Hydrogeomorphic variability and river restoration, 39–80.

3. Hydrogeomorphic Variability and River Restoration

D. R. Montgomery[1] and S. M. Bolton[2]

Abstract.–Hydrogeomorphic processes play key roles in creating, modifying, or destroying aquatic habitat and act as ecological disturbances that shape ecosystem characteristics and dynamics. Within the broad regional context set by general patterns of climate, physiography (geology and topography), and vegetation, the combined influences of the hydrologic, geomorphic, and vegetation regimes dominate the variability of river systems. Interactions among these regimes can strongly influence river ecosystems, and an understanding of the nature of these regimes and disturbance histories is crucial for setting restoration targets and interpreting the long-term ecological influences of hydrogeomorphic processes. It is difficult to design effective stream and channel restoration measures, or evaluate project performance, without an understanding of the pertinent geomorphic context, habitat-forming processes, and disturbance history. Of particular relevance are the main processes that transport and store water, sediment, and wood, and how differences in current and potential conditions are related to local conditions, basin-wide contexts, and the influences of human activities. Because stream and channel processes and characteristics vary regionally and throughout a drainage basin, there is no universal template for guiding restoration efforts. In designing restoration measures, it is essential to address trends and differences between current and potential conditions to ensure that restoration efforts are neither futile nor poorly matched to the site or system in question.

> *You cannot step in the same river twice, for the second time it is not the same river* –
> Heraclitus (535-475 BC)

Introduction

Rivers are dynamic systems subject to a wide range of hydrologic and geomorphic influences that exhibit substantial spatial and temporal variability. Coupled with a diverse and interdependent set of responses to changes in streamflow, sediment supply, and other internal or external conditions, this variability makes river restoration a complex and technically challenging endeavor. Therefore, an understanding of hydrogeomorphic variability in river ecosystems is central to devising effective ways to protect and restore river systems. No two rivers are exactly alike–each has its own history and geographical context. But general principles of hydrology and geomorphology can be used together with an understanding of the historical and contemporary context of an individual river to evaluate potential physical and biological responses to human activities and to guide restoration efforts (Figure 1). The nature or legacy of watershed processes determines the conditions and trends in valley segment characteristics such as the condition of the forest in the valley bottom or the sediment supply, which in turn influences channel-reach characteristics such as channel width or pool frequency. This chapter focuses on the hydrologic and geomorphic components of the river system.

---

[1] Department of Earth and Space Sciences, University of Washington, Box 351310, Seattle, WA 98195.
[2] Center for Water and Watershed Studies, University of Washington, Box 352100, Seattle, WA 98195.

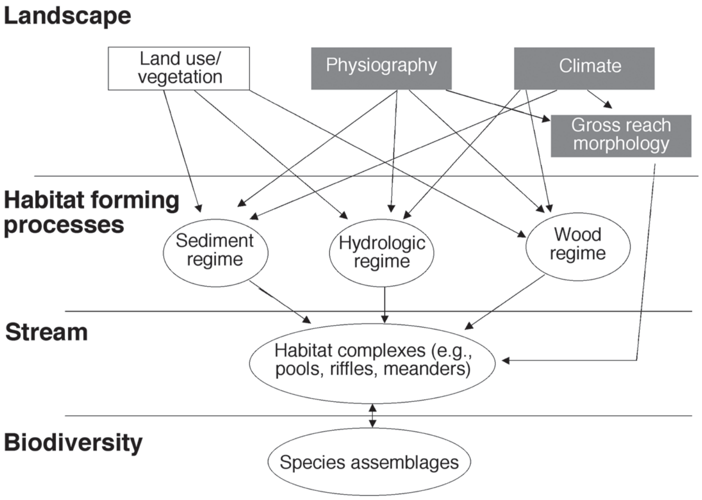

FIGURE 1.—Simplified schematic diagram of linkages between controls on watershed processes, the processes themselves, aquatic habitats, and biodiversity. Shaded boxes indicate those controls that are not directly affected by land use. Modified from Beechie and Bolton (1999).

Societal recognition of stream habitat degradation and impacts from various land-use practices, including those from forest harvesting, riparian grazing, channelization, and urbanization, motivates an ongoing expansion of efforts in and expenditures for stream restoration. Increasingly, restoration efforts focus as much on restoration of channel morphology and processes as on efforts to recover specific species or biological components, such as salmon or fish in general (Thorne et al. 1996). Given the extensive historical changes to rivers and the resulting physical, biological, and social constraints, most projects billed as river restoration actually achieve only some degree of river rehabilitation.[1]

Spatial variability in river systems is widely acknowledged to reflect a hierarchy of different influences across a range of scales. Frissell et al. (1986) identify five distinct hierarchical levels—geomorphic province, watershed, valley segment, channel reach, and channel unit—that reflect differences in processes and controls on channel morphology (Figure 2; Table 1). Each level of this spatial hierarchy provides a framework for addressing variability and processes at different levels of resolution.

In general, there is a relationship between the spatial scale of geomorphic processes and the degree of variability or the time scales over which these processes vary (Figure 3). Landscape- and watershed-scale features such as the relief of a mountain range, river longitudinal profiles, and the pattern of the channel network respond over geologic time to changes in tectonic and climate forcing (Chapter 2, this volume). At the other end of the spectrum, channel units such as individual pools and gravel bars can form or disappear during a single flow event. Although specific landscape features are temporally transient, the dynamic processes that shape and change local channel conditions can lead to relatively persistent characteristics when viewed or averaged over larger areas. A mountain range may remain steep even though it is eroded by periodic landsliding that reduces local slopes; a channel reach may retain a pool–riffle morphology over time even though locations of individual pools and riffles change frequently during high flows. The spatial and temporal variability of channel processes and conditions has important consequences for restoration efforts. Projects often are implemented over small areas and may be considered failures if

---

[1] Definitions and distinctions between terms are noted in the glossary at end of chapter.

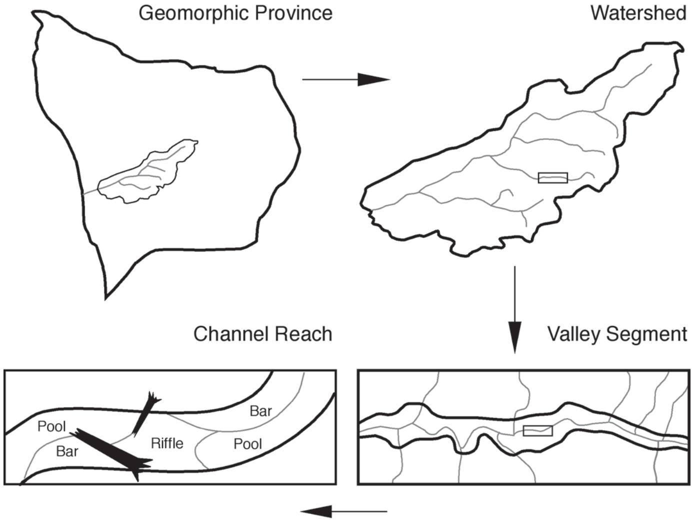

FIGURE 2.–Hierarchy of spatial scales in river systems. After Frissell et al. (1986) and from Montgomery and Buffington (1998).

TABLE 1.–Hierarchical levels of channel classification and typical associated spatial and temporal scales. After Frissell et al. (1986).

Classification level	Spatial scale	Temporal scale (years)
Channel/Habitat Units	1–10 m^2	<1
Pools		
Bars		
Shallows (riffles, rapids, steps)		
Channel Reaches	10^1–10^3 m^3	1–1,000
Colluvial Reaches		
Bedrock Reaches		
Free-formed Alluvial Reaches		
Cascade		
Step–Pool		
Plane–Bed		
Pool–Riffle		
Dune–Ripple		
Forced Alluvial Reaches		
Forced Step–Pool		
Forced Pool–Riffle		
Valley Segment	10^2–10^4 m^2	1,000 to 10,000
Colluvial Valleys		
Bedrock Valleys		
Alluvial Valleys		
Watershed	50–500 km^2	>10,000
Geomorphic Province	1,000 km^2	>10,000

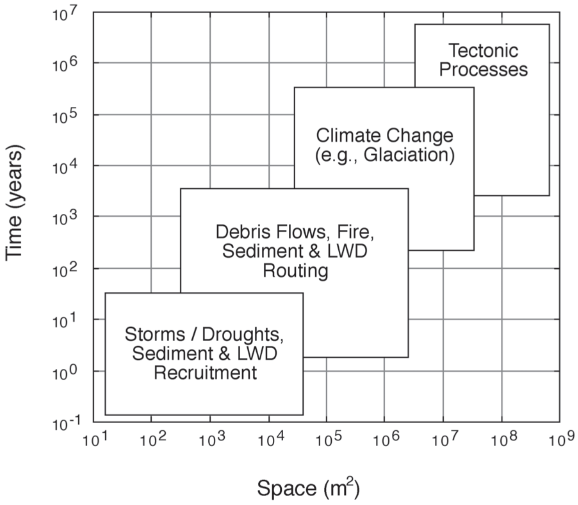

FIGURE 3.–Generalized spatial and temporal scales of influences on river systems. From Montgomery and Buffington (1998).

local as-built conditions do not persist (Frissell and Nawa 1992), as might be expected to result from efforts to stabilize an inherently dynamic system. Failure to acknowledge expected changes across space and through time in river systems can lead to inappropriate and ineffectual restoration actions or inappropriate interpretations of project failure (Sear 1994; Kondolf et al. 1996, 2001). Mimicry of geomorphic form does not necessarily restore essential geomorphic or hydrologic processes (Sear 1994; Thompson 2002).

Hydrogeomorphic processes such as floods and landslides act as ecological disturbances and play key roles in creating, modifying, or destroying aquatic habitat while shaping ecosystem dynamics and characteristics. What constitutes a disturbance will vary according to the system or community under consideration. The intensity of the impact, the size of the area affected, and the frequency of occurrence together define the disturbance regime associated with particular hydrogeomorphic processes. The disturbance regime sets the physical habitat template that influences potentially successful behavioral and life-history strategies of stream-dwelling organisms (Poff and Ward 1990). The combined effects of different disturbance processes, as characterized by the frequency, magnitude, and intensity of the effects on the organisms or habitat of interest, are necessary to evaluate the potential impacts of human actions, including restoration efforts, on aquatic ecosystems.

Concepts of hydrology and geomorphology essential for restoration projects include variability in time and space, and the influence of local and downstream effects on channel processes. In addition, river restoration efforts need to be founded on an understanding of characteristics and functional relationships that structure aquatic habitat, the influence of routing on impact propagation, and the role of disturbance history and legacies on current conditions and restoration potential. Geographic variations of climate, physiography (geology and topography), and vegetation impart a strong regional character to river systems. Therefore, restoration efforts require a strong regional context. Simply put, it is difficult to understand the condition of streams and design effective restoration measures without understanding their spatial context, the nature of habitat-forming processes, and disturbance history. Of particular relevance are the main processes that transport and store water, sediment, and wood; the relationship of differences in current and potential conditions to channel unit, reach, and watershed contexts; and the influence of human activities on channel characteristics and disturbance regimes.

The concept of process domains, distinct areas of a landscape that correspond with different disturbance regimes, has been proposed as a framework for integrating the inherent interplay of spatial and temporal variability in channel processes (Montgomery 1999; Winter 2001). Process domains occupy particular identifiable areas of a watershed, and in many cases the disturbance regimes associated with particular process domains can be generalized across areas with similar lithology and topography. As restoration frequently focuses on habitat characteristics, understanding the type of habitat-forming processes and disturbances that occur naturally at the project site and in the watershed will increase the likelihood of successful restoration actions.

A central theme of current thought on restoration is to address causes rather than simply manage symptoms (Beechie et al. 1996; Beechie and Bolton 1999; Richards et al. 2002); yet many failed river restoration efforts focused on a particular site and problem (symptom) and ignored the watershed context of space, time, and ecology (Ziemer 1997; Kondolf et al. 2001). Frissell and Nawa (1992) found that many instream structures moved or were buried either because the design of the structures was inadequate to withstand hydrologic variability, or channel changes overwhelmed the design. Frissell (1997) argues that explicit consideration of spatial and temporal patterns in the physical and biological functions of watersheds is necessary for successful restoration. Over the long run, focusing restoration activity on restoring natural processes and disturbance regimes can be cost-effective because of the lower maintenance costs for such projects. Restoring the natural processes that create stream habitat is likely to prove more successful in the long-term than creating fixed-location, site-specific habitat, which can require substantial ongoing maintenance (Beechie and Bolton 1999).

In addition to understanding geomorphological processes, river restorationists need to understand the ecology of the system targeted by restoration efforts. Focusing on needs of a single target species and life stage can unintentionally degrade the system for other species or life stages. For example, focusing on spawning reaches and water levels for chinook salmon *Oncorhynchus tshawytscha* may ignore or exacerbate the loss of off-channel habitat such as side channels, groundwater-fed floodplain channels, and ponds needed by juvenile coho salmon *O. kisutch*. Holistic channel restoration requires consideration of how hydrogeomorphic variability and processes influence habitat needs for a wide variety of species and life stages.

The degree to which river systems are amenable to restoration depends on the regional and watershed-specific hydrologic and geomorphic context and disturbance history. Asking appropriate questions can help identify important types of variability. How likely are extreme flows, high or low? What types of processes and intensities of disturbance can be expected in the reach of interest? How will the channel and any structures placed in the channel respond to these flows? Have land-use changes in the watershed rendered historical records of flow variability inadequate for estimating future flows? Will significant alterations in the original hydrologic regime limit restoration potential? And so on. Restoration efforts typically occur at a local scale, but it is necessary to understand the influence of the watershed-scale context to gauge the potential cumulative effect or benefit of particular restoration actions. This chapter discusses factors that influence hydrologic and geomorphic variability across space and through time with a focus on the variability of the water, sediment, and wood regimes.

Spatial and Temporal Variability in River Systems

Streams and rivers exhibit pronounced variability over four dimensions: lateral, vertical, longitudinal, and temporal (Ward 1989). These components of variability in river systems reflect systematic downstream or longitudinal variability, as well as important local effects. In general, in a given system, working *with* the natural processes that create habitat, rather than *against* them, should lead to more effective and sustainable restoration actions. But recovery by passive restoration may take an unacceptably long time, especially when populations of threatened or endangered organisms are at risk. Reestablishment of natural channel processes through passive restoration such as the regrowth of large wood can take a century or longer. In such situations active manipulation of the channel structure may be justifiable and desirable. Consequently, understanding hydrologic, sediment, and wood regimes in the watershed of interest is fundamental to sound restoration planning and design.

A hierarchical framework helps determine the need for and context of restoration efforts (Ziemer 1997). The regional salmon recovery framework developed for the Pacific Northwest by the Forest Ecosystem Management Assessment Team (1993) focused on four spatial scales for restoration planning: regional, large river basins, individual watersheds, and site-specific projects. The regional scale is useful for identifying how to allocate resources to best meet concerns over a multistate region. Major river basins within a region can be ranked based on opportunity and ability to achieve specific restoration objectives. Within large river basins, individual watersheds can be ranked to identify effective locations for accomplishing restoration objectives. Finally, sites within individual watersheds can be identified and specific projects can be designed to accomplish the objectives as identified at broader scales.

Temporal variability also comes into play when deciding over what timeframe the “success” of restoration projects should be evaluated. Many hydrogeomorphic disturbances have recurrence intervals on the order of decades or centuries, rather than seasons or years, and changes in climate or land use or both may preclude recovery of “natural” or “historical” flow regimes and thus of hydrogeomorphic processes to a previous state. Consequently, when developing a program of restoration, understanding hydrogeomorphic variability across spatial scales and through time provides an important context for understanding controls on channel processes and form (Lane and Richards 1997) and for developing or assessing restoration objectives, specific project designs, and monitoring strategies. In contrast to engineered structures, which typically have narrowly specified design tolerances, ecological engineering principles (Bergen et al. 2001) suggest that wide tolerances are more appropriate for river restoration efforts to accommodate uncertainty due to spatial and temporal variability in hydrologic and geomorphic processes.

Scales of Variability

The dynamic character of geomorphic and hydrologic processes and the resulting variability in aquatic habitat properties are highly dependent upon spatial location in the channel network. Headwater channels have different suites of habitat-forming processes and disturbance regimes than those found in low-elevation floodplain channels (Figure 4). Hillslope processes, disturbance regimes, and appropriate restoration actions will be very different in a region with steep slopes and shallow soils than in a region with gentle slopes and deep soils. When landscape controls such as climate, physiography, and vegetation overlap, distinct sets of habitat-forming processes can be recognized. Frameworks such as Omernik’s (1987) ecoregions can be used to divide a region or landscape into areas with similar disturbance and recovery processes based on climate, physiography, and vegetation.

Large rivers typically flow through several geomorphic provinces with different combinations of climate, physiography, and vegetation. Watersheds within a region often share general characteristics such as similar relief and landforms. Consequently, an understanding of the general controls and influences on channel processes, dynamics, and morphology can be reasonably generalized for most large watersheds within a geomorphic province. Regional relationships can be developed between drainage area, streamflow, substrate size, and other channel characteristics (Dunne and Leopold 1978; Knighton 1984), but such relationships tend to be general and often do not

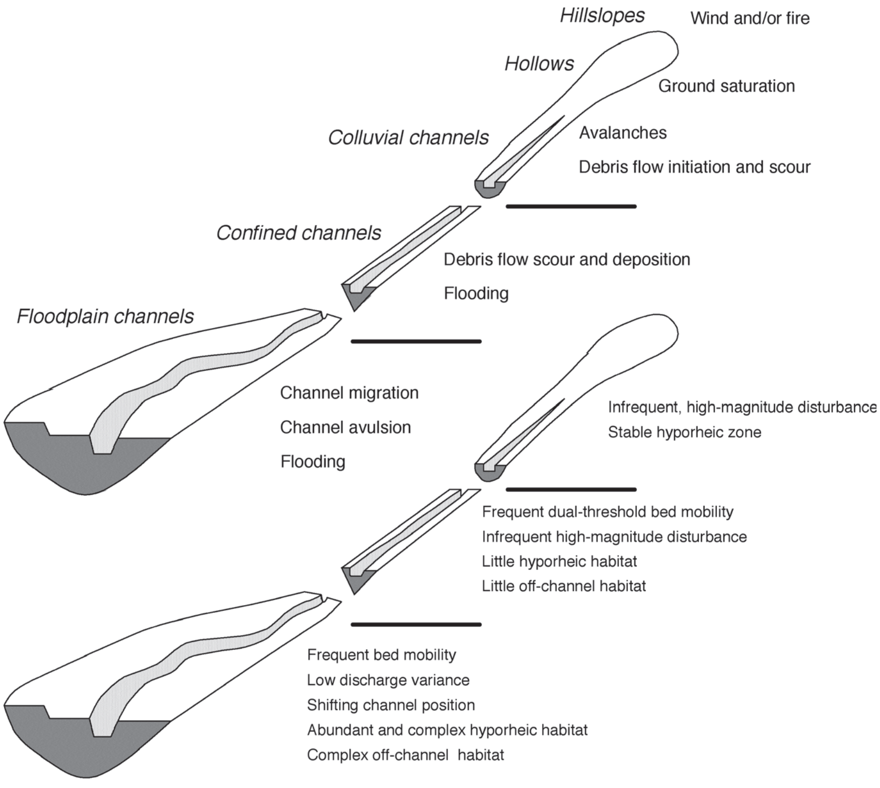

FIGURE 4.–Disturbance processes, associated process domains, and character of habitat variability typical of mountain-channel networks. From Montgomery (1999).

convey the range of variability within the general trends. Although geomorphic provinces are a useful scale at which to consider broad controls on habitat-forming processes at the watershed level, individual watersheds provide practical units for examining the specific influence of hydrogeomorphic processes on channel morphology and the effect of historical disturbance regimes on channel habitat. The spatial distribution of, and habitat characteristics associated with, specific channel units at particular places in a channel network reflect the influence of all higher levels of the spatial hierarchy discussed previously, as well as the associated temporal variability addressed in the following discussion.

Channel characteristics are influenced by local factors and systematic downstream changes in channel properties. In general, alluvial and bedrock channels tend to widen downstream in proportion to the square root of discharge or drainage area (Leopold and Maddock 1953; Carlston 1969; Parker 1979; Montgomery and Gran 2001). General downstream trends in channel width and depth are recognized as defining the downstream hydraulic geometry of rivers (Leopold and Maddock 1953). However, local lithologic differences, gradients in rock uplift rates, or accumulations of wood debris can impart substantial variability to the general downstream trend of channel widening. The hydraulic geometry of ephemeral headwater channels exhibits significant spatial and temporal variability due to the continual adjustment to stochastic disturbances (Rendell and Alexandar 1979). Local erosion or deposition associated with vegetation can control or perturb the width of small headwater channels (Zimmerman et al. 1967). In some channel systems, the width of channels in a watershed smaller than about 1 km^2 appears to be dominated by local controls such as bedrock outcrops, woody debris, or resistant bank materials, rather than systematic relationships structured by the progressive downstream increase in streamflow (Figure 5). The transition from an apparently stochastic control on channel width to the more systematic downstream relationships of traditional hydraulic geometry can be interpreted as the scale at which hillslope processes and local bank controls yield to fluvial processes as the dominant control on channel width. But even on larger rivers, local controls such as log jams can significantly affect local channel width (Figure 6).

A fundamental concept in geomorphology is that channel properties vary over a wide range of time scales ranging from response to individual storm or streamflow events to changes in tectonically driven plate motions. Temporal variability in hydrological processes imparts a dynamic character to many geomorphological processes that influence river ecosystems. Sediment transport processes, for example, tend to be event-driven and are therefore inherently punctuated in time. Temporal variability in geomorphic processes is controlled by variations in input properties—water, sediment, and wood—and the routing of these inputs through the channel network. Trends in response and recovery patterns from past inputs are keys to understanding controls on channel characteristics and evaluating the potential changes in them due to future events or actions, such as restoration efforts. Because channel processes and characteristics vary regionally and throughout individual drainage basins, no universal template exists for guiding channel restoration.

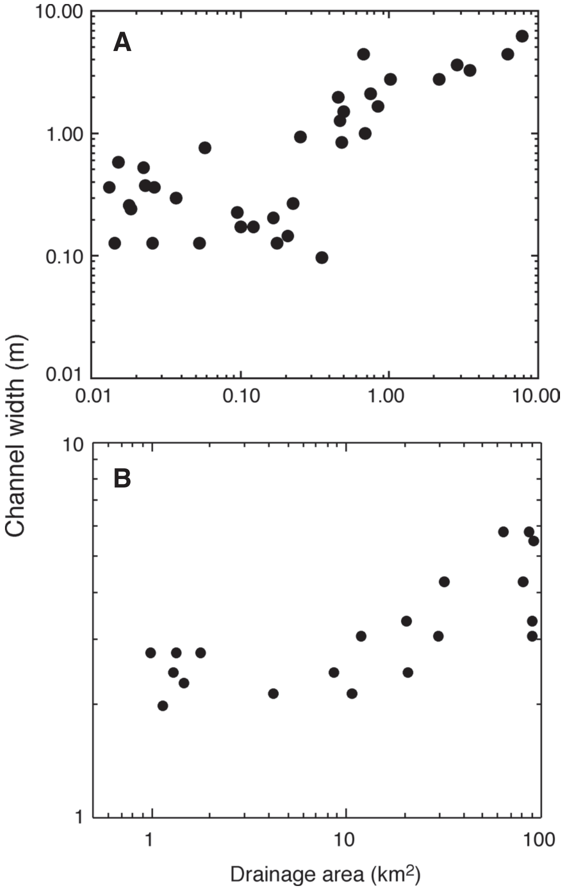

FIGURE 5.—Plot of channel width vs. drainage area for small drainage basins showing the lack of a systematic hydraulic geometry relationship for basins below 1 to 10 km^2 drainage area: (A) Deton Creek, Oregon, and (B) Pojaque River, New Mexico. Data for Pojaque River from Miller (1958).

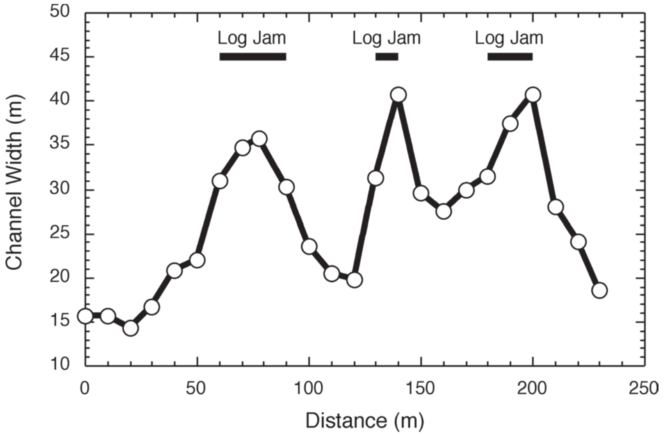

FIGURE 6.–Effects of large woody debris accumulations on channel width in the Tolt River, Washington. Note that log jams more than double the local channel width.

Understanding the channel unit, reach, and watershed-scale hydrogeomorphic context is a crucial component of any restoration project. Consequently, the following questions can help guide project development and evaluation:

- What and where is the source of the problem that the project seeks to correct? Can the problem be rectified at the source rather than trying to "fix" the stream?
- What is the expected natural spatial and temporal variation in the processes that historically created habitat and how have these processes been altered?
- Will the project help move the system towards reestablishment of natural habitat-forming processes? If not, is the project designed to function successfully in the face of altered habitat-forming processes?

Geomorphic Province/Regional Controls

The full range of hydrogeomorphic controls and processes does not occur in every region. Instead, the landscape-specific assemblage and arrangement of relevant geomorphic elements and process domains control many ecosystem structures and functions. Hence, the arrangement of landscape elements and dominance of geomorphic processes provide insight into landscape-scale disturbance regimes, and therefore insight into river ecosystems.

Three general factors–climate, physiography, and vegetation–dominate the regional hydrogeomorphic variability of natural channels. Climate sets the general amount and timing of precipitation and streamflow, as well as the type of variability to be expected spatially in addition to seasonally and interannually. Geologic structure and history control the distribution of rock types and properties, including the parent material for soils upon which topography develops. Topography, in turn, both governs and is shaped by the distribution and rates of geomorphic processes such as the delivery of water, organic material, and sediment to the stream network. The interaction of climate, geology, and topography determines potential natural vegetation complexes which then influence (and are influenced by) the hydrologic cycle. Regional variations in climate, physiography, and vegetation combine with spatial and temporal variability driven by hydrological and geomorphological processes to impart substantial variability to the habitat characteristics of river systems.

Understanding such variability is important for designing and evaluating channel restoration projects. For restoration purposes, knowledge of the historical conditions in the watershed and changes in habitat-forming processes over time, whether due to natural or human disturbances, is invaluable. For example, a high sediment supply is often assumed to be harmful to aquatic organisms. However, there are watersheds where background sediment production and transport are naturally high, such as in streams fed by glacial meltwaters or streams in areas of highly erosive geology. Where behavioral or biological adaptations have allowed local species to adjust to such conditions, attempts to control or decrease sediment production and transport can waste time and money.

Climate

Precipitation and streamflow are two important climate-driven hydrologic factors that vary in time and space. Everyone is familiar with the temporal variability in precipitation that defines daily weather. But regional variability in climate also profoundly affects river ecosystems through streamflow variability (see Chapter 2, this volume).

Various schemes have been developed that group geographic regions and expected surface-water runoff patterns based on climate (Beckinsale 1969; Watson and Burnett 1995; Poff 1996). Many individual states, in conjunction with local U.S. Geological Survey offices, have identified subregional areas with similar flow regimes (e.g., Williams et al. 1985). Using principle component analysis on 1,659 sites relatively free of human disturbance in the United States, Lins (1985) identified regional patterns in the variability of streamflow. Ecoregion maps of the United States (e.g., Omernik 1987; U.S. General Accounting Office 1994) are based in part on climate variability, but large rivers often cross many ecoregions and encounter different climates and land covers that differentially affect their flow regime from headwaters to mouth (Omernik and Bailey 1997). Recently, attempts to integrate physical and biological features into classifications for various streamflow characteristics have been made (Saxton and Shiau 1990; LeBoutillier and Waylen 1993; Magilligan and Graber 1995; Lecce 2000). Use of the appropriate classification depends upon the purpose and location of the restoration project and can aid in identifying the expected variability in streamflow.

Climate affects streamflow through the interactions between temperature and the type, amount, and season of precipitation. The seasonality of high vs. low flows and the extremes of high vs. low flows place limits on what organisms can flourish in and along streams. Climate also limits what can be achieved via restoration, as the interaction of organisms with their physical and biological environment constrains what is attainable in any restoration effort.

Temporal variability in precipitation or changes in temperature that affect snow levels are major climatic influences on hydrology and streamflow (e.g., Hartley and Dingman 1993). On a human timeframe, shifts in sea surface temperatures, such as the El Niño–La Niña oscillation, strongly affect streamflow (Philander 1990; Simpson and Cane 1993). Longer-term trends in climate also influence hydrologic variability, as changes in precipitation amounts and intensities translate into changes in streamflow depending on water storage and flowpaths in the watershed. Over time scales longer than historical instrument records, tree-ring reconstructions of climate document substantial century- to millennia-scale climate variability in the western United States (Graumlich 1987; Michaelsen et al. 1987; Scuderi 1990). Over even longer time scales, climatic and hydrologic changes associated with global episodes of glaciation or mountain building act as disturbance events with evolutionary significance.

The projected influence of global climate change also has implications for restoration planning. Glacial meltwater originating high in the Cascade Range sustains summer low flows in important salmon-bearing tributaries along the Columbia River in central Washington. Changes in summer low flows that are forecast to occur as the glaciers of the Cascade Range recede and eventually disappear should be considered in long-term restoration planning. Changes in snow level and the amount of precipitation stored over the winter due to climate change also are predicted to affect streamflow timing, duration, and amounts (e.g., Brubaker and Rango 1996; Leung and Wigmosta 1999).

Recognition of either trends or cycles (e.g., El Niño events) in climate, or its derivatives such as precipitation and streamflow, may decrease uncertainty in the conditions that a restoration project is expected to experience. This information should also be considered when assessing project effectiveness and whether the project has experienced the full range of expected conditions.

Physiography

Geology and topography are closely linked by relationships between rock uplift rates, rock erodibility, and landscape form over geologic time. Lithology (rock type) also affects soil characteristics that influence hydrologic response through variability in infiltration capacity and soil hydraulic conductivity due to differing proportions of sand, silt, and clay. Soil characteristics, also influenced by vegetation and climate, affect infiltration rates and soil moisture storage volumes, and thereby affect the flow paths, volume, and rate of water delivery to stream channels.

As the substrate upon which river networks develop, the bedrock geology and geologic structure of a landscape influence channels at spatial scales from the architecture of the branching pattern defined by the channel network to the durability and, therefore, size of the sediment it transports. Geologic structure influences drainage patterns through variability in erosion resistance: highly jointed rocks tend to form trellis-like networks with right-angle tributary junctions, whereas dendritic channel networks typically reflect flat-lying and more uniform lithology and structure. Lithology also influences topography through variability in erosion resistance. The slope, or gradient, of a river can change dramatically when crossing between rocks of variable erosion resistance (Hack 1957; Howard et al. 1994). In addition, lithology affects erodibility and the sediment supply to rivers. For example, the rocks of the Franciscan Assemblage in northern California have very high erosion rates that reflect their weak and highly sheared state resulting from a violent tectonic history. In contrast, the low erosion rates in the Sierra Nevada reflect the massive, erosion-resistant granite exposed across most of the higher elevation portions of the range. This backdrop of variable erosion rates affects the expected rates of sediment delivery and transport as well as sediment size.

Rock type also affects hydrologic processes. In some volcanic regions, such as the high Cascades of eastern Oregon or limestone areas in Kentucky, surface runoff is scarce and streamflow is fed by springs. The range of discharge variability in spring-dominated channels typically is narrow, with peak flows not much greater than average or even low flows. The relatively stable flow regime of spring-dominated channels leads to weak bar development and can allow growth of substantial aquatic vegetation (Whiting and Stamm 1995). The distinctive hydrology of these channels can impose significant differences in their form and dynamics relative to runoff-dominated channels (Whiting and Stamm 1995).

Another key river characteristic influenced by rock type is the durability and, therefore, size of bed-forming materials. On the basis of observations from field work in Oregon and Washington, we note strong geologically controlled contrasts in stream morphology between channels in the Coast Range and in the Cascades. In particular, the availability of boulders is markedly different between the volcanic Cascades and the sedimentary Coast Range. Boulder-strewn streambeds composed of relatively strong volcanic rocks are common in steep reaches of channel networks throughout the Cascades. In contrast, relatively few cobbles and boulders are found in Coast Range channels due to the propensity of the dominantly sandstone and siltstone bedrock to shatter upon wetting and drying. As a consequence of these differences in the durability of cobbles and boulders, bedrock channels are relatively rare in the Cascades, where boulders are available to provide the hydraulic roughness necessary to stabilize steep headwater streambeds. In contrast, bedrock channels are common in the Coast Range where the sandstone bedrock rapidly breaks down to gravel and sand, and the primary source of large roughness elements is instream logs (Massong and Montgomery 2000), the supply of which has been depleted in historical times owing to extensive logging and stream cleaning. In formerly glaciated areas, streambed sediments may be derived from relic glacial outwash deposits rather than local bedrock, thereby decoupling such influences on channel morphology from the local geology.

Topography influences runoff on several scales. Many processes within the hydrologic cycle, such as interception, evapotranspiration, infiltration, and runoff have been studied intensively at the hillslope scale (Dunne and Black 1970; Abrahams 1986; Anderson and Brooks 1996; Montgomery et al. 1997). These processes are highly nonlinear and spatially and temporally variable (Wood 1998), in part due to topographic variability in soil moisture, slope, vegetation, and runoff generation (Freeze 1980). Understanding the influence of location in a watershed, the hydrogeomorphic controls and disturbances pertinent to a site, and the nature of the soils and geology, in turn, foster understanding of how a site is likely to respond to proposed restoration actions.

Topography also is a primary influence on channel characteristics and processes. The ability of a river to erode its bed or transport sediment varies with streamflow and slope—bigger rivers flowing down steeper slopes erode faster than smaller rivers with gentler slopes. The trade-off between streamflow and slope is captured in the classical interpretation of the characteristic concave longitudinal profile of river systems as reflecting the adjustment of slope to the greater erosional power associated with the downstream increase in the size of rivers. Where rock uplift is driven by steady, spatially uniform tectonic forcing over geologic time, channel slopes evolve toward a steady-state concave upward profile that reflects a balance between uplift and erosion. In contrast, non-uniform rock uplift, variability in erosion resistance, glaciation, or other geological disturbances may introduce substantial variability to river longitudinal profiles (Seeber and Gornitz 1983; Howard et al. 1994; Seidl et al. 1994). The slope of a channel drives channel processes over short time scales and is itself modified by channel processes over geologic time.

Slope—the first derivative of topography—is a primary control on channel-reach morphology in mountain drainage basins. In terms of channel-bed characteristics, slope may be considered as an imposed variable that influences reach-scale channel architecture. Along an idealized concave river profile in mountainous terrain, we would expect a downstream sequence of channel types proceeding as colluvial, cascade, step–pool, plane–bed, and pool–riffle channel reaches (Figure 7) (Montgomery and Buffington 1997). However, this generalized downstream trend in channel types may be altered by disturbance history or landscape features such as where streams cross geologic contacts between rocks of different erosion resistance; where there are strong local controls on sediment supply, such as large wood debris or bedrock channels; where there are gradients in rock uplift rates; across discontinuities imposed by the specific tectonic or glacial history of the landscape; or where there is spatial variability in sediment supply.

Some channel properties, such as width and depth, vary primarily with drainage area. Other channel properties, such as hydraulic friction, vary with slope. Steeper channels generally have greater roughness, provided that sediment supply to the channel includes bed material large enough to be stable. The greater roughness of steeper channels retards flow enough that velocity typically increases downstream in natural channel networks, in spite of the decreasing slope (Leopold 1953). While this acts to decrease the downstream variability in average velocity of the reach, the turbulence imparted by the greater roughness of steep channels increases the spatial and temporal variability of velocity within a reach.

Vegetation

Variability in climate also indirectly influences the geomorphic variability of channels through

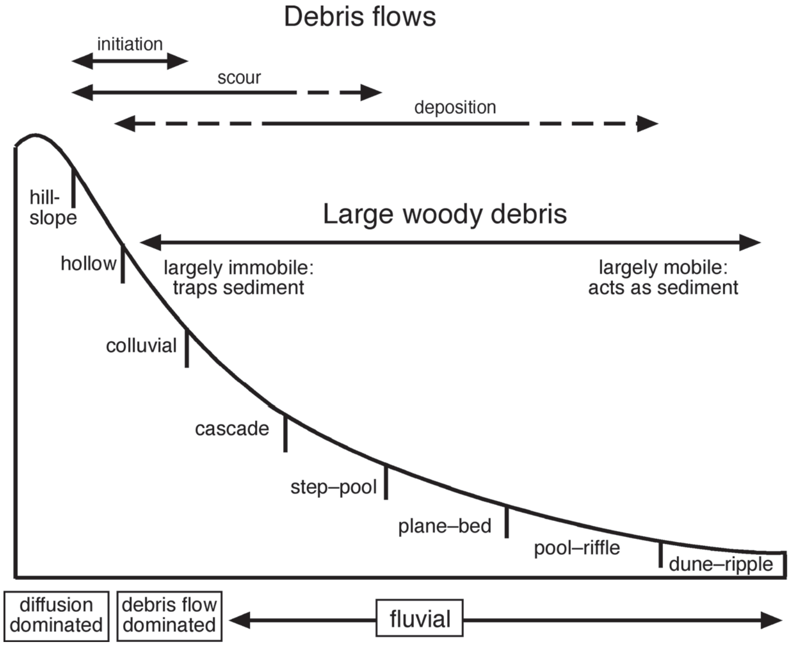

FIGURE 7.–Idealized longitudinal profile from hillslopes and unchanneled hollows downslope through the channel network showing the general distribution of alluvial channel types and controls on channel processes in mountain drainage basins. From Montgomery and Buffington (1997).

differences in the nature and type of vegetation that grows in an area. Much work has been done identifying vegetation zones based on climate, often as a function of elevation or latitude in a given area (Smith 1974; Pfister et al. 1977; Kimmens 1987). Vegetation is a major influence on stream channels, with the dominance of grass or forest being a key distinction. The roots of vegetation can provide substantial stability to streambanks (Smith 1976). Bank vegetation can be significant enough to influence channel pattern (Millar 2000), and Schumm (1968) hypothesizes that the first appearance of meandering channel deposits in the geological record reflects the evolution of land plants. Ward et al. (2000) and Michaelsen (2002) report a rapid change from meandering to braided river morphology coincident with the global plant die-off 250 million years ago at the Permian/Triassic mass extinction event. The presence of grass or forest on river banks influences channel width, although whether channels widen or narrow depends on the type of channel (cf., Davies-Colley 1997; Stott 1997; Trimble 1997). The presence or absence of trees large enough to provide stable wood to channels introduces a major source of geomorphic variability into streams and rivers (Keller and Swanson 1979; Nakamura and Swanson 1993; Abbe and Montgomery 1996). Wood recruitment, as a part of natural, habitat-forming processes, is discussed later in this chapter.

Watershed/Channel Network Level

The watershed defines the boundary for the processes generating sediment and runoff into channels and is a natural organizational unit for channel networks (Chorley 1969) and aquatic ecosystems (Lotspeich 1980). Although position in the channel network influences the effects of landscape assemblages on channel processes, the actual response of a channel also depends on its regional context and disturbance history. The location-specific array of process domains and the associated disturbance history are key to planning, designing, and implementing appropriate restoration actions. In general, but by no means always, the degree of temporal and spatial variability in geomorphic processes tends to decrease downstream, with headwater channels subject to greater variability in conditions (Figures 3 and 4).

In mountain channels, the sequencing of debris flow fans at tributary stream confluences can buffer downstream reaches from headwater disturbances originating in steep, headwater channels prone to debris flows. Debris flow fans approximately define the downslope limit of debris flow propagation, and their distribution through mountain-channel networks influences the disturbance regime in headwater channels. In addition, fans themselves can introduce significant variability in channel and habitat characteristics such as slope, valley bottom width, and pool frequency (Grant and Swanson 1995). A trellis-shaped channel network favors short runout debris flows by forcing deposition at right-angle tributary junctions (Johnson et al. 2000a), whereas a dendritic channel network favors longer runout debris flows, as deposition occurs farther down the channel network at lower slopes (Ikeya 1981; Takahashi et al. 1981). Unconfined channels with wide valley bottoms can be buffered from the direct influences of hillslope processes, whereas hillslope processes are a strong influence in confined channels with little to no valley bottom. In a landscape comprising bedrock hillslopes, alluvial fans, and wide valley bottoms, channels will be relatively buffered from local variability in hillslope processes. In contrast, channel processes will be strongly coupled to hillslope processes in a landscape with earthflow-dominated hillslopes, channels tightly confined in narrow valleys, and no debris fans. The design and evaluation of channel restoration projects should account for how watershed or landscape-specific types and arrangement of landscape elements and the architecture of the channel network itself influence hydrogeomorphic variability and river ecosystems.

Valley Bottom Level

Headwater reaches of mountain-channel networks tend to occupy erosional valley segments, whereas large floodplain rivers tend to occupy depositional areas of the landscape (Schumm 1977). Intervening channel segments act as transport routes that deliver sediment from upland sources to lowland sinks. These three broad types of channel function (source, conduit, sink) generally correspond with colluvial, bedrock, and alluvial valley segments, which are differentiated by the type of valley fill (Montgomery and Buffington 1998). Colluvial valleys have a small enough drainage area (typically <1 km^2) that fluvial processes are dominated by hillslope processes. Bedrock valley segments have sufficient transport capacity to allow frequent transport of sediment supplied from their watersheds. Consequently, little to no material is stored on the streambed, which may have only a thin cover of alluvium in active transport by fluvial processes. In contrast, alluvial valley segments store, as valley fill, significant amounts of material transported by the channel.

In wide alluvial valleys, retaining or reestablishing connectivity between the river and its floodplain may be one of the most important restoration objectives. Providing space for the channel to migrate and create or alter habitat maintains the patchwork of complexity that supports higher levels of biodiversity. Ward and Tockner (2001) illustrate how diversity of different groups of plants and animals varies from the center of the stream to the edge of the floodplain in large rivers. In areas where diking, draining, and channelization have isolated the river from the floodplain, restoring river–floodplain connections should be a priority. The general distribution of valley segment types provides a broad context for developing and evaluating the suitability of different types of restoration efforts.

Channel Reach Level

Distinct types of channel reaches can be defined based on the nature and organization of the channel-bed cover. Various types of alluvial channels reflect downstream trends in streamflow and channel slope, as well as local variability in the supply and size of the available bed-forming material. The distribution of specific channel types reflects the interplay of sediment supply and transport capacity across space and through time (Montgomery and Buffington 1997, 1998). In some channel systems, for example, the spatial distribution of different channel-reach types is well described on a plot of drainage area vs. slope (Figure 8). However, in some areas recent disturbance can mask such topographically driven relationships and obscure general trends in relative transport capacity. In addition, different reach types host different general types of aquatic habitat. In particular, differences in the balance between sediment supply and transport capacity can translate into differing degrees of sensitivity to human actions and responsiveness to restoration efforts.

Although many people automatically think of pool–riffle channels as the target channel type for restoration, other channel types may be more appropriate templates depending on the location in the landscape and controlling factors such as geology, topography, vegetation, and hydrologic regime. Consequently, analysis of watershed and channel reach processes that affect habitat should be completed *before* restoration efforts begin. Pool spacing presents a good example of the variability in the abundance of channel units among different types of channels. Step–pool channels have typical pool spacings of 1–4 channel widths per pool (CW per pool), whereas pool–riffle channels typically have a spacing of 5–7 CW per pool, and plane–bed channels usually have spacings of greater than 10 CW per pool (Montgomery et al. 1995). Introducing greater amounts

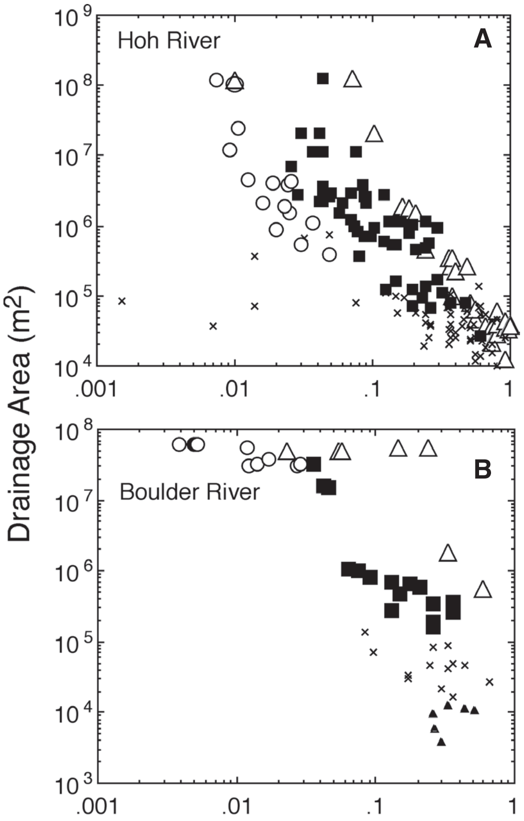

FIGURE 8.–Relationship between drainage area, slope, and channel types in the (A) Hoh and (B) Boulder river basins, Washington (Montgomery and Buffington 1997). ○ = pool–riffle and plane–bed channels; ■ = step–pool and cascade channels; Δ = bedrock channels; × = colluvial channels; and ▲ = unchanneled topographic hollows.

of wood debris increases pool frequency in plane–bed and pool–riffle channels, but may not increase pool abundance in step–pool channels.

In many historically forested watersheds, pools have been suggested as being a recently missing or depleted habitat component due to the lack of large woody debris (LWD). Consequently, addition of wood to streams is probably the most frequent restoration action taken in Pacific Northwest channels. But seldom is the time taken to evaluate whether the stream as a whole has the expected amount of wood or pools or both, let alone define the expected pool spacing. The context of channel type can help to evaluate the expected channel-unit type and frequency (such as pool spacing) as well as the potential influence of wood on pool formation for different channel reaches in a watershed.

Channel patterns range from relatively straight to meandering to braided to anastomosing, and they form a variety of patterns that grade together. Channel slope, streamflow, bed material size, and vegetation combine to influence which pattern the stream exhibits. For a given drainage area, braided channels tend to occur on slopes steeper than straight or meandering channels and generally have higher sediment loads relative to streamflow (Leopold and Wolman 1957). Schumm (1963) found that meandering was associated with cohesive sediment and little bed-load transport whereas braided channels typically had coarser non-cohesive sediments and more bed-load transport. An abundant supply of bedload (whether natural or anthropogenically induced), erodible banks, and highly variable streamflows facilitate development of a braided pattern. Changes in flow or sediment regimes (natural or anthropogenic) can shift channel patterns. The presence of cohesive vegetation as a bank-forming agent also influences transitions between meandering and braiding (Millar 2000). Restoration projects that impose a channel pattern that is not supported by the slope, sediment, streamflow, and vegetation through the channel reach will be difficult to maintain.

Channel Unit Level

Channel units—the smallest units into which channel morphology is typically divided—correspond to different habitat types for aquatic communities. Different types of channels host different varieties and associations of the basic channel units of bars, pools, and shallows. Some channel units are formed by the interaction of hydraulics and sediment transport, while others are forced by local flow obstructions such as stable wood debris. Bisson et al. (1982) identified a suite of different channel units that define specific habitat types, including many different types of pools. As certain sets of channel units are associated with certain channel types at the reach scale, the character of instream habitat covaries downstream with differences in channel type (Figure 7). Channel units are the most variable scale of channel characteristics. The number, type, location, and character of specific units may change as trees fall into the channel, boulders are rearranged during high flows, or pulses of sediment move through a reach. Such small features are those generally measured and monitored in stream-channel assessment, restoration, and monitoring programs. Although it may be easier to detect changes at the channel-unit scale than at broader spatial scales, it may be harder to interpret the causes or meaning of such changes. Poole et al. (1997) discuss the inadequacies of relying on changes in channel units for monitoring and management. Problems with using the channel-unit scale for habitat classification include lack of repeatability by different observers, lack of precision in unit classification, uncertain sensitivity of units to anthropogenic changes, and known sensitivity of habitat units to flow variation.

Hydrologic Regime

The hydrologic regime of a landscape incorporates downstream trends and temporal variability in streamflow. Various measures have been suggested as ways to characterize hydrologic regime including flow frequency, magnitude, rate of change, and duration (e.g., Poff 1996; Richter et al.

1997). Major components of the hydrologic regime important to restoration planning include the seasonal timing and duration of high and low flows (Poff and Ward 1989).

We selected five watersheds to illustrate the range of variations in seasonal timing and magnitude for hydrologic flows (Figure 9). The Chehalis River, Washington, exhibits several high flow periods in the fall and winter due to winter rains and some higher flows in spring from snowmelt. Summer flows are a fraction of the median annual flow. The Chestatee River, Georgia, shows above-median flows scattered throughout the year from rain storms with a cluster of higher flows in the early spring. Rock Creek, Montana, flows are close to median during the colder, winter months and show a period of high flow during spring snowmelt. Flow in the Santa Cruz River, Arizona, shows extended periods of median flow with occasional, large spikes due to intense summer thunderstorms. The Williams River, Vermont, has intermittently higher than median flows in the fall due to rain or rain-on-snow, a period of stable median flows in the colder winter months, and then a distinct snowmelt season in March and April with flows much higher than median flows. Such regional variation of streamflow is a normal component of the hydrologic regime and should be accounted for in restoration projects.

Restoration projects that are either washed away by floods or stranded by low flows may not provide the intended habitat benefit for instream organisms. Many stream assessments are conducted during the summer months when stream flow is low. This can result in underestimating the number or extent of channels that carry water during higher winter flows and the value of habitat that is dry when observed in the summer.

The season and form of precipitation are the major controls on the timing of flows. Two major components of climate change affect hydrology and streamflow: changes in precipitation amounts and changes in temperature that affect precipitation type (i.e., rain vs. snow). On a human (as compared with a geologic) timeframe, shifts in sea surface temperatures, such as the El Niño–La Niña oscillation, have been shown to affect streamflow. Most studies have looked at extreme hydrological events such as floods and droughts over various geographical regions. For example, floods are associated with El Niño in South America (Philander 1990) and droughts are associated with El Niño in Australia and Indonesia (Simpson and Cane 1993). Kahya and Dracup (1993) identified four regions in the USA (Gulf of Mexico, the Northeast, the North Central, and the

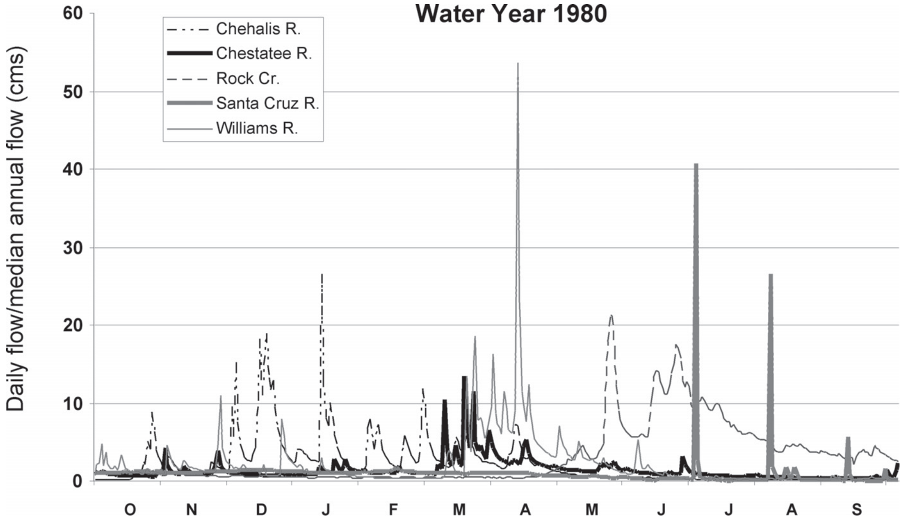

FIGURE 9.–Seasonal variation in streamflow timing and magnitude as measured by the ratio of daily flow to median annual flow. Data from Slack and Landwehr (1992).

Pacific Northwest) that can show significant streamflow responses to El Niño conditions. Awareness of the status of El Niño conditions and associated effects on precipitation and streamflow could be used to decide whether or when to install restoration projects that need time to stabilize before they can withstand flooding.

Karl and Knight (1997) examined changes in precipitation across the entire United States from 1910 to 1996 and found an increase of about 10%, largely due to heavy and extreme daily events. Changes in precipitation amounts and intensities will appear as changes in streamflow depending on water storage capabilities and flow paths in the watershed. Unknown or unacknowledged trends add uncertainty to hydrologic analyses used to design restoration projects and can increase the risk of inadequately designing projects.

Downstream Variability

In general, total streamflow increases with distance downstream as contributing area increases (e.g., due to more flow from tributaries). Exceptions include streams in areas of limestone geology, porous volcanic rocks, or major faults that provide pathways for surface water to flow underground (Riggs and Harvey 1990). Average annual streamflow-per-unit-area may increase, decrease, or be relatively stable as drainage area increases (Glymph and Holton 1969). For restoration purposes, the timing, duration, and magnitude of high and low flows are the most relevant characteristics of the hydrologic regime. As a flood wave moves downstream, its classification can change from a higher-magnitude, lower-frequency event to a lower-magnitude, higher-frequency event (Dunne and Leopold 1978). This is a consequence of routing and storage as well as temporal and spatial variation in precipitation and watershed drainage density. In addition, local features such as floodplains, beaver dams, wetlands, or lakes can buffer downstream channels from hydrogeomorphic variability. Hence, knowledge of position in the channel network and the sequencing of landscape elements is important for designing or assessing restoration projects.

In response to a precipitation event, peak-flow events become dampened as the watershed area increases (Figure 10). Rapid peak-flow responses commonly occur owing to sudden rainfall events in small watersheds. For example, in the Sleepers River, Vermont, three peak-flow responses followed three rainfall events in the smallest watershed area (0.2 mi^2). At the larger, 16-mi^2 area, the peaks became dampened into one event. Although the number of peak-flow events (in hr^{-1}) decreases as the drainage area increases, the absolute discharge rates (cfs) increase as floodwaters drain from larger areas.

Flood peaks move as a wave, first increasing and then decreasing downstream owing to translation (downstream movement with no change in shape) and attenuation (changes in shape and peak due to channel and valley storage of the water) (Dunne and Leopold 1978). Drainage area and channel characteristics influence the attenuation of flood peaks and most rivers exhibit a mix of translation and attenuation. Downstream attenuation of flood peaks is enhanced by wide valley bottoms, lack of confining terraces, and high hydraulic roughness. Such differences can introduce up to almost 50% variability in peak streamflows among watersheds (Woltemade and Potter 1994). In other words, changes in land use in a watershed that alter channel width and roughness will result in changes in expected peak flows.

If a restoration project is planned for an ungauged stream or a stream without a gauge nearby, then the changes in total flow and unit-area flow need to be considered when deciding which flows to use for design purposes. For river restoration efforts, the following high-flow characteristics are particularly useful for designing projects: volume of runoff, peak runoff, flow depth (stage), duration of high flow, area expected to be submerged by the flow, and the velocity of the flow. The predictability of seasonal timing of peaks is also important (Magilligan and Graber 1996; Burn 1997; Lecce 2000).

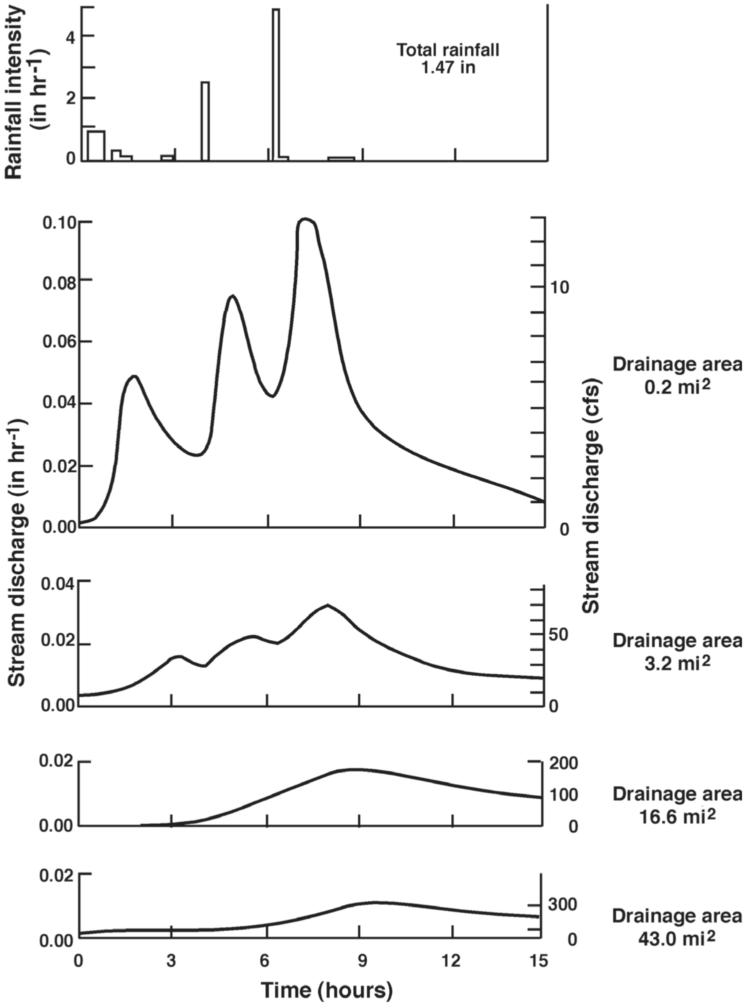

FIGURE 10.–Changes in flood peaks along the Sleeper's River, Vermont. From Dunne and Leopold (1978).

On large rivers, such as the Mississippi, historical records indicate that channelization in the form of levees and dikes has diminished the floodplain storage of water during floods, thereby creating higher depths (stages) of water for the same volume of water (e.g., Sparks 1995; Criss and Shock 2001). Recognition of this effect is not new. As far back as the mid-1800s, Ellet (1852) reported the following to Congress:

> The extension of the levees along the borders of the Mississippi, and of its tributaries and outlets, by means of which the water that was formerly allowed to spread over many thousand square miles of low lands is becoming more and more confined to the immediate channel of the river, and is therefore, compelled to rise higher and flow faster.… [F]uture floods throughout the length and breadth of the delta, and along the great streams tributary to the Mississippi, are destined to rise higher and higher, as society spreads over the upper States, as population adjacent to the river increases, and the inundated low lands appreciate in value.

Current restoration efforts that ignore the physical and historical factors driving hydrologic regimes may have similar unintended long-term results that can create more problems than they solve. It seems prudent that preservation of rivers that have seen minimal development and that retain most of their natural attributes should have priority over restoring degraded systems. On the basis of our current understanding of river ecology, restoration and rehabilitation should focus on maintaining and restoring interactions and processes that create and sustain habitat patches and successional stages (Jungworth et al. 2002).

Temporal Variability

Streamflow varies hourly, daily, monthly, seasonally, annually, and over longer periods. The meteorological factors that drive streamflow (precipitation, humidity, evapotranspiration, etc.) and streamflow itself are generally thought of as stochastic processes. This means that a process, such as peak flows, can never be estimated with certainty based on past values (Haan 1977). Depending on the period of record available for estimating peak flows, different levels of uncertainty exist (Table 2). If you want to have a 95% confidence level that the estimated value for the 10-year flood is within 10% of the actual value, you will need 90 years of data. If you only have 18 years of record, the predicted value will be within 25% of the actual value for the same confidence level. However, if trends are present in the controlling meteorological factors, then temporal variation in streamflow becomes more difficult to characterize (and analyze) and historical flows may not accurately represent future variability. For extreme floods, paleohydrology provides some help for events outside the range of historical data (e.g., Costa 1983). Extreme events are more critical for projects that involve human safety issues and may not be of concern for all restoration projects.

Long periods of above- or below-normal trends (Hurst et al. 1965) can be used to identify the degree of persistence of geophysical time series such as streamflow (Klemes 1974; Burges 1991). Colwell (1974) developed indices to describe predictability and constancy in temporal variability in physical and biological characteristics that can be used to describe streamflow and precipitation periodicity (Gan et al. 1991). Richter et al. (1997, 1998) describe a “range of variability” approach for assessing the critical role of hydrologic variability in sustaining aquatic ecosystems.

A stream’s flow variation reflects the physical and biological conditions in its watershed. Soil depth, permeability, texture, vegetation, land use/land cover, and drainage density all influence runoff generation and the storage and routing of water throughout the landscape. Precipitation rates and soil infiltration rates and depths are highly variable in space and time. Changing land uses can alter infiltration rates by changing vegetation coverage and interception capacity, increasing impervious areas where water cannot enter the soil column, and compacting or removing soil, which affects infiltration and total soil water storage (Saxton and Shiau 1990). Such changes alter the hydrologic regime and appear as changes in the number, frequency, size, timing, and duration of high and low flows.

If an instream restoration project is designed and implemented without an understanding of the range, duration, and timing of high and low flows, portions of the project site may be either submerged or high and dry at certain biologically critical times. Restoration projects should have

TABLE 2.—Length of record (years) required for a 95% confidence level in estimated peaks flows of different return periods.

Return period (years)	10% error in flow prediction (years of record)	25% error in flow prediction (years of record)
10	90	18
50	110	39
100	115	48

a specified design period over which they are expected to perform. The design of the project needs to reflect the range of expected variability in streamflows over that design period. If it does not, the project may be unlikely to meet its objectives.

Flow Duration

Flow-duration curves rank flows by size, regardless of when they occur. They are used to illustrate whether streams have a more stable baseflow regime or are subject to sudden changes in water level (Burt 1992). A steep flow-duration curve indicates a basin with highly variable flow, a quick response to precipitation, and little baseflow. Flatter slopes indicate more sustained and even flow, typically with a large groundwater component. Data from the Hydro-Climatic Data Network (Slack and Landwehr 1992) were compared for five rivers with similar basin sizes and land use across the United States (Table 3). The Santa Cruz River in Arizona has no flow about 20% of the time (Figure 11). On the basis of a measure of low flow—defined as "flow exceeded 95% of the time"—the Chestatee River in Georgia has the highest baseflow with the 95% exceedance flow equal to about 28% of the mean annual flow. For the Chehalis River in Washington, the 95% exceedance flow is about 5% of baseflow. This area has a dry summer regime with little precipitation during the growing season. Evapotranspiration depletes the soil storage and streamflows can be very low during long, dry, hot spells. The Chestatee River flows through a region with more summer rain so that soil moisture is regularly replenished except during severe droughts. Peak flows in the Santa Cruz River of more than 100 times the daily mean flow contrast with the other four streams where peak flows are about 10 times the daily mean flow.

Another aspect of flow duration is the length of time that high or low flows persist. Both the peak water level and the duration of high flows influence the effectiveness of structural responses such as dikes and sandbag levees. During the 1993 flooding on the Mississippi River, some dikes contained the peak flow but failed when exposed to an extended period of high water. It takes time for banks and levees to become saturated and less stable. Flow duration can be a critical factor determining the effect of high flows on channels (Costa and O'Connor 1995).

Peak Flow

Peak flow and return probability (frequency) information is needed when there is concern that

TABLE 3.—Characteristics of rivers chosen for analysis. Data from Slack and Landwehr (1992).

River	USGS ID	Period of record (water year)	Drainage area (km^2)	Gauge elevation (m)	Mean basin elevation (m)	Stream length (km)	Annual precipitation (mm)	Hydrologic regime
Williams R., Vermont	01153500	1941–1988	267	132	408	35	1,118	Snowmelt/ rain-on-snow
Chestatee R., Georgia	02333500	1944–1988	396	344	529	41	1,499	Rainfall
Rock Ck., Montana	06209500	1935–1982	321	1,859	2,908	33	1,016	Snowmelt/ thunderstorm
Santa Cruz R., Arizona	09480000	1950–1988	213	1,408	1,570	19	462	Summer thunderstorm, winter fronts
Chehalis R., Washington	12020000	1940–1988	293	92	305	42	2,311	Winter rain/ rain-on-snow

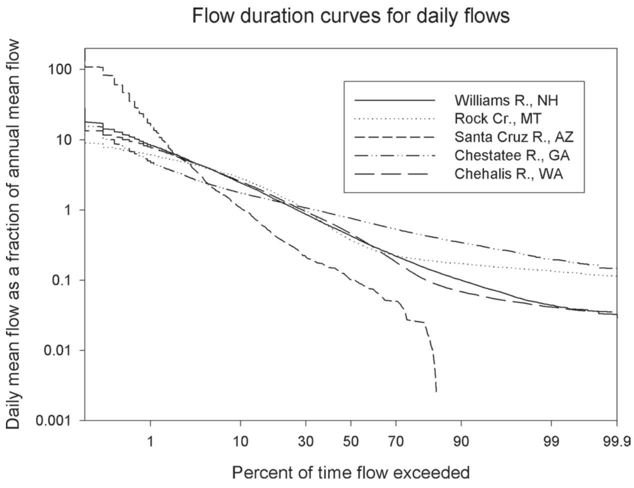

FIGURE 11.—Flow duration curves for five selected basins. Data from Slack and Landwehr (1992).

high water or changes in channel morphology may affect restoration projects. Flood probability and frequency are often used interchangeably but it is typically probability that is meant. Frequency is the number of occurrences and probability is the statistical likelihood of occurrence. In the United States, peak-flow data for a site or region are fit to a Log-Pearson III distribution to determine the probability of various peak-flow magnitudes (Cudworth 1989). Generally, we refer to different sizes of peak flow by the return period measured in years. Return period and probability of occurrence are the inverse of each other. The probability of a flood of a given return period is 1 per T where T is time in years. That is, a 10-year flood has a 1/10 or 10% chance of occurrence in any given year. This concept is commonly misunderstood. On average, there would be four 10-year floods in 40 years, but the statistical probability of getting exactly four 10-year floods in 40 years is 20%. If you wanted to have a 90% confidence level that your restoration project would last 10 years, you would need to design it to withstand the 95-year event.

A long period of flow records is required for a high level of confidence in return intervals for floods of a given size (Table 2). Few streams in the United States have the 90-year record of peak flows necessary to achieve 95% certainty of predicting the size of a 10-year flood within 10%. In addition, the size of floods of a given return period at a given location is not necessarily stable over long time periods owing to either climate changes or land-use changes (National Research Council 1999; Pinter et al. 2001).

The processes inherent in different process domains will determine the size and frequency of peak flows. Predicted magnitudes of peak flows of different recurrence probabilities for the five rivers used in the flow-duration example reflect their different climates and physiography (Figure 12). The break in slope visible in the Chehalis and Williams Rivers is typical of streams with mixed populations of floods (e.g., some peak floods due to rain, some to rain-on-snow, and some to snowmelt) (Cudworth 1989). In some areas, the 100-year flood (Q_{100}) is many times greater than the mean annual flood (Q_2), whereas in other areas Q_{100} is only slightly larger than Q_2 (Table 4). Keep in mind that the streamflow values in Table 4 have a level of uncertainty in them that is related to the period of record used to generate the values (Table 2).

Pitlick (1994) examined the relationship between peak flows, precipitation, and physiography using regionalized flood frequency curves for five regions of the western USA with similar physiography but different climates. In all regions, he found that mean annual peak flow was most highly correlated to drainage area and mean annual precipitation. No correlations were found

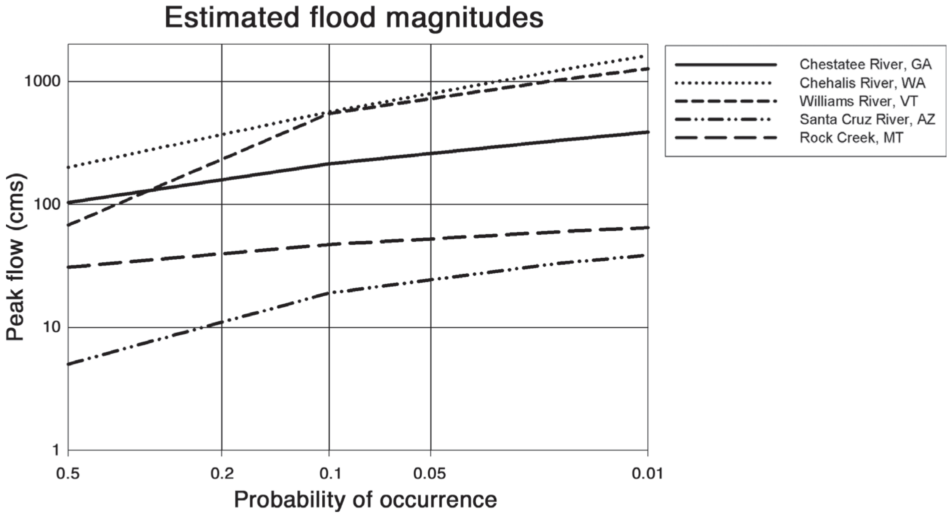

FIGURE 12.—Comparison of peak flows at various probabilities of occurrence for five watersheds. 0.1 probability = 10-year return period flood; 0.5 probability = 2-year flood. Lines based on the 2-, 10-, 50-, and 100-year flows using a Log Pearson III distribution method. Data from Slack and Landwehr (1992).

TABLE 4.—Estimated flood size ($m^3 s^{-1}$) for different flow frequencies from Log Pearson III analysis of Hydro-Climatic Data Network data. Data from Slack and Landwehr (1992).

	2-year (Q_2)	10-year (Q_{10}) ($m^3 s^{-1}$)	50-year (Q_{50}) ($m^3 s^{-1}$)	100-year (Q_{100}) ($m^3 s^{-1}$)	Q_{100}/Q_2 ($m^3 s^{-1}$)
Williams R., Vermont	68	547	1020	1270	18.6
Chestatee R., Georgia	102	212	331	385	3.8
Rock Cr., Montana	31	48	60	65	2.1
Santa Cruz R., Arizona	5	19	33	39	7.5
Chehalis R., Washington	198	566	1220	1610	8.1

between peak flow characteristics and physiography. He concluded that flood frequency distributions are a reflection primarily of variability in precipitation amount and intensity. He also concluded that flood variability (i.e., Q_{100}/Q_2) is largely a function of precipitation variability (i.e., instances where single storm events provide a higher proportion of annual precipitation). Rock Creek, Montana, illustrates the relatively flat flood frequency curves and consequently small Q_{100}/Q_2 ratios typical of snowmelt-dominated regions (Table 4).

Low Flows and Droughts

Droughts and low flows are also a component of hydrologic variability. Low flows are a seasonal occurrence related to precipitation, temperature, and evapotranspiration. During low flows, the flow generally is derived from groundwater inflow or sources such as lakes, springs, and glaciers (Rogers and Armbruster 1990). A drought is a period of below-average precipitation that lasts long enough to create a sustained period of less than normal low flows. Drought severity depends on the amount of precipitation deficiency, the duration of dryness, and the size of the area affected. Droughts are typically declared on the basis of one or more of seven criteria, five of which are indices (Palmer 1965, 1968; Gibbs and Maher 1967; Alley 1984; Wilhite and Glantz 1985; Doesken et al. 1991; Mckee et al. 1993). Examples of criteria for defining a drought include the following (Rogers and Armbruster 1990):

- Meteorological–when precipitation departs from normal.
- Agricultural–when the amount of moisture in the soil no longer meets the needs of a particular crop.
- Hydrological–when surface and subsurface water supplies are below normal.
- Socioeconomic–when physical water shortage begins to affect people.

Droughts have spatial and temporal components of variability. Severity and duration vary widely, from the below-average rainfall in Northern California for 1969 and 1970 (Matthai 1979) to the 1930s Dust Bowl period (Hoyt 1936) that affected 50 million acres of land and triggered a large-scale human migration. Droughts affect biological systems via the direct lack of water and through changes in stream water temperature and water quality (Murdoch et al. 2000; Caruso 2001). When droughts coincide with elevated air temperatures, they can result in unusually high stream temperatures with wider than normal daily fluctuations (Walling and Webb 1992). Daily temperature fluctuations may be less pronounced in large rivers during drought because of longer retention times and slower downstream transfer of flow (Walling and Carter 1980).

Restoration projects undertaken during recognized drought periods may have limited effectiveness until the drought is over owing to impaired water quality. Low flow periods can be a good time to work in the stream channel but if a project area is providing refugia for organisms affected by the drought, care must be taken to avoid additional harm.

Geomorphic Regime

Sediment delivery, transport, and storage processes can be highly variable along a single river system and among different watersheds. Understanding the historical types, rates, and distributions of geomorphic processes is necessary for sound restoration design. Creating spawning beds by adding gravel to a stream that receives high loads of fine sediments will be futile as the fine sediments quickly bury the gravels. Pools built in a system with a high sediment delivery rate may rapidly fill in. Understanding the historical and current geomorphic regime in a watershed will improve the design and longevity, and hopefully, the ecological function or value of restoration projects.

The morphology and dynamics of rivers and streams reflect the amount and size distribution of the sediment supply. Changes in the balance between sediment supply and transport capacity influence channel characteristics at scales ranging from pool size and depth (Lisle and Hilton 1999) to reach-scale channel types (Montgomery and Buffington 1997) and channel patterns (Church 1992). A project that seeks to establish or maintain a channel morphology that cannot be sustained by current, or likely future, geomorphic processes is destined to fail. Hence, evaluation of the geomorphic regime, and in particular sediment supply, transport, and storage, is important for assessing proposed restoration projects. Restoration projects undertaken in a stream reach where sediment supply greatly exceeds sediment transport are likely to be buried by sediment. Similarly, projects in a reach where transport greatly exceeds supply may be undercut and damaged as the stream incises.

The geomorphic regime of a landscape, watershed, or channel reach reflects variability in the size and amount of sediment supplied locally and from upstream, the mobility and type of transport of the channel-bed sediments, and the routing and storage of sediment through the channel network. A formal analysis of sources of sediment inputs, transport mechanisms and rates, and storage within a channel system is referred to as a sediment budget (Dietrich and Dunne 1978; Reid and Dunne 1996).

Sediment Supply and Delivery

River networks transport the products of physical and chemical weathering. The sediments produced by erosional processes are transported through the fluvial system to be deposited in floodplains, lakes, and ultimately ocean basins. The characteristics of the soil and weathered rock (together referred to as regolith) provide a reasonable representation of the size distribution of the sediment supply for a channel network in regions without substantial bedrock landsliding to introduce fresh rock and boulders directly to the channel. Substantial sorting of material occurs within the fluvial system as shown by comparing the general composition of hillside soils with the coarse (i.e., gravel, cobble, and boulder) streambeds typical of mountain channels.

The sediment regime of a channel also reflects the manner and frequency of sediment delivery from different sources. In mountainous terrain where debris flow processes dominate sediment delivery, headwater channels have a highly variable sediment regime in which periodic catastrophic events deliver substantial volumes of material. In contrast, lowland floodplain channels that are insulated from hillslope processes can have a relatively consistent sediment supply related to the frequency of high streamflow or bankfull flow events.

A dramatic example of extreme variability of sediment regimes is that of steep mountain channels subject to periodic scour by debris flows. Owing to relatively weak sediment transport by ephemeral flow and continuous delivery of soil from hillslope processes, the valleys occupied by these channels tend to fill over time with colluvium (unsorted hillslope-derived material). Periodic debris flows scour the valley to bedrock and deliver the colluvium that accumulated along the valley segment since the last debris flow to downstream channels. Hence, the morphology of these headwater channels alternates from a colluvial reach with a small ephemeral channel to a channel flowing over material deposited by debris flows or even bare bedrock. The proportion of time the channel exhibits either morphology depends upon the frequency of debris-flow events and the rate of colluvium accumulation between those events.

The morphology of lower-gradient channels can also change in response to changes in sediment supply. For example, rivers draining the flanks of Mount Pinatubo, Philippines, provide a dramatic example of temporal variability in channel type in response to changes in sediment loads. The 1991 eruption of Mount Pinatubo delivered 5–6 km^3 of pyroclastic flow deposits and approximately 0.5 km^3 of tephra-fall deposits to the flanks of the volcano (Newhall and Punongbayan 1996). Prior to the eruption, the Pasig-Potrero River was a relatively typical gravel–cobble bed mountain channel. Today, it is an incised, braided, sand- to gravel-bed river more than 150 m wide, with a mean slope of 0.020. Even at low flow, the water is turbid and opaque; submerged portions of the riverbed are a moving carpet of mobile grains, the largest of which protrude through the flow while rolling downstream as bedload. In other words, excess sediment supply can lead to a higher transport capacity through a decrease in bed roughness and critical shear stress (Montgomery et al. 1999; Hayes et al. 2002). In contrast, the less impacted rivers that are similar to the pre-eruption channel of the Pasig-Potrero are more typical single-thread, cobble–boulder bed mountain streams in which no sediment transport occurs during low flows.

In terms of restoring habitats in channels with different bed characteristics, it is important to understand reach-scale structures and processes when designing a project. Particular attention should be paid to ongoing, potential, or likely impact to the project site from local sediment sources or sediment delivery from upslope. The sediment regime set by the local and watershed-scale geomorphic contexts can help account for differences in slopes, bed roughness, and streamflow regimes when designing a restoration project.

Sediment Mobility and Transport

The mobility of the material forming the bed of a river has important effects on aquatic ecosystems and therefore on ecosystem restoration. If the bed is constantly mobile, then it is continuously disturbed and offers poor-quality, inhospitable substrate for most (if not all) organisms. If a streambed is relatively immobile, or only infrequently disturbed, then it can provide hospitable substrate for aquatic plants and animals. The frequency with which the bed is disturbed is a primary boundary condition on aquatic ecosystems.

There are several general types of bed mobility. Live-bed channels are those that are mobile at even low streamflows; that is, the bed is constantly mobile. Such channels are almost always fine-grained, typically sand-bed channels typical of lowland, low-gradient river channels. In contrast, threshold-bed channels are those in which the bed is mobile only above some threshold streamflow or flow depth. Gravel- and cobble-bed channels tend to have threshold streamflows that are some significant fraction of the bankfull streamflow. Bed mobility initiates over a range of streamflows (Wilcock 1993), and the identification of the bed-mobilizing flow depends on the method used to define the onset of bed mobility (Buffington and Montgomery 1997). In addition, different areas of a channel bed may have differential mobility, and small areas of the bed can convey most of the bed load (Lisle et al. 2000). Step–pool and cascade channels with mixed boulder- to gravel-size beds can have a dual mobility threshold in which finer-grained materials exhibit frequent mobility but the larger, framework-forming bed elements are mobile only during infrequent high flows. Hence, in mountain drainage basins there is a general downstream trend in the style and frequency of bed mobility: in the fluvial portion of the channel network, it progresses from multi-threshold headwater channels to threshold cobble- to gravel-bed channels, and eventually to live-bed channels.

Hydrologic variability driven by regional climate also leads to differences in bedload transport relationships between arid and temperate rivers, which are due to the development of a coarse surface layer or armor on the bed surface. The sustained falling limb of hydrographs in temperate rivers progressively sorts the material on the bed surface, leading to development of a bed coarser than the material in transport during high-flow events. This coarse surface layer is typically mobile only above some threshold streamflow, which is commonly somewhat less than the bankfull streamflow (Williams 1978). In contrast, the rapid hydrograph recession typical of arid rivers leads to bed surfaces with an unsorted composition similar to that of the material transported by the channel. The characteristically unarmored beds of arid rivers lead to much higher bedload transport rates than for comparable rivers in temperate regions (Larrone and Reid 1993). Hence, the hydrologic variability imparted by climate differences in arid and temperate regions leads to fundamentally different channel-bed dynamics and sediment regimes.

Sediment Routing and Storage

Sediment enters the channel network at different locations along the stream, and sediment travel time through the river network varies with the length, slope, and flow characteristics of the intervening channel segments. Consequently, the relative amplitude of sediment pulses decreases downstream even though the overall sediment load or fluvial streamflow typically increases with drainage area in a fashion similar to flood peaks. Hence, the temporal variability in streamflow and sediment transport is greater in small mountain channels than in large floodplain rivers. Mountain rivers typically have little floodplain area, and hillslopes are directly connected to the river system. The lack of floodplain storage leads to relatively efficient downstream routing, whereas large rivers typically have extensive floodplains that can store a substantial proportion of the sediment in transit through the channel system. For example, roughly a third of the total sediment load of the Amazon and Ganges-Brahmaputra river systems remains sequestered in long-term storage in extensive floodplain systems rather than being delivered to the oceans (Dunne et al. 1998; Goodbred and Kuehl 1998). The sediment delivery ratio, defined as the proportion of the sediment entering a channel reach that is delivered to downstream reaches, is high for mountain rivers owing to limited sediment storage, whereas the sediment delivery ratio for lowland rivers is low because of extensive sediment storage. In addition, sediment yields typically decline with increasing drainage area in large alluvial river systems owing to the long-term storage of material in floodplain sediments. Fryirs and Brierley (2000) illustrate how sediment storage and delivery has changed over time in a large Australian watershed as a function of valley and floodplain forms such as swamps, fills, and fans. Just as for planning dam projects, knowing the upstream sediment yield can be an important factor in designing and evaluating restoration projects.

Local features along a channel network can enhance or dampen hydrogeomorphic variability. Point sources of sediment inputs can reset downstream trends in grain size or channel type, thereby enhancing morphologic variability (Smith and Smith 1984; Harvey 1991; Rice and Church 1998). Lakes act as hydrologic storage elements and sediment traps that reduce the amplitude of variations in flow and sediment delivery to downstream channels. However, the geomorphic response to dams is complicated because of the combined effects of simultaneous changes in streamflow and sediment storage; the resultant effects depend on the specific context of the river in question (Williams and Wolman 1984). Small sediment storage elements, such as log jams, can also store substantial amounts of sediment in mountain river systems (e.g., O'Connor 1994). Montgomery et al. (1996) show that local sediment storage by large log jams controlled the distribution of bedrock and alluvial channel reaches in mountain channels in the southern Olympic Peninsula of Washington State. The local hydraulic changes associated with stable log jams can significantly affect even relatively large alluvial rivers (Abbe and Montgomery 1996). In addition, abundant wood debris can increase the variability in grain size along alluvial rivers through changes in local shear stress and channel roughness at the reach scale (Buffington and Montgomery 1999). Conversely, the removal of logs from small headwater channels can decrease channel stability and result in delivery of a pulse of stored sediment to downstream channels (Bilby 1984). Changes in the abundance and nature of local storage elements for water and sediment can substantially affect hydrogeomorphic variability in river systems (see also McKenney et al. 1995). Restoration projects need to consider their potential impacts on sediment routing and storage, as well as the likely impacts of potential upstream changes on project performance.

Vegetation Regime

The type, health, and age of vegetation growing in and around channels can be a primary influence on channel morphology and processes. Site-potential vegetation varies with climate and physiography, but land use has substantially altered vegetation in many regions. Vegetation is more easily manipulated and managed than climate and physiography. Many areas of the USA were originally forested, and the removal of forests or replacement of native vegetation with non-native vegetation has affected how trees and wood interact with the stream channel. Flow alteration can also significantly affect riparian vegetation species composition and succession. Many floodplain species depend on (1) seasonal flooding and drying for reproduction and dispersal (e.g., Stromberg 1997; Rood et al. 1999; Deiller et al. 2001), (2) the various geomorphic units adjacent to the stream (Bendix and Hupp 2000), and (3) flood frequency (e.g., Friedman et al. 1996; Webster and D'Angelo 1997; Chapter 5, this volume).

Vegetation such as trees, grasses, and shrubs can locally influence streams and rivers as part of the boundary condition acting on a channel whereas the effects of more durable wood involve recruitment, transport, and decay. McKenney et al. (1995) documented the effect of woody vegetation on channel morphogenesis in Ozark streams in Missouri and Arkansas. Headwater channel morphology was typically bedrock controlled, but in watersheds larger than 100–200 km^2, woody vegetation played a significant role in stabilizing channel morphology and creating sediment deposition. Conversely, the local geomorphic context can dominate the variability in wood loading in forest channels (Wing and Skaugset 2002). Hence, there is a strong potential for feedback between vegetation, channel form, and channel processes.

Wood is a natural and important feature of streams that flow through forests. Assessing instream wood amounts and relating current conditions to activities such as channel cleaning or changes in forest structure help identify whether wood needs to be considered during restoration design. The most effective way to restore wood to streams is to reestablish the forest structure that used to provide wood to the stream through natural processes. In some cases, interim solutions are needed until the forest structure is restored, a process which may take decades. Just as important is to remember that not all streams evolved in forest systems. Adding wood to such streams can cause undesired bank erosion, stream widening, and downstream aggradation.

Wood is an important component of streams and rivers from physical and biological points of view. Understanding the regime that governs the delivery, transport, and storage of wood in a channel system is important for designing effective river restoration. Physical effects of instream wood include focusing stream energy that creates pools around LWD (Cherry and Beschta 1989); changing flow directions and velocities (Gippel 1995; Gregory and Bisson 1997); providing hydraulic roughness that affects velocity profiles (Buffington and Montgomery 1999); trapping and retaining organic materials such as leaves, needles, and fish carcasses (Culp et al. 1996); and trapping coarse sediment that creates bars or islands (Abbe and Montgomery 1996). Biologically, wood provides habitat and perches for aquatic insects, amphibians, birds, and riparian mammals (Borchardt 1993); structure and nutrients for microbiological organisms important to the aquatic ecosystem (Bilby and Ward 1989); a stable substrate for aquatic and semi-aquatic plant communities (Maser and Sedell 1994); and cover and shade for juvenile and adult fishes (Bisson et al. 1987). Sedell et al. (1984) estimated that salmonid production in wood-deficient streams can be increased several times by raising the wood load.

Changes in the recruitment, transport, and storage of wood in streams can affect the physical and biological condition of the stream. The size and species of wood delivered to the stream, the recruitment mechanisms, and the specific role of wood in the stream all vary geographically. Much of this variability is due to the influence of wood size and channel size in controlling the stability and retention of wood delivered to channels. The relative importance of the major disturbances that deliver wood to the stream vary by region but in general include insect outbreaks, fire, floods, debris flows, wind storms, and snow avalanches. These disturbances affect the age, diameter, and species of trees recruited to channels, as well as the initial distribution of wood that enters the fluvial environment. As for sediment, the wood regime can be assessed using a mass balance approach to characterize the wood budget for a channel (Swanson et al. 1982; Cummins et al. 1983).

Wood Recruitment: Supply and Delivery Processes

The quantity and characteristics of wood delivered to a channel depend on the nature of the forest supplying the wood and the processes that introduce wood into the channel. Tree fall can directly deliver trees to channels from streamside forests (McDade et al. 1990). Slope instability and particularly debris flows or large earthflows can deliver substantial amounts of wood debris to headwater channels from hillside forests (Grant and Swanson 1995; Johnson et al. 2000b). Bank erosion can introduce standing trees and wood debris stored in floodplain sediments into channels (Murphy and Koski 1989; Piégay et al. 1999). In general, the importance of bank erosion increases and landsliding decreases downstream; therefore, wood recruitment processes differ longitudinally along rivers.

Wood Mobility and Transport

A tree that falls into a river may remain intact or break into smaller, more mobile pieces. Depending upon the relative size of the tree and the channel it fell into, a tree may remain where it entered the channel or be transported downstream to eventually leave the river system. The size of stable

LWD increases as a river widens downstream (Lienkaemper and Swanson 1987; Bilby and Ward 1989), and configurations in which LWD is organized in river systems change commensurately. The strong influence of large, key pieces of LWD on stabilizing other debris in log jams is well known (Keller and Tally 1979; Nakamura and Swanson 1993; Abbe and Montgomery 1996). Although the specific types of log jams vary with position in the channel network (Abbe and Montgomery 1996), a general pattern of wood transport may be recognized based on channel size relative to log size. In headwater channels, even relatively small logs typically remain close to where they fall and wood debris is therefore arrayed in random orientations, whereas in larger channels wood is more mobile and tends to become reorganized into discrete accumulations and log jams.

Throughout the drainage basin of the Queets River, a large drainage with old-growth forests on the Olympic Peninsula, Washington, logs larger than about half the bankfull depth in diameter and half the channel width in length are large enough to function as stable key pieces (Abbe and Montgomery 1996). The role of key pieces also appears crucial for triggering geomorphologic effects of LWD in large rivers. River systems with stable LWD can trap and retain smaller, mobile debris (Collins et al. 2002).

In addition to the size of the logs and the channel, other factors also influence the transport of wood debris. The species of wood debris influences the stability of instream wood through its density. Although wood generally has dry density between 0.3 and 0.7 gm cm^{-3} (Harmon et al. 1986), and therefore floats, saturated wood has a specific gravity greater than water and therefore can remain stable in certain circumstances even if submerged. Shape is another primary influence on the stability of wood debris. For example, an attached rootwad elevates a log's center of mass, and hence the presence of a rootwad can control log stability (Abbe 2000; Braudrick and Grant 2000). Widely spreading or multiple-stemmed hardwoods are more prone to forming individual, stable snags than are conifers whose cylindrical form is more readily transported and routed through river systems, resulting in the propensity for logs to accumulate in discrete jams. In addition to flood magnitude, controls on wood debris stability, and therefore its geomorphological effects, depend on regional factors (such as the size and shape of wood delivered to the channel) and location in the channel network.

Wood Storage

The amount of wood stored varies greatly among river systems and can exhibit substantial variability over time within a single river system. Harmon et al. (1986) analyzed the biomass of wood stored in channel systems in different types of forest regions and found substantial differences in wood loads between redwood forest (≈1,000 m^3 ha^{-1}), coniferous forest (≈200 m^3 ha^{-1}), mixed conifer/hardwood forest (≈100 m^3 ha^{-1}), and deciduous forest (≈30 m^3 ha^{-1}). In addition to storage in the active channel, substantial amounts of wood can be stored via burial in floodplain sediments because wood can persist for thousands of years under anaerobic conditions (Becker and Schmirer 1977; Nanson et al. 1995).

Regionality and Interactions Among Regimes

Regional variation among the hydrologic, geomorphic, and vegetation regimes imparts a strong regional character to river systems. Each regime has different global archetypes: the hydrologic regime differs in arid, tropical, temperate, and polar regions; the geomorphic regimes of mountains differ from those of lowland regions; and the vegetation regime reflects the dominance of forest, grassland, or shrub/scrub communities. Different combinations of these regimes lead to different types of river systems.

Restorationists need to recognize that habitat-forming processes influenced or controlled by the hydrologic, geomorphic, and vegetation regimes interact with and affect one another. Because the history and current setting of each watershed is unique, simple 'cookbook recipes' for restoration are not attainable. Management practices need to be flexible and based on an understanding of forms and processes over time (e.g., Brierly and Fryirs 2000). The timing and amount of water delivery to the stream is affected by the amount and type of vegetation in the watershed. The delivery and transport of sediment and wood is a function of hydrological processes in the watershed. Interaction between the sediment and wood regimes of a river system can influence channel characteristics and dynamics and, therefore, aquatic habitat. Wood debris can trap and store large amounts of bedload sediment (O'Connor 1994; Montgomery et al. 1996), and log jams can act as sediment storage elements that damp highly variable inputs of sediment and thereby reduce the temporal variability in sediment transport rates (Massong and Montgomery 2000; Lancaster et al. 2001). Consequently, channel systems with high debris loading may be relatively buffered from stochastic inputs of sediment from hillslope processes whereas channel systems lacking abundant, stable in-channel wood may be very sensitive to temporal variability in sediment inputs. Understanding the nature and strength of interaction between the three regimes (hydrologic, geomorphic, and vegetative) is essential for evaluating restoration targets and for interpreting the long-term ecological influences of hydrogeomorphic processes.

Because of regime interactions and interdependencies, some geomorphic settings pose much lower risk for restoration activities such as reintroduction of wood debris, bank stabilization efforts, or rehabilitation or construction of off-channel water bodies. Spring-fed or lake-moderated systems with low or strongly buffered water and sediment supplies generally have more stable channels and present a higher likelihood of success for physical modifications of channel structure. In contrast, some sites present a naturally high risk of project failure. For example, channels perched on alluvial fans pose a high risk of degrading if wood is removed, or of avulsing or braiding if wood is added. Restoration projects focused on recreating pools using large woody debris are ill advised in places where ongoing deposition will rapidly bury the structures and fill in any associated pools. Depending upon the context of a site, potential indicators of ongoing channel disturbance can include (1) braided channels with little vegetation on bars and banks, (2) evidence of high rates of bedload transport such as unusually extensive bars for the geomorphic setting, (3) well-sorted stripes of fine sediment in the active channel, (4) bermed or channelized sections of river, and (5) chronic hillslope instability that delivers sediment to the channel. Evaluating the geomorphic context of a project site and its drainage basin is usually necessary to determine whether restoration actions are likely to succeed or fail.

Applications to Channel Restoration

Channel restoration projects generally involve modifying one or more of the three regimes discussed previously (hydrologic, geomorphic, vegetation). Projects that address only specific channel characteristics are typically rehabilitation projects in that they do not recreate or restore channel processes capable of sustaining those conditions. The most efficient and effective restoration approach will depend on the particular circumstances of the channel in question as well as the specific project objectives. Examples of how the three regimes, and interactions among them, frame restoration approaches serve to illustrate the importance of conceptual models of hydrogeomorphic processes in river restoration efforts.

Channel Maintenance Flows

The hydrologic regime of most rivers in the United States has been modified to some degree by human actions. Current management is increasingly focusing attention on how to set flow regimes in regulated or managed channels to maintain channel form and ecological functions. Environmental considerations in setting instream flows in managed or regulated rivers have focused on setting the minimum flows needed to provide habitat for organisms of interest or concern, usually fishes. These approaches are generally based on habitat preferences that can be characterized in terms of flow depth or velocity. For example, the instream flow incremental flow methodology (Bovee 1982) and the physical habitat simulation model known as PHABSIM (Milhous et al. 1984) have been used in many studies to evaluate the amount of habitat usable by particular species as a function of discharge. A major concern with such approaches for determining minimum flows in regulated rivers is that they determine flows needed to maintain the use of habitats but not the habitat themselves (Whiting 2002). Higher flows are generally required to form and maintain habitat. On California's Trinity River, for example, flows needed to maintain the streambed substrate are 20 times greater than predicted by flow-based habitat availability models (Woo 1999). Although there is no simple methodology to determine the flows needed to maintain a channel, the closer a restoration project is designed relative to the natural flow regime, the more likely it will be ecologically effective and sustainable (Poff et al. 1997).

Different aspects of the hydrologic regime of a channel maintain different elements of channel habitat or form. In gravel-bed channels, flows from about half the bankfull discharge to the bankfull level are typically needed to mobilize the streambed and thereby flush interstitial fines from the gravel (Pitlick and Van Streeter 1998). Similarly, maintenance of channel form is typically assumed to require 1.5- to 2-year flows; that is, approximately bankfull discharge (e.g., Kondolf 1998). Floodplain maintenance flows require flows greater than bankfull to deliver sediment to the floodplain surface (Whiting 1998). Evaluation of the hydrologic regime necessary to maintain riparian vegetation also needs to include the seasonality and timing of flows and their relationship to the species of interest (Stromberg and Patten 1990). Restoring channel-maintenance flows is an essential component of programs to restore highly regulated rivers systems. Although the problem of setting channel maintenance flows can be complex, the natural flow regime generally provides the best target or reference frame against which to set and evaluate restoration objectives (Poff et al. 1997; Whiting 2002).

Wood and Sediment Storage: Bedrock Channels of the Oregon Coast Range

The widespread occurrence of channel bottoms with exposed bedrock in the Oregon Coast Range has led to ongoing restoration efforts aimed at increasing the extent of gravel-bed channels. Two divergent, but not mutually exclusive, views of the cause of extensive bedrock channel reaches have been proposed. Benda and Dunne (1997) propose that the bedrock channel beds in the Oregon Coast Range reflect a low sediment supply with a strong temporal variability in sediment delivery from periodic landsliding. Montgomery et al. (in press) propose that the extent of bedrock channels in the Oregon Coast Range primarily reflects a lack of sediment storage due to a dearth of stable wood and log jams. These different views of the causal forcing lead to divergent views of how to restore gravel beds to Oregon Coast Range channels. On the basis of the interpretation of a low sediment supply, some have argued for the need to introduce sediment more frequently to the channel network, as could be done by logging on potentially unstable ground. In contrast, the interpretation of inadequate gravel storage suggests that reintroduction of stable in-channel wood debris to trap sediment should be the focus of restoration efforts aimed at increasing the extent of gravel streambeds.

Dewberry et al. (1998) note that obstructions formed by debris-flow deposition at tributary junctions were associated with alluvial reaches along the mainstem of Knowles Creek in the central Oregon Coast Range. On the basis of this observation, they built log jams along the mainstem of Knowles Creek to try to convert bedrock reaches to alluvial reaches. They noted extensive trapping of gravel in the first season after installation of log structures, indicating that the extensive bedrock morphology of the mainstem of Knowles Creek was due to a dearth of sediment storage elements. The results of Dewberry's restoration efforts along Knowles Creek strongly support the interpretation that the extensive bedrock channels found in Knowles Creek today are not forming simply due to a low sediment supply. Rather, their current extent appears to reflect a dearth of in-channel wood debris.

Other stream-channel restoration programs in the Oregon Coast Range provide additional evidence for the importance of wood debris in aquatic habitat formation and sediment retention (House and Boehne 1985, 1986; House et al. 1991; House 1996). Restoration projects showing major increases in the extent of spawning gravel within a year of log-jam construction confirm that the extensive bedrock channel reaches in Oregon Coast Range streams are due to the lack of log jams that store sediments, and the effects of past log drives and debris flows that scoured channels to bedrock. For example, the boulder-bed channel of Tobe Creek filled with coarse gravel during the first major winter freshet following construction of channel-spanning gabion and log structures (House and Boehne 1986). Similar gabion and log barriers constructed in Lobster Creek resulted in a substantial decrease in the extent of bedrock bed in treated reaches during the first post-construction high flows (House and Boehne 1985; House 1996). Fully and partially spanning log structures constructed in Elk Creek trapped sufficient bedload to increase the extent of gravel substrate by 44- to 50-fold (House et al. 1991). These experiences in stream restoration efforts throughout the Oregon Coast Range demonstrate the effects of log jams on the extent of gravel streambeds. Although the present extent of bedrock channel reaches in the Oregon Coast Range undoubtedly reflects an excess of transport capacity over sediment supply, it appears that the present abundance of bedrock reaches arose not simply from a naturally low, stochastic, or depleted sediment supply, but instead (or also) reflects the loss of instream obstructions as a result of historical, region-wide clearing of logs and log jams from channels and harvesting of mature riparian trees.

Flow Variability and Sediment Transport: The Colorado River Experiment

Closing of Glen Canyon Dam in 1963 resulted in a loss of almost 60 million metric tons per year of sediment and radically altered the flow regime through the Grand Canyon of the Colorado River (Webb et al. 1999). Flow that typically ranged from 28 $m^3 s^{-1}$ to over 3,500 $m^3 s^{-1}$ was altered in magnitude, duration, frequency, and timing by dam operations. The combination of sediment retention in the impounded reservoir and decreased flow variability led to significant downstream changes in the Grand Canyon. Sand bars gradually disappeared, marsh and sand-bar vegetation flourished, water clarity increased, and aquatic and terrestrial species compositions shifted. After 15 years of studies on the current state of the Colorado River ecosystem through the Grand Canyon, approval was given for the first rigorous test of using the experimental release of high flows to restore the dynamic fluvial landforms and aquatic and terrestrial habitat along the river corridor (Patten and Stevens 2001).

In March 1996, a 7-day controlled flood of 1,274 $m^3 s^{-1}$ was initiated. The timing was earlier and the volume much lower than historical peak flows, but it was the largest flow in over a decade since the high water years of the early 1980s resulted in some uncontrolled high flows on the Colorado River. The choice of flood level and timing was a compromise between water availability, endangered species concerns, and lost power generation revenues. In terms of pre-dam floods, the recurrence interval was 1.25 years or a probability of occurrence of 0.80. For the post-dam period, the recurrence interval was closer to 5 years or 0.20 probability of occurrence (Patten et al. 2001).

An extensive monitoring system was in place before, during, and after the releases to examine physical and biological changes from Lake Powell through the Grand Canyon. Here we focus on the role of hydrologic variability and geomorphic processes. Two scales are considered. The large spatial-scale control is based on geological history and manifests itself in the bedrock lithology and size and number of debris fans that partially block the river flow. Where erodible rock occurs at river level, the valley is wider and flatter, and flood stress is typically lower. In reaches with hard bedrock, the valley is narrower, and increased flows tend to exert higher shear stresses. At the small spatial scale, habitat distribution and locations of scour and fill areas are affected by the location of debris fans. The low velocity of ponded water upstream of debris fans creates sandy beaches, which become heavily colonized by vegetation in the absence of flood events. Large eddies with low velocity occur downstream of the debris fans. In the absence of floods, these backwater areas aggrade and are colonized by vegetation.

The experimental flood reworked debris-fan faces where the vegetation was less than 10 years old. Flows were not high enough to scour out vegetation that was more than 10 years old. In certain places, vegetation was buried with sediments. The size of the deposited sediments coarsened over the duration of the flood. Initial deposits of silts and clays were flushed out as high flows continued. The primary objective of the flood was to mobilize sediments from the streambed and redeposit them in eddies and along the shore. Post-flood studies found significant deposition on sand bars, which made the sand bars taller but not broader. Subsequent “normal” dam release flows eroded the base of the sand bars and many collapsed back into the streambed. Debris fans were partially reworked. Scientists suggested that in order to rework the debris fans, floods should be large in size but shorter in duration, more like a typical pre-dam flash flood (Schmidt et al. 2001).

Another concern with dam operations was the ongoing erosion of downstream sand bars and beaches. Sand bars in the canyon create areas of low-velocity or stagnant flow used by endangered native fish, and they also contain archeological resources. Sand deposited by flood flows maintains sand bars, and lower flows between floods erode bars. The experimental flood tested the assumption that sand delivered from tributaries between floods would be available to rebuild sand bars during controlled flood releases. But even low flows rapidly route sand delivered by tributaries through the canyon, and an increase in sand bar area resulting from the 1996 experiment was short lived due to the relationship between the hydrologic and geomorphic regime (Rubin et al. 2002).

Conclusions

River systems are dynamic. Restoration projects that do not acknowledge and plan for expected variability in habitat-forming processes associated with the hydrologic, geomorphic, and vegetation regimes are unlikely to be successful in the long term. Some of the ecological problems that restoration is intended to alleviate are caused by wanting to control or contain the natural variability of the processes and disturbances that create and maintain the system, such as floods, landslides, fires, and insect outbreaks. Although it is easier to address symptoms rather than causes, acknowledging and applying what we do know about the variability of the hydrologic, geomorphic, and vegetation regimes (also known as the water, sediment, and wood regimes), and the land-use actions that alter them, will result in better long-term restoration results.

Acknowledgments

We thank Mike Church, Tom Lisle, Frank Magilligan, Lee MacDonald, and Pat Slaney for critical, insightful, and very useful reviews of a draft manuscript. We also thank the University of Washington graduate students in the Department of Earth & Space Sciences and Center for Water and Watershed Studies for many stimulating discussions concerning the geomorphic and hydrologic variability of river systems and the implications for riverine ecosystems.

References

Abbe, T. B. 2000. Patterns, mechanics and geomorphic effects of wood debris accumulations in a forest river system. Ph.D. thesis. University of Washington, Seattle.

Abbe, T. B., and D. R. Montgomery. 1996. Interaction of large woody debris, channel hydraulics and habitat formation in large rivers. Regulated Rivers: Research and Management 12:201-221.

Abrahams, A. D., editor. 1986. Hillslope processes. Allen and Unwin, Inc., Winchester, Massachusetts.

Alley, W. M. 1984. The Palmer drought severity index: limitations and assumptions. Journal of Climate and Applied Meteorology 23:1100-1109.

Anderson, M. G., and S. M. Brooks. 1996. Advances in hillslope processes. Volumes 1 and 2. John Wiley and Sons, New York.

Becker, B., and W. Schirmer. 1977. Palaeoecological study on the Holocene valley development of the River Main, southern Germany. Boreas 4:303-321.

Beckinsale, R. P. 1969. River regimes. Pages 455-471 *in* R. J. Chorley, editor. Water, earth and man. Methuen, London.

Beechie, T., E. Beamer, B. Collins, and L. Benda. 1996. Restoration of habitat-forming processes in Pacific Northwest watersheds: A locally adaptable approach to salmonid habitat restoration. Pages 48-67 *in* D. L. Peterson, and C. V. Klimas, editors. The role of restoration in ecosystem management. Society for Ecological Restoration, Madison, Wisconsin.

Beechie, T., and S. Bolton. 1999. An approach to restoring salmonid habitat-forming processes in Pacific Northwest watersheds. Fisheries 24(4):6-15.

Benda, L., and T. Dunne. 1997. Stochastic forcing of sediment routing and storage in channel networks. Water Resources Research 33:2865-2880.

Bendix, J., and C. R. Hupp. 2000. Hydrological and geomorphological impacts on riparian plant communities. Hydrological Processes 14:2977-2290.

Bergen, S. D., S. B. Bolton, and J. L. Fridley. 2001. Ecological engineering: design based on ecological principles. Ecological Engineering 18:201-210.

Bilby, R. E. 1984. Removal of woody debris may affect stream channel stability. Journal of Forestry 82:609-61.

Bilby, R. E., and J. W. Ward. 1989. Changes in characteristics and function of woody debris with increasing size of streams in western Washington. Transactions of the American Fisheries Society 118:368-378.

Bisson, P. A., J. L. Nielsen, R. A. Palmason, and L. E. Grove. 1982. A system of naming habitat types in small streams, with examples of habitat utilization by salmonids during low streamflow. Pages 62-67 *in* N. B. Armantrout, editor. Proceedings of a symposium on acquisition and utilization of aquatic habitat inventory information. Western Division of the American Fisheries Society, Portland, Oregon.

Bisson, P. A., R. E. Bilby, M. D. Bryant, C. A. Dolloff, G. B. Grette, R. A. House, M. L. Murphy, K V. Koski, and J. R. Sedell. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present and future. Pages 143-190 *in* E. O. Salo, and T. W. Cundy, editors. Streamside management: forestry and fishery interactions. University of Washington, Institute of Forest Resources, Seattle.

Borchardt, D. 1993. Effects of flow and refugia on drift loss of benthic macroinvertebrates: implications for habitat restoration in lowland streams. Freshwater Biology 29:221-227.

Bovee, K. D. 1982. A guide to stream habitat analysis using the instream flow incremental methodology. U.S. Fish and Wildlife Service. Instream Flow Information Paper 12, FWS/OBS-82/26.

Braudrick, C. A., and G. E. Grant. 2000. When do logs move in rivers? Water Resources Research 36:571-583.

Brubaker, K. L., and A. Rango. 1996. Response of snowmelt hydrology to climate change. Water, Air and Soil Pollution 90:335-343.

Brierley, G. J., and K. Fryirs. 2000. River styles, a geomorphic approach to catchment characterization: implications for river rehabilitation in Bega catchment, New South Wales, Australia. Environmental Management 25:661-679.

Buffington, J. M., and D. R. Montgomery. 1997. A systematic analysis of eight decades of incipient motion studies, with special reference to gravel-bedded rivers. Water Resources Research 33:1993-2029.

Buffington, J. M., and D. R. Montgomery. 1999. Effects of hydraulic roughness on surface textures of gravel-bed rivers. Water Resources Research 35:3507-3521.

Burges, S. J. 1991. Some aspects of hydrologic variability. Pages 275-280 *in* Committee on Climate Uncertainty and Water Resources Management, Water Science and Technology Board, Commission on Geosciences, Environment, and Resources. Managing water resources in the west under conditions of climate uncertainty. Proceedings of a colloquium, Scottsdale, Arizona, November 14-16, 1990. National Academy Place, Washington, D.C.

Burn, D. H. 1997. Catchment similarity for regional flood frequency analysis using seasonality measures. Journal of Hydrology 202:212-230.

Burt, T. P. 1992. The hydrology of headwater catchments. Pages 3-28 *in* P. Calow and G. E. Petts, editors. The rivers handbook. Blackwell Scientific Publications, London.

Carlston, C. W. 1969. Downstream variations in the hydraulic geometry of streams: special emphasis on mean velocity. American Journal of Science 267:499-509.

Caruso, B. S. 2001. Regional river flow, water quality, aquatic ecological impacts and recovery from drought. Journal of Hydrological Sciences 46:677-700.

Cherry, J., and R. L. Beschta. 1989. Coarse woody debris and channel morphology: a flume study. Water Resources Bulletin 25:1031-1036.

Chorley, R. J. 1969. The drainage basin as the fundamental geomorphic unit. Pages 77-99 *in* R. J. Chorley, editor. Water, earth, and man. Methuen, London.

Church, M. 1992. Channel morphology and typology. Pages 126-143 *in* P. Calow, and G. E. Petts, editors. The rivers handbook. Blackwell Scientific Publications, London.

Church, M. 2002. Geomorphic thresholds in riverine landscapes. Freshwater Biology 47:541-557.

Collins, B. D., D. R. Montgomery, and A. Haas. 2002. Historic changes in the distribution and functions of large woody debris in Puget Lowland rivers. Canadian Journal of Fisheries and Aquatic Sciences 59:66-76.

Colwell, R. K. 1974. Predictability, constancy, and contingency of periodic phenomena. Ecology 55:1148-1153.

Costa, J. E. 1983. Paleohydraulic reconstruction of the flash-flood peaks from boulder deposits in the Colorado Front Range. Geological Society of America Bulletin 94:986-1004.

Costa, J. E., and J. E. O'Connor. 1995. Geomorphically effective floods. Pages 45-56 *in* J. E. Costa, A. J. Miller, K. W. Potter, and P. R. Wilcock, editors. Natural and anthropogenic influences in fluvial geomorphology. American Geophysical Union, Geophysical Monograph 89. Washington, D.C.

Criss, R. E., and E. L. Shock. 2001. Flood enhancement through flood control. Geology 29:875-878.

Cudworth, A. G., Jr. 1989. Flood hydrology manual. U.S. Department of Interior, Bureau of Reclamation, Denver, Colorado.

Culp, J. M., G. J. Scrimgeour, and G. D. Townsend. 1996. Simulated fine woody debris accumulations in a stream increase rainbow trout fry abundance. Transactions of the American Fisheries Society 125:472-479.

Cummins, K W., J. R. Sedell, F. J. Swanson, G. W. Minshall, S. G. Fisher, C. E. Cushing, R. C. Petersen, and R. L. Vannote. 1983. Organic matter budgets for stream ecosystems: problems in their evaluation. Pages 299-353 *in* G. W. Minshall, and J. R. Barnes, editors. Stream ecology: application and testing of general ecological theory. Plenum, New York.

Davies-Colley, R. J. 1997. Stream channels are narrower in pasture than in forest. New Zealand. Journal of Marine and Freshwater Research 31:599-608.

Deiller, A. F., J. Walter, and M. Tremolieres. 2001. Effects of flood interruption on species richness, diversity and floristic composition of woody regeneration in the upper Rhine alluvial hardwood forest. Regulated Rivers: Research and Management 17:393-405.

Dewberry, C., P. Burns, and L. Hood. 1998. After the flood: The effects of the storms of 1996 on a creek restoration. Restoration and Management Notes 16:174-182.

Dietrich, W. E., and T. Dunne. 1978. Sediment budget for a small catchment in mountainous terrain. Zeitschrift für Geomorphologie, Supplementband 29:191-206.

Doesken, N. J., T. B. McKee, and J. Kleist. 1991. Development of a surface water supply index for the western United States. Climatology Report Number 91-3. Colorado State University, Fort Collins, Colorado.

Dunne, T., and R. D. Black. 1970. Partial area contributions to storm runoff in a small New England watershed. Water Resources Research 6:1296-1311.

Dunne, T., and L. Leopold. 1978. Water in environmental planning. W. H. Freeman and Company, New York.

Dunne, T., L. A. K. Mertes, R. H. Meade, J. E. Richey, and B. R. Forsberg. 1998. Exchanges of sediment between the flood plain and channel of the Amazon River in Brazil. Geological Society of America Bulletin 110:450-467.

Ellet, C., Jr. 1852. Report of the overflows of the delta of the Mississippi. The War Department, Washington, D.C.

Forest Ecosystem Management Assessment Team. 1993. Forest ecosystem management: An ecological, economic, and social assessment. U.S. Government Printing Office 1993-793-071.

Freeze, R. A. 1980. A stochastic-conceptual analysis of the rainfall-runoff process on a hillslope. Water Resources Research 16:391-408.

Friedman, J. M., W. R. Osterkamp, and W. M. Lewis, Jr. 1996. Channel narrowing and vegetation development following a Great Plains flood. Ecology 77:2167-2181.

Frissell, C. A. 1997. Ecological principles. Pages 96-115 *in* J. E. Williams, C. A. Wood, and M. P. Dombeck, editors. Watershed restoration: principles and practices. American Fisheries Society, Bethesda, Maryland.

Frissell, C. A., W. J. Liss, C. E. Warren, and M. D. Hurley. 1986. A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. Environmental Management 10:199-214.

Frissell, C. A., and R. K. Nawa. 1992. Incidence and causes of physical failure of artificial habitat structures in streams of Western Oregon and Washington. North American Journal of Fisheries Management 12:182-197.

Fryirs, K., and G. J. Brierley. 2001. Variability in sediment delivery and storage along river courses in Bega catchment, NSW, Australia: implications for geomorphic river recovery. Geomorphology 38:237-265.

Gan, K. C., T. A. McMahon, and B. L. Finlayson. 1991. Analysis of periodicity in streamflow and rainfall data by Colwell's Indices. Journal of Hydrology 123:105-118.

Gibbs, W. J., and J. V. Maher. 1967. Rainfall deciles as drought indicators. Bureau of Meteorology. Bulletin No. 48. Commonwealth of Australia, Melbourne.

Gippel, C. J. 1995. Environmental hydraulics of large woody debris in streams and rivers. Journal of Environmental Engineering 121:388-395.

Glymph, L. M., and H. N. Holton. 1969. Land treatment in agricultural watershed hydrology research. Pages 44-68 *in* W. L. Moore, and C. W. Morgan, editors. Effects of watershed change on streamflow. American Society of Civil Engineers, New York.

Goodbred, S. L., Jr., and S. A. Kuehl.1998. Floodplain process in the Bengal Basin and the storage of Ganges-Brahmaputra River sediment: an accretion study using 137Cs and 210Pb geochronology. Sedimentary Geology 12:239-258.

Grant, G. E., and F. J. Swanson. 1995. Morphology and processes of valley floors in mountain streams, western Cascades, Oregon. Pages 83-101 *in* J. E. Costa, A. J. Miller, K. W. Potter, and P. R. Wilcock, editors. Natural and anthropogenic influences in fluvial geomorphology. American Geophysical Union. Geophysical Monograph 89. Washington, D.C.

Graumlich, L. J. 1987. Precipitation variation in the Pacific Northwest (1675–1975) as reconstructed from tree rings. Annals of the Association of American Geographers 77:19-29.

Gregory, S. V., and P. A. Bisson. 1997. Degradation and loss of anadromous salmonid habitat in the Pacific Northwest. Pages 277-314 *in* D. J. Stouder, P. A. Bisson, and R. J. Naiman, editors. Pacific salmon and their ecosystems: status and future options. Chapman and Hill, New York.

Haan, C. T. 1977. Statistical methods in hydrology. Iowa State University Press, Ames.

Hack, J. T. 1957. Submerged river system of Chesapeake Bay. Geological Society of America Bulletin 68:817-830.

Harmon, M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. V. Gregory, J. D. Lattin, N. H. Anderson, S. P. Cline, N. G. Aumen, J. R. Sedell, G. W. Lienkaemper, K. Cromack, and K. W. Cummins. 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15:133-302.

Hartley, S., and S. L. Dingman. 1993. Effects of climatic variability on winter–spring runoff in New England river basins. Physical Geography 14:379-393.

Harvey, A. M. 1991. The influence of sediment supply on the channel morphology of upland streams: Howgill Fells, northwest England. Earth Surface Processes and Landforms 16:675-684.

Hayes, S., D. R. Montgomery, and C. Newhall. 2002. Fluvial sediment transport and deposition following the 1991 eruption of Mount Pinatubo. Geomorphology 45:211-224.

House, R. A. 1996. An evaluation of stream restoration structures in a coastal Oregon stream 1981–1993. North American Journal of Fisheries Management 16:272-281.

House, R. A., and P. L. Boehne. 1985. Evaluation of instream enhancement structures for salmonid spawning and rearing in a coastal Oregon stream. North American Journal of Fisheries Management 5:283-295.

House, R. A., and P. L. Boehne. 1986. Effects of instream structures on salmonid habitat and populations in Tobe Creek, Oregon. North American Journal of Fisheries Management 6:38-46.

House, R. A., V. Crispin, J. M. Suther. 1991. Habitat and channel changes after rehabilitation of two coastal streams in Oregon. Pages 150-159 *in* J. Colt, and R. J. White, editors. Fisheries Bioengineering Symposium, Bethesda, Maryland.

Howard, A. D., W. E. Dietrich, and M. A. Seidl. 1994. Modeling fluvial erosion on regional to continental scales. Journal of Geophysical Research 99:13971-13986.

Hoyt, J. C. 1936. Droughts of 1930–34. U.S. Geological Survey. Water Supply Paper 680.

Hurst, H. E., R. P. Black, and Y. M. Simaika. 1965. Long-term storage–an experimental study. Constable, London.

Ikeya, H. 1981. A method for designation for areas in danger of debris flow. Pages 576-588 *in* T. R. H. Davies, and A. J. Pearce, editors. Erosion and sediment transport in Pacific rim steeplands. International Association of Hydrological Sciences Publication 132.

Johnson, A. C., D. N. Swanston, and K. E. McGee. 2000a. Landslide initiation, runout, and deposition within clearcuts and old-growth forests of Alaska. Journal of the American Water Resources Association 36:17-30.

Johnson, S. L., F. J. Swanson, G. E. Grant, and S. M. Wondzell. 2000b. Riparian forest disturbances by a mountain flood–the influence of floated wood. Hydrological Processes 14:3031-3050.

Jungworth, M. S. Muhar, and S. Schmutz. 2002. Re-establishing and assessing ecological integrity in riverine landscapes. Freshwater Biology 47:867-887.

Kahya, E., and J. A. Dracup. 1993. U.S. streamflow patterns in relation to the El Niño/southern oscillation. Water Resources Research 29:2491-2504.

Karl, T. R., and R. W. Knight. 1997. Secular trends of precipitation amount, frequency and intensity in the United States. Bulletin of the American Meteorological Society 79:231-241.

Keller, E. A., and F. J. Swanson. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surface Processes 4:361-380.

Keller, E. A., and T. Tally. 1979. Effects of large organic debris on channel form and fluvial processes in the coastal Redwood environment. Pages 169-197 *in* D. D. Rhodes, and G. P. Williams, editors. Adjustments of the fluvial system. Kendall-Hunt, Dubuque, Iowa.

Kimmens, J. P. 1987. Forest ecology. MacMillan Publishing Company, New York.

Klemes, V. 1974. The Hurst phenomenon: a puzzle. Water Resources Research 20:675-688.

Knighton, D. 1984. Fluvial forms and processes. Edward Arnold, London.

Kondolf, G. M. 1998. Development of flushing flows for channel restoration on Rush Creek, California. Rivers 6:183-193.

Kondolf, G. M., J. C. Vick, and T. M. Ramirez. 1996. Salmon spawning habitat rehabilitation on the Merced River, California: An evaluation of project planning and performance. Transactions of the American Fisheries Society 125:899-912.

Kondolf, G. M., M. W. Smeltzer, and S. F. Railsback. 2001. Design and performance of a channel reconstruction project in a coastal California gravel-bed stream. Environmental Management 28:761-776.

Lancaster, S. T., S. K. Hayes, and G. E. Grant. 2001. Modeling sediment and wood storage and dynamics in small mountainous watersheds. Pages 85-104 *in* J. B. Dorava, D. R. Montgomery, B. Palcsak, and F. Fitzpatrick, editors. Geomorphic processes and riverine habitat. American Geophysical Union, Washington, D.C.

Lane, S. N., and K. S. Richards. 1997. Linking river channel form and process: Time, space and causality revisited. Earth Surface Processes and Landforms 22:249-260.

Laronne, J., and I. Reid. 1993. Very high rates of bedload sediment transport by ephemeral desert rivers. Nature 366:148-150.

LeBoutillier, D. W., and P. R. Waylen. 1993. Regional variations in flow-duration curves for rivers in British Columbia. Physical Geography 14:359-378.

Lecce, S. A. 2000. Spatial variations in the timing of annual floods in the southeastern United States. Journal of Hydrology 235:151-169.

Leopold, L. B. 1953. Downstream change of velocity in rivers. American Journal of Science 251:606-624.

Leopold, L. B., and T. Maddock. 1953. The hydraulic geometry of stream channel and some physiographic implications. U.S. Geological Survey. Professional Paper 252.

Leopold, L. B., and M.G. Wolman. 1957. River channel patterns–braided, meandering, and straight. U.S. Geological Survey. Professional Paper 282B.

Leung, L. R., and M. S. Wigmosta. 1999. Potential climate change impacts on mountain watersheds in the Pacific Northwest. Journal of the American Water Resources Association 35:1463-1472.

Lienkaemper, G. W., and F. J. Swanson. 1987. Dynamics of large woody debris in streams in old-growth Douglas-fir forests. Canadian Journal of Forest Research 17:150-156.

Lins, H. F. 1985. Interannual streamflow variability in the United States based on principal components. Water Resources Research 21:691-701.

Lisle, T. E., and S. Hilton. 1999. Fine bed material in pools of natural gravel-bed channels. Water Resources Research 35:1291-1304.

Lisle, T. E., J. M. Nelson, J. Pitlick, M. A. Madej, and B. L. Barkett. 2000. Variability of bed mobility in natural, gravel-bed channels and adjustments to sediment load at local and reach scales. Water Resources Research 36:3743-3755.

Lotspeich, F. B. 1980. Watersheds as the basic ecosystem: this conceptual framework provides a basis for a natural classification system. Water Resources Bulletin 16:581-586.

Magilligan, F. J., and B. E. Graber. 1996. Hydroclimatological and geomorphic controls on the timing and spatial variability of floods in New England, USA. Journal of Hydrology 178:159-180.

Maser, C., and J. R. Sedell. 1994. From the forest to the sea: The ecology of wood in streams, rivers, estuaries, and oceans. St. Lucie Press, Delray, Florida.

Massong, T. M., and D. R. Montgomery. 2000. Influence of lithology, sediment supply, and wood debris on the distribution of bedrock and alluvial channels. Geological Society of America Bulletin 112:591-599.

Matthai, H. F. 1979. Hydrologic and human aspects of the 1976-77 drought. U.S. Geological Survey. Professional Paper 1130.

McDade, M. H., F. J. Swanson, W. A. McKee, J. F. Franklin, and J. Van Sickle. 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington. Canadian Journal of Forest Research 20:32-330.

McKee, T. B., N. J. Doesken, and J. Kleist. 1993. The relationship of drought frequency and duration to time scales. Pages 179-184, Preprints, 8th Conference on Applied Climatology, 17-22 January, Anaheim, California.

McKenney, R., R. B. Jacobson, and R. C. Wertheimer. 1995. Woody vegetation and channel morphogenesis in low-gradient, gravel-bed streams. Geomorphology 13:175-198.

Michaelsen, J., L. Haston, and F. W. Davis. 1987. 400 years of central California precipitation variability reconstructed from tree-rings. Water Resources Bulletin 23:809-818.

Michaelsen, P. 2002. Mass extinction of peat-forming plants and the effect on fluvial styles across the Permian-Triassic boundary, northern Bowen Basin, Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 179:173-188.

Milhous, R. T., D. L. Wegner, and T. Waddle. 1984. Users guide to the physical habitat simulation system (PHABSIM). Instream Flow Information Paper 11 (revised). U.S. Fish and Wildlife Service. FWS/OBS-81/43.

Millar, R. G. 2000. Influence of bank vegetation on alluvial channel patterns. Water Resources Research 36:1109-1118.

Miller, J. P. 1958. High mountain streams: Effects of geology on channel characteristics and bed material. New Mexico Institute of Mining and Technology. Memoir 4. Socorro.

Montgomery, D. R., T. M. Massong, and S. C. S. Hawley. In press. Debris flows, log jams and the formation of pools and alluvial channel reaches in the Oregon Coast Range. Geological Society of America Bulletin.

Montgomery, D. R. 1999. Process domains and the river continuum. Journal of the American Water Resources Association 35:397-410.

Montgomery, D. R., T. B. Abbe, N. P. Peterson, J. M. Buffington, K. M. Schmidt, and J. D. Stock. 1996. Distribution of bedrock and alluvial channels in forested mountain drainage basins. Nature 381:587-589.

Montgomery, D. R., and J. M. Buffington. 1997. Channel reach morphology in mountain drainage basins. Geological Society of America Bulletin 109:596-611.

Montgomery, D. R., and J. M. Buffington. 1998. Channel processes, classification, and response potential. Pages 13-42 *in* R. J. Naiman, and R. E. Bilby, editors. River ecology and management. Springer-Verlag, Inc., New York.

Montgomery, D. R., J. M. Buffington, R. Smith, K. Schmidt, and G. Pess. 1995. Pool spacing in forest channels. Water Resources Research 31:1097-1105.

Montgomery, D. R., W. E. Dietrich, R. Torres, S. P. Anderson, J. T. Heffner, and K. Loague. 1997. Piezometric response of a steep unchanneled valley to natural and applied rainfall. Water Resources Research 33:91-109.

Montgomery, D. R., and K. B. Gran. 2001. Downstream variations in the width of bedrock channels. Water Resources Research 37:1841-1846.

Montgomery, D. R., M. S. Panfil, and S. K. Hayes. 1999. Channel-bed mobility response to extreme sediment loading at Mount Pinatubo. Geology 27:271-274.

Murdoch, P. S., J. S. Baron, and T. L. Miller. 2000. Potential effects of climate change on surface-water quality in North America. Journal of the American Water Resources Association 36(2):347-366

Murphy, M. L., and K V. Koski. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. North American Journal of Fisheries Management 9:427-436.

Nakamura, F., and F. J. Swanson. 1993. Effects of coarse woody debris on morphology and sediment storage of mountain stream system in western Oregon. Earth Surface Processes and Landforms 18:43-61.

Nanson, G. C., M. Barbetti, and G. Taylor. 1995. River stabilization due to changing climate and vegetation during the late Quaternary in western Tasmania, Australia. Geomorphology 13:145-158.

National Research Council. 1999. Improving American river flood frequency analysis. National Academy Press, Washington, D.C.

Newhall, C. G., and R. S. Punongbayan, editors. 1996. Fire and mud: eruptions and lahars of Mount Pinatubo, Philippines. Philippine Institute of Volcanology and Seismology, Quezon City, and University of Washington Press, Seattle and London.

O'Connor, M. D. 1994. Sediment transport in steep tributary streams and the influence of large organic debris. Ph.D. dissertation. University of Washington, Seattle.

Omernik, J. M. 1987. Ecoregions of the coterminous United States. Annals of the Association of American Geographers 771:118-125.

Omernik, J. M., and R. G. Bailey. 1997. Distinguishing between watersheds and ecoregions. Journal of the American Water Resources Association 33:935-949.

Palmer, W. C. 1965. Meteorological drought. U.S. Department of Commerce Weather Bureau. Research Paper No. 45. Washington, D.C.

Palmer, W. C. 1968. Keeping track of crop moisture conditions, nationwide: the new Crop Moisture Index. Weatherwise 21:156-161.

Parker, G. 1979. Hydraulic geometry of active gravel rivers. Journal of the Hydraulics Division, ASCE 105 HY9:1185-1201.

Patten, D. T., D. A. Harpman, M. I. Voita, and T. J. Randle. 2001. A managed flood on the Colorado River: background, objectives, design and implementation. Ecological Applications 11:635-643.

Patten, D. T., and L. E. Stevens. 2001. Restoration of the Colorado River ecosystem using planned flooding. Ecological Applications 11:633-634.

Pfister, R. D., B. L. Kovalchik, S. F. Arno, and R. C. Presby. 1977. Forest habitat types of Montana. USDA Forest Service. General Technical Report INT-34.

Philander, S.G. 1990. El Niño, La Niña, and the Southern Oscillation. Academic Press, Inc., San Diego, California.

Piégay, H., A. Thévenet, and A. Citterio. 1999. Input, storage and distribution of large woody debris along a mountain river continuum. The Drôme River, France. Catena 35:19-39.

Pinter, N., R. Thomas, and J. Wlosinski. 2001. Assessing flood hazard on dynamic rivers. EOS, Transactions, American Geophysical Union 82(31):333, 338-339.

Pitlick, J. 1994. Relation between peak flows, precipitation, and physiography for five mountainous regions in the western USA. Journal of Hydrology 158:219-240.

Pitlick, J., and M. M. Van Streeter. 1998. Geomorphology and endangered fish habitats of the upper Colorado River 2. Linking sediment transport to habitat maintenance. Water Resources Research 34:303-316.

Poff, N. L., and J. L. Ward. 1989. Implications of streamflow variability and predictability for lotic community structure: A regional analysis of streamflow patterns. Canadian Journal of Fisheries and Aquatic Sciences 46:1805-1818.

Poff, N. L. 1990. Physical habitat template of lotic systems: recovery in the context of historical pattern of spatiotemporal heterogeneity. Environmental Management 14:629-645.

Poff, N. L. 1996. A hydrogeography of unregulated streams in the United States and an examination of scale-dependence in some hydrological descriptors. Freshwater Biology 36:71-91.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. D. Richter, R. E. Sparks, and J. C. Stromberg. 1997. The natural flow regime. BioScience 47:769-784.

Poole, G. C., C. A. Frissell, and S. C. Ralph. 1997. In-stream habitat unit classification: inadequacies for monitoring and some consequences for management. Journal of the American Water Resources Association 33:879-896

Reid, L. M., and T. Dunne. 1996. Rapid evaluation of sediment budgets. Catena, Reiskirchen, Germany.

Rendell, H., and D. Alexander. 1979. Note on some spatial and temporal variations in ephemeral channel form. Geological Society of America Bulletin 90:761-772.

Rice, S., and M. Church. 1998. Grain size along two gravel-bed rivers: statistical variation, spatial pattern and sedimentary links. Earth Surface Processes and Landforms 23:345-36

Richards, K., J. Brasington, and F. Hughes. 2002. Geomorphic dynamics of floodplains: ecological implications and a potential modeling strategy. Freshwater Biology 47:559-579.

Richter, B. D., J. V. Baumgartner, D. P. Braun, and J. Powell. 1998. A spatial assessment of hydrologic alteration within a river network. Regulated Rivers: Research and Management 14:329-340.

Richter, B. D., J. V. Baumgartner, R. Wigington, and D. P. Braun. 1997. How much water does a river need? Freshwater Biology 37:231-249.

Riggs, H. C., and K. D. Harvey. 1990. Temporal and spatial variability of streamflow. Pages 81-96 *in* M. G. Wolman, and H. C. Riggs, editors. Surface water hydrology: the geology of North America V O-1. Geological Society of America, Boulder, Colorado.

Rogers, J. D., and J. T. Armbruster. 1990. Low flows and hydrologic droughts. Pages 121-130 *in* M. G. Wolman, and H. C. Riggs, editors. Surface water hydrology: the geology of North America V O-1. Geological Society of America, Boulder, Colorado.

Rood, S. B., K. Taboulchanas, C. E. Bradley, and A. R. Kalischuk. 1999. Influence of flow regulation on channel dynamics and riparian cottonwoods along the Bow River, Alberta. Rivers 7:33-48.

Rubin, D. M., D. J. Topping, J. C. Schmidt, J. Hazel, M. Kaplinski, and T. S. Melis. 2002. Recent sediment studies refute Glen Canyon Dam hypothesis. EOS, Transactions, American Geophysical Union 83:273, 277-278.

Saxton, K. E., and S. Y. Shiau. 1990. Surface waters of North America; Influence of land and vegetation on streamflow. Pages 55-80 *in* M. G. Wolman, and H. C. Riggs, editors. Surface water hydrology: the geology of North America V O-1. Geological Society of America, Boulder, Colorado.

Schmidt, J. C., R. A. Parnell, P. E. Grams, J. E. Hazel, M. A. Kaplinski, L. E. Stevens, and T. L. Hoffnagle. 2001. The 1996 controlled flood in Grand Canyon: flow, sediment transport and geomorphic change. Ecological Applications 11:657-671.

Schumm, S. A. 1963. Sinuosity of alluvial rivers on the Great Plains. Bulletin of the Geological Society of America 74:1089-1100.

Schumm, S. A. 1968. Speculations concerning paleohydrologic controls of terrestrial sedimentation. Geological Society of America Bulletin 79:1573-1588.

Schumm, S. A. 1977. The fluvial system. Wiley, New York.

Scuderi, L. A. 1990. Tree-ring evidence for climatically effective volcanic eruptions. Quaternary Research 34:67-85.

Sear, D. A. 1994. River restoration and geomorphology. Aquatic Conservation: Marine and Freshwater Ecosystems 4:169-177.

Seeber, L., and V. Gornitz. 1983. River profiles along the Himalayan Arc as indicators of active tectonics. Tectonophysics 92:335-367.

Sedell, J. R., J. E. Yuska, and R. W. Speaker. 1984. Habitats and salmonid distribution in pristine, sediment-rich river valley systems: S. Fork Hoh and Queets River, Olympic National Park. Pages 33-46 *in* W. R. Meehan, T. R. Merrell, Jr., and T. A. Hanley, editors. Fish and wildlife relationships in old-growth forests. American Institute of Fishery Research Biologists.

Seidl, M. A., W. E. Dietrich, and J. W. Kirchner. 1994. Longitudinal profile development into bedrock; an analysis of Hawaiian channels. Journal of Geology 102:457-474.

Simpson, J. J., and M. A. Cane. 1993. Annual river discharge in Southeastern Australia related to El Niño–Southern Oscillation of sea surface temperature. Water Resources Research 29:3671-3680.

Slack, J. R., and J. M. Landwehr. 1992. Hydro-Climatic Data Network: a U.S. Geological Survey streamflow data set for the United States for the study of climate variations, 1874–1988. U.S. Geological Survey. Open-file report 92-129.

Smith, D. G. 1976. Effect of vegetation on lateral migration of anastomosed channels of a glacier meltwater river. Geological Society of America Bulletin 87:857-860.

Smith, N. D., and D. G. Smith. 1984. William River: An outstanding example of channel widening and braiding caused by bed-load addition. Geology 12:78-82.

Smith, R. L. 1974. Ecology and field biology, 2nd edition. Harper and Row, New York.

Sparks, R. E. 1995. Need for ecosystem management of large rivers and their floodplains. Bioscience 45:168-182.

Stott, T. 1997. A comparison of stream bank erosion processes on forested and moorland streams in the Balquhidder catchments, central Scotland. Earth Surface Processes & Landforms 22:383-399.

Stromberg, J. C. 1997. Growth and survivorship of Fremont cottonwood, Goodding willow, and salt cedar seedlings after large floods in central Arizona. Great Basin Naturalist 57:198-208.

Stromberg, J. C., and D. T. Patten. 1990. Riparian vegetation instream flow requirements: a case study from a diverted stream in the eastern Sierra Nevada, California, USA. Environmental Management 14:185-194.

Swanson, F. J., R. L. Fredrickson, and R. M. McCorison. 1982. Material transfer in a western Oregon forested watershed. Pages 233-266 *in* R. L. Edmonds, editor. Analysis of coniferous forest ecosystems in the western United States. Hutchinson Ross, Stroudsburg, Pennsylvania.

Takahashi, T., K. Ashida, and K. Sawai. 1981. Delineation of debris flow hazard areas. Pages 589-560 *in* T. R. H. Davies, and A. J. Pearce, editors. Erosion and sediment transport in Pacific rim steeplands. International Association of Hydrological Sciences Publication 132.

Thompson, D. M. 2002. Long-term effect of instream habitat-improvement structures on channel morphology along the Blackledge and Salmon Rivers, Connecticut, USA. Environmental Management 29:250-265.

Thorne, C. R., R. G. Allen, and A. Simon. 1996. Geomorphological river channel reconnaissance for river analysis, engineering and management. Transactions of the Institute for British Geographers 21:469-483.

Trimble, S. W. 1997. Stream channel erosion and change resulting from riparian forests. Geology 25:467-469.

U.S. General Accounting Office. 1994. Ecosystem management: approach. U.S. General Accounting Office. GAO/RCED-94-111. Washington, D.C.

Walling, D. E., and R. Carter. 1980. River water temperatures. Page 49 *in* J. C. Doornkamp, and K. J. Gregory, editors. Atlas of drought in Britain 1975-76. Institute of British Geographers, London.

Walling, D. E., and B. W. Webb. 1992. Water quality: physical characteristics. Pages 48-72 *in* P. Calow and G. E. Petts, editors. The rivers handbook. Blackwell Scientific Publications, Oxford.

Walter, H. 1985. Vegetation of the earth and ecological systems of the geo-biosphere. Springer-Verlag, Berlin.

Ward, J. V. 1989. The four-dimensional nature of lotic ecosystems. Journal of the North American Benthological Society 8:2-8.

Ward, J. V., and K. Tockner. 2001. Biodiversity: towards a unifying theme for river ecology. Freshwater Biology 46:807-819.

Ward, P., D. R. Montgomery, and R. Smith. 2000. Altered river morphology in South Africa associated with the Permian-Triassic mass extinction. Science 289:1740-1743.

Watson, I., and A. D. Burnett. 1995. Hydrology: an environmental approach. CRC Lewis Publishers, Boca Raton, Florida.

Webb, R. H., J. C. Schmidt, G. R. Marzolf, and R. A. Valdez, editors. 1999. The controlled flood in Grand Canyon. American Geophysical Union, Washington, D.C.

Webster, J. R., and D. J. D'Angelo. 1997. A regional analysis of the physical characteristics of streams. Journal of the North American Benthological Society 16:87-95.

Whiting, P. J. 1998. Floodplain maintenance flows. Rivers 6:160-170.

Whiting, P. J. 2002. Streamflow necessary for environmental maintenance. Annual Reviews of Earth and Planetary Science 30:181-206.

Whiting, P. J., and J. Stamm. 1995. The hydrology and form of spring-dominated channels. Geomorphology 12:233-240.

Wilcock, P. R. 1993. Critical shear stress of natural sediments. Journal of Hydraulic Engineering 1199:491-505.

Wilhite, D. A., and M. H. Glantz. 1985. Understanding the drought phenomenon: the role of definitions. Water International 10:111-120.

Williams, G. P. 1978. Bank-full discharge of rivers. Water Resources Research 144:1141-1154.

Williams, G. P., and M. G. Wolman. 1984. Downstream effects of dams on alluvial rivers. U.S. Geological Survey. Professional Paper 1286.

Williams, J. R., H. E. Pearson, and J. D. Wilson. 1985. Streamflow statistics and drainage-basin characteristics for the Puget Sound region, Washington. Vol. II. U.S. Geological Survey. Open-File Report 84-144-B.

Wing, M. G., and A. Skaugset. 2002. Relationships of channel characteristics, land ownership, and land use patterns to large woody debris in western Oregon streams. Canadian Journal of Fisheries and Aquatic Sciences 59:796-807.

Winter, T. C. 2001. The concept of hydrologic landscapes. Journal of the American Water Resources Association 37:335-349.

Woltemade, C. J., and K. W. Potter. 1994. A watershed modeling analysis of fluvial geomorphologic influences on flood peak attenuation. Water Resources Research 30:1933-1942.

Woo, S. 1999. The Trinity River train gathers steam, but will the fish be on board? U.S. Water News 16(1):9.

Wood, E. F. 1998. Scale analyses for land-surface hydrology. Pages 1-29 *in* G. Sposito, editor. Scale dependence and scale invariance in hydrology. Cambridge University Press, Cambridge, United Kingdom.

Ziemer, R. R. 1997. Temporal and spatial scales. Pages 80-95 *in* J. E. Williams, C. A. Wood, and M. P. Dombeck, editors. Watershed restoration: principles and practices. American Fisheries Society, Bethesda, Maryland.

Zimmerman, R. C., J. C. Goodlet, and G. H. Comer. 1967. The influence of vegetation on channel form of small streams. Pages 255-275 *in* Symposium on river morphology. International Association of Hydrological Sciences Publication 75.

Glossary

Channel reach	A morphologically similar length of channel, typically many channel widths long.
Channel unit	Morphologically distinct areas within a channel reach typically less than several channel widths in length, including pools, riffles, bars, steps, cascades, and rapids.
Disturbance	A process or event that alters habitat structure or directly impacts the health or survival of an organism or population.
Disturbance regime	The integrated distribution of disturbance intensity, magnitude, frequency, and duration.
Geomorphic province	Regions of similar land forms bounded by major physiographic, climatic, and geological features that exhibit comparable hydrologic, erosional, and tectonic processes.
Process domain	A spatially definable area characterized by a common disturbance regime.
Restoration	Restoration means not only reestablishing prior conditions but reestablishing the processes that create those conditions. An understanding of the nature, scope, and extent of historical changes is needed to define a reference against which to set restoration objectives.
Rehabilitation	Rehabilitation aims to improve river conditions rather than reestablish natural processes that historically created desired conditions. An understanding of the nature, scope, and extent of historical changes is needed to increase the likelihood of project success under existing conditions.
Valley segment	A portion of the valley system with similar morphologies and geomorphic processes.
Watershed	The drainage area upslope of any point along a channel network. For many purposes, watersheds of 50–500 km^2 provide practical planning units.