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Dynamic Landscape Systems

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Overview

- Dynamic landscape processes influence the supply, storage and transport of water, sediment, and wood, thereby shaping many aspects of riparian and aquatic habitats. These processes comprise the disturbance regime of a watershed.
- The study of natural disturbance (and cumulative effects) in riverine and riparian areas requires a fundamental shift in focus from individual landscape elements (such as a forest, a hillslope, and a stream reach) over short timescales (years) to populations of landscape elements over long time scales (decades to centuries). The study of landscapes as a system expands the focus from predictions about exact future states to predictions about the relationships between large-scale properties of landscapes (i.e., climate, topography, and channel networks) and the long-term behavior of aquatic systems.
- Temporal patterns of landscape behavior are best described by frequency distributions which estimate the probability of a specific event occurring. Likewise, describing spatial patterns amongst a population of landscape elements in any year requires proportioning their characteristics amongst the range of all possible environmental conditions, and this also is best described by frequency distributions.
- Characteristics of landscapes that vary naturally over time can be described by four components: (1) climate, which drives environmental variability; (2) topography, which comprises a population of diverse hillslopes that creates spatial variability in the sediment and wood supplied to channels; (3) channel networks, which govern how sediment and wood are routed through a population of linked stream reaches and unevenly redistributed in time and space; and (4) basin history, which effects the volume of sediment and wood stored on hillslopes and in stream channels, and which influences how sediment and woody debris are redistributed during storms, fires, wind, and floods.
- The study of landscapes as systems, focusing on the collective behavior of populations of landscape elements over time, provides the necessary framework for investigating natural disturbance and cumulative effects. The field application of this framework provides insights into how channel and riparian morphologies are related to the recent environmental history of a watershed.

Introduction

Powerful climatic and geomorphic processes shape the landscape of the Pacific coastal ecoregion. Climatic conditions produce wildfires and windstorms that modify large tracts of forests, enabling new species to contribute to a diversity of forest ages and structures. Fires, in particular, controlled the age distribution of natural forests prior to fire suppression throughout most of the mid- and southern parts of the Pacific coastal ecoregion (Teensma 1987, Morrison and Swanson 1990, Agee 1993). Fires and storms trigger geomorphic processes such as bank erosion, surface erosion and gullying, and shallow and deep landslides; processes which control the supply of sediment and wood to streams (Dietrich and Dunne 1978, Swanson 1981, Swanston 1991). Once in stream channels, sediment and wood are transported episodically and redistributed unevenly through the channel network by floods.

Collectively, these climatic and geomorphic processes comprise the disturbance regime of a watershed. The term disturbance refers to a disruption in an environment that leads to a biological response (Pickett and White 1985). Fully understanding the role of disturbance in shaping aquatic ecosystems requires estimating its regime frequencies, magnitudes, and spatial distributions of landscape processes. Likewise, cumulative effects (because they involve a history of human activities dispersed in time and space) can beviewed as a modification of a regime—a shift in frequency, magnitude, and spatical distribution of processes.

Disturbance is embodied in the temporal behavior of a single (or set of interacting) landscape element(s), such as forests, hillsides, and streams over decades to centuries. However, in any year, the history of a dynamic climate or the history of disturbance is represented by the environmental condition of a population of landscape elements (e.g., hundreds to thousands of forest stands, hillsides, or stream reaches). Therefore, the study of disturbance fundamentally involves changes over time and populations of landscape elements.

Natural disturbance is of great interest to researchers and natural resource managers because dynamic (temporal) aspects of landscapes are an inherent characteristic of ecosystems in the region (Swanson et al. 1988), and because natural disturbance can be contrasted with human impacts or disturbances to reveal the long-term consequences of resource management. The study of disturbance in landscapes of the Pacific coastal ecoregion has focused primarily on processes in terrestrial environments such as revegetation following volcanism (Franklin 1990), fires (Teensma 1987, Morrison and Swanson 1990), wind (Borman et al. 1995), snow avalanches (Hemstrom and Franklin 1982), and rockfalls (Oliver 1981). Although some of the disturbances influencing aquatic systems have been recognized, they have not been well quantified (Everest and Meehan 1981, Sedell and Swanson 1984, Minshall et al. 1985, Frissell et al. 1986, Resh et al. 1988, Naiman et al. 1992). As a consequence, descriptions of streams in the context of their watersheds have emphasized spatial determinism (which include classification systems of channel morphology and stream biota) (Vannote et al. 1980, Frissell et al. 1986, Rosgen 1995, Montgomery and Buffington 1997, Chapters 2 and 5). Given the importance of disturbance in aquatic systems, why has disturbance been difficult to define?

Most quantitative theories of landscape processes, and their derivative predictive models, address the behavior of a single landscape process (such as fire, flooding, sediment transport, and slope stability), or a single landscape element (such as an individual forest stand, hillslope, or stream reach), over short time scales; for example, responses to a single fire, storm, or flood. Disturbance regimes (and cumulative effects which can be viewed as an alteration of a regime) in aquatic systems remain unquantified largely because theories and models designed to predict numerical solutions about exact future states of single processes at small scales (e.g., a few years) are inappropriate for understanding behavior of populations of processes occurring at larger scales (e.g., decades to centuries). Limitations in data and computing power, and the unpredictability of the weather, further confound applications of data-intensive, small-scale theories and models to the problem of predicting long-term ecosystem behavior.

Understanding the consequences of disturbance (or cumulative effects) in aquatic systems requires a fundamental shift in focus from individuals to populations (of landscape elements) and from short- to long-time scales. For example, the behavior of a population of landscape elements (such as all point sources of sediment and wood in a watershed), and the interaction of that population with other populations (such as a set of linked stream reaches comprising a whole network) involves routing materials over time between highly variable hillslope sources and stream reaches. The outcome of the collective behavior of such populations, represented, for example, in the characteristic frequencies and magnitudes of sediment transport and storage in a channel network, reflect a system property of a landscape. The term *system*, in this context, refers to the interacting group of landscape elements (i.e., topography, vegetation, soils, fires, rainstorms, channel geometry, and so on) that give rise to such long-term patterns of behavior. Hence, the study of aquatic disturbance (or cumulative effects) lies within the domain of the study of landscapes as systems

The study of landscapes as systems is different than the study of single landscape elements over short time scales. Viewing the behavior of a forest, a hillslope, or a stream channel over decades to centuries requires replacing predictions about exact future states with more general predictions of long-term patterns of behavior. This demands a degree of simplification in scientific analysis and description, referred to as *coarse graining* (Gell-Mann 1996), and the use of estimated probability distributions to overcome lack of scientific understanding and data, computing limitations, and uncertainty about future climate. Such an approach can be used to parlay empirical knowledge and theory available at smaller spatial and temporal scales to produce new understanding of landscape behavior (theories, models, and hypotheses) at larger scales.

Long-term patterns of landscape-behavior, including disturbance regimes, are best described in terms of frequency distributions from which estimates of probability of occurrence can be made. Likewise, describing the environmental condition of a population of similar landscape elements in any year (governed by climate history and land use) requires proportioning characteristics among the range of all possible environmental conditions. This also is best described by frequency distributions, and in this chapter aspects of long-term patterns of landscape behavior, or natural disturbance are described in terms of those statistical measures. A new system-scale framework is described using field data and simulation models to describe aspects of long-term behavior or natural disturbance in the Oregon Coast Range and in southwestern Washington.

Components of Dynamic Landscape Systems

The study of landscapes as systems (in terms of populations of upland or riparian forests, hillsides, and stream channels that vary naturally over time) focuses on four basic components: (1) climate, which drives environmental variability and emphasizes the importance of time in a landscape systems perspective; (2) topography, which represents a population of diverse hillslopes responsible for the spatial variability of sediment and wood sources; (3) channel networks, which govern how sediment and wood delivered from interactions between climate and topography are transported downstream through a population of linked stream reaches; and (4) basin history, which governs the volume of sediment and wood stored on hillslopes and in stream channels in any year, and thereby influences how sediment and woody debris are redistributed during future storms, fires, and floods.

Climate

In Washington, Oregon, and northern California the contemporary climate has been in place for the past several thousand years resulting in relatively stable vegetative communities (Heusser 1977, Leopold et al. 1982, Brubaker 1991). Nevertheless, smaller-scale variations in climate (decades to centuries), such as the neoglaciation of the seventeenth and eighteenth centuries, have influenced erosion and channel morphology in mountain areas (Church 1983).

The following discussion of climate concentrates on the effects of precipitation, flooding, and fire. Although not discussed here, windstorms are also important controls on the age distribution of forests along coastal areas and in northern parts of the region (southeast Alaska), and windthrow may be an important modifier of soil chemistry and vegetation productivity (Borman et al. 1995).

Precipitation

Precipitation (rain and snow), as the source of groundwater and stream flow, is the primary natural driver of change in Pacific Northwest forest and stream environments. Long-lasting, intense rainstorms saturate soils and trigger shallow landslides and debris flows, even under forest canopies (Figure 11.1) (Pierson 1977, Dietrich and Dunne 1978, Hogan et al. 1995). High seasonal rainfall accelerates movement of deep-seated landslides and earth flows. When it is not raining, forests become dry and the potential for wildfire increases (Agee 1993). Temporal variation in precipitation creates seasonal

FIGURE 11.1. Aerial photograph taken in 1939 of a 4th-order basin in the western Olympic Mountains, Washington. The storm of record (1934) triggered numerous debris flows (indicated by arrows) that deposited into the main channel. Orme (1990) and Hogan et al. (1995) estimated the frequency of such concentrated landsliding based on precipitation alone to be between 40 and 70 years in the northwestern part of the region.

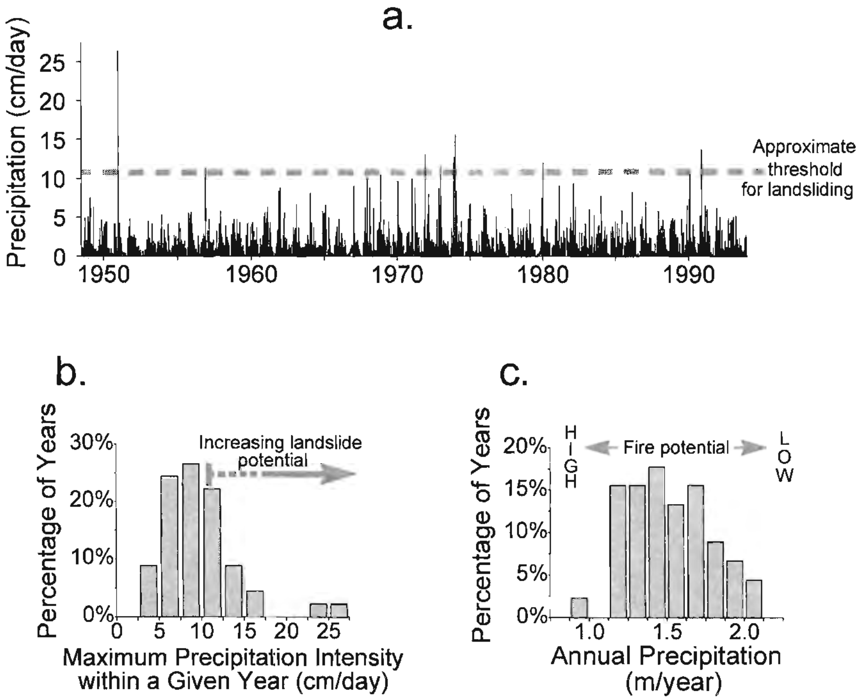

FIGURE 11.2. (a) A time series records the sequence of rain (and snow) storms over 47 years at the Randle Ranger Station in southwestern Washington. The sequence of rainstorms initiates temporal variability in the landscape by triggering landslides, generating floods, and creating drought conditions conducive to wildfire. The rainfall threshold for triggering landslides is estimated from an empirical relationship among rainfall intensity, duration, and landslide occurrence (Caine 1980). (b) A frequency distribution of daily maximum precipitation indicates the proportion of time that landslides can be generated (approximately 33% of the time or once every three years). (c) The frequency distribution of annual total rainfall indicates the amount of time that wildfires may be triggered due to moisture deficits (<1.0 m/yr occurs less than 3% of the time).

changes in stream flows and annual fluctuations in flood peaks, in sediment delivery to stream channels, and in fire potential.

A sequence of daily precipitation measured over 47 years for a site in southwestern Washington (Figure 11.2a) indicates that rainfall varies widely (0 to 25 cm in one day). Despite this variability, these data are useful for evaluating the influence of local climate on channel and floodplain morphologies. The frequency of storms that trigger landslides, for example, is indicated by a threshold estimated from an empirical relationship among rainfall intensity and duration, and landslide occurrence (Caine 1980). Sometimes several landslide-triggering storms occur in one year or in consecutive years; and sometimes nearly a decade passes with no large storms at all.

The role of precipitation in landslide or fire generation is best viewed through a frequency distribution. By condensing data in the time series of precipitation (Figure 11.2a) to a distribution of values, information on the temporal sequence of events is lost but insight as to how often an event of a given magnitude occurs is gained (Figures 11.2b and 11.2c). For example, the frequency of storms that trigger landslides is about once every three years (e.g., approximately 33% probability in any year, Figure 11.2b) and provides information on how often landslide debris might be expected to enter channels in that landscape. Likewise, the potential for large, intense fires increases dramatically when the annual precipitation total is less than 1.0m, but such low values of annual precipitation occur only about 3% of the time (Figure 11.2c). Hence, fire-producing droughts are much rarer than landslide-triggering storms.

Floods

Ultimately streambeds, banks, and riparian floodplains are shaped by the temporal sequence of flows and sediment loads carried through the channel. Although sediment may arrive directly from adjacent slopes, most material found in the streambed and floodplain has been carried some distance from upstream. The size and frequency of floods determine the capacity of a stream to move sediment into or out of a channel and to overflow its banks. Thus, the relationship between floods (potential sediment transport capacity) and sediment supply (the history of erosion) ultimately controls the ability of floods to modify channels and floodplains, and to create channel refuge habitats, such as wood jams and side channels (Chapter 2).

The temporal variation of flows typical of Pacific coastal streams is illustrated by the time series in Figure 11.3a and the associated frequency distribution of discharge measured at a gaging station in southwestern Washington (discharge varies from 2 to 200m^3/s) (Figure 11.3b). Approximate thresholds for bed mobilization (i.e., bedload sediment transport) and overbank flows are determined from substrate size, channel width, and bank height for the gauged channel with a drainage area of 200km^2 (Figure 11.3a). Frequency of channel-forming events can be defined by representing the time

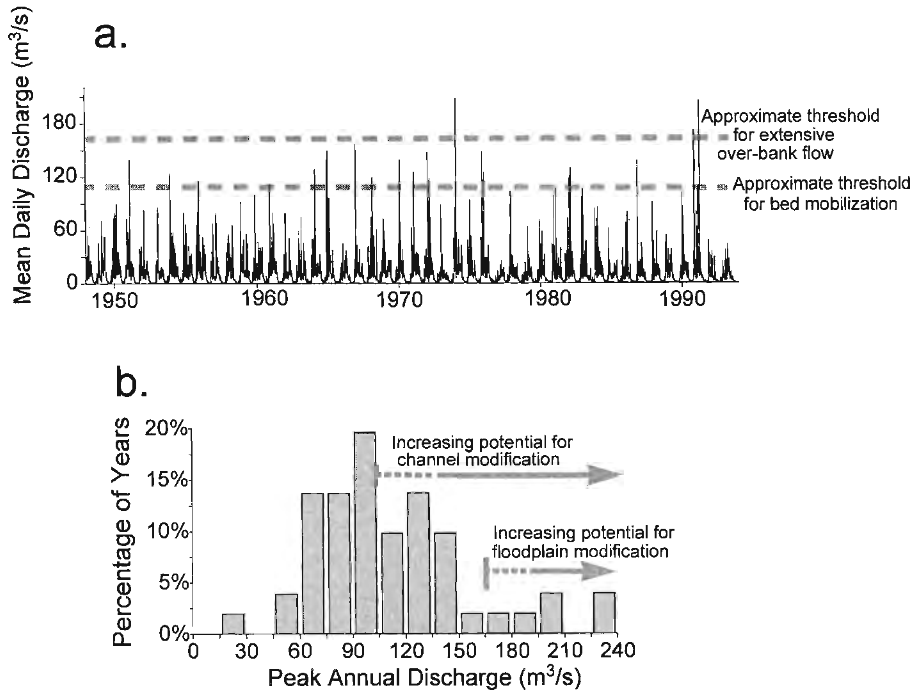

FIGURE 11.3. (a) A time series of channel discharge dictated by the sequence of rainfall (and snowfall) over previous days or weeks. In this case, the extent of channel and floodplain modification varies greatly from year to year because only large flows (>100m^3/sec) are capable of moving sediment from or onto the channel bed, eroding banks, and inundating floodplains. (b) Frequency distribution of floods derived from time series of stream discharge in Figure 11.3a. Frequency of bedload transport is about 30% while overbank flows occur 10–15% of the time.

series of flows as a frequency distribution. For example, floods transport bedload approximately once every three years (e.g., 33% of winter floods) (Figure 11.3b). The opportunity for floodplain modification is much less, only about 7% (once about every 14 yrs). This indicates that the frequency of floods is sufficient to redistribute the sediment that originates from frequent landslides.

Floods are also important for transporting and redistributing wood as well as creating log jams. Floods large enough to transport wood may occur frequently, but transport of wood depends on the wood supply as well as piece length and slope (Nakamura and Swanson 1993). Therefore, the transport of woody debris by stream flow (and the development of debris jams) strongly depends on the temporal sequence of flooding magnitude and wood supply, the same way sediment transport depends on the temporal sequence of flood magnitude and erosion.

Fire

Periodic droughts, strong east winds, and the massive buildup of woody fuels create conditions favorable for fire, particularly in the southern and middle Pacific coastal ecoregion (Agee 1993). The frequency and magnitude (intensity and size) of fires strongly influence the distribution of forest ages, the recruitment of wood to streams, and the frequency and magnitude of erosion.

Fire influences erosion by destroying vegetation and by sharply decreasing the rate at which water infiltrates into soil. Roots of trees and shrubs reinforce soils laterally and bind thin soil to partially fractured bedrock. As a consequence, landslides and debris flows are more likely to occur after fires destroy vegetation and when root strength is lowest (O'Loughlin 1972). Thus, forest mortality by fire increases the potential for landslides and debris flows (Figure 11.4) (Swanson 1981, Benda and Dunne 1997). Fires in drier areas with hydrophobic soils can lead to widespread surface erosion, gullying, and the release of large quantities of sediment to the valley floor (Klock and Helvey 1976).

Variation in the frequency of fires across the Pacific coastal ecoregion is controlled by the frequency of ignitions (i.e., by lightning), the frequency and severity of droughts, the availability of combustible organic material, and topography. In addition, ignitions by Native Americans may have been an important factor in certain parts of the region (Schoonmaker et al. 1995). Low-frequency, high-intensity fires associated with high tree mortality are referred to as stand-replacing fires (Agee 1993). The average time interval between stand-replacing fires (the mean fire recurrence interval or fire cycle) at a specific location in a landscape has been estimated in various parts of the Pacific coastal ecoregion and is about 400 years for cedar (*Thuja plicata*)/spruce (*Picea sitchensis*)/hemlock (*Tsuga heterophylla*) forests of the Olympic Peninsula, Washington (Agee 1993); 200 to 300 years for the Douglas-fir (*Psuedotsuga mensiezii*)/western hemlock (*Tsuga heterophylla*) forests of the central Oregon Coast Range (Teensma et al. 1991, Long 1995); 150 to 200 years for Douglas-fir/western hemlock forests in the western Cascade Mountains of Washington and Oregon (Teensma 1987, Morrison and Swanson 1990), and 80 to 100 years for lodgepole pine (*Pinus contorta*) forests in southwestern Oregon (Gara et al. 1985).

Variation in fire frequency affects the frequency and location of erosion and wood input to streams (i.e., by determining rates of mortality and stand age) and therefore the disturbance regime of the channel. Different parts of the landscape burn at different frequencies, depending on the topography. North-facing slopes are typically moister and cooler than south-facing slopes and are therefore less susceptible to stand-replacing fires, particularly in the wetter areas of the ecoregion. Ridges and low-order valleys (e.g., 1st- and 2nd-order) are more susceptible to fire than nearby larger valley floors because fires tend to burn upslope. A fire simulation model, using fire probabilities obtained from field data in a 500 km^2 area in southwest Washington, illustrates how different topographic positions result in different fire regimes (Figure 11.5). Although fire recurrence intervals in the landscape of southwestern

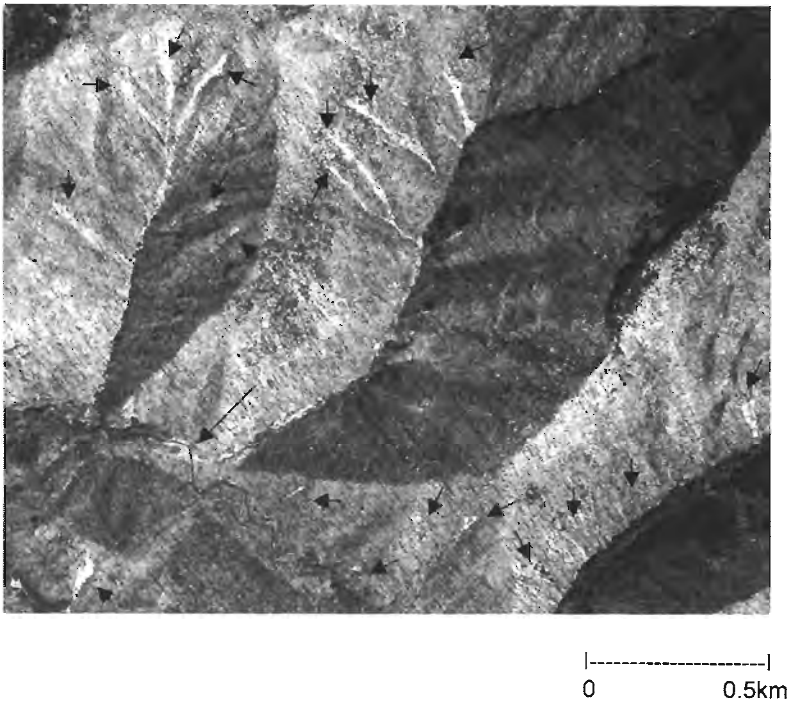

FIGURE 11.4. Several large and intense fires between 1933 and 1939 in the north-central Oregon Coast Range (the Tillamook fires) caused widespread forest death and created a forest of standing, dead trees in a portion of the Kilchus River basin. Aerial photographs (1954, 1:12,000-scale) reveal a concentration of shallow landslides (small arrows) in the burned area. Some of the failures triggered debris flows in 1st- and 2nd-order channels (large arrow) and deposited sediment directly into a 4th-order channel (Benda and Dunne 1997a).

Washington averages 300 years, fire intervals of 150 years occur on ridges and in low-order stream valleys (e.g., 1st- and 2nd-order), and fire intervals can exceed 500 years for wide and low-gradient valley floors.

Topography

The second component in the study of landscapes as dynamic systems is the diverse population of topographic patterns in a watershed which creates a discontinuous and spatially variable supply of sediment and wood to channel networks. Interactions between climate and topography are fundamental components shaping landscapes. In the Pacific coastal ecoregion intense rain and wind result in erosion and flooding that form stream and valley floor morphologies, especially after widespread fire. Heterogeneous topography coupled with a dynamic climate results in a supply of sediment and wood to streams that varies temporally as well as spatially. Although this chapter focuses on contemporary climate, it also recognizes that present erosion rates are influenced by past climate processes.

Sediment Supply

In terms of a landscape system, topography is represented as a population of diverse hillslopes and hence a population of diverse erosion sources. Two areas (the Oregon Coast Range and southern Cascade Mountains of Washington) illustrate how diverse topography leads to spatially variable sediment supply (Figure 11.6a and 11.6b). Two types of mass movement occur in the highly dissected, low-relief topography of the Oregon Coast Range: one is shallow landslides from steep, unchanneled swales (referred to as bedrock hollows) and the other is debris flows from 1st- and 2nd-order channels spaced along both sides of the main river at irregular intervals (Figure 11.6a). Landslides or debris flows emanating from any one site are rare, but mass wasting at the watershed scale (containing thousands of landslide sites) is a common occurrence (illustrated later in this chapter).

A population of landslides and debris flows over the entire channel system has a large and persistent influence on the valley floor environment. The immediate short-term effects of mass wasting are readily apparent as the large influx of sediment and wood overwhelms the capacity of the Oregon Coast Range stream to transport material downstream (deposited sediment buries the channel), the average size of channel substrate decreases, and riparian vegetation is destroyed. Over time the stream gradually removes much of the deposited material, larger particles (boulders) are exposed and new plant communities are established (Chapter 12). Persistent, long-term morphologic effects include creation of log jams, development of terraces, accumulation of boulders, and construction of debris fans that force the channel against the opposite valley wall (Benda 1990). The density and location of these

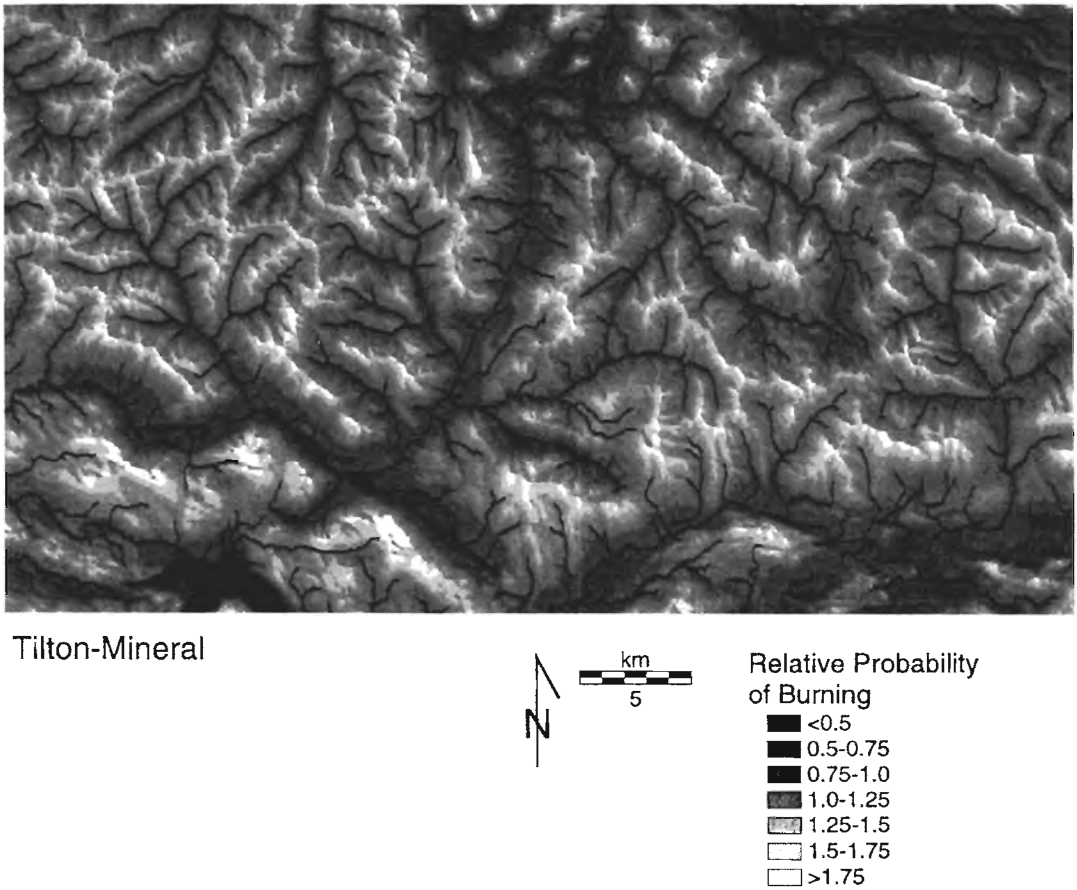

FIGURE 11.5. Topographic controls on fire. Standage maps obtained from 1939 aerial photography over a 1000 km^2 area in southwest Washington indicate correlations between forest age and slope aspect (southwest facing slopes burn most frequently) and local relief (ridge tops burn more frequently than valley floors). These empirical relationships were used to construct this map which shows the relative likelihood of fire over time as a function of topography. Values are normalized so that the average over the entire area equals unity. In this area, fire cycles are predicted to be less than 200 years on ridge tops and greater than 500 years on valley floors, with a mean of 280 years. Channel network is indicated by black lines and ridges and south facing slopes are indicated by lighter shading.

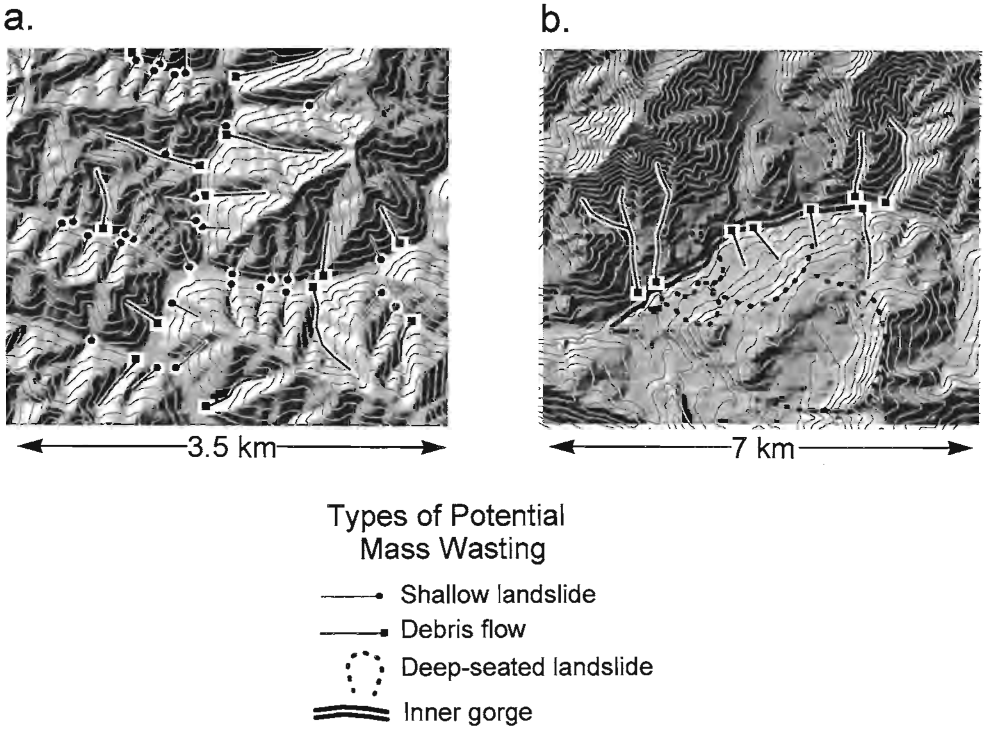

FIGURE 11.6. (a) High density of shallow landslides and debris flows characterizes the highly dissected terrain of the Oregon Coast Range. (b) In contrast, pervasive deep-seated landslides have modified the topography in the southern Cascade Mountains of Washington, resulting in a lower density of debris flows and a higher density of small shallow landslides along inner gorges. Regional variation in the processes and spatial patterns of erosion leads to regional differences in the frequency and magnitude of sediment and wood supply to streams.

deposits throughout the channel system (Figure 11.6a) dictates the type, diversity, and distribution of many of the channel and riparian environments within the watersheds.

The southern Cascade Mountains illustrate a different and more complex topography, one smoothed by extensive deep-seated landslides (Figure 11.6b). Compared to the Oregon Coast Range, a greater diversity of mass wasting processes is active, including deep-seated bedrock landslides at a variety of spatial scales and pervasive shallow landslides in inner gorges. The spatial density of shallow landslides adjacent to streams is greater than in the Oregon Coast Range partly because steep inner gorges have formed at the toes of large deep-seated landslides. In contrast, the spatial density of debris flows is lower, in part, because deep-seated landslides have lowered midslope gradients. Deep-seated landslides likewise have altered channel and valley floor morphology, creating local low-gradient areas upstream of slides and local steepening at the downstream slide edges. Channels are confined within inner gorges where deep-seated landslides have created narrow valley floors.

Together, topography and climate create a pattern of sediment supply to stream channels that is variable in space and time. The status of sediment storage in any particular channel depends on the population of all upstream sediment sources from the numerous hillslopes.

Wood Supply

The supply of woody debris to streams is also influenced by climate and topography. The size of trees that fall into streams depends on tree age which is controlled, in part, by the frequency of fires, windstorms, or erosion. For example, fires generally do not consume entire trees and the majority of dead trees fall within several decades after a fire (Agee 1993) leading to large fluctuations in the size and number of trees recruited to small channels.

Concentrating on fire in this example, the change in in-stream wood volume over time differs for two different fire regimes (Figure 11.7a). Stand-replacing fires every 500 years

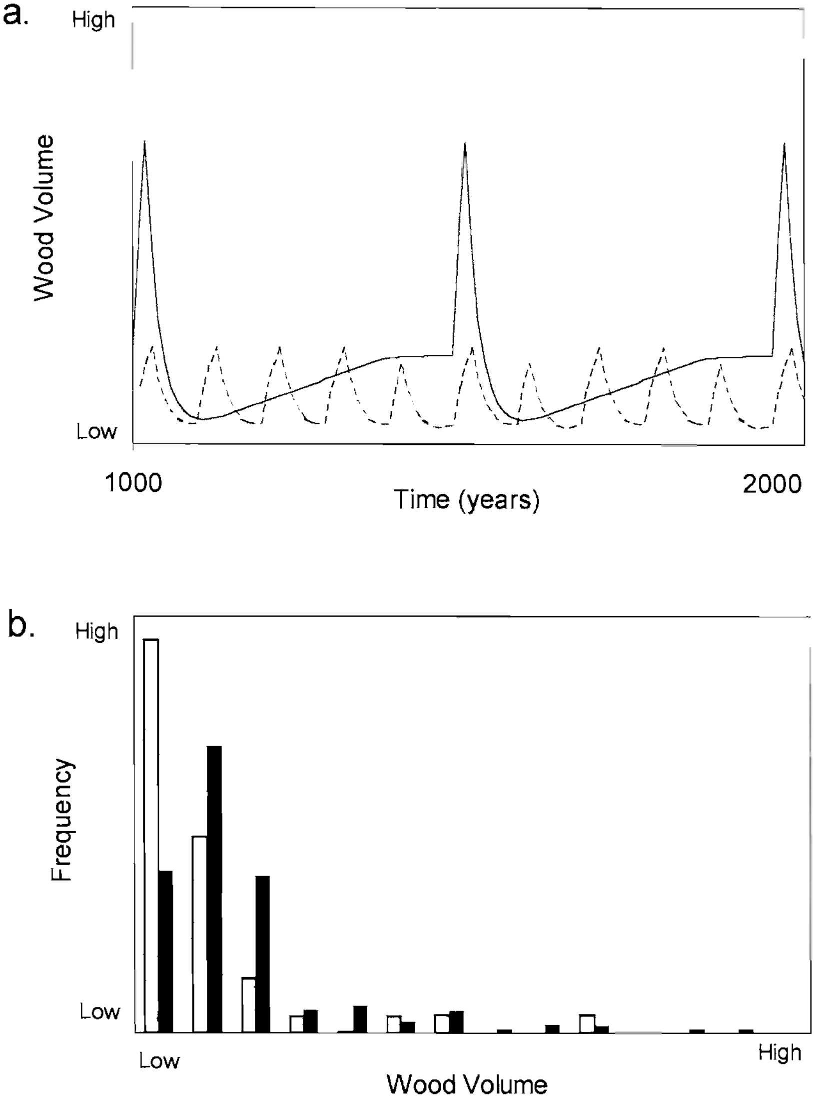

FIGURE 11.7. (a) The changing in-stream volume of wood for two different fire regimes, and (b) their accompanying frequency distributions predicted by a simulation model. The 500-year fire cycle (——; solid shading) yields abrupt and large increases in wood supply after a fire, and almost all of the time large volumes of wood are present in the channel. In contrast, the 100-year fire cycle (-----; no shading) results in lower volumes of wood, and a lower range of variability in wood loading.

(similar to the fire frequency in the coastal rain forest of Washington) leads to abrupt and large increases in wood supply as trees killed by fire fall to the ground less than 50 years later. After this initial large input of wood, wood supply slowly increases from stand mortality as standing biomass increases. In contrast, more frequent fires every 100 years (similar to drier forests of eastern Washington and Oregon) result in a smaller punctuated supply of wood because large amounts of biomass do not accumulate. The difference between the two simulated fire regimes is apparent in the frequency distributions (Figure 11.7b). The distribution of wood volume for the 100-year fire cycle indicates the dominance of low-wood supply conditions. But perhaps more importantly, the figure shows that lower volumes of wood are common. In contrast, the frequency distribution for the 500-year fire cycle shows significantly higher wood volumes for large portions of the time, and very low volumes of wood are rare. The predicted frequency distributions from these two fire regimes allow consideration of how in-stream volumes of wood change as one moves from coastal rain forests to drier interior forests.

The variability in fire frequency for different parts of the Pacific coastal ecoregion also contributes to a spatially variable wood supply at the watershed scale. Different parts of watersheds burn at different frequencies (Figure 11.5), with small, steep valleys having a higher fire frequency compared to wider valley floors.

Other processes influencing input of woody debris to streams include bank erosion, land slides and debris flows. In large streams woody debris is commonly recruited by bank erosion, which can occur every several years (Keller and Swanson 1979). Landslides and debris flows (and snow avalanches), with or without fires, are also important sources of woody debris (Swanson and Lienkaemper 1978, Chapter 13, this volume). In the Queen Charlotte Islands, British Columbia, landslides under forest canopies, with a recurrence interval of approximately 40 years, result in large numbers of debris jams (Hogan et al. 1995). Although landslides and debris flows may only contribute minor volumes of woody debris because of their low frequencies compared to decay rates, during periods of disturbance wood loading by mass wasting may overwhelm all other sources of wood.

The ability of woody debris to affect channel morphology depends on stream size (Bilby and Ward 1989). Even large rivers can be greatly influenced by wood (Sedell and Frogatt 1984, chapters 12 and 13, this volume). Trees falling into a stream reach significantly modify stream morphology in several ways (Chapters 2 and 13). For instance, scouring of the channel bed around the downed trees modifies aquatic habitats as, pools, side channels, and sediment storage areas are formed (Keller and Swanson 1979, Sullivan et al. 1987). In addition, log jams create small terrace-like deposits along valley floors (Kochel et al. 1987) and stabilize portions of floodplains allowing development of mature conifers (Abbe and Montgomery 1996). Woody debris jams temporarily store significant amounts of sediment (Megahan 1982), although eventually, decaying jams release stored sediment. High sediment supply in concert with debris jams can lead to channel avulsions and the isolation of jams from active channels.

Hierarchical Patterns of Channel Networks

The third component of landscapes viewed as systems is the population of linked stream reaches arrayed in a hierarchical channel network. Two aspects of hierarchical channel networks are considered: how fluctuations in sediment supply (and transport) are mixed and modulated downstream through the network and how different sediment transport regimes are abruptly joined at tributary confluences.

Fluctuations in Sediment Supply and Channel Morphology

Recall that the first two components of a dynamic landscape, climate and diverse topography (viewed as a population of erosion and wood sources), result in a punctuated supply of sediment and wood to channels. The sudden deposition of sediment into a channel previously carrying little sediment may create temporary zones with greater sediment volume and higher sediment transport rates that can either remain stationary (such as point bars) or migrate downstream in the form of a sediment wave (Beschta 1978, Church 1983, Benda and Dunne 1997). Dimensions of recognizable sediment waves range between several hundred to several thousand meters in length and from one half to four meters in height (Church 1983, Pickup et al. 1983, Madej and Ozaki 1996). Sediment waves also may disperse rapidly in steeper, confined channels, such as in canyons. Channel beds that do not undergo major fluctuations in sediment supply may exhibit relative stability (i.e., no sediment waves and little scour and fill).

Within the channel networks sediment waves (or an accumulation of sediment) may merge downstream because the velocity of bedload particles (annual transport distance) generally decreases downstream. Accumulations of sediment or large sediment waves have formed in mainstem channels from erosion in numerous tributary subbasins (Jacobson 1995, Madej and Ozaki 1996). In addition, sediment waves may merge and travel serially downstream when a climatic disturbance (e.g., storm or fire) occurs over a large area of a watershed and releases sediment in numerous adjacent tributaries that all join to become a single larger channel (Benda 1994).

If fluctuations in sediment supply are of sufficient magnitude, a cycle of scour and fill creates floodplains and terraces (Gilbert 1917, Hack and Goodlett 1960, Griffiths 1979, Pickup et al. 1983). This cycle, thus, can lead to formation of new riparian areas and may reset the age of riparian vegetation. Fluctuations in sediment supply, in conjunction with floods, also creates side channels on newly formed terraces and slough channels in low-gradient floodplains, that provide critical refuge habitats.

Fluctuations in sediment supply also lead to changes in channel morphology. Transient increases in sediment supply in the form of waves lead to temporary increases in the widths of channels and floodplains (Beschta 1984, James 1991), fining of the substrate (Coates and Collins 1984, Roberts and Church 1986), braided channels (Roberts and Church 1986), decreasing pools in conjunction with increasing riffles (Madej and Ozaki 1996), and death of riparian forests (Janda et al. 1975). Passage of sediment waves on a variety of scales leads to frequent bed filling and scouring which creates a channel environment unfavorable for fish spawning (Nawa et al. 1989). However, sediment waves also cause bank erosion and tree fall which forms pools and creates sediment storage areas, including spawnable riffles.

Tributary Confluences and Discontinuities in Transport Regimes

Different sediment transport regimes (i.e., process, frequency, magnitude, and particle sizes) are abruptly joined at tributary confluences. For example, a discontinuity in transport process often occurs where 1st- and 2nd-order channels, that are prone to debris flows, join higher-order channels. Debris flows transport large volumes and sizes of sediment and wood into lower-gradient channels. As a consequence, such confluences may be characterized by boulder deposits, fans, terraces and debris jams (Benda 1990, Grant and Swanson 1995, Hogan et al. 1995). Discontinuities in transport regimes also occur at confluences of large streams. An increase in the probability of sedimentation at, and immediately downstream of, confluences results from a higher proportion of bedload compared to the main river (Benda 1994).

Basin History

Basin history is the fourth component influencing landscape characteristics. The temporal sequence of past climatic and erosional events (that has either supplied or removed sediment and wood from hillsides or channels) influences how sediment and wood are redistributed during future storms, fires, and floods.

The history of soil moisture over a winter period (i.e., numerous storms) affects the rate of stream flow and soil stability (Pierson 1977) which affects stream power and the rate of sediment transport and the volume of sediment supply (through bank erosion and landslides) during any individual storm. Each storm alters the distribution of sediment, so that the volume and location of sediment stored in a channel reflects the sequence of storms over several decades to a century. Hence, the temporal ordering of storms and associated erosion in a basin greatly influences channel response and controls cycles of sedimentation and erosion of valley floors and channels (Beven 1981).

The amount of sediment stored on hillslopes that may ultimately become incorporated into landslides and debris flows also is affected by basin history. The timing of a landslide or debris flow is influenced by the rate of sediment accumulation since the time the site last failed (Sidle 1987, Dunne 1991). Hence, longer periods between landslide-triggering events at the watershed scale (e.g., involving a population of landslide sites) will likely result in a greater volume of sediment and wood released to a channel network.

Glaciation strongly influences both local and landscape-scale geomorphic processes. Late Pleistocene glaciation (e.g., 12,000–15,000 yrs ago) created large valley floor reservoirs of outwash sand and gravel, and lacustrine deposits of silt and clay in some of the northern areas of the Pacific coastal ecoregion. These glacial deposits initiated new mechanisms of erosion (i.e., deep-seated landslides in glacial sediments) and increased erosion rates for thousands of years after the glacier retreated (Church and Ryder 1972, Benda et al. 1992). In the 17th and 18th centuries smaller alpine glacial events in some areas, such as British Columbia, caused shorter-term changes in sediment supply and sediment transport (Church 1983).

Dynamic Landscape Systems: Populations of Elements and Time

Studying the system properties of landscapes focuses on relationships among the major attributes of climate, topography, networks, and basin history and, hence, the space-time structure of material fluxes and aquatic morphologies. The remaining portion of this chapter describes some of these relationships, including how effects of scale and channel networks cause shapes of frequency distributions to evolve downstream. Biological aspects of landscape systems and general applications to land use are also presented.

Observed records (e.g., rainfall in Figure 11.2a) are typically too short to fully characterize relatively rare events such as fires, storms, and landslides. Empirical distributions can be combined with numerical models designed to simplify certain small-scale hillslope and channel processes to characterize behavior over longer time periods. Use of such coarse-grained models allows problems of increasing complexity to be addressed, leading to testable predictions (hypotheses) on landscape-scale patterns of behavior (Benda and Dunne 1997).

Temporal Sequencing of Storms, Fires, and Floods, and Dynamic Channel Behavior

A large flood may not cause major channel changes in the absence of sediment to transport. However, in the presence of large quantities of sediment originating from recent erosion, the same flood may cause large modifications to channels and floodplains. The key to understanding the dynamic behavior of channels is the short-term (years to decades) synchronicity of climatic events that produce erosion and flooding. For example, a sequence of stand-replacing fires followed within a decade or two by large storms may lead to concentrated landslides because this is the period of low root strength prior to revegetation (Figure 11.4). In drier areas, where fires create soils prone to surface erosion, a fire-storm sequence may result in massive influx of sediment to channels and valley floors.

Using an example from a computer simulation of the steep, highly dissected central Oregon Coast Range where shallow landslides and debris flows are dominant erosion processes, the sequence of rainstorms (Figure 11.8a) and fires (Figure 11.8b) governs the

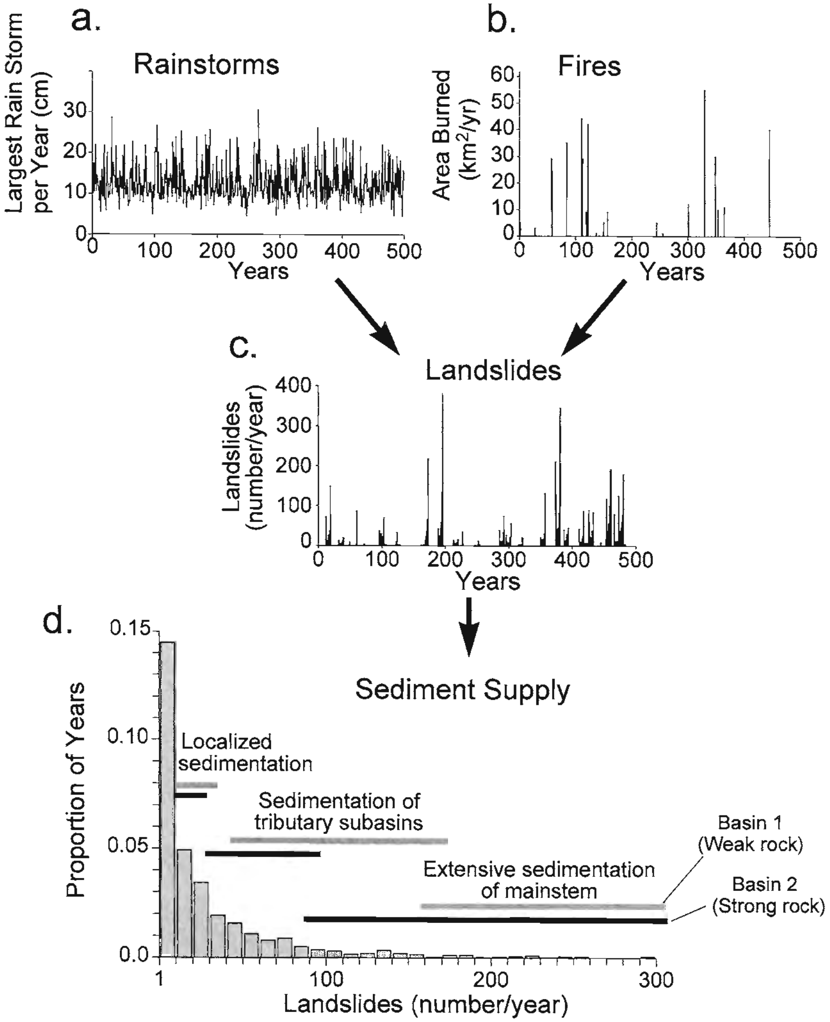

FIGURE 11.8. A sequence of rainstorms (a) and fires (b) generates a sequence of landslides within a basin (c) which results in an intermittent sequence of sediment delivery to the channel system. The time sequence of sediment supply is represented as a distribution (d) indicating how likely various magnitudes of sedimentation occur. Channel response depends on the size distribution and durability of the sediment delivered.

sequence of erosional events (Figure 11.8c). The time series of sediment supply is represented as a frequency distribution (Figure 11.8d) to predict the long-term pattern of sediment input to a channel network.

Considering the timing of sediment supply to a network (Figure 11.8c) in the context of the timing of large floods is necessary to anticipate the ability of erosion or floods to modify channels and floodplains, and ultimately aquatic habitats. By considering the frequency distribution of sediment supply (Figure 11.9a) in concert with the frequency distribution of floods (Figure 11.9b), the frequency distribution of channel and floodplain changes can be conceptually portrayed (Figure 11.9c). This distribution illustrates how often certain channel and floodplain changes are likely to occur and therefore provides insight on how the channel and floodplain will evolve over time and space.

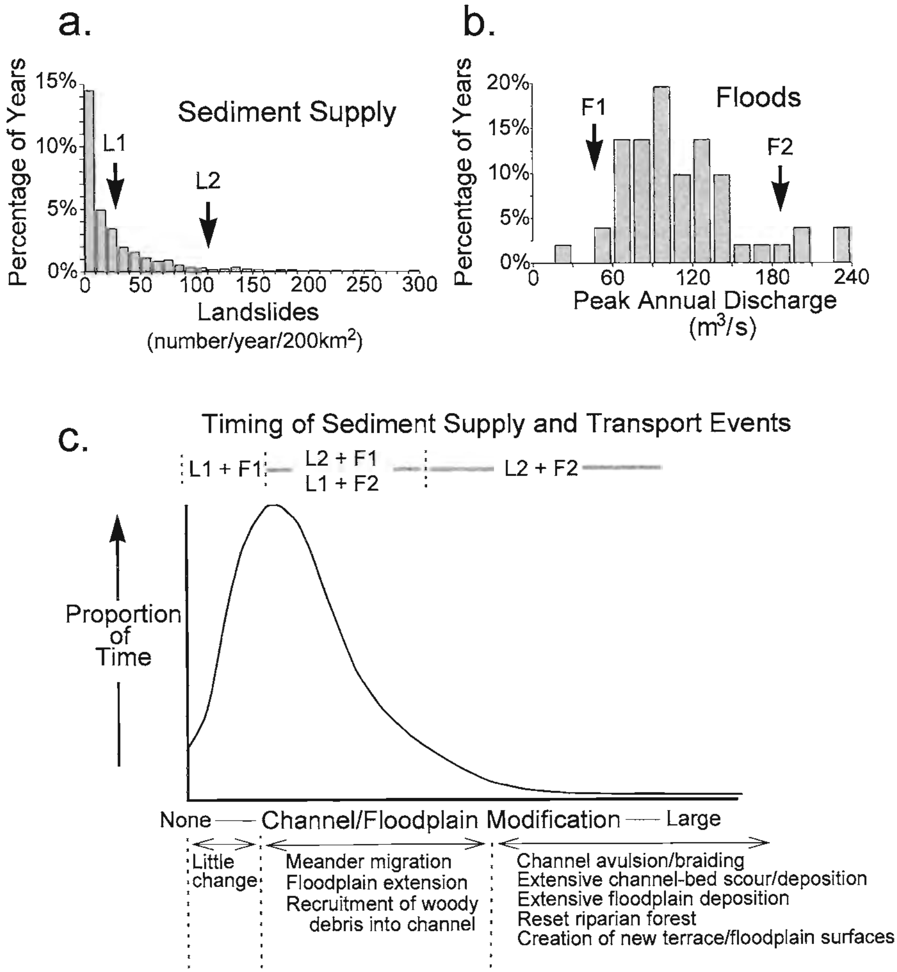

FIGURE 11.9. The extent to which floods affect channel and floodplain characteristics depends on the volume of sediment and the size of the flood (i.e., temporal sequencing). Hence, the frequency with which impacts of a given magnitude occur depends on the frequency distribution of sediment input to the channel system (a), the frequency distribution of flood flows (b), the persistence of sediment in the channel, and (c) the relative timing between these events. Relative timing between flooding (F) and sediment supply from landslides (L) is indicated by L1 + F1 and so on.

An example from Idaho illustrates this concept. In the summer of 1995, a stand-replacing fire with an estimated recurrence interval of approximately 150 years was followed very shortly thereafter by an extreme rainstorm triggering widespread surface erosion and gullying, accompanied by floods and fluvial mobilization of sediment in channels. The result was widespread sedimentation throughout an entire network of channels, which caused channel avulsions and braiding, floodplain deposition, and the creation of new terrace and floodplain surfaces (Figure 11.10). In the frequency distribution of channel changes (Figure 11.9c). this type of event would be located in the right tail indicating how often new terraces. floodplains, and channels (e.g., aquatic and riparian habitats) are formed along the valley floor. In the absence of the fire, a flood of similar magnitude likely would be located in the left hand tail of the distribution in Figure 11.9c. resulting in only minor changes to channels and floodplains. The influence of sediment supply on the geomorphic impacts of floods also has been documented in British Columbia (Church 1983), northern California (Madej and Ozaki 1996), and New Zealand (Beschta 1984).

Effect of Hierarchical Networks and Spatial Scale on System Properties

Viewing topography as a population of hillslopes and sediment sources means that the number of sediment sources and the number of linked stream reaches increases with the spatial scale of the basin and with distance downstream. In addition, frequency of climatic perturbations, such as fires and storms, also increases as basin area increases. As a consequence, the system properties of landscapes, as represented in frequency distributions of environmental conditions, evolves with scale and distance downstream through a network.

Topography as a Population of Hillslope Sediment Sources

The effects of increasing basin area on the dynamic behavior of channels can be illustrated with a simulation model. The model is applied to a 6th-order 200 km^2 basin in the Oregon Coast Range where erosion is dominated by debris flows (e.g., Figure 11.6a) following fires and storms (Benda and Dunne 1997). Episodes of concentrated landslides occur within burned areas during rainstorms for a decade or so after a stand-replacing fire, with fewer landslides at other times and places. The frequency of concentrated landslides predicted within a 3 km^2 3rd-order basin is about once every 200 years with 2 to 13 landslides per fire episode (approximately the 20 yr period following a fire with reduced rooting strength) (Figure 11.11a). As the basin area increases to 25 km^2, the frequency of landslides increases to once every 50 to 100 years with 5 to 165 landslides per fire or storm episode (Figure 11.11b). Finally, at a basin area of 200 km^2, landslides are relatively common with about 10 landslides occurring every few years (Figure 11.11c). Figure 11.11a–c show that the likelihood of landslides increases with basin size because a larger drainage area encompasses a greater number of potential landslide sites and the potential for a greater number of fires and storms. Thus, the frequency and magnitude of sediment supply to channels increases downstream in a channel

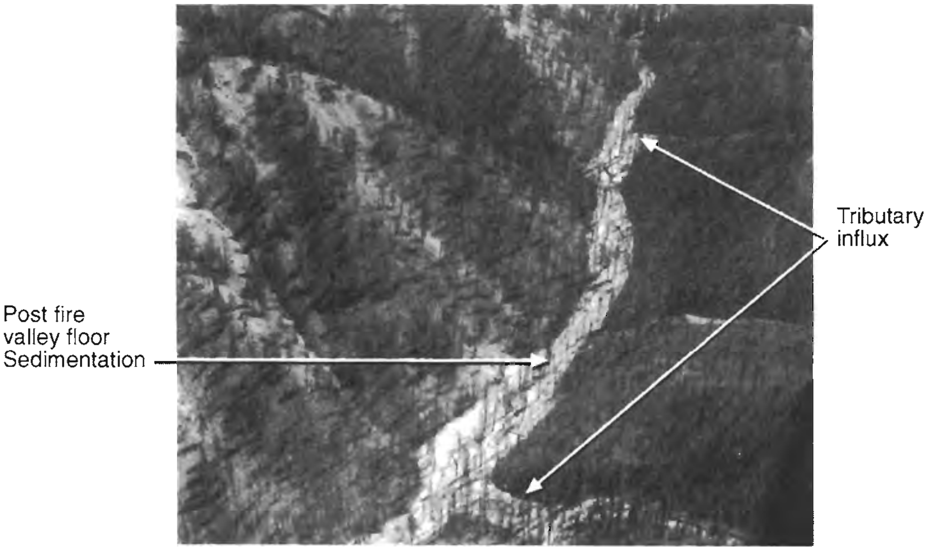

FIGURE 11.10. Gully erosion after a fire caused channel and valley floor sedimentation in a basin in Idaho. Such events correspond to the right hand tail in the distribution shown in Fig. 11.9c.

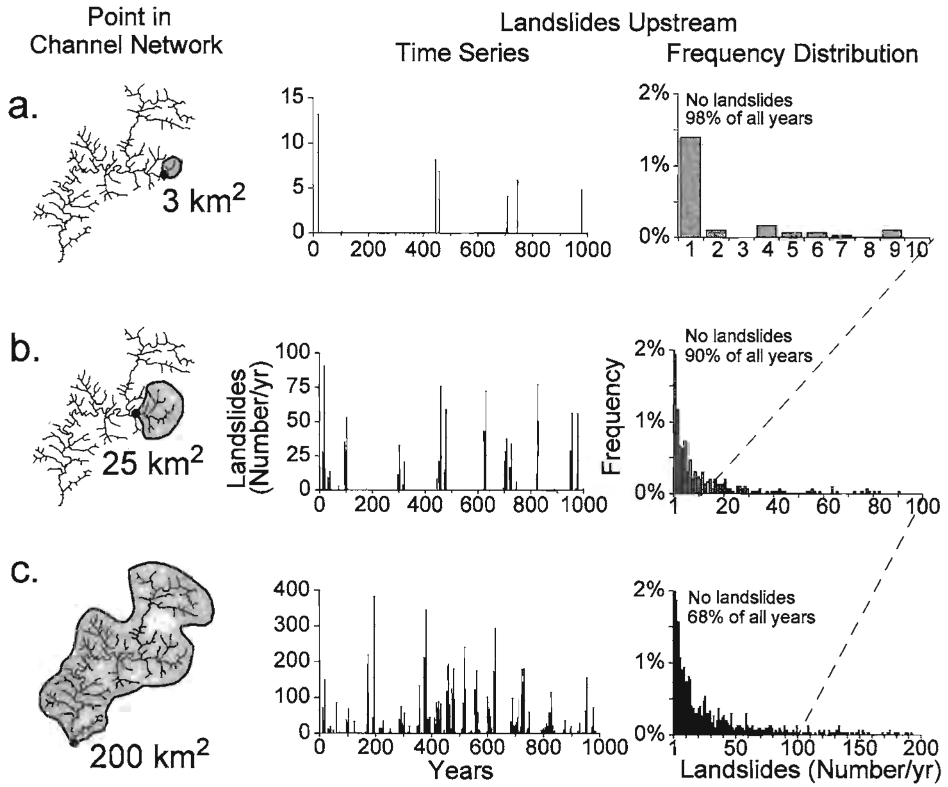

FIGURE 11.11. A 1000-year simulation of landslides in a 200-km^2 basin in the Oregon Coast Range indicates that the likelihood of landslides and associated sediment and wood delivery to the channel system increases with increasing basin area. (a) A 3-km^2 headwater basin experiences infrequent landslides. (b) A 25-km^2 tributary subbasin contains a greater total number of potential landslide sites and is more likely to include a fire: hence, landslides occur more frequently and in greater numbers within this larger area. (c) Numerous subbasins and a vary large number of potential landslide sites are contained within the entire 200-km^2 basin. Landslides occur somewhere within the basin a third of all years. On rare occasions, when large fires are followed by intense storms, well over 100 landslides can occur within the basin in a single year.

network, and has important consequences for the dynamic behavior of sediment transport, channel sediment storage, and channel morphology.

Channel Networks as a Population of Linked Stream Reaches

The simulation model also can be used to illustrate how variations in the supply of sediment from landslides and debris flows over long time periods (Figure 11.11a–c) interact with a converging hierarchical channel network (Benda and Dunn 1997). Again, the model is applied to a 200 km^2 basin in the Oregon Coast Range.

The model predicts an inherent imbalance between sediment supply and transport in 3rd-order channels resulting in centuries of sediment poor conditions interrupted by decades of sediment rich conditions after fires and major storms (Figure 11.12a). In the Oregon Coast Range, sediment poor conditions are characterized by bedrock channels with accumulations of boulders next to debris flow fans and bedrock outcrops. Woody debris, in single pieces and jams, creates local areas of sediment storage. Sediment rich conditions, in contrast, are characterized by gravel and cobble bed channels with buried boulders; some wood may be buried under gravel. The frequency in fluctuations in channel-stored sediment increases with basin area and corresponding stream size (Figure 11.12a–c) because of an increasing number of landslide and debris flow source areas and increasing probability of fires (i.e., fire occurrence increases with basin area). However, the magnitude of sediment supply fluctuations (i.e., represented as sediment depth in Figure 11.12a–c) decreases downstream in the Oregon Coast Range because of mechanical breakdown of weak sandstone bedload and widening channels.

The many small channels in the branching, hierarchical network (represented as 3 km^2 basins in Figure 11.12a) deliver small, disparate

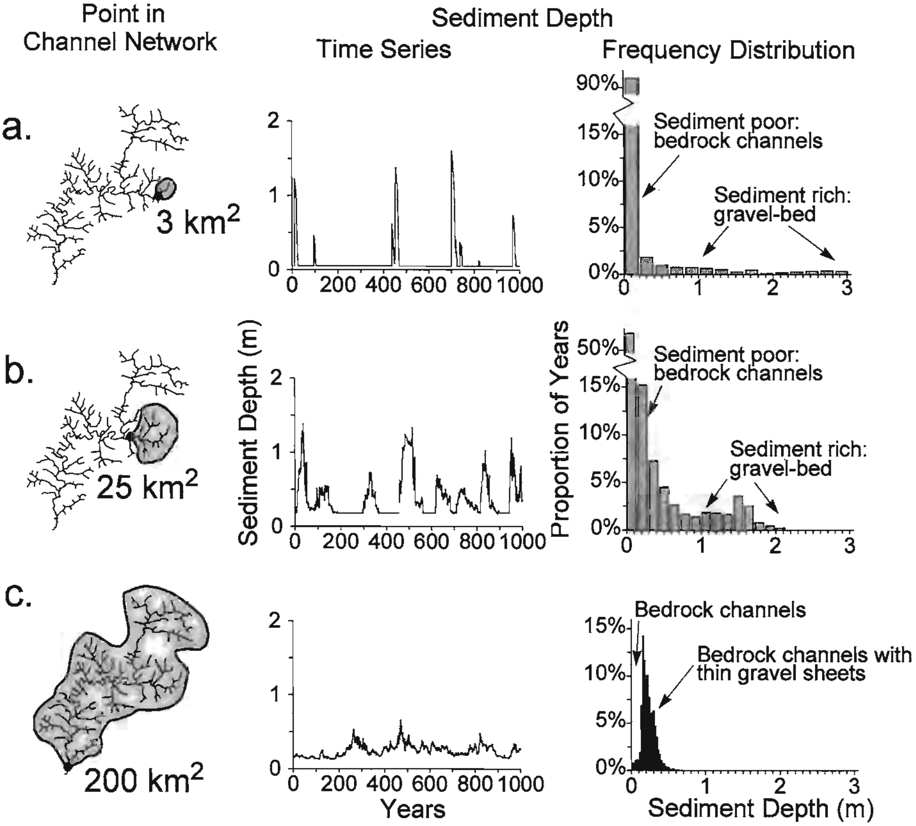

FIGURE 11.12. Sediment depth as a function of time and position in the channel network corresponding to the time series and frequency distributions of landslides shown in Figure 11.11. The volume of sediment found within the channel depends on the number, frequency, and distance to upstream sediment sources. (a) For a small channel draining a 3-km^2 headwater basin, upstream sediment inputs from landslides are infrequent and the channel is generally sediment poor, although periods of deep burial can occur. (b) A larger channel draining 25-km^2 has a greater frequency of upstream sediment inputs so that the channel here contains sediment of appreciable depths (>0.2 m) a larger proportion of the time. Since the channel is larger and sediment must, on average, be carried a longer distance through the channel to this point, sediment depths rarely exceed 1 m. (c) A great number of upstream sediment sources are integrated at the mouth of the 200-km^2 basin, resulting in a relatively constant volume of sediment at this point. In all cases, the time series of sediment depths show fluctuations at several time scales: long-term fluctuations are dictated by the frequency of large fires, shorter term fluctuations are a consequence of annual variability in flood peaks. The depth of sediment in large part determines channel-bed morphology.

sediment pulses to larger channels while decreasing stream power in the main channel promotes accumulation of the pulses (Figure 11.12b). The simulation model predicts that 10 to 30% of bed material is transported in sediment waves (0.5 m thick and sufficient to change channel morphology) depending on stream size, with the greatest proportion carried as waves in the center of the network. In a drainage area of 200 km^2, the sediment supply is relatively continuous and the magnitude of sediment transport variations is diminished, although small, biologically relevant fluctuations in channel-stored sediment continue (Figure 11.12c).

The right-skewed distribution of sediment storage at 3 km^2 indicates that the range of variability is high but that the most probable condition is one of low sediment supply (Figure 11.12a). The shift of the distribution towards the right at 25 km^2 indicates a reduction in the range of variability but an increase in likelihood of sediment in storage as many more hillslope sediment sources are integrated (Figure 11.12b). The more symmetrical distribution at 200 km^2 (Figure 11.12c) indicates that variation in sediment depth is more evenly distributed about the mean, although low sediment storage is the most probable condition because of rapid breakdown of weak sandstone bedload and wide channels. Hence, the branching, hierarchical network results in an evolution of sediment distributions downstream.

Classification of Landscape System Behavior

The system behavior of a landscape, embodied in the form of frequency distributions, can be classified to describe how frequencies and magnitudes in the supply and storage of sediment and woody debris (or the range and magnitude of variability in these materials) vary through a network. Such a dynamic or disturbance-based classification system explicitly links channel behavior to basin climate and to the behavior (in time and space) of the upstream population of sources of sediment and wood.

The model predictions of frequencies and magnitudes of sediment supply for the 200 km^2 basin in the Oregon Coast Range (Figure 11.11a–c) and sediment routing (Figure 11.12a–c) are used to classify the entire 3rd- through 6th-order network (Table 11.1). A similar classification system based on wood loading and routing also could be developed but is not included in this example.

The morphological consequences of the fluctuations in sediment supply (Table 11.1) are controlled partly by certain valley and channel characteristics that vary spatially through the channel network, but that are constant in time.

Table 11.1. Classification of a 200 km^2 channel network in the Oregon Coast Range based on the frequency and depth of sediment deposition causing channel aggradation. The effects of tributary confluences are not included. Low-frequency (fewer than once every two centuries), high-magnitude (thickness greater than 1.0 m) events occur in low-order channels; high-frequency (every five to ten years), low-magnitude (0.3 m) events occur in high-order channels. The central part of the network (drainage areas of 20–50 km^2) has the highest probability of encountering significantly aggraded channels.

		Channel aggradation				
Stream order	Drainage area (km^2)	Frequency	Magnitude Avg/Max (m)	Duration Avg/Max (yrs)	Channel length Avg/Max (km)	Substrate
Low	0.5–1.0	<0.05	0.6/2.5	2/20	0.2/2	Bedrock/boulders
↓	1–10	0.20	0.5/2.5	5/80	0.5/10	Gravel/bedrock
	10–35	0.25	0.5/2.0	5/90	1/12	Gravel/bedrock
	35–70	0.20	0.4/1.5	10/120	1/8	Bedrock/boulders
High	70–200	0.10	0.3/0.5	1/80	0.2/4	Bedrock/boulders

Adapted from Benda and Dunne (1997).

For example, the response of a channel segment to variations in sediment supply depends greatly on channel gradient and confinement. Spatial patterns of channel gradient and confinement have been used to stratify channel networks into broad zones of general channel types (e.g., step-pool channels with steep, bedrock floors covered with boulders or flatter meandering pool-riffle channels) (Rosgen 1995, Montgomery and Buffington 1997, Chapters 2 and 5, this volume). Spatially deterministic classification schemes predict a general morphological state and aid in estimating the sensitivity of channel reaches to change, such as fluctuations in sediment supply. A landscape systems-level classification system estimates the frequency, duration, and magnitude of likely changes. In addition, because the systems-level classification scheme is based on the entire frequency distribution (Figures 11.8 and 11.9), insights into how the formation of floodplains and terraces vary in the network also are gained.

Aquatic Biology at the Landscape Systems Level

Aquatic habitat is often viewed at the habitat unit scale (e.g., individual pools, riffles). Although this is an important scale of observation, understanding landscapes as systems requires that the focus on individual units shift to a focus on the population of units and the behavior of the population over time as dictated by the dynamic interactions of climate, topography, and channel networks. Hence, the contextual focus is on process linkages and time, rather than the state of habitat at any one site in a year.

A landscape systems perspective requires that the focus of climatic and geomorphic processes (such as storms, fires, floods, and landslides) be expanded beyond terms of environmental damage. Poor environmental conditions associated with these events can be short lived. Dynamic landscape processes also leave long-term legacies in the form of habitat development in channels, floodplains, and valley floors. Hence, dynamic processes must be viewed as both an environmental risk but also as a mechanism creating habitat, including refugia. In addition, aquatic organisms living in a dynamic environment have evolved a suite of adaptations for survival (Chapters 9, 10, 12, and 17).

Environmental Risk

Many environmental risks arise naturally from interactions between climate and geomorphology. For example, in the absence of side channels and woody debris jams (which act as habitat refugia), annual winter floods with high velocity flows flush juvenile and adult fish downstream, resulting in high mortality rates. Bedload transport during floods causes bed scour and fill (often linked with fluctuating sediment volume) that excavates or buries redds (areas within stream gravel beds where fish have deposited eggs) (Nawa et al. 1989). In contrast, low flows prevent access to spawning areas decreasing available spawning area for adult anadromous fish as well as increasing temperatures which also may lead to reduced survival (Reiser and Bjornn 1979). Erosion delivers fine sediment that fills inter-gravel spaces and thus reduces oxygen flux, which causes fish eggs to suffocate (Everest et al. 1987). In addition, mass wasting buries instream aquatic habitat (Everest and Meehan 1981).

Habitat Development Including Refugia

Processes creating environmental risks also create reach-scale babitats, including refugia. Wind, bank erosion, landslides, and fire all supply woody debris to the channel, where it accumulates in jams forming areas with low water velocities (including deep pools). These low velocity areas around debris jams provide refuge for adult and juvenile fish during winter floods (Dolloff 1983, Sullivan et al. 1987). In addition, boulders deposited in channels by mass wasting are used by fish as low-velocity refugia (Everest and Meehan 1981).

Large floods, often in conjunction with high sediment supplies and woody debris jams, cause temporary channel braiding which creates side channels (Keller and Swanson 1979), both in mountain valley floors and along lower-gradient floodplains (Church 1983). Debris jams formed during floods also contribute to the formation of side channels and mid-channel islands (Abbe and Montgomery 1996). Side channels, which may persist for decades or longer, are utilized by fish escaping the high flows and velocity of the active channel during individual storms or during entire winters (Scarlett and Cederholm 1984, Sullivan et al. 1987).

At the reach scale, habitat refugia act in the context of the environmental risks just described. However, refugia also occur at a variety of spatial scales including subbasins or watersheds (Sedell et al. 1990). Relatively infrequent but large magnitude events (e.g., fires, large storms) trigger widespread erosion and an increase in sediment supply which decreases both vertical and lateral channel stability (Figure 11.10). Thus, refugia at the reach scale may not be available or may require time to develop, and the environmental risk to fish may be high enough to result in local extirpations (Reeves et al. 1995). Nearby basins untouched by fires or storms may have more stable channels and pose less environmental risk and, thus, function as watershed-scale refugia. Fish may escape to less hostile subbasins of a watershed and, eventually, some may recolonize newly forming habitats in the previously impacted subbasins. Recall, however, that large quantities of sediment and wood moving into channels during low frequency, high magnitude storms or fires, and which initially created an environmental risk, may evolve over decades to centuries into channel habitats.

Because processes creating environmental risks also create habitats, the regime of landscape processes (frequency, magnitude, composition, and spatial distribution) is central to understanding this duality. Frequency distributions of floods (Figure 11.3), erosion (Figure 11.11), and sediment transport (Figure 11.12) help to quantify changes in channel environments (e.g., Figure 11.9c) and therefore provide a measure to understand how environmental risk and refugia are related. For example, flows that transport bedload occur approximately 70% of the time in 5th-order channels in southwestern Washington (Figure 11.3b) which suggest that flow velocities capable of scouring redds and flushing fish downstream (e.g., an environmental risk) occur an average of once every year. However, the same frequency distribution also reveals that major floods capable of bank erosion and tree recruitment (i.e., the formation of habitat refugia) occur about 10 to 15% of the time (once every 5 to 7 yrs). Hence. consideration of cumulative effects at the system level should seek to understand how the relative proportions of environmental risk versus habitat development have changed due to land uses.

Biological Adaptations

The ability of fish to move from risk prone areas to low velocity refugia during floods, and to utilize changing habitat conditions during storms, is based on a suite of behavioral adaptations. These adaptations include juvenile and adult movements to avoid or utilize changing habitat conditions over days (i.e., a single storm) to years at the reach to watershed scales (Quinn 1984, Reeves et al. 1995). In addition. fish encountering potentially hostile conditions during spawning tend to lay a large numbers of eggs (Heard 1991), an adaptation to potentially high rates of egg loss caused by scour (which varies from year to year).

Dynamic Fish Habitat and Community Structure

The variations in channel sediment storage predicted by the simulation model in the Oregon Coast Range (Figure 11.12a–c) cause variations in fish habitat. Fires and large storms occurring asynchronously across the Oregon Coast Range create a spatial diversity of channel morphologies (in several adjacent basins with channel segments of similar gradient and drainage area). For example, in Knowles Creek basin (5th-order, 30 km^2), an absence of recent wildfires has contributed to a low sediment supply. the channel is dominated by bedrock, and pools are shallow. Harvey Creek basin, burned by a forest-replacing wildfire in the late 1800s, contains large volumes of sediment, is dominated by a gravel substrate, contains deep pools that dry up in the summer. Franklin Creek contains an intermediate volume of sediment and has the greatest diversity of substrates and pool depths.

Each of the three different channel morphologies contain different fish communities (Reeves et al. 1995). Knowles Creek has only a single species, coho salmon (*O. kisutch*). Franklin Creek, with a greater diversity of substrate sizes, accommodates a greater diversity of species: 85% coho salmon, 13% steelhead trout (*O. mykiss*), and 2% cutthrout trout (*O. clarki*). Harvey Creek is also dominated by coho salmon, with only incidental portions (1% each) of steelhead and cutthrout trout. Although the relative differences are not great, there is a significant correlation between species diversity and sediment supply.

Linking the field data on channel morphology, fish community structure, and estimates of sediment depth to the probability distribution of predicted sediment depth previously discussed (Figure 11.12b) indicates how often each of the fish habitat conditions are likely to occur, either in a particular stream reach over time or across many stream reaches of similar channel slope and drainage area at a single time. The predicted frequency distribution of sediment volume (Figure 11.12b) suggests that the low sediment supply of Knowles Creek (dominated by coho salmon) is the most-commonly occurring environmental state in the central Oregon Coast Range (about 70% of the time). The effects of large organic debris were not considered and may include create. Locally increased habitat and fish diversity. The frequency distribution in Figure 11.12b also suggests that the sediment rich state of Harvey Creek would be fairly infrequent, occurring perhaps less than 10% of the time. In addition, the intermediate sediment storage state of Franklin Creek with a higher fish diversity, is predicted to occur about 15 to 20% of the time.

The comparison of field studies of habitats and fish communities with model predictions of long-term channel behavior (Figure 11.12b) provides insights into natural disturbance or habitat diversity. This comparison suggests that under natural conditions in the central Oregon Coast Range, with it's low fire frequency (about 300 yrs), habitat diversity is relatively low. Model predictions coupled with field observations also suggest that if the frequency of disturbance is slightly higher (a fire cycle of 150 to 200 yrs, for example), the higher sediment (and wood) supply could potentially increase habitat diversity.

Applications to Watershed Science and Management

On close examination stream channels are extremely complex. Valley-floor conditions vary reach by reach and are governed by the vagaries of local topography and the history of mass wasting. Bed texture and slope vary over the scale of meters and are altered by every log that falls into the channel. Sediment transport, even under steady flow, varies across channels and from moment to moment. The sediment under one's feet may have originated from a fire several hundred years ago 20 kilometers upstream or it may have originated from nearby bank erosion during the last flood. Hence, stream channels contain information over all length and time scales, providing a classic definition of a complex system (Bak 1994).

A Field Perspective

A basic rule of streams, particularly at small scales, is spatial variability and, if one returns to a certain stream reach year after year, temporal variability. Anticipating spatial and temporal variability in stream morphology is exceedingly difficult because of the complex environmental interactions. Compounding this problem is the uncertainty about recent basin history that may be responsible for present channel morphology.

Although interpreting the origin and significance of small-scale channel and habitat features is important, the study of landscapes as systems provides other insights into channel morphology and the watersheds in which they are embedded. A systems perspective helps define the range and magnitude of variability that may be encountered in the field (i.e., through the use of frequency distributions) and, furthermore, some of the morphological consequences of that variability (e.g., long-term legacies in the form of terrace formation). Moreover, frequency and probability distributions contain information on how the major landscape properties of climate, topography, channel networks, and basin history are linked to channel changes. Interpreting channel conditions using frequency distributions means interpreting the environmental status of the watershed and its potential for providing sediment and wood.

Applying the landscape systems perspective to watersheds requires measurements and monitoring that seek to quantify the range of natural characteristics in channels, floodplains, terraces, fans, and forests. In dealing with a population of channel reaches the complexities of an individual reach, or the variation that occurs from reach to reach, becomes less important. The systems approach focuses instead on the range and relative abundance of certain channel attributes found within the entire population of reaches. Furthermore, for a population of channel features, the systems perspective endeavors to link how the shapes of the frequency distributions are controlled by interactions among climate, topography, and channel network structure, focusing mostly on the recent basin history. A landscape perspective represents a more coarse-grained approach to stream or watershed interpretation, similar to the coarse grained approach of making simplifications when applying quantitative theories and models of small-scale processes to larger-scale behavior through the use of simulation models.

The Problem of Cumulative Effects, Natural Disturbance, and Habitat Diversity

Concerns over how human activities, including fishing, forestry, and agriculture impact fish populations in the Pacific coastal ecoregion are often condensed into three broad concepts: cumulative effects, natural disturbance, and habitat diversity. Cumulative effects in streams is the accumulation and manifestation of human activities dispersed in space and time at any point in a channel network (Chapter 19). Information on natural disturbance provides an important baseline from which to interpret the ecological significance of cumulative effects or a long history of human impacts. Habitat diversity is related to natural disturbance through fires, storms, and floods occurring asynchronously that create a mosaic of habitats in watersheds or across landscapes in any year.

Cumulative effects, natural disturbance, and habitat diversity have two important things in common. First, they all pertain to the system behavior of a landscape. That is, they pertain to the behavior (or the condition in any year) of a population of landscape elements, such as upland and riparian forest stands, erosion sources, channel and valley floor environments, and fish stocks, over periods relevant to the governing physical processes (commonly decades to centuries). Second, they all remain poorly defined despite significant scientific efforts to address them in the past. For example, a credible scientific method for measuring or predicting cumulative effects in streams is lacking because of the difficulty in applying existing quantitative theories and models (such as for sediment transport and slope stability) that focus on small-scale landscape behavior (e.g., a hillslope or stream reach over a few years) to populations of hillslopes and stream reaches which have evolved over long time periods. Further, the aquatic or riparian natural disturbance regime has never been fully defined for any landscape for the same reason.

The inability to make significant progress in defining natural disturbance regimes in terrestrial or aquatic systems, or in measuring or predicting cumulative effects, largely is due to an absence of scientific theory explaining landscape behavior in terms of a population of landscape elements over appropriate temporal and spatial scales. Moreover, the availability of theories addressing landscape processes that act at small spatial and temporal scales often form the scientific basis for evaluating many broader environmental issues precisely because of the absence of system-scale theory. Unfortunately, the specific models cannot successfully address system-scale questions of cumulative effects, natural disturbance, and habitat diversity. The landscape systems framework described in this chapter could potentially be expanded into a methodology for evaluating and predicting cumulative effects because it deals with populations of landscape elements over time as well as the condition of populations of elements in any year.

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