 4). Within this framework, physical domains can be identified for channels formed by fluvial versus mass wasting processes (domains 2 and 1 on Figure 4), bedrock versus alluvial channels (2b and 2a, respectively), and various alluvial chan-

A

B

Figure 3. Photographs of (A) a cascade channel (North Fork Payette River, Idaho) and (B) the confluence of a dune-ripple and a pool-riffle channel (South and Middle Forks of the Payette River, Idaho; photograph courtesy of Carter Borden).

nel types (within domain 2a). Characteristics of these alluvial channel types are summarized in Table 1 and further described elsewhere (Montgomery and Buffington 1997, 1998). Figure 4 provides a conceptual framework for the interactions between watershed conditions, channel characteristics, and channel type discussed previously (Figure 1). For example, greater valley slope and channel confinement create channels with steeper bed slopes, larger particle sizes, and lower width-to-depth ratios, giving rise to systematic changes in channel morphology (e.g., changes in alluvial channel type from dune-ripple through cascade morphologies).

Although not shown in Figure 4, riparian vegetation and in-channel woody debris can significantly influence channel characteristics and morphology. Woody debris and bank vegetation can alter channel hydraulics, rates of sediment transport, storage, and supply, grain size, bed and bank topography, bed slope, and channel width, depth and pattern (e.g., Hogan 1986; Bisson et al. 1987; Smith et al. 1993a,b; Keller et al. 1995; Buffington and Montgomery 1999a; Abbe 2000). By modifying channel characteristics and local watershed conditions (streamflow, sediment supply, and topography), riparian vegetation and woody debris can force different alluvial channel types in

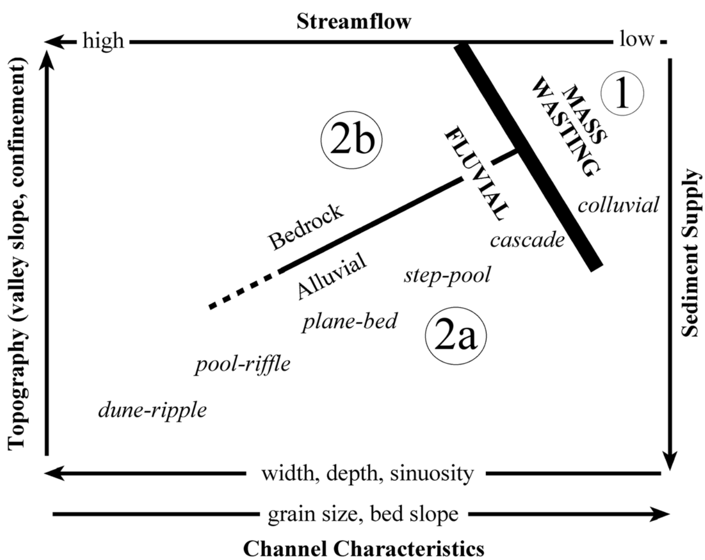


Figure 4. Influence of watershed conditions (streamflow, sediment supply, and topography) and channel characteristics on channel reach morphology (after Mollard [1973]). Numbered items indicate process domains: mass wasting (1), fluvial (2), alluvial channels (2a), and bedrock channels (2b). See text for further discussion.

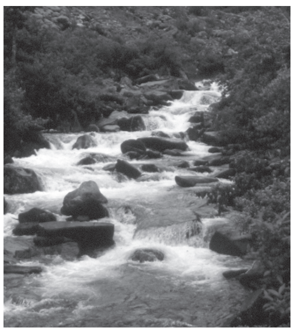
Table 1. Alluvial channel types

Type, Typical Slope (m/m), and Bed Material	*Description*
 dune-ripple, <0.001, sand	Low-gradient, unconfined, sand-bed rivers occupying large alluviated valleys and typically decoupled from hillslopes. Variety of mobile bed forms (ripples, dunes, sand waves, plane-bed, and antidunes) that depend on Froude number and transport intensity. Well-defined floodplain morphology with a bankfull recurrence interval of roughly 1-2 years. Bankfull discharge also is the effective discharge (that which transports the most sediment over the long term). Transport-limited, with a low threshold for bedload transport (ratio of bankfull shear stress to critical stress for incipient motion [τ/τ_c] is on the order of 10-100).
 pool-riffle, 0.001-0.02, gravel and cobble	Alternating pool and bar topography caused by oscillating lateral flow that forces local flow convergence (pool scour) and divergence (bar deposition). Moderate- to low- gradient, unconfined channels, with coarse bed material and typically extensive floodplains. Two-phase bedload transport, characterized by supply-limited transport of fine grains over an immobile armor during low flows, and transport-limited motion of most available particle sizes during high flows that mobilize the armor. Bankfull discharge is the effective discharge and has an approximately 1-2 year recurrence interval. Potential for extensive salmonid spawning and rearing habitat.

Table 1. Alluvial channel types (continued).

Type, Typical Slope (m/m), and Bed Material	*Description*
 plane-bed, 0.01-0.4, gravel, cobble, and some boulder	Long reaches of glide, run, or riffle morphology lacking significant pool or bar topography. Low width-to-depth ratios and moderate values of relative submergence (ratio of bankfull flow depth to median particle size) damp lateral flow oscillations that would otherwise create an alternate bar morphology. Susceptible to obstruction-forced pool formation. Moderate-gradient channels with coarse bed materials and variable floodplain extent. Bed surface is typically armored, with a near-bankfull threshold for significant bedload transport (τ/τ_c is on the order of 1). Two-phase transport. Bankfull discharge is likely the effective discharge, with an approximately 1-2 year recurrence interval. Potential for extensive salmonid spawning habitat.
 braided, <0.03, sand to boulder	Multi-thread rivers with large width-to-depth ratios and moderate slopes. Individual threads may have a pool-riffle morphology or a bar-riffle morphology lacking pools. Pool scour commonly occurs where braid threads converge. Braiding results from high sediment loads or channel widening caused by bank destabilization. Braided channels in the Pacific Northwest commonly occur 1) as glacial outwash channels, 2) in locations overwhelmed by a locally high sediment supply, 3) in alluvial valleys where banks have been destabilized by riparian cutting or livestock trampling, or 4) in semi-arid regions with insufficient riparian vegetation to stabilize banks composed of cohesionless sediments.

Table 1. Alluvial channel types (continued).

Type, Typical Slope (m/m), and Bed Material	*Description*
 step-pool, 0.02-0.08, cobble and boulder	Repeating sequences of steps and plunge pools formed by wood debris, resistant bedrock, or by boulders that accumulate either as kinematic waves or as macroscale antidunes. Steep-gradient, confined channels, with little floodplain development, and directly coupled to hillslopes. High transport capacities that efficiently transport cobble- to sand-sized material on an annual basis. Amplitude and wavelength of steps and pools may be adjusted to maximize hydraulic resistance and stabilize channel form. Alternatively, hydraulic roughness provided by bed topography may be adjusted so as to equilibrate rates of sediment supply and bed load transport capacity, thereby providing a mechanism for channel stability. Quality of pool habitat depends on plunge pool geometry and associated hydraulics. Limited salmonid spawning extent (backwater environments and pool tails).
 cascade 0.04-0.25 boulder	Chaotic arrangement of boulder-sized bed material and continuous macroscale turbulence. Typically confined by valley walls and directly coupled to hillslopes. Steep gradients and relatively deep, concentrated flow allow efficient transport of cobble- to sand-sized sediment during annual floods, but movement of the channel-forming boulders requires infrequent large floods. Little sediment storage due to shallow depth to bedrock and lack of floodplain development. Limited salmonid spawning sites (channel margins and backwater environments). Infrequent, turbulent pools of small volume.

portions of the landscape where they would not otherwise occur (Montgomery et al. 1995; 1996a; Montgomery and Buffington 1998).

Relative differences in the role of fluvial versus hillslope processes and the extent of bedrock versus alluvial control on channel characteristics naturally divide Pacific Northwest channel systems into three generalized process domains (headwater channels, confined channels in steep valleys, and unconfined alluvial channels in low-gradient valleys) (Montgomery 1999). However, differences in physiography and geologic history cause channel processes and response potential to differ between similar process domains in Lowland and Upland channels of the Puget Sound.

Headwater Channels in the Cascade Range and Olympic Mountains

Channels and valleys in headwater regions of the Puget Upland are characterized by steep slopes and are strongly influenced by hillslope processes, particularly mass wasting. Sediment shed from hillslopes gradually accumulates to form colluvial wedges in topographic hollows and valley fills along ephemeral streams in headwater valleys (Dietrich et al. 1982, 1986). Fluvial sediment transport in these colluvial channels is weak and ineffective (Montgomery and Buffington 1997), and consequently these channels are shallow surficial features that do not significantly influence valley form and landscape evolution. Instead, headwater valleys are maintained by catastrophic failure of accumulated colluvial soils during storm events. The resulting debris flows typically scour downslope colluvial channels to bedrock before depositing a slug of sediment once they reach slopes of 3° to 6°, encounter objects they cannot entrain, or lose momentum rounding tight corners through the channel network (Benda and Cundy 1990). Soil-mantled hillslopes are particularly susceptible to failure following loss of vegetative root strength due to fire or timber harvest. Root strength offered by vegetation is a primary factor holding soils on steep slopes in many Pacific Northwest landscapes (Schmidt et al. 2001). Depending on the recency of debris flow activity, headwater valleys may host either colluvial or bedrock channels.

Headwater Channels in the Puget Lowland

Unlike their counterparts in the Upland, headwater channels of the Puget Lowland are commonly very low gradient, originating on glacial till-mantled plateaus that perch shallow groundwater and locally support lakes or wetlands as the upstream-most expression of surface water. Sediment delivery to these headwater reaches is slow, and even in free-flowing reaches the stream power is very low, limiting both sediment transport and development of alluvial channel morphology. In the 13,000 years since deglaciation, these channels have accomplished little modification of this topography, but their morphology can be quite responsive to changes in either discharge or sediment loading as a consequence of watershed disturbance. Increased discharge, a typical result of urban development, commonly results in channel expansion and offers the potential of far more catastrophic incision farther downstream where gradients steepen (Booth 1990). Increased sediment loading, from either urban or agricultural activities, can result in rapid aggradation of headwater channels. The hillslope processes common in headwater mountain drainage basins of the Pacific Northwest, notably debris flows, rapid stormflow response over thin soils, and delivery of large bedrock clasts to the channel, are almost entirely absent in headwater channels of the Puget Lowland. Hence, headwater channels in the Puget Lowland are more sensitive to changes in basin hydrology and surface erosion processes than are headwater channels in the Puget Upland.

Confined Channels in the Cascade Range & Olympic Mountains

Farther downslope, drainage area increases and fluvial processes increasingly dominate channel morphology in Puget Upland channels. Confined fluvial channels in the Cascade Range and Olympic Mountains can exhibit either bedrock or alluvial channel types (cascade and step-pool morphologies, Table 1). Bedrock channels formed by fluvial processes are located in steep- to moderate-gradient portions of the network that occupy bedrock-walled valleys. Bedrock channels formed by fluvial processes occur where transport capacity is greater than bed load sediment supply, whereas alluvial channels occur where sediment supply exceeds transport capacity (Gilbert 1914). Montgomery et al. (1996a) demonstrated that a slope and drainage-area framework could delineate the occurrence of bedrock versus alluvial channel types in channels that are not strongly influenced by woody debris. By equating relations for transport capacity and sediment supply, they solved for an inverse relationship between drainage area and the critical slope needed to maintain a bedrock channel free of alluvial cover. The resulting critical-slope function is region-specific and depends on local conditions of geology, climate, and sediment supply (both volume and size) (Massong and Montgomery 2000).

The presence of woody debris along a bedrock channel may in some instances trap enough sediment to convert the channel to a forced alluvial channel floored by gravel (Montgomery et al. 1996a). The nature of the sediment supplied to the channel (and in particular its durability) strongly influences the extent of bedrock and alluvial channel types in steep, confined channels lacking woody debris, and thereby the sensitivity of these channels to loss of wood. The sedimentary rocks of the Olympic Peninsula rapidly disintegrate into fine sediment once introduced into the channel. Consequently steep, confined channels supplied with such sediment will tend to form bedrock channels unless sufficient woody debris is available to maintain an alluvial bed. In contrast, bedrock reaches are less common in the Washington Cascade Range where durable volcanic rocks form the primary sediment supply for confined channels in steep valleys.

Confined Channels in the Puget Lowland

In many parts of the Puget Lowland, stream channels drop steeply over an eroded edge of the headwater plateaus and enter a high-gradient, confined ravine where the intrinsic ability of the flow to transport sediment, and the rate at which sediment is delivered to the channel from adjacent hillslopes, both increase dramatically in comparison to upstream reaches. This zone commonly corresponds to parts of the underlying geologic strata dominated by noncohesive sandy sediment that is very easily eroded by running water and relatively poor in coarse gravel that might otherwise help armor the streambed and reduce the rate of vertical incision (Chapter 2). In undisturbed settings, vertical channel stability has been achieved primarily through abundant wood debris that can dissipate a significant amount of the shear stress applied to the channel bed and banks. Where logs are no longer present, or where their contact with the streambed has been undermined by increased flows, vertical stability can be lost rapidly. The resulting channel incision can proceed for up to many tens of meters until some combination of reduced channel gradient, resistant geologic layer at depth, or increased sediment delivery from oversteepened channel banks reestablishes an equilibrium profile.

Unconfined Alluvial Channels in the Puget Sound Region

Characteristics of low-gradient unconfined alluvial channels (dune-ripple and pool-riffle morphologies, Table 1) vary with differences in watershed conditions (e.g., sediment supply and stream discharge) in the Puget Sound region. Unconfined channels draining the Puget Upland are supplied with a mixture of glacial sediments and igneous and metamorphic rock fragments, whereas those draining the Puget Lowland tend to be supplied with abundant quantities of glacial sediments that span a wide range of grain sizes from silt to cobble. Moreover, differences in physiography and geologic history influence valley formation and degree of channel confinement, which in turn affect channel type and associated habitat characteristics in low-gradient alluvial channels. In some cases, low-gradient rivers in the Puget Sound region occupy broad troughs carved by glacial meltwater that have filled with river deposits since deglaciation (Chapter 2). In other cases, low-gradient rivers have carved valleys into the regional outwash plain. In contrast to steep confined channels where vertical stability of the bed is an important issue, lateral stability is a primary concern in low gradient channels. These channels build their floodplains by both overbank deposition during floods and bedload deposition as the channel moves laterally. Hence, the entire active floodplain may be considered the overflow channel and generally defines the channel-migration zone.

Restoring Riverine Ecosystems

Recognition of the characteristic ranges of channel conditions associated with each channel type is critical for successful restoration. Restoration projects that impose channel morphologies in environments that are outside of their characteristic ranges will not be self-maintaining and may prove unstable. For example, bar deposition and creation of a self-formed pool-riffle morphology typically will not occur on stream gradients greater than about 2% (Kinoshita and Miwa 1974; Church and Jones 1982; Florsheim 1985). Consequently, a pool-riffle morphology placed on a stream gradient >2% is unlikely to be maintained unless pool scour and bar deposition are forced by in-channel flow obstructions (Lisle 1986). Similarly, for a given discharge and grain size, there is a critical slope above which meandering channel patterns cannot be maintained (Leopold and Wolman 1957; Ferguson 1987; Knighton and Nanson 1993).

Field data from North America and Europe demonstrate that alluvial channel morphology varies systematically with channel gradient, width-to-depth ratio, and relative submergence (ratio of bankfull flow depth to median grain size) (Figure 5), supporting the hypothesis that different channel morphologies result from mutual adjustment of channel characteristics to imposed watershed conditions (Figures 1 and 4). Although there is considerable overlap, each alluvial channel type has characteristic distributions and combinations of channel gradient, relative submergence, and width-to-depth ratio that co-vary with one another (Figure 6). Knowledge of these or other

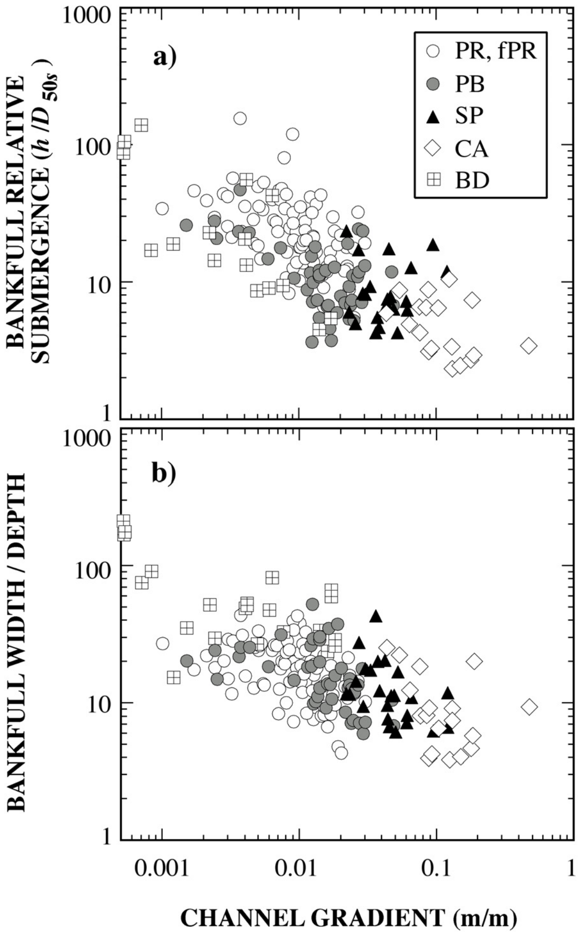


Figure 5. Slope versus a) relative submergence and b) width-to-depth ratio for pool-riffle (both self-formed (PR) and obstruction-forced (fPR); reference numbers 6, 8-13), plane-bed (PB; 6, 8-13), step-pool (SP; 6, 9, 11, 14), cascade (CA; 11), and braided (BD; 1, 3-5, 7) channel morphologies. Numbers following morphologic codes 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). (Modified from Buffington et al. [in press]).

appropriate channel characteristics can help to define restoration objectives and limitations. In particular, one could use observed ranges of channel characteristics for different channel types to develop target conditions for designing a desired channel type, or to assess what channel type is likely to be the stable morphology for given watershed conditions.

Regime Diagrams for Alluvial Channels

Regime diagrams (also referred to as state diagrams) can be used to quantify physical controls on reach-level channel type by dividing different channel morphologies into distinct domains describing the physical regime (state) that gives rise to a given channel type. Regime diagrams have been used for a variety of purposes, such as: (1) to stratify morphologic phases of sand-bed channels (Gilbert 1914; Shields 1936; Simons and Richardson 1966; Ikeda 1989); (2) to examine limits of bar formation in gravel-bed rivers (Florsheim 1985); and (3) to distinguish controls on straight, meandering, and braided channel patterns (Leopold and Wolman 1957; Parker 1976).

Here, we separate alluvial channel types as a function of Ikeda's (1989) channel form index and flow intensity. The form index is defined as the product of channel slope (S) and bankfull width-to-depth ratio (W/h). Flow intensity is defined as the ratio of the bankfull shear velocity to the critical value for initiating bed load transport (u^*/u^*_{c50}, similar to Olsen et al.'s (1997) bed stability index)

$$\frac{u^*}{u^*_{c50s}} = \sqrt{\frac{\tau}{\tau_{c50s}}} = \sqrt{\frac{\rho g h S}{\tau^*_{c50s}\left(\rho_s - \rho\right) g D_{50s}}} = \sqrt{\frac{h^* S}{\tau^*_{c50s} R}} \tag{1}$$

where τ is the total bankfull boundary shear stress determined as a depth-slope product, (ρghS) τ_{c50} is the critical shear stress for motion of the median surface grain size (D_{50s}) and is determined from the Shields (1936) equation, ρ and ρ_s are the fluid and sediment densities, respectively, g is gravitational acceleration, τ^*_{c50} is the dimensionless critical stress for incipient motion of D_{50s} (set equal to 0.03 [Buffington and Montgomery 1997]), h^* is the relative submergence (h/D_{50s}), and R is the submerged specific gravity of sediment [$(\rho_s-\rho)/\rho$, set equal to 1.65].

Ikeda's regime diagram was developed for sand-bed morphologies, but it also does a reasonable job of partitioning the variety of channel types found in the Pacific Northwest (Figure 7). Although there is considerable overlap amongst channel types, distinct fields are identified for self-formed pool-riffle, braided, step-pool, and cascade channel types. Plane-bed channels

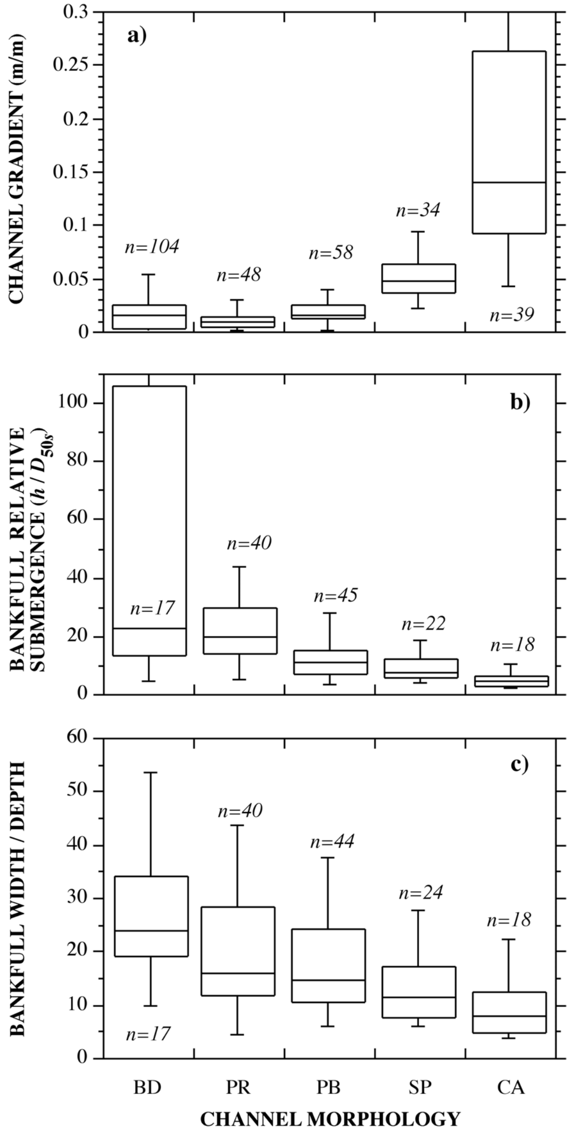


Figure 6. Distributions of channel gradient, relative submergence, and width-to-depth ratio for data of Figure 5. The line within each box indicates the median value, box ends are the inner and outer quartiles and whiskers are the inner and outer tenths of the distribution. Additional slope data from Fahnestock (1963) are added for braided reaches in panel a. (modified from Buffington et al. [in press]). See Figure 5 caption for definition of channel-type abbreviations.

define a subfield within the pool-riffle space and, on average, exhibit a narrower and higher range of form index than pool-riffle channels. Obstruction-forced pool-riffle channels occur across the entire pool-riffle space, including the plane-bed subfield. The occurrence of forced pool-riffle channels in both the plane-bed and self-formed pool-riffle fields is consistent with Montgomery et al.'s (1995) hypothesis that woody debris can create a forced pool-riffle morphology in channels that would otherwise have either a self-formed pool-riffle or plane-bed morphology. The sloping regime boundaries between channel types in Figure 7 are discriminated by both the channel form and flow intensity indices, whereas flow intensity alone appears to separate braided channels from step-pool and cascade morphologies.

Regime diagrams are useful for identifying physical domains of different channel morphologies, but most regime diagrams are not complete physical models. For example, there is no hypothesized relationship between the dimensionless parameters used in Figure 7, nor is there any *a priori* prediction of how different channels might plot within the framework of the figure. In contrast, Parker (1990) developed a more physically complete regime diagram that couples equations for streamflow, bed load transport, and channel characteristics (grain size, flow depth, and slope).

The Parker framework relates dimensionless bed load transport rate (q_b*) to dimensionless streamflow per unit width (q*), reminiscent of Lane's (1955) proportional relationship between discharge and bed load transport rate. The dimensionless bed load transport rate is defined here from the Meyer-Peter and Müller (1948) equation as:

$$q_b^* = 8(\tau^* - \tau^*_{c50s})^{1.5} \tag{2}$$

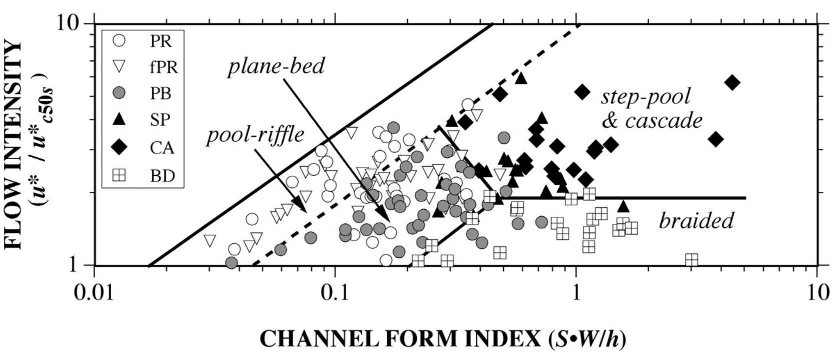


Figure 7. Ikeda-type regime diagram for data of Figure 5. See Figure 5 caption for definition of channel-type abbreviations.

where τ^* is the bankfull Shields stress ($\tau^*=hS/RD_{50s}=h^*S/R$). In this framework, q_b^* is the equilibrium transport rate (input equals output), and thus an indicator of sediment supply as well. The dimensionless specific streamflow is defined as

$$q^* = \frac{<u>h}{\sqrt{RgD_{50\,s}}\ D_{50\,s}} \tag{3}$$

where $<u>$ is the vertically-averaged velocity determined here from the law of the wall (Keulegan 1938):

$$<u> = \frac{u^*}{k}\ln\left(\frac{0.4h}{z_0}\right) \tag{4}$$

In (4), κ is von Karman's constant [0.408, Long et al. (1993)] and z_0 is the height above the bed where the velocity profile goes to zero. The Whiting and Dietrich (1990) approximation is used to define z_0 as $0.1D_{84}$, where D_{84} is the surface grain size for which 84% of the sizes are smaller. For a log-normal grain size distribution, D_{84} can be expressed in terms of the median grain size and the grain-size standard deviation (σ)

$$D_{84} = 2^{-(\phi_{50}-\sigma_\phi)} = D_{50}2^{\sigma_\phi} \tag{5}$$

where ϕ_{50} is the median grain size in $\log_2$ phi units (Krumbein 1936) and σ_ϕ is the grain-size standard deviation in the same units. The σ_ϕ value is set equal to 1.21 ± 0.01, which is an average value for rivers with median grain sizes in the range of 8 to 256 mm (Buffington 1999). Inserting (4) into (3), with the above definitions, yields

$$q^* = \frac{\sqrt{\tau^*}}{k}h^*\ln\left(\frac{4h^*}{2^{-\sigma}}\right) = \frac{\sqrt{h^*S/R}}{k}h^*\ln\left(\frac{4h^*}{2^{-\sigma}}\right) \tag{6}$$

Within this framework, different channel types exhibit subparallel trends of q_b^* as a function of q^* (Figure 8). The data stratify themselves by differences in channel gradient (S), relative submergence (h^*), and excess shear stress (τ^*/τ^*_{c50s}), paralleling systematic differences in those values previously discussed (Figure 5). In particular, as one moves from pool-riffle to cascade channel types, in a direction perpendicular to the trend of each data set, there is a general increase in channel gradient, excess shear stress, and dimensionless bed load transport rate (q_b*), while dimensionless specific discharge (q*) decreases. For a given value of dimensionless discharge, higher bed load transport rates are achieved in step-pool and cascade channels through greater values of both channel gradient and excess shear stress (Figure 8). Conversely, lower-gradient pool-riffle and plane-bed channels can achieve bed load transport rates similar to steeper-gradient cascade and step-pool channels by having larger values of specific discharge due to greater relative submergence and less hydraulic resistance.

Although the above analysis remains a simplified representation of channel processes, it provides some insight regarding the mutual adjustment of channel characteristics, streamflow, and equilibrium transport rate amongst different channel types. In particular, Figure 8 demonstrates a quantitative linkage between these factors that supports the hypothesis that different channel types result from mutual adjustment of channel characteristics (S, h*) for imposed watershed conditions (q*, q_b*). Hence, these different fields formalize the trade-offs in S, h*, and channel type in response to variations in q* and q_b*.

Channel Response Models

River and stream restoration projects are experiments in channel response. Channels are nonlinear systems that dynamically respond to restoration activities, which frequently involve large scale manipulation of channel dimensions, substrate, or planform. Consequently, an understanding of the potential magnitude and style of channel response is needed to address how a channel should be modified to produce the desired objectives and how the project site and neighboring channel reaches will respond to the planned restoration activities.

Many workers have proposed channel response models in which channel characteristics and watershed conditions (streamflow and sediment supply) are related to one another via empirical or theoretical proportionalities (Lane 1955; Schumm 1971; Santos-Cayudo and Simons 1972; Nunnally 1985; Clark and Wilcock 2000). Although qualitative channel response models are useful because they are easy to apply, quantitative models are attractive because they allow numeric prediction of response magnitudes. These predictions are not possible with simple proportionalities, such as the relationship of stream power to sediment size and flux developed by Lane and others.

Parker's (1990) state diagram is an example of an explicit model that can be used to examine mutual interactions between channel characteristics and to identify likely trends and magnitudes of channel response to specific restoration actions. To illustrate this framework, we review and elaborate upon several of Parker's disturbance scenarios. Parker's regime diagram was originally intended for gravel-bed rivers, but the physical equations and response concepts are applicable to alluvial channels in general (Figure 8). The model assumes a straight, wide channel.

In Scenario 1 (shown by Vector 1 in Figure 8), an increased sediment load (larger q_b*) is imposed on the channel, while streamflow (q*) remains constant. According to the model predictions, this is accomplished, in part, by increasing channel slope (S), which is a typically observed response to a large increase in sediment supply. A high sediment supply may overwhelm the channel transport capacity, causing aggradation and a gradual increase in channel slope. Given sufficient time, slope-driven increases in boundary shear stress and channel capacity will match the imposed sediment load, resulting in a new state of channel equilibrium (Gilbert 1917). Increased sediment load also may cause textural fining (decreased grain size) that smoothes the bed and allows greater bed load transport (larger value of excess shear stress, τ^*/τ^*_{c50s}), thereby providing an additional mechanism for equili-

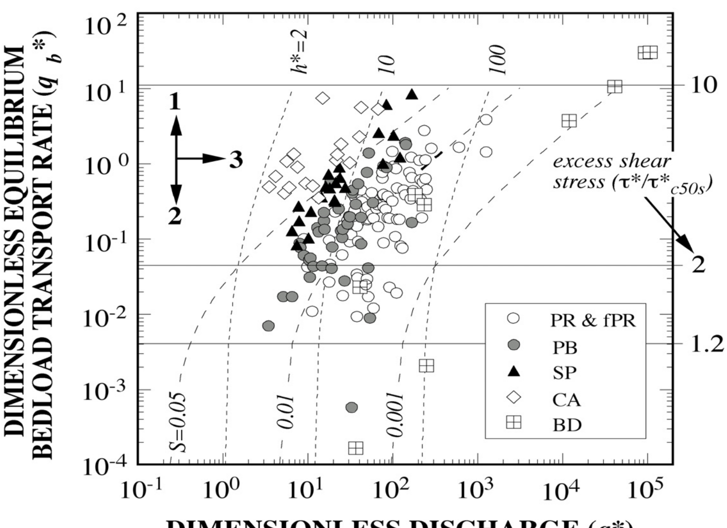


Figure 8. Parker-type regime diagram for data of Figure 5. See Figure 5 caption for definition of channel-type abbreviations. S is channel slope, h* is relative submergence (ratio of flow depth to median surface grain size, h/D_{50s}), and τ^*/τ^*_{c50s} is excess shear stress. Vectors 1-3 indicate disturbance scenarios discussed in the text.

brating rates of sediment supply and bed load transport (Dietrich et al. 1989; Buffington and Montgomery 1999b). In general, the expected response for Scenario 1 is aggradation and textural fining. Conversely, a reduced sediment supply (Scenario 2) is expected to cause channel degradation and textural coarsening if discharge remains constant. This type of response is commonly observed below dams (Gilbert 1917; Komura and Simmons 1967; Williams and Wolman 1984).

In Scenario 3, an increase in streamflow is imposed with no change in the volume or size distribution of the bed load supply (constant q^*_b). The elevated discharge initially causes a transport capacity in excess of sediment supply, resulting in surface coarsening (armoring) and channel degradation (decline in S) similar to Scenario 2. Decreasing slope, in turn, increases flow depth and relative submergence (larger value of h^*), thereby reducing bed roughness and increasing channel conveyance (discharge capacity).

Parker's framework also can be used to examine more complex disturbance scenarios, such as simultaneous perturbations of both discharge and sediment supply (following vectors between those shown in Figure 8), or nonlinear disturbance paths. As presented here, the model cannot be used to examine potential changes in channel width because discharge and sediment supply are nondimensionalized by width. However, the model could be reformulated to explicitly account for channel width. Channel responses predicted from Parker's framework are comparable to those obtained from qualitative response models, but Parker's approach has the advantage of being able to predict specific magnitudes of channel response.

Restoration Limitations Imposed by Channel Type, with Special Reference to Salmonids

Each channel type imposes characteristic physical processes and boundary conditions that must be considered when assessing channel condition and designing restoration projects. For example, the pools and gravel substrates that compose important components of salmonid habitat are limited to specific channel types and may be difficult to create or maintain in certain other channel types or in certain locations within a watershed. The absence of pools or suitable spawning gravels may be a natural condition in some channel types and thus would require heroic efforts to change and maintain.

Table 2 identifies the relative potential for different channel types to produce some of the physical components of salmonid habitat (pools, spawning "gravels," and side-channel refugia). The magnitude and frequency of naturally occurring habitat disturbances are also assessed based on associa-

Table 2. Relative potential to produce specified components of salmonid habitat, and typical frequency and magnitude of habitat disturbances due to natural processes.

Channel Type	*Pools*	*Spawning "gravel"*	*Side Channels*	*Habitat Disturbances*	
				Frequency	*Magnitude*
dune ripple	moderate	none	high	high	low
pool-riffle	high	high	high	moderate	moderate
plane bed	low	high	moderate	moderate	moderate
step-pool	high	low	low	low	high
cascade	low	low	low	low	high
colluvial	low	low	none	low	high
bedrock	low	low	none	low	high
braided	high	high	low	moderate	moderate

tion of channel type with typical process domains. For example, steep-gradient cascade and step-pool channels are prone to infrequent, catastrophic disturbance (e.g., by debris-flow passage) that may extirpate a local salmonid population. In contrast, effects of catastrophic events in any given headwater basin become progressively diffused as they move down the channel network to lower-gradient pool-riffle and dune-ripple channels. Consequently, lower-gradient channels typically experience frequent, but only low to moderate-magnitude disturbances for salmonids.

Suitable habitat for salmonids is predominantly found in the lower gradient alluvial channel types (dune-ripple, pool-riffle, and plane-bed), with habitat becoming progressively more marginal in step-pool and cascade channels (Montgomery et al. 1999). Although salmonid habitat is limited in these steeper channels, those channels nevertheless make up the majority of the stream network in mountain drainage basins. Thus a large percentage of the total available habitat will likely be found in these channel types.

Pool-riffle and plane-bed channels are particularly responsive to obstruction-forced scour, and thus they are likely candidates for restoration projects focused on increasing the number and diversity of pool habitats. In forested environments, wood is an effective flow obstruction that creates a variety of pool types and hydraulic conditions (see review by Buffington et al. [in press]). Moreover, pool spacing is inversely related to wood piece frequency across a broad range of physiographic environments of western North America (Figure 9). Although pool spacing varies tremendously for a given wood-debris frequency, the data tend to stratify by physiographic province and section, likely reflecting region-specific differences in hydrology, sediment supply, land use, and wood characteristics (tree species and size). Urban channels of the Puget Lowland, in particular, have some of the lowest wood frequencies and highest pool spacings in the Pacific coastal region (Horner et al. 1997). Although the relationship between pool spacing and obstruction frequency has received considerable attention in recent land management practice (Chapter 14), pool scour is influenced by a variety of other factors, including obstruction size and type, sediment supply, and channel dimensions (width, depth, slope, and grain size), each of which must be considered when designing restoration and management strategies for pools in alluvial channels (Buffington et al. in press).

The quality of spawning gravels offered by different alluvial channel types depends on local sediment supply (volume and size), absolute shear stress of the flow (and thus channel competence and potential bed-material size), and the spatial variability of shear stress within a reach. Plane-bed reaches may

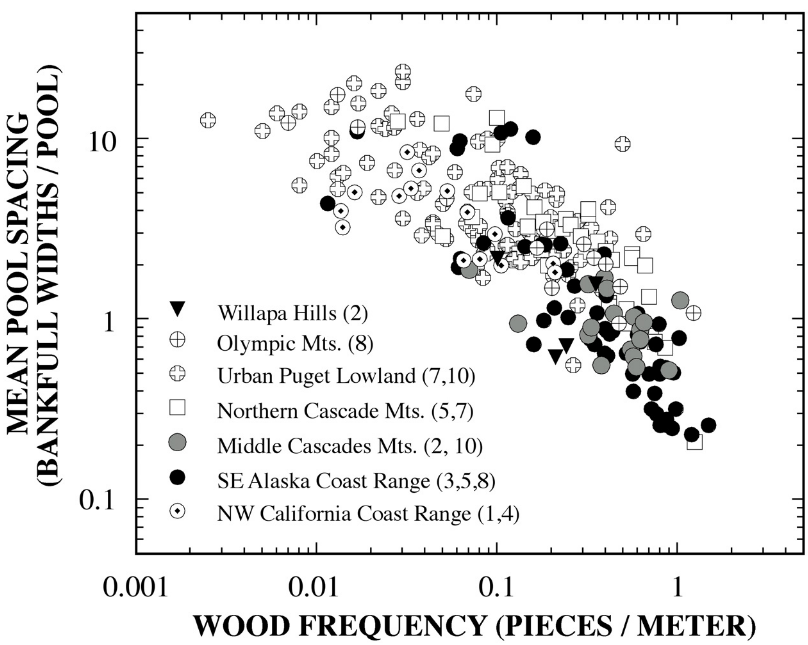


Figure 9. Average pool spacing as a function of wood piece frequency in pool-riffle and plane-bed channels. Numbers in parentheses indicate data sources: (1) Florsheim (1985), (2) Bilby and Ward (1989; 1991) (slopes <2%), (3) Buffington and Montgomery (unpublished data), (4) Keller et al. (1995), (5) Montgomery et al. (1995), (6) May (1996), (7) Beechie and Sibley (1997) (slopes <2%), (8) Buffington and Montgomery (1999a), (9) Larson (1999), and (10) Turaski (2000).

offer abundant gravels and cobbles, but they are typically monotextural (Buffington and Montgomery 1999a), reflecting the relatively uniform shear stress acting along the channel length. In contrast, pool-riffle and wood-forced pool-riffle channels are characterized by bed surfaces composed of textural patches (grain-size facies) that provide a range of particle sizes and associated habitats (Buffington and Montgomery 1999a). Textural patches likely result from spatial divergence of shear stress and sediment supply forced by channel obstructions (such as wood debris and bed and bank topography).

Pools and backwater gravel deposits can be enhanced in step-pool and cascade channels, although the effort required to modify the boulder-sized bed materials make such projects costly. Moreover, the physical processes acting in these channels (high transport capacities, flashy hydrographs, and potential debris-flow passage) make enhancement projects more prone to failure and therefore costly to maintain.

Identification of Restoration Opportunities

Recognition of the physical controls on reach-scale morphology facilitates rapid assessment of where to focus restoration or maintenance efforts. For example, digital elevation models can be used to predict channel type as a function of stream gradient. This information might be used to identify potential locations of existing salmonid habitat, or to develop strategies for optimizing habitat in unrealized areas. For example, studies of forest channels in Washington and Alaska indicate that bar and wood roughness may reduce channel competence and surface grain size to levels usable for salmonid spawning in channels that would otherwise be too coarse (Buffington and Montgomery 1999a). Application of a model for predicting bed surface grain size using digital elevation models indicates that hydraulic roughness due to woody debris has the potential to significantly increase spawning habitat availability in mountain drainages basins of western Washington (Buffington 1998). Digital elevation models can also be used to predict the occurrence of bedrock versus alluvial channel types as a function of slope and drainage area (Montgomery et al. 1996a; Massong and Montgomery 2000). Such predictions could be used either to assess current alluvial habitat, or to examine the potential for "reclaiming" alluvial habitat through introduction of wood in otherwise bedrock reaches. Ranges in channel gradient also could be used to identify reaches potentially susceptible to conversion from a forced pool-riffle to plane-bed morphology upon loss of wood.

Spatial Linkages and Temporal Variations

Drainage basins are composed of landscape elements (such as hillslopes, lakes, alluvial valleys, and tidal zones) that are connected to one another via the channel network. The types and arrangement of landscape units and their characteristic process domains influence biological systems and community structure (Montgomery 1999; Rieman et al. in press). Analysis of how different components of a watershed are connected to and influenced by one another over multiple spatial and temporal scales is necessary for accurate interpretation of watershed conditions and for developing strategies to maintain or restore riverine ecosystems. Restoration projects frequently focus on the immediate, local problem but neglect the larger watershed processes and linkages. This tends to result in a reactive approach that provides short-term solutions for local issues but may not address underlying problems. Because river channels link watershed elements and their processes, the root cause of a problem may be distant both in space and time. Consequently, a holistic approach is needed for understanding how disturbances propagate through a basin and for understanding what factors limit production of desirable morphologies and aquatic habitats.

Identifying the multiple spatial and temporal scales of events and processes influencing a particular location within a watershed is not a trivial problem. Some of the larger influences on watershed processes are readily discernable, such as the control of Pleistocene glaciation on river systems in the Puget Lowland (Chapter 2), or the influence of the Bonneville Flood on the Snake River (O'Connor 1993). Other effects are more subtle and not as easily identifiable. In addition, processes and morphologies may be oscillating over time due to periodic disturbances, as well as evolving toward new states due to longer and larger forcing (e.g., response to geologic and climatic disturbances).

Restoration of Puget Sound Rivers

Many Puget Sound rivers have been so altered by urbanization, agriculture, timber harvest, channelization, and flow regulation that it is difficult to envision their historic appearance, let alone quantitatively reconstruct those conditions. Even if it were possible to understand completely the historic physical and biological processes of Puget Sound rivers, it is unlikely that those systems could be restored (*sensu stricto*) to their naturally functioning state given the enormous social and economic costs that would be required to relocate homes, businesses, and infrastructure that currently blanket the landscape. Consequently, land managers and environmental engineers working in the Puget Sound region are faced with limitations concerning the location and extent of possible restoration activities. These limitations are ancillary to the natural physical controls on channel morphology and watershed processes and may complicate restoration design in the Puget Sound region.

Consequently, planning and design of river restoration programs in the Puget Sound, as elsewhere throughout the Pacific Northwest, rests on three fundamental components. First, an understanding of the physical setting and potential of the channel in question is essential. Second, knowledge of the historical context and changes to both the river and its watershed are required. Third, clear policy objectives are necessary for using these first two components to develop programs likely to achieve desired objectives. Restoration programs that neglect any of these three elements are less likely to succeed.

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