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Effects of post-wildfire erosion on channel environments, Boise River, Idaho

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Abstract

What is the geological or ecological context that earth scientists, biologists, and resource managers use to understand large-scale watershed disturbances, such as fires, mass wasting, and floods? We address this question using a field study of post-fire channel changes in the Boise River basin in central Idaho based on surveys of over 27 km of channels. Intense rill and gully erosion from the Rabbit Creek fire (1995) greatly increased sediment supply to numerous third- through sixth-order valley floors. We concentrated our field study where recently aggraded and enlarged alluvial fans impinged on channels in drainage areas of 100–350 km^2. Alluvial fans that had enlarged because of post-fire sedimentation triggered a number of morphological changes in channels and valley floors. Alluvial fans created nick points in receiving channels that caused an increase in channel gradient immediately downstream of fans and a decrease in channel gradients upstream of fans for distances up to 4 km. Wide floodplains, side channels, and the beginning of terrace construction were associated with increased sediment storage in proximity to aggraded fans. Fan-related changes in channel gradients also affected the spatial distribution of channel substrates. Studies across western North America indicate that periodic, large influxes of sediment to channels are a fundamental part of stream ecosystems. In addition, new perspectives in riverine ecology focus on the patchy distribution of aquatic habitats. Our study integrates those two perspectives by illustrating how fire-related sediment production coupled with irregularly spaced tributary junctions contributed to the formation of certain types of riverine habitats.

Keywords: Aquatic habitat; Fire; Landslide; Erosion; Tributary; Fan

1. Introduction

Disturbances, such as wildfires, mass wasting, and floods are an intrinsic part of natural and managed landscapes and they can have short-term, detrimental effects and long-term importance for land and stream form development. Yet, the role of disturbances in stream ecosystems is not well understood. What aspects of disturbances are beneficial or harmful? How does land management affect natural disturbance regimes? How are extreme erosion events considered in the context of scientific assessments, resource management, and regulatory policies? For the most part, these questions remain unanswered and the effects of disturbance on riverine ecosystems usually focus on short-term negative impacts (e.g., Rinne, 1996). Consequently, natural disturbance represents a dilemma for natural resource management.

The role of disturbance in stream ecosystems can be addressed with concepts, simulation models, and field studies, or ideally some combination of all three. New

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concepts include recognition that disturbance is an integral part of watershed ecosystems (Resh et al., 1988; Swanson et al., 1988; Naiman et al., 1992; Reeves et al., 1996; Benda and Dunne, 1997a,b; Poff et al., 1997; Montgomery, 1999). In a more theoretical context, disturbance can be viewed as an outcome of probability distributions of climate, topography, and vegetation interacting with branching channel networks (Benda et al., 1998). Simulation modeling represents a relatively new tool that has been used to study landscape dynamics over centuries at watershed scales (10^1 to 10^2 km^2), including forest fires and changing vegetation ages (Van Wagner, 1978; Wimberly et al., 2000), landslides and debris flows (Benda and Dunne, 1997a; Lancaster et al., 2002), sediment routing (Benda and Dunne, 1997b), and recruitment of large wood (Benda and Sias, 2003; USFS, 2003). However, new concepts and simulation models, by themselves, are not adequate for understanding disturbance in stream ecosystems because they have a limited ability to evaluate small-scale physical and biological processes, including effects of fluctuating sediment supplies on channel and valley morphology. Moreover, new conceptual frameworks and model predictions must be tested and evaluated using field data.

In this paper, we take an empirical approach and present a descriptive field study from the Boise River basin that illustrates how disturbance, specifically punctuated sediment supply following wildfire, impacts channel and valley morphology in a forested ecosystem. The conceptual framework used to guide our study is the one proposed by Benda and Dunne (1997a,b) in which periodic stochastic forcing of erosion and sediment supply to a channel network from fires and large storms results in concentrations of sediment in certain parts of channel networks, particularly near tributary confluences. In addition to evaluating that prediction, we documented how punctuated increases in sediment storage affect channel and valley morphologies.

2. Study areas

We surveyed portions of fourth- through sixth-order channels in three streams (Fig. 1, Table 1). The Boise River basin is located 150 km northeast of Boise, Idaho and within the granitic batholith of the Sawtooth Mountains. Climate is continental and characterized by an average precipitation of 500 mm per year, the majority falling as snow in winter months, particularly at higher elevations. Summers are dry with frequent thunderstorms, a source of wildfires in the region (other papers in this volume discuss the fire regime in the Boise River basin). Vegetation is dominated by Ponderosa pine (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*). Topography in the study area is generally steep, with slopes ranging between 20 and 40°.

2.1. Methods

The objective of this study was to examine the effects of punctuated erosion and sediment supply on channel and valley morphology of large, fish-bearing streams. Punctuated refers to an abrupt, large, and temporary increase in erosion and sediment supply associated with fires and storms (sensu Benda and Dunne, 1997a,b). The study was accomplished by selecting a series of channel segments that traversed areas where post-fire erosion had created large alluvial fans that overlapped channel segments that did not contain fan deposits. Study segments ranged in length from 2.9 to 16.3 km (Table 1). Continuous field measurements (tallied over reach lengths of 10–100 m) were obtained within each study segment including: (1) channel azimuth; (2) channel gradient; (3) channel

Table 1
Summary of physical characteristics of the three study reaches in the Boise River watershed

Study segment	Reach length (m)	Drainage area (km^2)	Mean gradient (%)	Mean width (m)	Dominant substrate	Dominant channel type
Sheep Creek	2900	80–130	3.1	9	Cobble/boulder	Step-pool
Crooked River	8200	20–140	1.6	16	Gravel/cobble	Pool-riffle
North Fork Boise River	16300	200–580	1.4	32	Cobble/gravel	Pool-riffle

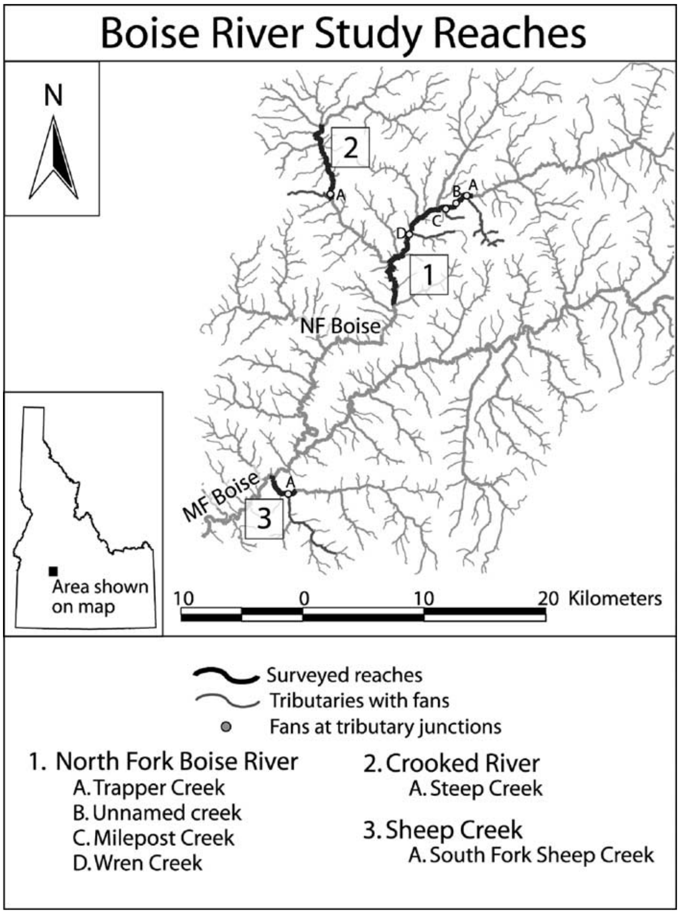

Fig. 1. Twenty-seven kilometers of river in the Boise River basin were surveyed to document the effects of punctuated erosion following the Rabbit Creek fire (1995) on alluvial fans and channel morphology.

width (bankfull, i.e., to base of vegetation); (4) floodplain width (areas accessible to overbank flow and that contained fine-grain overbank deposits and no coniferous trees); (5) valley width (area accessible to river migration and less than 2 m above current channel bed); (6) substrate; (7) old terraces (maximum 2 m above bankfull channel elevation and vegetated with trees with a minimum 20 cm dbh); (8) reoccupied terraces (former terraces that were being flooded, contained overbank deposits, and numerous dead trees, including conifers); (9) channel type (braided, pool-riffle, step-pool, cascade, etc.); (10) pools (minimum depth of 1 m); (11) side channels (that receive overbank flow); and (12) location of tributaries, lateral extent of fans, and other valley features, including canyons, major river bends, and rockfall deposits. Gradients, dimensions of channels and valleys, and azimuths were measured with a laser range finder. Alluvial fans were classified as recently active and rejuvenated (i.e., aggraded with large volumes of post-fire sediment) or inactive if they had not received recent large quantities of sediment. We refer to channels that create alluvial fans as ‘‘contributing channels’’ and the channels the fans enter and impinge upon as ‘‘receiving channels’’.

3. Results

A stand-replacing wildfire (Rabbit Creek Fire) in south-central Idaho in 1995 followed by intense summer thunderstorms in 1996 resulted in localized and intense rill erosion and gullying in the North and Middle Forks of the Boise River drainage (Istanbulluoglu et al., 2003). The sediment released by the fire inundated the valley floors of several fourth-order basins and created large alluvial fans at their confluences with larger channels (Fig. 2A). The fire-related erosion also supplied massive amounts of large wood to channels (Fig. 2B), the majority of which was removed to protect bridges. The effects of punctuated sediment supply, in the form of alluvial fans, were studied at three different spatial scales in the study area. Within the surveyed channel sections, six recent alluvial fans at tributary junctions had significant effects on the receiving channels.

Three recently active alluvial fans intersecting Sheep Creek, Crooked River, and North Fork Boise

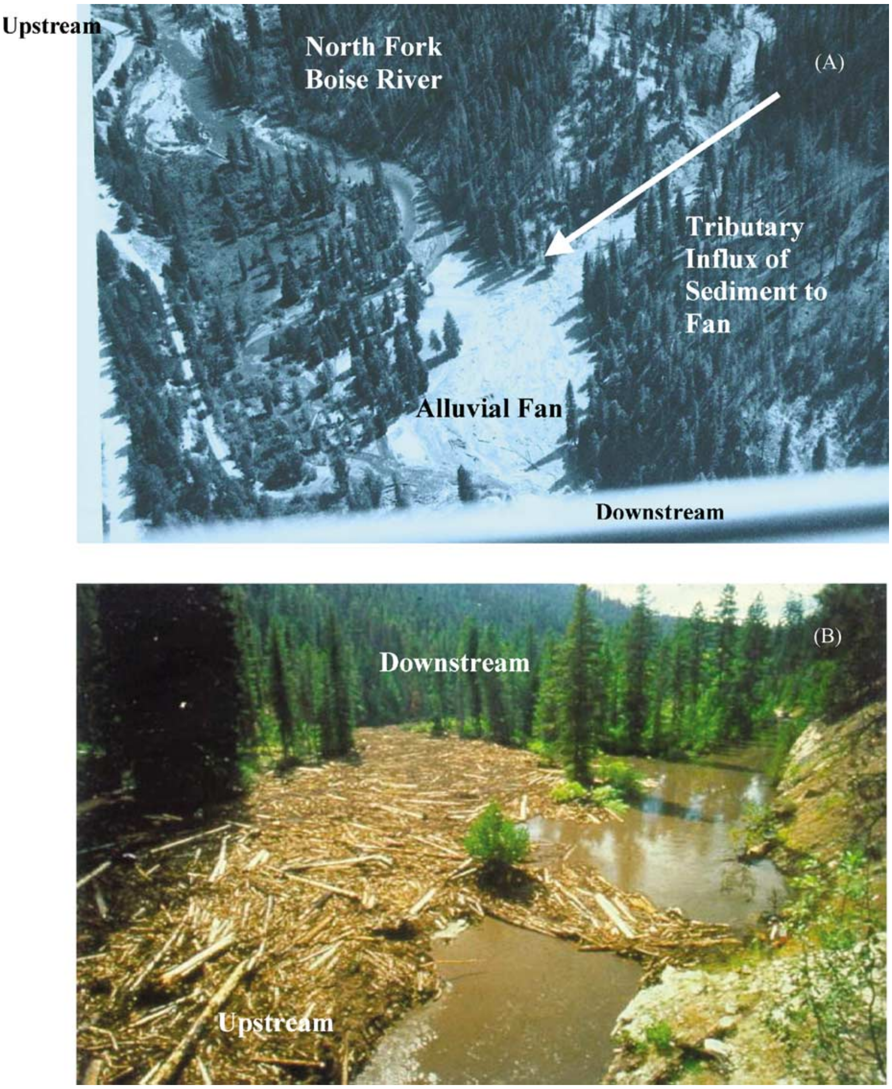

Fig. 2. The Rabbit Creek wildfire in 1995 and a summer thunderstorm the following year triggered intense erosion and increased sediment supply that rejuvenated a number of alluvial fans in the North Fork Boise River watershed. (A) The alluvial fan of Trapper Creek (drainage area 10 km^2) enlarged during post-fire sedimentation and impinged on the North Fork Boise River at a drainage area of approximately 220 km^2 (photo: Steve Toth). (B) Large influxes of wood accompanied the post-fire sedimentation event in the North Fork Boise River (photo: USFS). However, virtually all large wood was removed to protect downstream bridges.

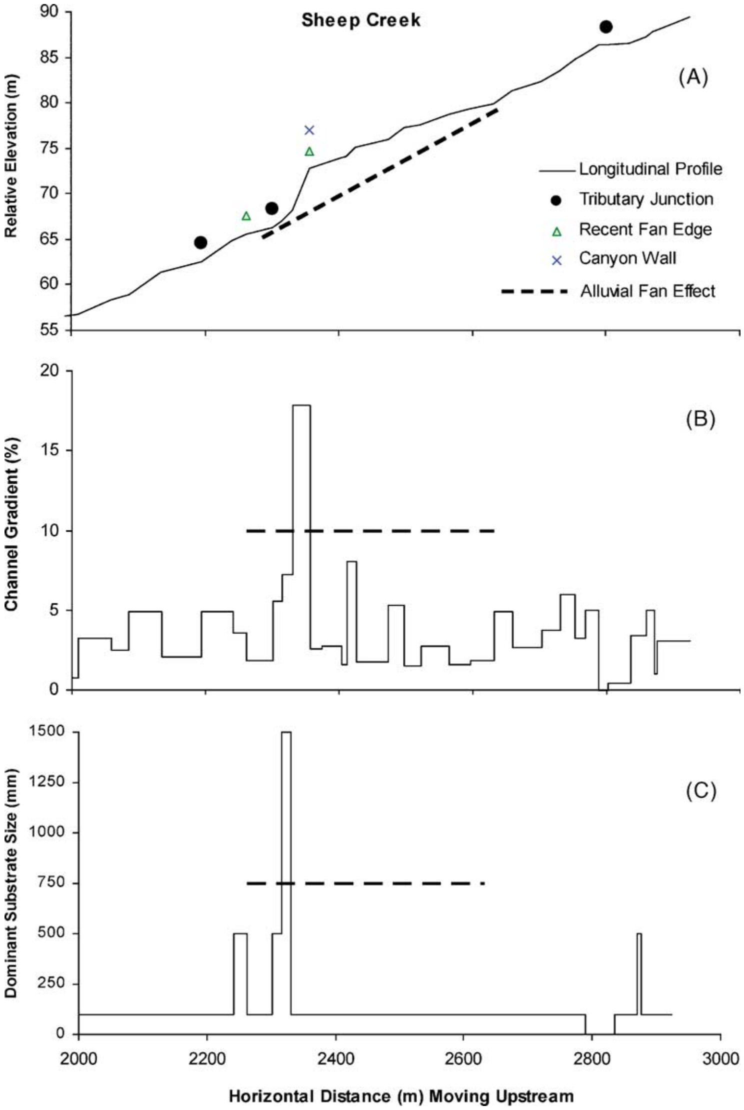

Fig. 3. (A) Longitudinal profile of Sheep Creek (drainage area 107 km^2) reveals a "step" created by a rejuvenated alluvial fan originating from South Fork Sheep Creek (31 km^2). The dashed line represents an estimate of the profile in the absence of the fan sediment wedge. (B) The alluvial fan impacted mainstem Sheep Creek by increasing channel gradient downstream of the fan and decreasing the gradient upstream of it. (C) The fan partly consisted of boulders that created a cascade on Sheep Creek at the downstream end of fan and caused finer grained sediment to deposit upstream of the fan. Dashed lines in (B) and (C) indicate the limits of the fan apparent in (A).

River were associated with local steepening in the receiving channel downstream of the fan for 50, 250, and 400 m, respectively (Figs. 3–5, Table 2). Moreover, the three fans were associated with a local flattening of the longitudinal profile in the receiving channels upstream of the confluences for 250, 450, and 1100 m. In Sheep Creek, the alluvial fan (from South Fork Sheep Creek, basin area 31 km^2) increased the slope downstream in the receiving channel to 14% and decreased the slope upstream to 2.6% (Fig. 3A and B, Table 2). In the Crooked River, the alluvial fan (from Steep Creek, basin area 8 km^2) increased the slope downstream to 4% and decreased the slope upstream to 0.2% (Fig. 4A and B, Table 2). In the North Fork

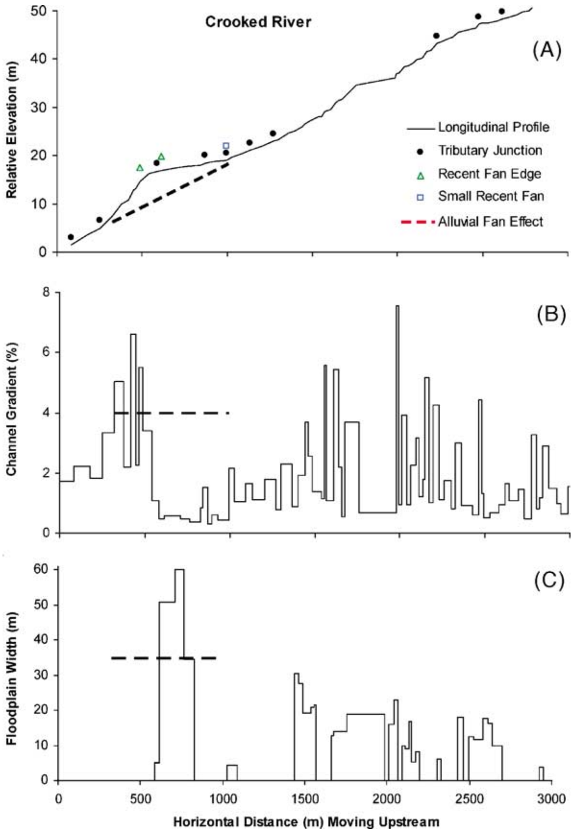

Fig. 4. (A) Longitudinal profile of Crooked River (drainage area 140 km^2) showing a step caused by the rejuvenated alluvial fan from the Steep Creek tributary (8 km^2). The dashed line represents an estimate of the profile in the absence of the fan sediment wedge. (B) The recently active alluvial fan caused an abrupt change in the channel gradient of Crooked River by decreasing gradient upstream of the fan and increasing gradient downstream of the fan. (C) The alluvial fan was associated with the widest floodplains in the Crooked River. Dashed lines in (B) and (C) indicate the limits of the fan apparent in (A).

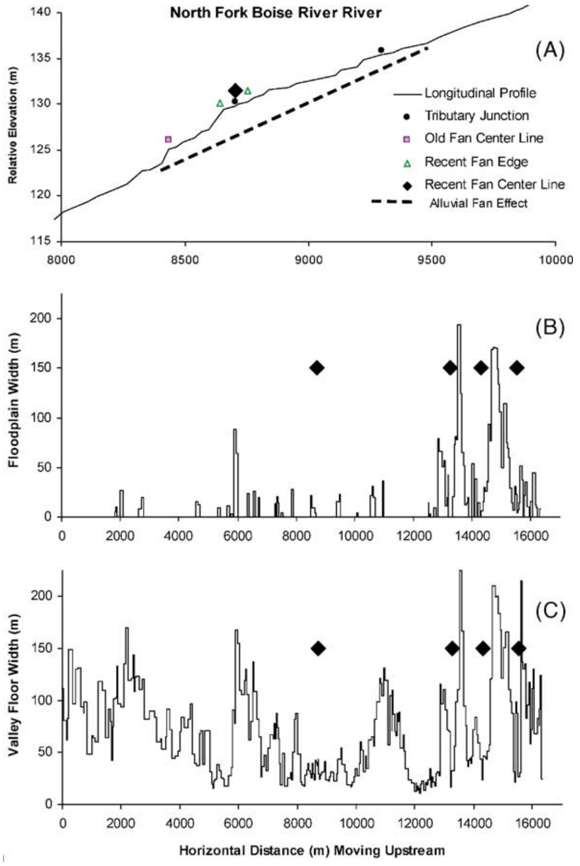

Fig. 5. (A) Longitudinal profile of North Fork Boise River (drainage area 350 km^2) showing a step caused by the rejuvenated alluvial fan from Wren Creek (11 km^2). The dashed line represents an estimate of the profile in the absence of the fan sediment wedge. (B) The width of the floodplain in the vicinity of the Wren Creek fan remained narrow because of confining valley floors (C). However, floodplain widths were highest in the vicinity of three other rejuvenated fans located between 13,500 and 16,000 m (B) where wide valley floors allowed channel meandering to occur (C).

Boise River, the alluvial fan (from Wren Creek, basin area 11 km^2) increased the slope downstream to 2.2% and decreased the slope upstream to 0.9% (Fig. 5A, Table 2).

In the 50 m of Sheep Creek located immediately downstream of the fan, the channel contained the largest substrate (boulders) compared to mostly cobble and gravel substrate in the remaining 3 km of the surveyed segment. Along 250 m of Crooked River immediately upstream of the alluvial fan, reduced channel gradients were associated with floodplain widths of 50 to 60 m compared to an average floodplain width of approximately 15 m along the remainder of the study segment. In addition, gravel and pebble substrate dominated in the low-gradient and wide floodplain area in the 450 m reach upstream of the fan. The remainder of Crooked River was dominated by cobbles and boulders. In contrast, the reduction in channel gradients upstream of the Wren Creek fan in the North Fork Boise River (Fig. 5) was not accompanied by increasing floodplain width. The alluvial fan entered the Boise River in a narrow valley

Table 2
Summary of alluvial fan impacts on receiving channels, including increases and decreases in channel gradients downstream and upstream of fans

Study area	Drainage area (km^2)[a]	Mean gradient (%)[b]	Downstream of fan: slope (%)[c], length (m)[d]	Upstream of fan: slope (%)[c], length (m)[d]	Total affected length (m)[e]
Sheep Creek	107	3.1	14/50	2.6/250	300
Crooked River	140	1.6	4/250	0.2/450	700
North Fork Boise River	340	1.4	2.2/400	0.9/1100	1500

[a] Area of receiving channel at the fan.

[b] Slope of receiving channel over the entire surveyed segment.

[c] Slope of receiving channel immediately downstream of fan apex.

[d] Affected length of receiving channel.

[e] Total effected length of receiving channel upstream and adjacent to fan.

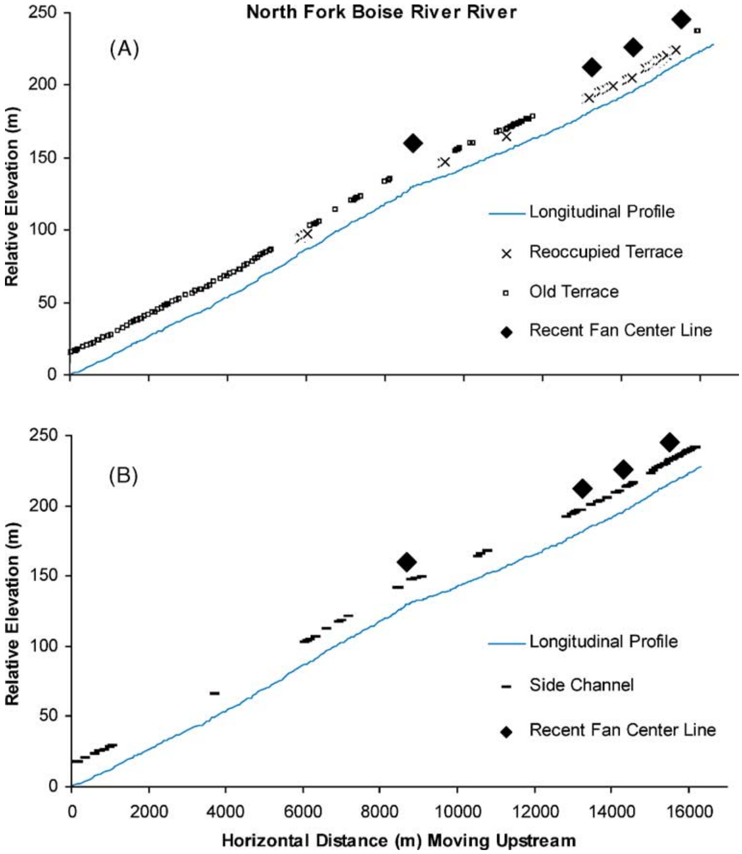

Fig. 6. (A) Old terraces (2 m above bankfull flow) are ubiquitous along the entire surveyed reach of the North Fork Boise River. However, ‘‘reoccupied terraces’’ (those that have recently been covered with overbank flows and fine sediment) were concentrated in the upper 4 km of channel in the vicinity of three active alluvial fans. This suggests that channel aggradation post-fire is linked to terrace formation. (B) The highest concentration of side channels was also associated with channel aggradation immediately upstream of the active alluvial fans in the upper 4 km of the surveyed channel.

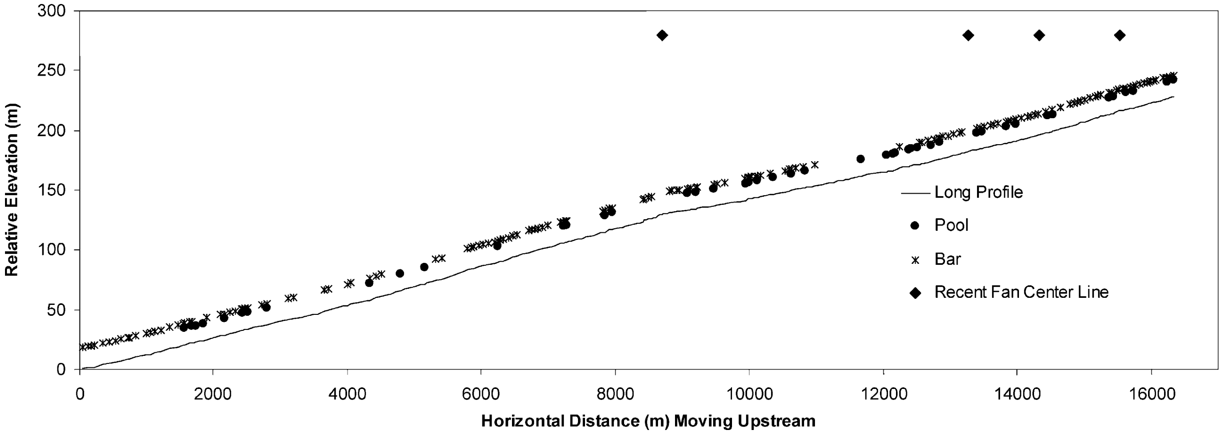

Fig. 7. Number and location of large pools (>1 m residual depth) along 16 km of the North Fork Boise River in relation to recently active alluvial fans.

that precluded formation of wider floodplains. Field surveys revealed that the widest floodplains (100–200 m) along 16 km of the Boise River were concentrated in a 4 km zone (13,000–15,500 m, Fig. 5B) associated with three other recently active and large alluvial fans. This zone coincided with wide valley floors that could accommodate formation of wide floodplains. Floodplains ranged in width from zero (in canyons) to generally less than 20 m throughout the remainder of the surveyed segment.

Evidence for channel aggradation in the North Fork Boise River included terraces (vegetated with conifers, many of which were dying) where recent floods led to overbank sedimentation, a landform we refer to as reoccupied terraces. Because channel aggradation followed by incision is a recognized process for creating cut- and fill-terraces, we inferred that aggradation of existing terrace surfaces was a process by which new terraces form, or existing terraces rejuvenate, in the Boise River basin. Field surveys revealed that the highest concentration of reoccupied terraces occurred in close proximity to the three recently active alluvial fans in the North Fork Boise River, despite the ubiquitous occurrence of older terraces throughout the study segment (Fig. 6).

Channel aggradation can also cause streams to braid, a process that can create side channels following a lowering of sediment supply and channel incision (Miller and Benda, 2000). The greatest concentration of side channels in the North Fork Boise River were also associated with three recently active alluvial fans in an area that overlapped with the zone of reoccupied terraces. In our surveys of the Crooked and North Fork Boise rivers (study segments that traversed both aggraded and unaggraded channels), pool counts did not reveal any spatial pattern. In the North Fork Boise River, the highest density of large pools appears to be located in areas affected by recently active alluvial fans (Fig. 7).

4. Discussion

4.1. Effects of post-fire increased sediment supply on channel morphology

Our field study illustrates that a punctuated increase in sediment supply following fire can lead to widespread channel aggradation of entire fourth-order valley floors (e.g., Trapper Creek) and the concentration of sediment at tributary confluences. These finding are consistent with predictions of stochastic watershed behavior by Benda et al. (1998). Moreover, rejuvenated alluvial fans in the Idaho study area caused sediment storage to increase upstream in the receiving channel because of reductions in channel gradient. Benda and Dunne (1997b) referred to this process as interference, i.e., fans interfering with sediment transport upstream of them causing local increases in sediment storage.

Our analysis also illustrated how alluvial fans, rejuvenated by post-fire erosion, can significantly influence the morphology of receiving channels. In Sheep Creek, the local steepening of the longitudinal profile immediately downstream of fans was accompanied by an accumulation of boulders. Boulder accumulations at tributary junctions are a classic signature of fans in many landscapes (Benda, 1990; Grant and Swanson, 1995), and flash floods that transport boulders through arroyos form many of the famous rapids in the Grand Canyon (Burke et al., 2003). In this study, fans also acted as nick points that reduced channel gradients and increased sediment storage in the receiving channel upstream of fans for distances of hundreds to thousands of meters, an effect most apparent in the Crooked and North Fork Boise rivers. The greater distance of altered channel gradients upstream of fan nick points appeared to be caused by interference of sediment transport from upstream in the receiving channel.

Rejuvenated alluvial fans also created wider floodplains in the Crooked and North Fork Boise rivers. In Crooked River, fan-related floodplain widths were 40–50 m, but average 10 m in unaffected areas. In the Boise River, floodplains 50–200 m wide located upstream of active fans contrasted with those 10–20 m wide throughout the rest of the study segment. Floodplains are important ecologically because they attenuate the scouring effects of floods and hence can function as refugia for aquatic organisms. In addition, floodplains can increase the diversity of riparian plants by providing surfaces that are frequently flooded, compared to terraces and toes of hillslopes.

Wide floodplains upstream of active fans were also associated with side channels. Side channels can provide important refuge habitats for fishes during floods and microhabitats for certain species of aquatic vertebrates and invertebrates (Sullivan et al., 1987). The highest density of side channels in the North Fork Boise River was in the upper 4 km of the study segment in close association with three recently active alluvial fans, wide floodplains, and rejuvenated terraces (e.g., Small, 1973). Although side channels can also form at log jams (e.g., Harwood and Brown, 1993; Collins et al., 2002), minimal large wood was present in the Boise River basin study reaches. Side channels that receive overbank flow were typically associated with aggraded channels and channel braiding.

Low terraces compose an important riverine landform because they can influence riparian forest composition (Nierenberg and Hibbs, 2000). Terraces often form during cycles of aggradation and degradation (Beschta, 1984; Nakamura, 1986; Miller and Benda, 2000) and cut-and-fill terrace formation appears to be a dominant process in the Boise River, although a reduction in sediment supply and channel incision will be required to complete this cycle.

Large influxes of sediment can lower pool density, a detriment to aquatic organisms, including fish (Madej and Ozaki, 1996). This process was not observed in either the Crooked or North Fork Boise rivers. In contrast, the density of large pools appeared to increase in the zone of active alluvial fans and channel aggradation in the upper 4 km of the North Fork Boise River study segment. The association of numerous large pools with a high density of gravel bars suggests that meandering and channel impingement on hard points (i.e., bedrock valley slopes) may preserve pool formation despite increased sediment supply and storage. Undoubtedly, the removal of virtually all large wood in the North Fork Boise River after the 1996 storm presumably reduced the potential for pool formation.

Photographs taken immediately following the Rabbit Creek fire showed extensive tree mortality, including riparian areas. Post-fire toppling of dead trees can be a major source of wood to streams. A theoretical analysis of the century-scale wood budget in semi-arid areas (similar to south-central Idaho) predicted that post-fire wood recruitment can account for up to 50% of the total wood recruitment to streams (Benda and Sias, 2003). In addition, post-fire erosion and floods transported extremely large volumes of wood into channels, including in the North Fork Boise River. The punctuated recruitment of wood to channels by post-fire toppling of dead trees and bank erosion should have major, long-term consequences for many aspects of channel and floodplain morphology, including physical heterogeneity in the impacted reaches.

Another type of fire impact in the North Fork Boise River drainage occurred in small ($\sim$10 km^2) basins. In at least two tributaries to the North Fork Boise River (Trapper and Wren Creek basins), entire valley floors were inundated with sediment. In this environment, short-term detrimental effects on aquatic biota may be significant (e.g., Rinne, 1996). Although we did not survey these channels, it is anticipated that as sediment

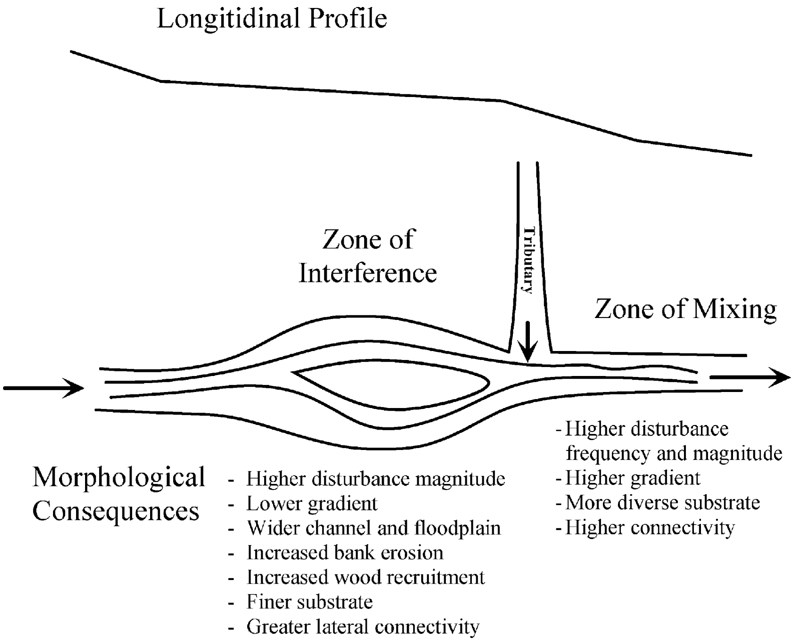

Fig. 8. Large influxes of sediment from tributary basins in Idaho affected the morphology of the receiving channel in proximity to rejuvenated alluvial fans (e.g., Fig. 2A). Effects upstream of fans include decreases in channel slope, increases in floodplain width, decreases in substrate size, increases in side channels, and terrace rejuvenation. Effects downstream of fans include channel steepening and boulder-dominated cascade morphology. Increased channel instability may also lead to greater lateral connectivity between channels and their floodplains and terraces, and hence increased wood recruitment. The zone of fan influence may expand during large sedimentation events and contract during periods of low watershed disturbance.

supply lowers, channels should incise and new terraces should form, indicating that large sedimentation events can completely reconstruct small valley floors.

In summary, our field data provide preliminary field evidence of how tributary junctions act as important response points in networks, particularly following large, punctuated increases in sediment supply (Fig. 8). Changes in sediment storage in proximity to junctions can lead to significant alterations in valley and channel morphology. Alterations included increases in channel gradients downstream of fans and decreases in gradient upstream of them for hundreds to thousands of meters. Increased sediment storage resulted in decreased substrate sizes and increased floodplain widths, terrace formation (or rejuvenation), and side channels. Channel braiding may also increase bank erosion and therefore wood recruitment. In addition, channel instability (i.e., meandering and braiding) due to increased sediment supply may increase lateral connectivity (i.e., channels interacting with their floodplains and terraces) and vertical connectivity, defined as increased hyporheic exchange because of enhanced sub-channel flow in buried paleochannels (Edwards, 1998).

The discussion of post-fire effects, using the Rabbit Creek fire in Idaho as an example, has concentrated on the constructive effects, namely formation of riverine landforms (i.e., fans, floodplains, terraces, side channels). However, fire-induced increases in sediment supply can also have negative consequences, including immediate burial of existing habitat and direct mortality of aquatic biota. These effects may be short-lived compared to riverine landforms constructed by fires, but they should be taken into consideration when evaluating the ecological effects of wildfires.

4.2. *The ubiquitous nature of punctuated sediment supply*

The erosion regime in Idaho that includes a stochastic and punctuated component is not unique compared to other mountainous landscapes in North

America. Erosion typically depends on a threshold being exceeded, such as rainfall-triggered landsliding (Caine, 1990), or sheetwash and gullying that is dependent on soil hydrophobicity following fires (Heede, 1988). In North America, punctuated erosion is characteristic of sediment regimes in mountain drainage basins, including in the southern coastal chaparral (Rice, 1973); Cascade humid mountains (Swanson et al., 1982); Pacific coastal rainforests (Dietrich and Dunne, 1978; Roberts and Church, 1986; Hogan et al., 1995; Benda and Dunne, 1987), Appalachian Mountains (Hack and Goodlett, 1960); and in the intermountain and highland arid regions (Meyer et al., 1995; Wohl and Pearthree, 1991; Robichaud and Brown, 1999). Hence, information on decade- to century-scale erosion regimes in numerous landscapes indicates that periodic, large influxes of sediment to channels are an intrinsic part of stream ecosystems.

Although punctuated sediment routing from small, headwater streams commonly involves debris flows, fluvially driven gully erosion may also be common, as evidenced in Idaho. In general, reduced potential for fluvial sediment transport in headwater streams encourages long-term (10^1 to 10^2 year) buildup of sediment and its eventual evacuation by debris flows or gullies. The sediment retentive nature of headwater streams (composing up to 70–80% of channel networks) results from a suite of factors, including small drainage areas that limit flow, stepped longitudinal profile that limits shear stress, high surface roughness that limits fluvial sediment transport and encourages sediment deposition, and accumulation of cohesive sediments that are difficult to entrain (Benda and Dunne, 1987).

4.3. Punctuated sediment supply and formation of alluvial fans

There has been a tendency among some scientists, resource managers, regulators, environmental groups, and the public to underrate the dynamic behavior of watersheds. It is important to consider that part of this perspective is reinforced by definitions of some terms commonly used in describing watersheds. Two examples are given below.

The classic definition of an alluvial fan is "an outspread, gently sloping mass of alluvium deposited by a stream, especially in an arid or semi-arid area where a stream issues from a narrow canyon onto a plain or valley floor" (Bates and Jackson, 1984). The spatially deterministic focus of this definition omits the factor of time, or a punctuated sediment supply, in fan construction. In the North Fork Boise River, alluvial fan development followed intense, post-fire erosion. Aerial photography of the fan depicted in Fig. 2 prior to the 1995 fire showed a much smaller fan that was truncated by the North Fork Boise River, suggesting that fan development in this region may be linked to, or enhanced by, large sedimentation events, possibly following fires. This perspective is supported by an analysis of fan stratigraphy in Idaho by Meyer et al. (this issue) that shows moderate to large sediment influxes (most associated with fires) create the bulk of alluvial fan deposits. The role of punctuated sediment supply in development (or rejuvenation) of alluvial fans has also been documented at Yellowstone Park following fires (Meyer et al., 1995) and in arid basins in southwestern United States (Beaty, 1974). The perspective of an erosion regime characterized by punctuated, high magnitude events is consistent with current understanding of long-term erosion regimes in Idaho. For instance, the average erosion rate estimated over approximately 50 years in areas of Idaho (including our study area), was, on average, 17 times less than the erosion rate estimated over several thousands of years using cosmogenic dating, suggesting that erosion regimes that encompass the study area are dominated by low-frequency, high-magnitude events (Kirchner et al., 2001). The stochastic behavior of erosion can also be viewed theoretically, in which punctuated erosion represents the right-skewed tail of the probability distribution of sediment supply (Benda and Dunne, 1997a,b).

The classic definition of an alluvial fan contributes to the perception that mountain watersheds are intrinsically stable and that disturbances (such as fires and post-fire erosion) are something to be avoided, and if they occur, the impacted watersheds should be restored. However, it appears that large-scale and punctuated sediment delivery linked to disturbances, such as fires, is responsible for forming major alluvial landforms, such as fans. The development of such large landforms and their consequences on channel and valley morphology should have important ecological consequences.

4.4. Punctuated sediment supply and formation of alluvial terraces

The conventional definition of an alluvial terrace is ‘‘a series of level surfaces in a stream valley flanking and more or less in parallel to the stream channel and represents the dissected remnants of an abandoned floodplain, streambed, or valley floor produced during a former stage of erosion and deposition’’ (Bates and Jackson, 1984). In this context, ‘‘stage’’ refers to stages of landscape age, that being youth, maturity, and old age (Bates and Jackson, 1984); these temporal divisions, may denote major geologic epochs, including glacial cycles. Although this definition of alluvial terraces includes time, the time scale addresses millennia or longer. This definition of a major landform that excludes processes operating over contemporary time (i.e., 10^1 to 10^2 years) reinforces the perspective that watersheds are fundamentally stable environments.

Our field observations suggest that heightened sediment supply and storage associated with post-fire erosion in Idaho creates terraces. In this view, terraces form during a cycle of channel aggradation followed by channel incision when sediment supply is subsequently reduced. The process of creating cut-and-fill terraces has been documented in other regions (Beschta, 1984; Nakamura, 1986; Miller and Benda, 2000). The location of reoccupied terraces up and downstream of recently active alluvial fans also suggests that terrace formation may occur coincidentally with the expansion of fans during heightened sediment supply, particularly upstream of fans (e.g., Small, 1973). The process of terrace formation during punctuated sediment supply is consistent with our knowledge of long-term erosion regimes in Idaho (Kirchner et al., 2001).

4.5. Ramifications for fluvial geomorphology and riverine ecology

Our study support emerging perspectives in fluvial geomorphology and riverine ecology. To appreciate the evolution in thinking about river networks, we provide a brief history. Several dominant themes have emerged over the last 50 years regarding the relationship between river networks and aquatic ecology. Early work focused on central tendencies (spatial and temporal averages) of physical processes and forms moving downstream, including channel slope, width, and depth (Leopold et al., 1964); flow (Leopold and Maddock, 1953); sediment transport and deposition (Schumm, 1977); bank erosion (Hooke, 1980); and channel process and form (Church and Kellerhals, 1978). A continuum of gradual downstream change in process and form is consistent with the concept of graded streams or regime channels (Leopold and Maddock, 1953) and the dominant-discharge principle that views frequent floods (2-year bankfull flows) as the major channel forming process (Wolman and Miller, 1970; Ackers and Charlton, 1970). These perspectives generally ignore the variability in channel properties that can be imposed by tributary confluences, other topographic heterogeneities, and disturbance. Similarly, the textbook definitions of alluvial fans and terraces described earlier also promote a steady-state view of watersheds.

Downstream changes in average hydraulic geometry were used by aquatic ecologists to make ecological predictions, such as the River Continuum Concept (Vannote et al., 1980). Spatially averaged central tendencies in channel slope, sediment supply, transport potential, and channel morphology, including substrate size, are also used to classify physical channel attributes into domains reflecting basin or stream size (Kellerhals et al., 1976; Rosgen, 1994; Montgomery and Buffington, 1997). Again, the role of time, or disturbance, is generally omitted from these frameworks.

The recognition that dynamic processes (disturbances) can alter the physical environment (Pickett and White, 1985; Resh et al., 1988) represents a relatively new theme in the study of rivers. Moderate to large landscape-scale fluctuations in the supply and storage of sediment and organic material create gullies, channels, fans, terraces, floodplains, side channels, and boulder deposits, habitats not formed during more quiescent times. Many perspectives in riverine ecology incorporate disturbance, including the flood pulse (Junk et al., 1989); ecotone (Naiman et al., 1988); natural flow regime (Poff et al., 1997); patch dynamics (Townsend, 1989); landscape dynamics (Benda et al., 1998); and process domain (Montgomery, 1999) concepts.

Coinciding with an interest in disturbance, riverine habitats have also been viewed as a mosaic of dynamic patches (Townsend, 1989) governed by variation in deterministic factors (i.e., geology, topography, etc.), and disturbance, a perspective similar to landscape ecology (Swanson et al., 1988; Benda et al., 1998; Montgomery, 1999). At the scale of entire networks, effects of topographic variation, or nick points, on riverine habitats (i.e., canyons, unconstrained areas, landslide deposits, etc.) have been documented (Grant and Swanson, 1995; Baxter and Hauer, 2000). The idea of a patchy discontinuum of habitats is also reinforced by field measurement and modeling that indicate the importance of channel network structure, especially tributary junctions, on channel morphology and aquatic organisms (Minshall et al., 1985; Benda and Dunne, 1997b; Rice et al., 2001; Poole, 2002). Despite the significance of tributary junctions, the integration of tributaries within river-network-scale paradigms remains limited because of incomplete understanding of morphological characteristics of tributary environments, how disturbances affect them over time, and how network topology, through junctions, affects habitats. Hence, present geomorphic characterizations of river systems emphasize linearity that virtually ignores the effects of confluences within a branching network (Fisher, 1997).

Our field study of channel effects associated with post-fire erosion in the Boise River basin, Idaho, compliments and reinforces the perspective of a patchy distribution of riverine habitats, and furthermore, how tributary junctions may contribute to the discontinuous nature of riverine morphology. Moreover, our analysis integrates the effects of tributary junctions on mainstem rivers within the context of disturbance. Specifically, the effects of tributary confluences may be most pronounced and longitudinally extensive during large, punctuated increases in sediment and wood supply and may be responsible for landforms such as fans, terraces, wide floodplains, boulder cascades, and side channels. This study supports the theoretical perspective coupling probability distributions of watershed processes (a parameter that defines the frequency and magnitude relationship of disturbance regimes) with channel network structure (Benda and Dunne, 1997a,b; Benda et al., 1998; USFS, 2003; Miller et al., this issue).

5. Conclusions

Because disturbances may contribute to or govern significant aspects of physical heterogeneity and perhaps biological diversity in rivers, certain types of disturbances can be viewed as positive events in the life of a watershed. Moreover, when human activities, such as stream cleaning, log drives, diking, riparian logging, and damming, have simplified channels and decreased physical heterogeneity, disturbances in the form of fires, floods, and mass wasting may be a benefit in the long-term because they may increase physical and biological diversity. With this perspective, certain types of watershed disturbances do not need to be "restored" so that a watershed can "recover," but rather the disturbance itself may be an agent of recovery. This view has been proposed for landslide disturbances in forested ecosystems (Reeves et al., 1996) and flooding-related disturbances in regulated rivers (Yin, 1998). Nevertheless, land uses, such as timber harvest and fire suppression, can alter the frequency and magnitude of natural disturbances with unknown long-term consequences. Further work is needed to decipher how disturbance regimes in managed landscapes differ from those in natural systems.

Stream disturbances, such as fires, landslides, and floods, should be considered over larger temporal and spatial scales (decades to centuries over hundreds to thousands of square kilometers) if their roles in forest and stream ecosystems are to be understood. From a management and regulatory perspective, therefore, the focus should shift from individual projects and stream reaches to decadal planning horizons across entire watersheds and landscapes. The question: "what is the condition of an individual stream segment or small tributary valley and how does it change over time?" may change to "what is the condition of an entire population of stream segments in a large watershed and how do management activities shift the cumulative distribution of that population over decades?"

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