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Factors Controlling Availability of Spawning Habitat for Salmonids at the Basin Scale

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Introduction

Measures of habitat attributes are well defined at the unit (1–10 m) and reach (10–1,000 m) scales, but observations at these scales can miss interactions over larger spatial extents (Fausch et al. 2002). Attributes that characterize upstream basin properties can exhibit relationships to fish abundance unresolved at the reach scale (Feist et al. 2003), so that aquatic habitats are increasingly being examined in terms of basin-scale metrics (Hughes et al. 2006). Basin-scale attributes found to correlate with spawner abundance include road density (Baxter et al. 1999), the proportion of basin area: with hillslope gradients below a certain threshold, in certain forest types, in certain land uses, and in certain rock types (Pess et al. 2002; Feist et al. 2003; Steel et al. 2004). Such attributes serve as indicators of process types and rates in a basin, gauging levels of erosion and sediment transport and recruitment of large wood to channels.

Here, we review studies describing geomorphic processes affecting physical habitat, particularly salmonid spawning habitat as influenced by the supply, movement, and storage of coarse sediment through a channel network. Our examples are drawn primarily from the mountainous terrain of the Pacific Northwestern United States. Although not exhaustive, we examine processes of sediment supply and transport that operate in all rivers; the implications for spawning habitat depend on the spatial and temporal distribution of process rates, which vary both locally and regionally. Such a framework can help quantify these variations and guide development of analysis tools and collection of data to characterize basin-wide controls on habitat formation and alteration.

Habitat requirements for salmonid spawning are fairly specific: a stable channel formed in clean gravel of the appropriate size with abundant hyporheic flow (Kondolf 2000). The prerequisites for developing such habitat are also fairly specific: a valley-floor and channel configuration that promotes alluvial deposition of gravels, conditions that exist within a limited range of channel sizes and gradients. Once this range is determined, it is relatively straightforward to delineate the extent of a river system potentially suitable for habitat formation (Lunetta et al. 1997; Buffington et al. 2004; Burnett et al. 2007). This is a useful exercise: it lays out the stage on which watershed processes act to form the habitats required for successful spawning. This can be a rather large stage, with many simultaneous, interacting scenes and numerous actors.

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The theatrical metaphor serves as a convenient framework to describe the geomorphic interactions that create and modify spawning habitat within a river basin. For simplicity, the framework is scripted to focus on the stage, sets, and actors individually—though we recognize that complex interdependencies among these elements are essential to the plot. The channel network and the basin it drains form the spatial template, the stage on which dynamic processes act to construct and modify habitats needed for spawning (Figures 1 and 2). Transient aspects form the sets, including the valley-floor landforms modified during floods, the bed texture, bed forms, geometry, and location of alluvial channels, and the abundance of large wood. The actors are the floods that move sediment, the storms that trigger erosion, the fires, and other disturbances that kill vegetation and increase erosion rates. By modifying these processes, humans too are primary actors in this play.

The Stage

As a river is followed downstream, its average depth, discharge, and gradient vary systematically as drainage area increases (Leopold and Maddock 1953) with accompanying changes in stream type and bed texture (Montgomery and Buffington 1997). The downstream evolution of river characteristics provides the basic template for the distribution of habitat types and biological processes along a river corridor (Vannote et al. 1980; Montgomery 1999; Church 2002). Regional climate is an important control on the rate at which conditions evolve downstream, but reach-to-reach details of

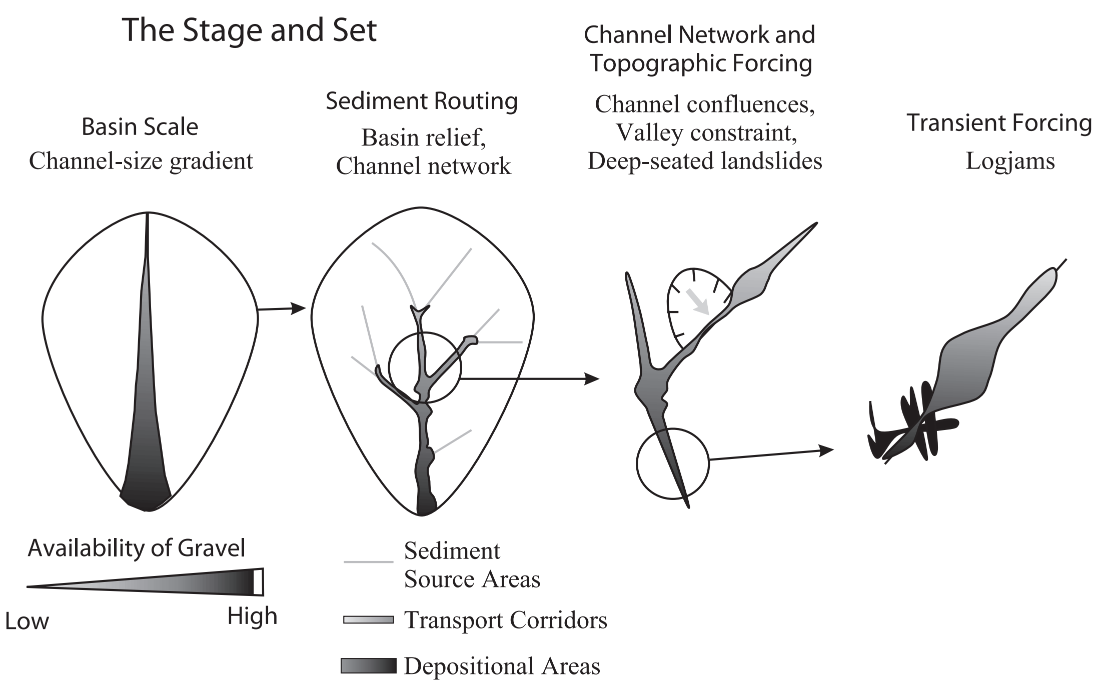

Figure 1. A drainage basin forms the stage on which dynamic processes act to create and destroy habitat features. Basin size determines the range of channel types. Basin topography determines what processes of sediment production are active and where sediment is introduced to the channel system. This sediment is routed through a branched channel network. Local effects of valley constraint, tributary fans, landslides, and logjams are overprinted on the systematic downstream evolution in sediment transport rates and storage volumes.

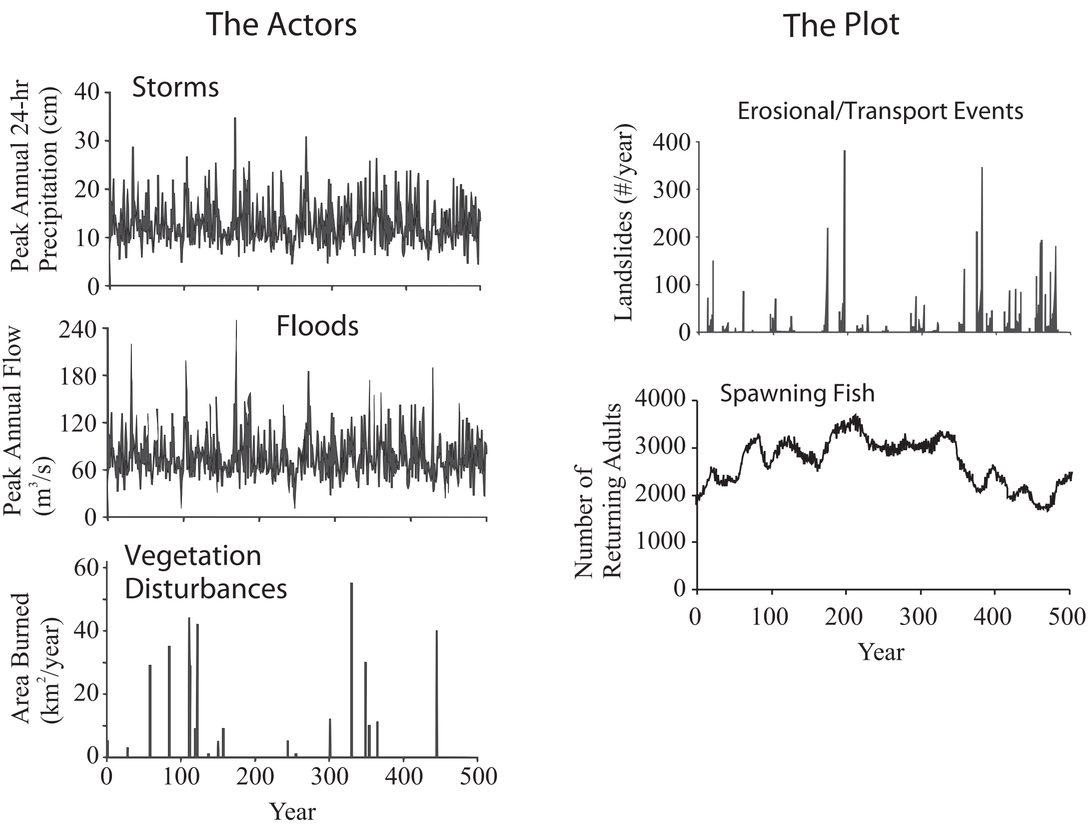

Figure 2. Storms, floods, and vegetation disturbances (e.g., fires) act to drive a sequence of events that move sediment into and through the channel network. Together, these create temporal and spatial fluctuations in the abundance and distribution of channel gravels and associated spawning habitat, which may drive fluctuations in the number of successfully spawning fish. These graphs are from a simulation over a 200-km^2 basin in southwest Washington (U.S. Forest Service 2003).

this evolution, particularly discontinuities in general trends, depend on variations in material properties and topographic factors specific to each basin. The spatial distribution of rock types, geologic structures, soils, and topography thus form the appropriate stage for considering the processes that create and modify salmonid spawning habitats within a drainage basin. We discuss each component in turn and highlight some analytical techniques that are available to characterize these over broad spatial extents. We concentrate on topography, however, because topographic data are generally available at higher resolution than geologic or soils mapping and because many geologic effects are manifest in basin topography.

Geology and Soils

The spatial distribution of bedrock lithologies, geologic structures, unconsolidated deposits, and soils profoundly influence basin hydrologic and geomorphic processes. As examples, aquifer properties and the degree to which groundwater outflow reduces discharge variability can vary with bedrock lithology (Sear et al. 1999); lithology determines the durability of gravel clasts in fluvial transport (Kodama 1994) and influences the proportion of fine sediment in channel beds (Sable and Wohl 2006); for similarly sized basins, channel gradient and type can vary with basin lithology (Hicks and Hall 2003); and finally landslide types, rates, and locations vary with rock type and bedding orientations (Roering et al. 2005). Geologic and soils mapping provide information about the types of surface deposits and bedrock lithologies found in a basin. Recent studies show that even simple characterizations of geology, such as the proportion of basin area in a particular rock type (Feist et al. 2003), the proportion of basin area with particular surface deposits (Pess et al. 2002), or the presence of certain rock types (Steel et al. 2004), are useful indicators of spawning success.

Geologic factors that influence basin hydrologic and geomorphic processes are reflected in basin topography. For example, drainage density can vary with bedrock lithology (Tucker et al. 2001) so that for a given climatic regime variations in drainage density can reflect different geologic controls on basin hydrology. Variations in bedrock lithology and structure affect mass-wasting processes, which in turn alter hill-slope topography. Roering et al. (2005), for example, used topographic attributes to identify sites of deep-seated landsliding in sandstones of the Oregon Coast Range, which they then correlated with lithologic and structural attributes of the underlying bedrock. Active tectonic uplift affects river profiles and influences the distribution of channel gradients relative to channel size (Kobor and Roering 2004), which then affects the proportion of the channel network available for habitat formation. In many cases, geologic and tectonic controls on geomorphic processes need not be explicitly characterized because they are manifest in basin topography, which is more highly resolved with available data.

Topography

Data and tools for analysis of topography have expanded dramatically with widespread availability of digital elevation models (DEMs; e.g., Gesch et al. 2002) and development of geographic information system-based methods for extraction of topographic variables. Now, hillslope characteristics, channel networks, and reach attributes are routinely derived from DEMs (Buffington et al. 2004; Benda et al. 2007; Burnett et al. 2007). We examine the use of topographic data to characterize three aspects of basin-wide controls on habitat formation: (1) production and routing of sediment to channels, (2) valley configurations that promote fluvial deposition, and (3) channel confluences.

Sediment inputs to channels.—Even within channels having the right size and gradient for accumulation of spawning gravels, spawning tends to be concentrated in certain areas (Isaak and Thurow 2006). A variety of factors determine where these areas are located, including a source for suitably sized gravel relatively free of sands and silts (Kondolf 2000). Delineation of gravel and fine-grained sediment sources may further resolve areas conducive to habitat creation and areas subject to habitat degradation. For certain rivers in Washington State, for example, Martin et al. (2004) found that Chinook salmon *Oncorhynchus tshawytscha* preferentially built redds downstream of mass-wasting sites that provided a source of gravel. In other cases, accelerated landsliding and surface erosion, particularly from forest roads, have elevated levels of fine-grained sediment in channel beds, with detrimental effects on spawning success (Platts et al. 1989; Hartman et al. 1996).

Surface erosion and mass wasting are driven by gravitational potential energy provided by topographic relief, and mobilized sediment is routed through flow pathways determined by surface topography. Sediment inputs to channels thus occur at distinct locations that can be identified from basin topography. For example, landslides of shallow soils occur on steep topographically convergent slopes (Sidle and Ochiai 2006). Such landslides can trigger debris flows that travel long distances and provide an important mechanism of sediment delivery and disturbance to streams in mountainous terrain (Benda 1990; Roghair et al. 2002). Travel length for debris flows varies with gradient and topographic confinement along the travel path (Fannin and Rollerson 1993). To identify channel locations subject to debris-flow inputs in the Oregon Coast Range, Miller and Burnett (2007) and Burnett and Miller (2007) associated mapped landslide and debris-flow track locations to attributes of local topography inferred from 10-m DEMs. Modeled probabilities for debris-flow initiation and delivery identify potential sediment sources within a watershed (Figure 3) and highlight channels subject to sediment inputs from debris flows (Figure 4). Spatially distributed, topographically driven models have also been developed for other erosional processes (Van Rampaey et al. 2001; Istanbulluoglu et al. 2003).

Valley configuration.—For most mountain rivers, the gradual downstream evolution in channel form and type is disrupted by changes in valley geometry. Variations in valley width, cross-sectional shape, and longitudinal gradient influence the suite of processes that move sediment to and through channels, with corresponding variations in the depth of alluvial deposition, the texture of alluvial deposits, constraint of the channel, and characteristics of floodplain and riparian areas. Changes in bedrock resistance to erosion lead to changes in valley width, with wider valleys in weaker rocks (Brocard and van der Beek 2006). Large landslides can

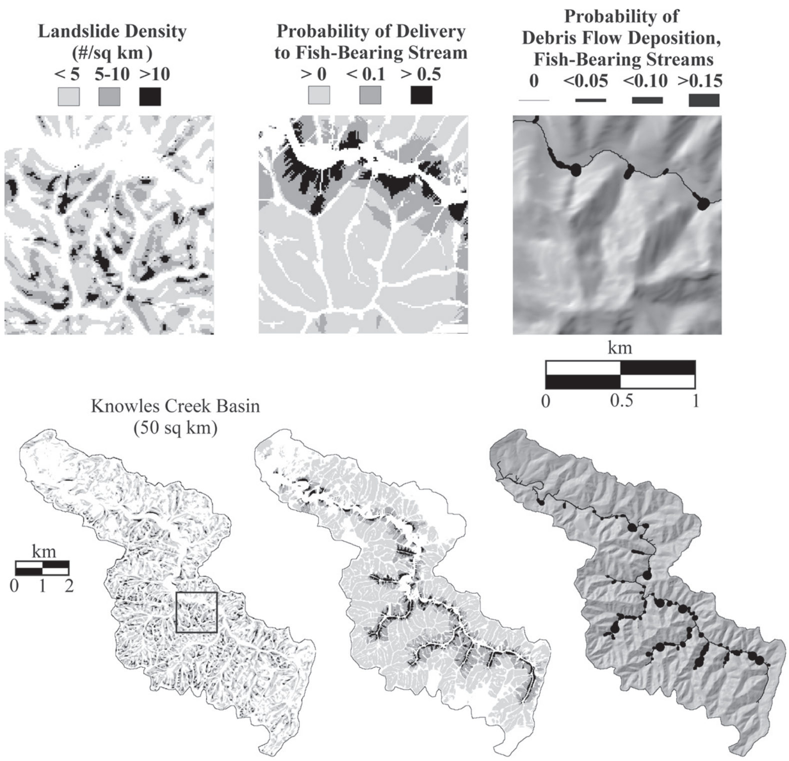

Figure 3. Sediment delivery to streams tends to be concentrated in specific topographically determined locations. Using a model calibrated to a large regional storm (Burnett and Miller 2007; Miller and Burnett 2007), we show how landslide density and the probability of debris-flow delivery from hillslope locations to fish-bearing streams varies as a function of topographic location for Knowles Creek basin in the Oregon Coast Range. Together, these factors determine the probability of debris-flow deposition in fish-bearing streams. At the site scale, we resolve specific points of debris-flow delivery. At the scale of Knowles Creek basin, we resolve sub-basin variability in landslide and delivery potential and reach-scale variation in the potential for debris-flow deposition.

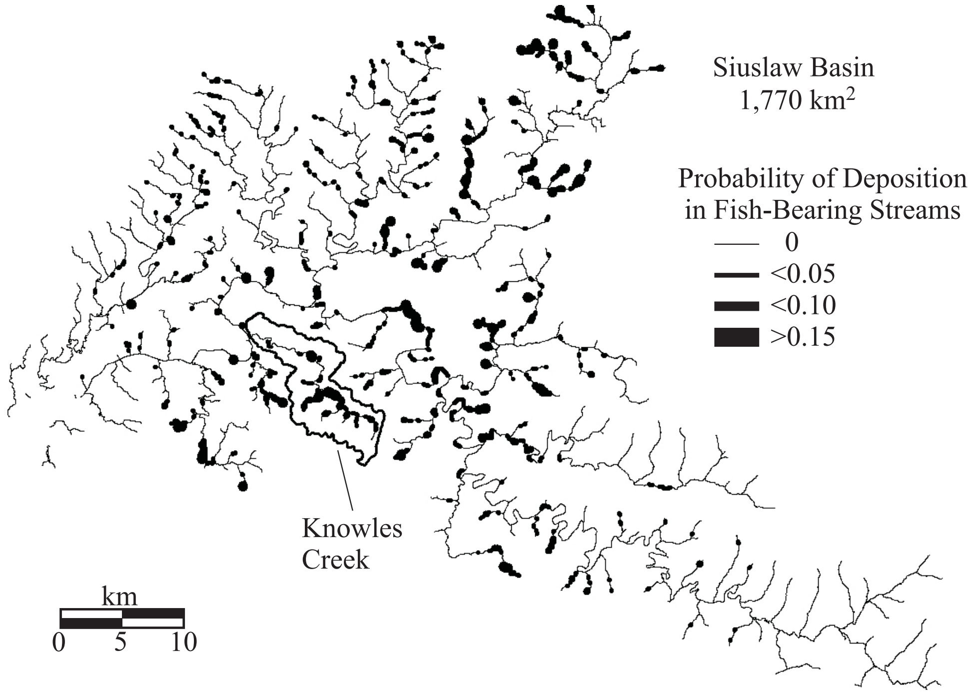

Figure 4. Probability for debris-flow delivery to fish-bearing streams over the Siuslaw River basin, Oregon Coast Range. At this scale, basin-to-basin differences are resolved in the abundance of debris-flow delivery points. Basins with greater debris-flow potential likely experience greater temporal and spatial variability in fluvial sediment fluxes. Probability for debris-flow delivery was modeled using the methods of Miller and Burnett (2007) and Burnett and Miller (2007).

cause valley-floor widening and reductions in channel gradient upstream of the landslide, with corresponding valley constraint and steepening of channel gradient adjacent to the landslide (Korup et al. 2006). Fans at tributary confluences can have similar effects (Benda et al. 2004a). Alpine glaciation creates distinct valley morphology with persistent effects on fluvial processes (Brardinoni and Hassan 2006). Alluvial and strath terraces, representing past sediment-supply and transport regimes, can confine channels on valley floors (Rot et al. 2000).

Wide valleys can serve as reservoirs of alluvial substrates in which self-formed alluvial channels and associated landforms and habitats can develop (McDowell 2001). Narrow valleys offer fewer opportunities for storage and serve as corridors of sediment transport. Longitudinal variations in valley constraint drive extensive hyporheic flow through wide, alluvial segments (Edwards 1998). Variations in valley width can create a sequence of alluvial floodplains bounded by confined, canyon reaches, like "beads on a string" (Stanford and Ward 1993), with spawning habitat concentrated in the alluvial beads (Baxter and Hauer 2000). Although the factors shaping valleys are complex and varied, valley shape is expressed in topographic features that can be mapped from DEMs. The spatial distribution of valley constraint, taken together with channel size and gradient, imposes intrinsic, landscape controls on the abundance and location of habitats. When mapped, these reveal intrinsic controls that vary among river systems (Figures 5 and 6) and provide basin-wide indicators of potential fish distribution and productivity (Burnett et al. 2007).

Channel confluences.—Channel confluences are sites of fluvial interactions that

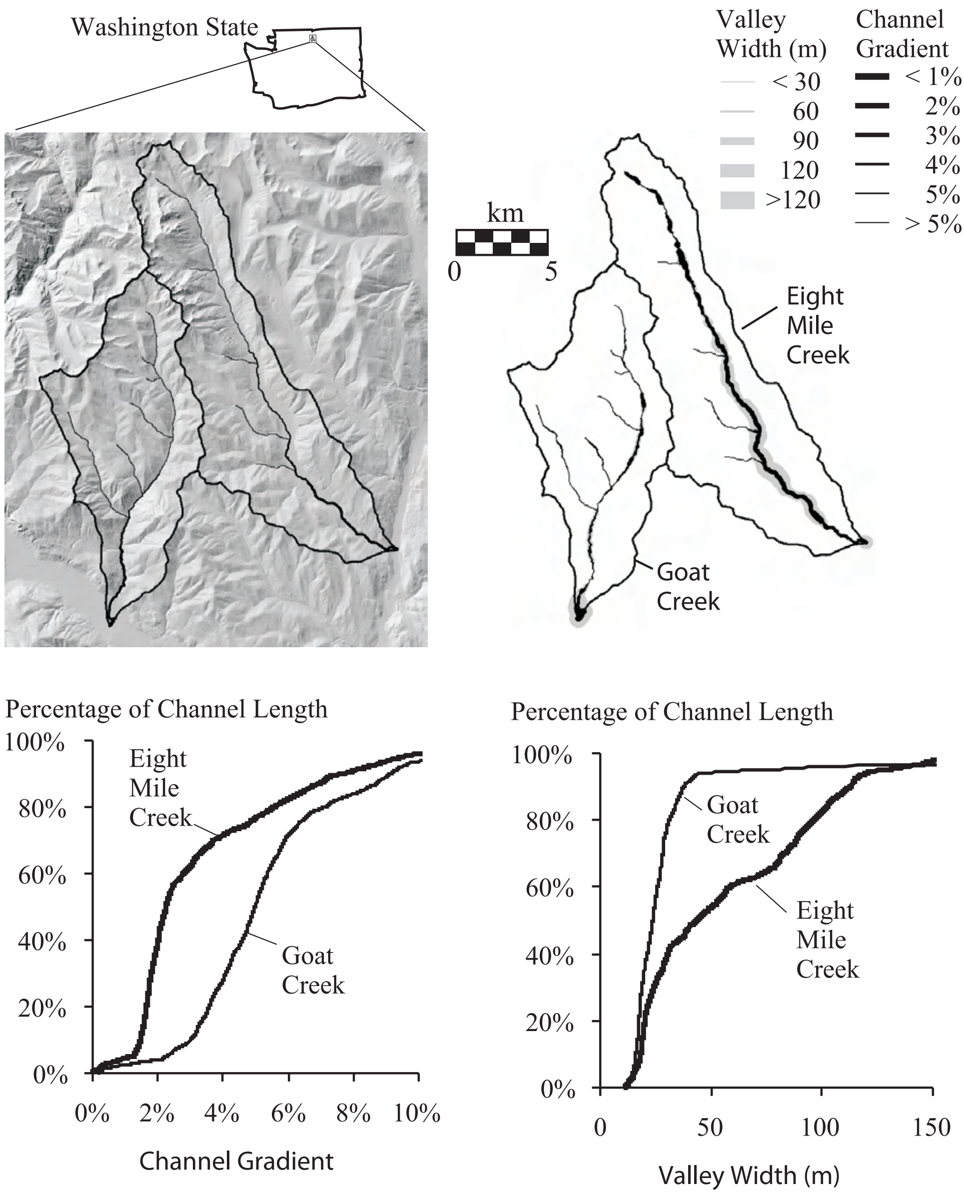

Figure 5. Intrinsic controls imposed by channel size/gradient and valley width on the distribution of potential habitat-forming channels. Eight Mile Creek (120 km²) and Goat Creek (93 km²) basins, in the North Cascade Range of Washington State, show how differences in valley geometry create large differences in the abundance of low-gradient, unconstrained channels, even in adjacent basins.

create unique morphology and heightened geomorphic activity (Benda et al. 2004a). Tributaries are input locations for water and sediment, with effects on channel geometry, bar formation, and bed texture in the receiving stream (Best 1986; Rice et al. 2001). Fans formed at tributaries affect valley morphology and channel conditions. Coarse sediment inputs from tributaries can provide spawning substrate to gravel-poor main-stem channels (Martin et al. 2004). Tributary junctions contribute to habitat heterogeneity within a

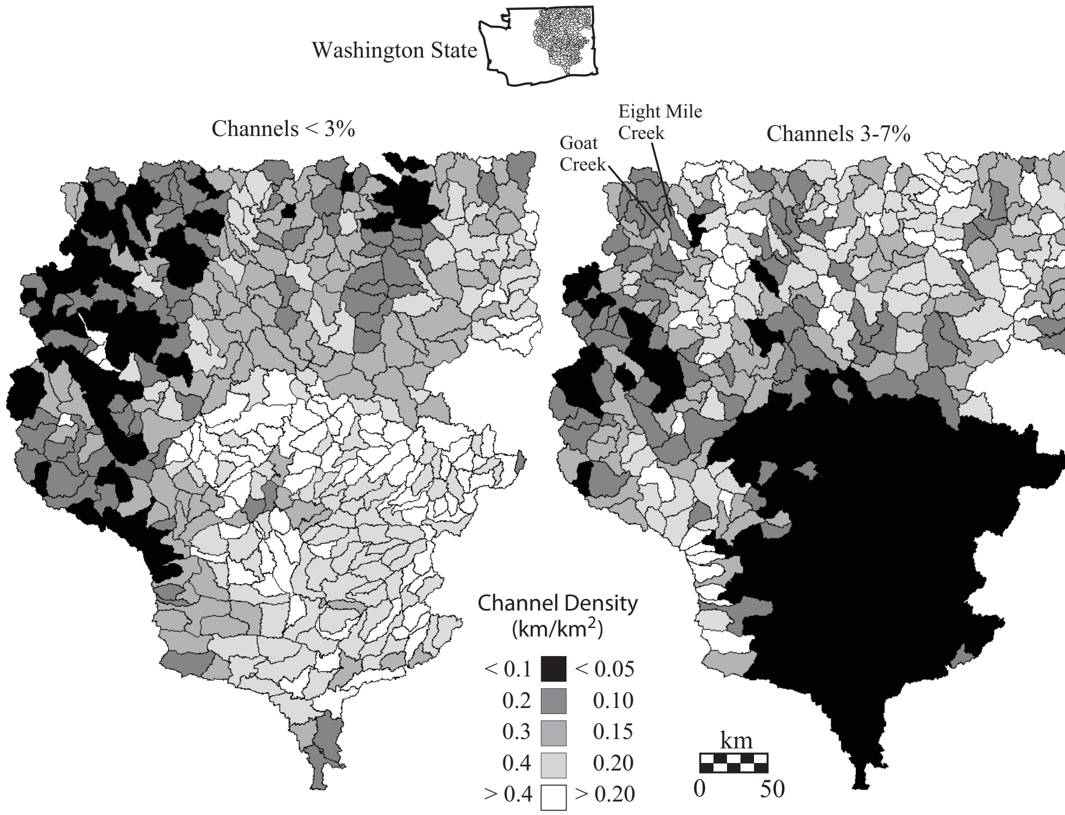

Figure 6. Variation in the abundance of potential habitat-forming channels in the upper Columbia River basin (56,500 km^2). Low-gradient (<7%), unconstrained (ratio of valley-floor to channel width > 5) channel density (km/km^2) varies in response to basin-to-basin and regional differences in basin topography and valley geometry for sixth-level hydrologic units basins (average size 120 km^2). Low densities prevail for channel gradients less than 3% in high-relief basins in the north and west portion of the drainage, whereas low-relief basins in the southwest portion of the drainage have almost no unconstrained channels with gradients between 3% and 7%. A portion of this figure was first presented in Benda et al. 2007.

basin (Benda et al. 2004b; Kiffney et al. 2006; Rice et al. 2006), with consequences specific to each site.

Benda et al. (2004a) used case studies from across the western United States to estimate the probability of observing geomorphic changes associated with tributaries in terms of the relative size of the tributary and receiving channel (expressed as drainage area). This probability is large when the two channels are of nearly equal size and diminishes as the ratio of the tributary to mainstem drainage areas decreases. Although this characterization ignores other controls, such as valley geometry or basin geology, it provides a simple method for broad-scale estimation of tributary influences. Tools are now available for use with DEMs (Benda et al. 2007) to map channel networks and assign a geomorphic relevance to each tributary junction (Figure 7). The density of geomorphically relevant tributaries can then be calculated in terms of number per channel length or number per unit area. This density varies across the landscape (Figure 8) in response to differences in basin shape and network structure (Benda et al. 2004a). The number of geomorphically relevant tributaries decreases in the downstream direction. In the headwaters, many tributaries

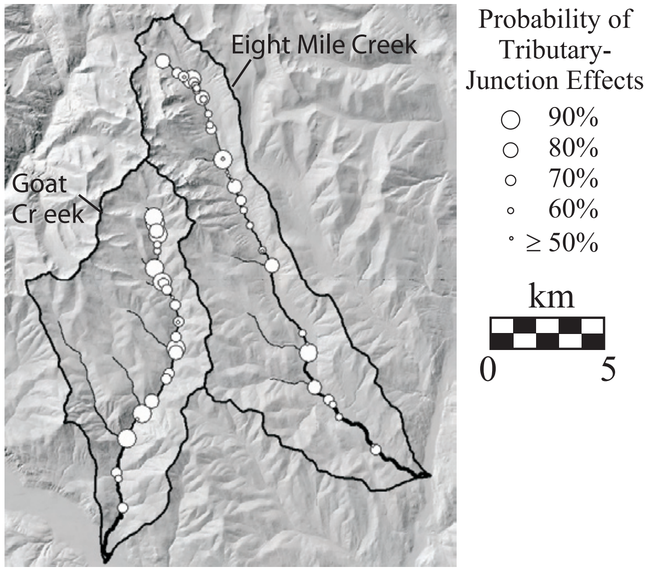

Figure 7. Potential for tributary junction effects. The number and spacing of tributary junctions varies along the main-stem channels of Eight Mile and Goat creeks. The narrow shape of the Eight Mile basin favors small tributaries relative to main-stem size, with a corresponding lower number and greater average spacing between tributary junctions.

are of comparable size and channel-junction effects may be common. As the main stem grows downstream, comparably sized tributaries are less common and the spacing between junction effects increases.

The Set

In viewing basin geology and topography as a relatively static stage, we consider the more transient features associated with the deposition and erosion of sediment and wood as components of the set for each act. These components differ with position in the channel network in correspondence with the changing suite of geomorphic attributes associated with different process domains (Montgomery 1999). We describe the sets in reach-specific terms because the stage presented by any basin determines the specific assembly of reach-scale sets that then constrain the basin-wide suite of habitats available to spawning fish. Two types of features are examined: valley-floor landforms created and modified by sediment transport and in-channel wood.

Valley-Floor Landforms

Mass wasting and fluvial processes arrange sediment on the valley floor into a variety of landforms that vary with position in the channel network and influence the creation of spawning habitat. Low-order (Horton-Strahler stream order) channels high in the network are small and tend to be steep, with corresponding bedrock, colluvial, cascade, and step-pool channel types (Montgomery and Buffington 1997). These channels can compose the majority of the total channel length (Benda and Dunne 1997b) and can provide spawning habitat for a variety of salmonid species (Bryant et al. 2004; Wigington et al. 2006). The headwater valley floors that contain these channels tend to be closely linked to hillslope mass-wasting and erosion processes (May and Gresswell 2004). Debris-flow fans constrict valley floors, alter channel gradient, and contribute boulders and woody debris to the channel (Benda 1990; Wohl and Pearthree 1991), which contributes to physical heterogeneity along channel corridors (Benda et al. 2003b). In steep channels,

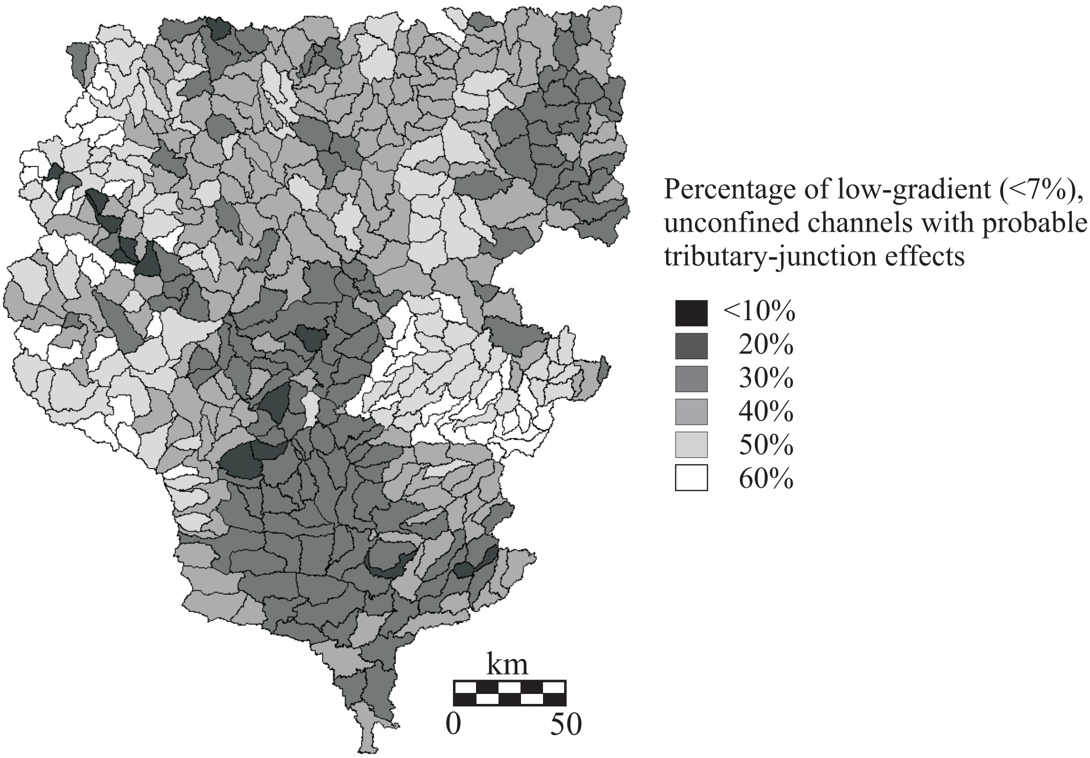

Figure 8. Potential for tributary effects through potential spawning channels in the upper Columbia River basin. Variation is examined among sixth-level hydrologic units.

locations for gravel accumulation tend to be limited (Kondolf et al. 1991) and boulders and wood can trap gravel (Montgomery et al. 1996).

As we move downstream, alluvial landforms and fluvial processes increase in precedence over colluvial landforms and mass wasting processes. Channels become larger and of lower gradient, with associated plane-bed, pool-riffle, and dune-ripple channel types (Montgomery and Buffington 1997; Flores et al. 2006) and meandering or braided plan form. Valleys are filled with sediment carried there by the river itself and channels reside in self-formed flood plains. Sediment is supplied by fluvial transport from upstream, by bank erosion of floodplain sediments (Payne and Lapointe 1997) and by tributary inputs (Rice et al. 2001). Despite their self-formed nature, these channels exhibit a remarkable degree of spatial heterogeneity (Ward et al. 2002). Variations in bed texture, presence of bed forms, changes in flow direction (meander bends), and constrictions in valley width create local zones of hyporheic inflow and outflow (Edwards 1998; Malard et al. 2002) that affect spawning locations (Baxter and Hauer 2000; Geist et al. 2002). Changes in channel geometry (Best 1986) and bed texture (Rice et al. 2001) can occur at channel confluences. Side channels and sloughs can provide spawning habitat (Eiler et al. 1992).

Large Wood

The abundance of wood in a channel varies over time in response to forest disturbances and the function of wood varies with channel size, gradient, and sediment supply. Wood in jams and single pieces can trap spawning gravels, provide cover from predators, and cause flow diversions that scour pools (Bilby and Bisson 1998). Channel-spanning logjams can store sufficient sediment to provide persistent alluvial cover in what would otherwise be bedrock reaches (Montgomery et al. 1996). These effects, integrated over a basin, can have a large impact on spawning habitat abundance (Buffington et al. 2004). Streamside forests are an important source of wood for all channel types (McDade et al. 1990; May and Gresswell 2003), so the amount and characteristics of wood in a channel reflect characteristics of riparian forests in a basin (Hedman et al. 1996; Burnett et al. 2006). Regional differences in tree sizes, stem densities, and species composition imply regional differences in wood loading of streams (Benda et al. 2002). Likewise, the history and spatial extent of riparian forest disturbances, both natural (stream channel dynamics, wildfires, and blowdown) and anthropogenic, affect the available supply of wood to stream channels (Ralph et al. 1994; Collins et al. 2002; Benda and Sias 2003).

In small streams, stand mortality is a primary source of wood, with potentially important inputs from landsliding (May and Gresswell 2003; Reeves et al. 2003). As streams increase in size downstream, bank erosion and channel migration become increasingly significant sources for wood recruitment (Martin and Benda 2001). Channel constraint and other limits to bank erosion and lateral channel movement can reduce wood recruitment (Rot et al. 2000). The delivery of wood by fluvial transport varies with the size of the wood piece relative to the size of the stream (Lienkaemper and Swanson 1987). Thus, the spacing and size of wood accumulations vary with stream size (Bilby and Ward 1989) and with position in the channel network (Benda and Sias 2003). Individual pieces predominate in small streams, with the number of pieces dependent on the rate of recruitment from adjacent forests. As channels become larger downstream, wood is more likely to be transported and caught in jams, ever larger key pieces are required to form jams, and processes of jam formation change, leading to increased average spacing between jams and systematic variation in the abundance of different jam types (Abbe and Montgomery 2003).

A variety of models have been developed to characterize reach-scale wood recruitment to channels (Gregory et al. 2003). These models continue to mature as additional data are collected (controls on tree-fall direction, Sabota et al. 2006), as disturbance mechanisms are incorporated (Bragg 2000; Benda and Sias 2003) and as they are extended to entire channel networks (U.S. Forest Service 2003).

The Actors

Having set the stage, we now introduce the actors: a basic suite of dynamic processes—storms, floods, wild fires, and other vegetation disturbances (many human induced)—that act to create and modify river habitats. The cast of characters is largely controlled by regional climate, which determines the magnitude and frequency of erosion-triggering storms, sediment-transporting floods, and vegetation-destroying fires.

Whether an actor plays the lead or a supporting role in modifying channel habitat can vary with position on the stage. Erosional events may play the lead for small, headwater basins, for which extensive vegetation disturbances followed by high-intensity storms (Miller et al. 2003) can result in extensive landsliding and gullying. The juxtaposition of a major vegetation disturbance and a large storm is relatively rare, so recurrence intervals of extreme events in a single headwater basin may span centuries. Downstream in larger channels, flood flows are among the lead actors altering channel habitats. The periodicity of flood-driven changes depends on the hydrologic regime of the basin and on the stability of channel elements (Poff et al. 1997; Molnar et al. 2002). Rivers subject to high seasonal flows, from snowmelt for example, may experience annual mobilization of gravel beds; rivers with less seasonal variability, from groundwater-dominated discharge for example (Sear et al. 1999) or with coarse surficial lag deposits, may have long, multiyear intervals between bed-mobilizing events. As a result of flood flows, channel sediment is mobilized, beds are scoured (DeVries et al. 2001), and bedforms move; banks are eroded and channels migrate laterally; riparian trees are recruited to streams (Martin and Benda 2001); side channels can be created and re-excavated (Miller and Benda 2000); and channels overflow their banks and avulse. Changes in channel geometry and planform can significantly alter patterns of hyporheic flow (Wondzell and Swanson 1999). Storm- and flood-driven modifications are spatially and temporally distinct events that initiate a trajectory of successional changes in riparian vegetation and channel conditions.

These dynamic processes create physical heterogeneity along a river corridor (Richards et al. 2002; Benda et al. 2004b). The degree of heterogeneity may evolve in step with periods of heightened basin disturbance. For example, observed impacts of debris-flow deposition vary over time, starting with catastrophic disturbance of channel conditions, rapid initial recovery (Lamberti et al. 1991; Roghair et al. 2002), and leaving wood and boulders that persist in the channel for decades to centuries (Benda 1990; Wohl and Pearthree 1991). Channel conditions in debris-flow-prone basins may thus depend in part on the age distribution of debris-flow deposits. A large storm can trigger extensive landsliding (Robison et al. 1999) that may significantly alter this age distribution (Benda et al. 2004a).

Together, the temporal and spatial sequence of fires (and other vegetation disturbances), storms, and floods define a regional natural disturbance regime to which salmonid populations are adapted (Reeves et al. 1995). The disturbance regime affects the rate of supply and size distribution of sediment and wood entering a channel reach, which influences channel form, bed texture, and the frequency of channel change (Church 2006). Consequently, the regional disturbance regime, acting in the context of basin geology and topography, determines the spatial distribution, temporal variability, and stability of available spawning habitat. Changes in the supply and transport of sediment, water, and wood associated with human and natural modifications to disturbance regimes can affect spawning habitats. Large, punctuated inputs associated with erosional and landslide events can cause extreme local changes to channel form and bed texture (Hoffman and Gabet 2007), chronic increases in supply can cause persistent channel changes (Platts et al. 1989) that may progress downstream (Madej and Ozaki 1996), and flow regulation can reduce the frequency of sediment-transporting flows with profound effects on channel environments (Ligon et al. 1995).

The Plot

The story involves interactions between storms, floods, and vegetation disturbances that drive episodic movement of sediment through a basin in a stochastic sequence of events. The abundance, type, and distribution of spawning habitats found in any basin at any time depend on the preceding sequence of events—the story line up to that point. Channel responses to sediment inputs and floods are a function of position in the channel network, of local valley geometry, and of the channel and riparian landforms and wood present at the time of the event. Hence, the nature of habitat variability depends on the frequency and magnitude of disturbance events, position on the stage, and components of the set. These processes act not only within the constraints imposed by the stage and sets in any particular basin, they can also construct and modify these features. All these interdependencies may seem to pose daunting complexity; yet, river systems exhibit a great deal of regularity.

Systematic downstream variations in transport and storage processes (Montgomery 1999) coupled with the routing of material through a branched and hierarchical channel network (Benda and Dunne 1997a) organize physical habitat dynamics into certain regular and predictable patterns (Benda et al. 2004b). With this understanding, patterns of spatial and temporal heterogeneity in spawning habitat can be anticipated in terms of regional disturbance regimes and basin-specific topographic controls. Likewise, the effects of changes in this regime, such as fire suppression and extensive timber harvests, or changes in topographic controls, such as channel revetments and dam construction, can be anticipated in terms of their effects on the frequency and magnitude of fluctuations in sediment transport and storage throughout a channel network.

Routing Through a Branched, Hierarchical Network

It is useful to view the channel network as a signal processing system. The signals are sediment pulses supplied by erosional events. As sediment is carried intermittently downstream by floods, the signals are dispersed and attenuated. Two types of temporal evolution have been observed for sediment pulses. In some cases, large sediment inputs (e.g., a landslide, Sutherland et al. 2002; a fan at a tributary junction, Hoffman and Gabet 2007) have created stationary zones of high sediment storage that dissipated over time. In other cases, spatially extensive, transient increases in sediment supply have created a zone of high sediment storage that moved downstream (e.g., Madej and Ozaki 1996). The abundance, location, and spacing of sediment inputs (landslide sites, tributary junctions) are determined by basin topography. The number of upstream sediment sources encompassed within the drainage area to a reach increases downstream, whereas the magnitude of channel responses to these inputs decreases with increasing channel size. As the signals interact, sediment pulses may cease to be individually recognizable, but the cumulative effects of multiple inputs may create variations in sediment storage volumes that vary in frequency and magnitude systematically downstream.

In mountain drainages, headwater channels can experience large increases in sediment input associated with episodes of landsliding and erosion—often fire-related—with persistent impacts to channel and riparian morphology (Cenderelli and Kite 1998; Miller and Benda 2000; Benda et al. 2003a) and recurrence intervals that may span centuries (Istanbulluoglu et al. 2004; May and Gresswell 2004). Although occurring relatively infrequently in these small basins, such episodes can affect an entire headwater drainage and the resulting increase in sediment supply can be very large relative to more typical conditions.

Lower in the channel network, channels are larger and require correspondingly larger volumes of sediment to trigger significant changes to channel morphology. The additive influence of many upstream supply events may be sufficient to create fluctuations in sediment supply that persist for years to decades (Jacobson 1995), but the magnitude of channel changes associated with these fluctuations are likely to be small compared to extreme events in headwater channels. Thus, the frequency of supply fluctuations increases downstream, but the sizes of the fluctuations relative to the average become progressively smaller (Benda et al. 2004a). The details will vary with the lithologies, erosional processes, and disturbance regimes particular to each region, but the evolution from large, infrequent changes high in the network to smaller, more frequent changes lower is a prediction based on expected effects of routing through a branched, hierarchical channel network (Benda et al. 2004b).

Spatial Organization of Temporal Variations

Fluctuations in the rate of sediment transport and the volume of sediment storage have effects on channel morphology that differ throughout the channel system, depending on how each channel reach responds to changes in sediment supply. Montgomery and Buffington (1997) characterized reach-scale response in terms of channel gradient and confinement. Steep, confined channels act as transport corridors and show little or transient response to changing sediment supply, whereas low-gradient, unconfined channels exhibit greater, more prolonged responses, which include changes in the volume of in- and off-channel sediment, changes in bed texture and the proportion of fine sediment, and changes in the number and mean depth of pools. The nature of channel response to changing sediment supply evolves downstream in correspondence with increasing channel size and decreasing channel gradient. Overprinted on this general trend are local variations associated with effects on channel gradient and confinement of bedrock outcrops, terraces, fans at tributary junctions, and changing valley widths. A map of sediment storage across a channel network might show distinct zones of heightened in-channel sediment storage associated with these features. Over time, individual zones may expand during periods of high sediment production in the basin and shrink or even disappear during periods of low sediment production.

Systematic trends in the location, size, and spacing of valley-floor features that affect channel gradient and confinement impose corresponding trends in location, size, and spacing of these sensitive zones. For example, the average spacing of tributary junctions and associated fans generally increases downstream as the main-stem channel increases in size (Benda et al. 2004a). Likewise, the frequency with which expansions and contractions of these sensitive zones occur might vary systematically downstream along the channel network in step with trends in the frequency of fluctuations in sediment supply. In headwater areas, these zones might undergo centuries of quiescence punctuated by infrequent periods of intense activity. In main-stem channels draining thousands of headwater basins, sensitive channel reaches may experience relatively minor adjustments to varying sediment supply over periods of years to decades.

Closing

We have described a story line of in-channel sediment storage and flux variations dependent on characteristics of the stage, set, and actors. We suspect that many aspects of the plot can be inferred from geologic and topographic attributes specific to each basin in conjunction with measures of climate that characterize the frequency and magnitude of sediment-mobilizing events. These concepts lead to hypotheses regarding the location, frequency, and magnitude of changes in channel conditions throughout a drainage basin (Benda et al. 2004b), which imply corresponding changes in the abundance and quality of available spawning habitat. In identifying the processes that change these habitats and the time scales involved, we may also characterize the degree to which spawning habitat locations and extents change over time in response to natural disturbances and to systematic changes associated with human activities and climate change.

Predictions of temporal variability in spawning habitat require characterizations of basin geology, topography, network structure, vegetation cover, erosion dynamics, and climatic forcing that include interactions over large time and space scales (Miller et al. 2003). Data (e.g., 10-m DEMs and 25-m satellite imagery) for basin-wide, reach-scale characterizations of these attributes are increasingly available. Such data have been used to identify sediment routing pathways (Burnett and Miller 2007) and to estimate available habitat types and provide quantitative assessments of habitat loss and degradation due to human activities (Sheer and Steel 2006). Likewise, basin-specific models incorporating dynamic processes of sediment supply and routing have been developed (Benda and Dunne 1997a, 1997b; Gabet and Dunne 2003; Istanbulluoglu et al. 2004; Singer and Dunne 2004; Doten et al. 2006). Such models can be used to predict spatial and temporal variations in habitat types, quality, and abundance (U.S. Forest Service 2003) and may provide a means to evaluate basin-wide controls on spawning habitat and to assess the cumulative effects of widespread impacts from human activities and climate change (Dunne et al. 2001). Modeling interactions over temporal and spatial scales that are difficult to sample physically (with field surveys for example) may provide insights that are empirically inaccessible, but also presents challenges in finding data sets to test model predictions. The plot will continue to unfold as new tools and ideas are put to the test.

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