Bank Erosion as a Desirable Attribute of Rivers

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Bank erosion is integral to the functioning of river ecosystems. It is a geomorphic process that promotes riparian vegetation succession and creates dynamic habitats crucial for aquatic and riparian plants and animals. River managers and policymakers, however, generally regard bank erosion as a process to be halted or minimized in order to create landscape and economic stability. Here, we recognize bank erosion as a desirable attribute of rivers. Recent advances in our understanding of bank erosion processes and of associated ecological functions, as well as of the effects and failure of channel bank infrastructure for erosion control, suggest that alternatives to current management approaches are greatly needed. In this article, we develop a conceptual framework for alternatives that address bank erosion issues. The alternatives conserve riparian linkages at appropriate temporal and spatial scales, consider integral relationships between physical bank processes and ecological functions, and avoid secondary and cumulative effects that lead to the progressive channelization of rivers. By linking geomorphologic processes with ecological functions, we address the significance of channel bank erosion in sustainable river and watershed management.

Keywords: bank erosion, riparian ecology, fluvial geomorphology, sediment, aquatic ecology

Bank erosion is a natural geomorphic process or disturbance that occurs during or soon after floods. Riverbanks are transitional boundaries, or ecotones, between the aquatic and terrestrial ecosystems, and they frequently change under naturally dynamic hydrologic conditions. Although abundant evidence suggests that bank erosion is a necessary ecological process (Piegay et al. 1997, 2005), current river management, and sometimes even restoration strategies, calls for channel bank infrastructure, that is, hard structural elements intended to arrest bank erosion (also called revetment, erosion control, or bank stabilization structures). Such strategies often focus on human values that include property damage and land loss, flood hazards (Piegay et al. 1997, Casagli et al. 1999), and potential impacts to aquatic habitat from bank-derived fine sediment contributions (EPA 2007). Often, projects labeled as "restoration" focus principally on bank stabilization. However, static banks are not the norm, and static rivers and streams do not sustain ecosystems. Despite this, in response to the notion that bank erosion is deleterious, the construction of bank infrastructure has become pervasive over the past century as an increasing population and associated development encroach on riparian landscapes. Thus, bank erosion management is a significant ecological issue.

In this article, we review the ecological significance of a range of geomorphic bank erosion processes and show that the cumulative effect of progressive bank stabilization structures is to limit riparian function and diminish habitat for riparian species. Our objectives are to (a) synthesize geomorphic and biological literature through principles that highlight the importance of bank erosion processes as disturbances integral to components of riparian ecosystems at a variety of scales; (b) identify the effects of channel bank infrastructure on riverbank and riparian ecology; (c) identify failures of current policies to manage channel bank erosion; and (d) present a rationale and framework for alternatives to such policies. The alternatives are intended to aid the development of river management and policy that promote healthier geomorphological and ecological functions in river systems where bank erosion is an issue of concern.

Geomorphic and ecologic significance of banks and bank erosion

We define "riverbank," in a geomorphic context, as the landform distinguished by the topographic gradient from the bed of a channel along the lateral land-water margin up to the highest stage of flow or up to the topographic edge where water begins to spread laterally over the floodplain surface. Bank erosion refers to the erosion of sediment from this distinct landform. Eroded sediment moves along the topographic gradient laterally toward the channel or in the downstream direction. Banks are often characterized by bare sediment, live vegetation, or snags (Roy et al. 2003). In an ecological context, riverbanks are an important component of riparian zones. Bank habitat and function are to some degree inseparable from functions within the larger riparian zone; here we take a broader view of natural banks and bank erosion as they influence riparian areas. Ecologically

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functioning riparian zones provide a variety of resources and are vital centers of biodiversity (Gregory et al. 1991, Naiman et al. 1993, 2005, Ward and Tockner 2001, NRC 2002). The main functions of riparian zones are related to fluvial hydrology and sediment dynamics; retention and cycling of nutrients and pollutants; and maintenance of habitat for wildlife, including invertebrates, amphibians, reptiles, birds, and mammals (NRC 2002). In the following sections, we review elements of banks and bank erosion that create physical and biological heterogeneity and riparian diversity. We focus discussion of bank processes and functions around principles that illustrate the significance of bank erosion and natural banks as desirable attributes of rivers:

- Bank erosion provides a sediment source that creates riparian habitat.
- Active banks create and maintain diverse structure and habitat functions.
- Riparian vegetation promotes bank stability and contributes large woody debris.
- Bank erosion modulates changes in channel morphology and pattern.

Channel banks form a significant ecotone between aquatic and terrestrial ecosystems with diverse structure and habitat functions; this article forms the critical basis for discussions of the effects of and alternatives for channel bank infrastructure.

Bank erosion provides a sediment source that creates riparian habitat. Diverse bank erosion processes occur as sediment cycles through the continuum of headwater to lowland environments within a watershed (figure 1). The dominant bank erosion process in each part of the watershed is influenced by the size of the channel, discharge, and flow strength (Couper 2004), with the dynamic nature of erosion processes depending in part on sediment supply and transport regime (Benda et al. 2004). Fluvial deposits vary dynamically from the headwaters to the lowland (Church 2000). Bank erosion from headwater areas provides a source of weathered sediment that is stored for varying periods in downstream alluvial deposits (Gomi et al. 2002).

Bank erosion is a considerable sediment source in some rivers (Trimble 1997); however, the sediment supply is not always deleterious. Bank erosion supplies coarse sediment to channels—a size fraction that is necessary to form the physical structure of aquatic habitat. Coarse sediment, supplied from upstream and stored as channel-bed material and bedforms, makes up substrate important for macroinvertebrates. Such coarse-grained substrate promotes oxygen exchange, provides interstitial space for protection from predators, serves as attachment sites for filter feeders, and provides a food source for periphyton (Wood and Armitage 1997). In contrast, when the sediment supply is large relative to transport capacity, such that aquatic habitat is buried, or when fine-sediment contributions from bank erosion are excessive, habitat damage may occur. In streams with large sediment inputs derived from bank erosion, there is often concern that changes in water quality due to large fine-sediment loads affect aquatic habitat (EPA 2007). Large fine-sediment inputs may affect groundwater-surface water exchange, a factor in fish and benthic invertebrate habitat (Lisle 1989, Kondolf et al. 2006). Processes that include infiltration of fine-grained sediment into coarser channel substrate may in turn impede intergravel water flow in the hyporheic zone, consequently reducing oxygen levels to benthic organisms.

As a physical process that supplies and delivers sediment, bank erosion is critical for creating habitat at the watershed scale (figure 1). Riparian area structures are influenced by variations in geomorphic processes and in the resulting valley bottom deposits, including floodplains and bars (Gregory et al. 1991). Floodplain ecosystems, a critical component of riparian ecosystem diversity (Ward and Stanford 1995, Stanford et al. 1996), are sustained by periodic erosion and sedimentation during floods (Junk et al. 1989, Bayley 1991, 1995, Florsheim and Mount 2002). Bank erosion also contributes sediment to fluvial deposits, such as sandbars in the Platte River, that are important to migrating whooping cranes (*Grus americana*). Resting on the bars during their migration, these birds have long sight lines and are isolated from predators (NRC 2002, Graf 2005).

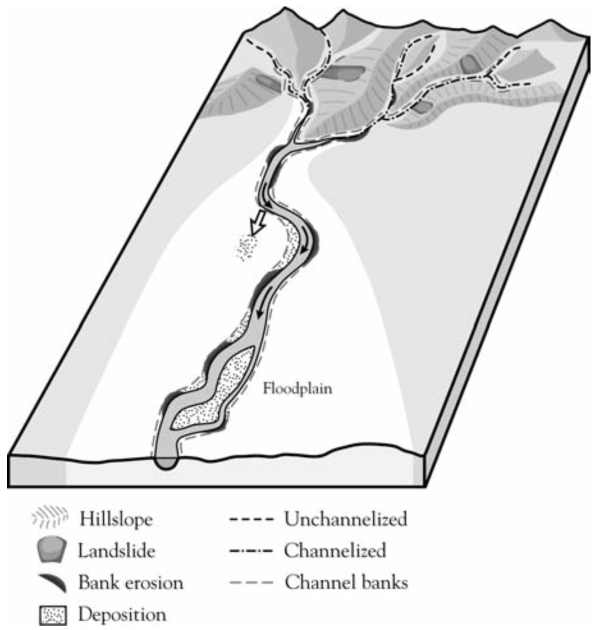

Figure 1. Illustration of a river network from headwater to lowlands. Bank erosion is one component of the sediment cycle throughout an idealized river network. In the headwaters of watersheds, banks are the boundary between upland terrestrial and aquatic ecosystems. In lowland areas, channel banks are commonly the transitional area between floodplain and aquatic habitats. Sediment eroded from hill slopes in headwater areas is transported downstream and stored in deposits (such as terraces, floodplains, bars, and channel substrate) that provide habitat for aquatic and riparian organisms.

Active banks create and maintain diverse natural structure and habitat functions. As a transitional zone within riparian ecotones, riverbanks accommodate highly dynamic environmental conditions. Banks can modulate floodwater surface elevations and have variable moisture regimes that satisfy the requirements of diverse plant species (NRC 2002). Banks provide habitat at different elevation zones needed by flora and associated fauna adapted to flood pulses rising along the bank (Junk et al. 1989). Habitats along the bank gradient are exposed to various flood frequencies, durations, and magnitudes (NRC 2002, Naiman et al. 2005). Thus, riparian plant communities closest to a channel are colonized by fast-growing, water-adapted sedges, rushes, grasses, herbs, and seedlings of shrubs and trees, whereas terrestrial vegetation is deterred because of frequent flooding (Gregory et al. 1991, NRC 2002). At higher elevations on the bank, riparian plant communities include trees such as cottonwood (*Populus*), willow (*Salix*), and alder (*Alnus*), whose roots are adapted to periodic floods (NRC 2002). Vines such as the riverbank grape (*Vitis riparia*) climb riparian trees, and wildlife consume their fruit. Streamside trees that overhang the channel are an allochthonous source of organic material that provides food and cover for fish. Additionally, organic material from riparian vegetation is a primary food source for invertebrates from all of the guilds, including filter feeders, shredders, scrapers, and predators (NRC 2002). Streamside trees offer shade that modifies aquatic microclimates and maintains lower water temperatures (NRC 2002). Bank erosion alters the gradient of vegetation during floods, and thus modifies the habitats and functions of the riparian ecosystem. Bank erosion that locally opens the tree canopy increases primary production and energy flow through the food web, leading to greater production of invertebrates and fish (Naiman and Bilby 2001).

The channel banks and vegetation within riparian areas make up the substrate for insects emerging from the water, and those insects provide a food source for breeding and migrating birds (Benke and Wallace 1990, Graf et al. 2002). Dense, newly established vegetation patches formed following erosional, depositonal, or flood disturbances offer habitat for diverse bird species (table 1).

Amphibians that require water for part of their life cycle, such as frogs, toads, and salamanders, rely on bank microhabitat for dispersal onto land after emerging from the water (NRC 2002). Many reptiles require functioning riparian areas to complete their life cycles. For example, the wood turtle (*Clemmys insculpta*) establishes nesting burrows in recently deposited, unconsolidated sediments of riparian areas (Vogt 1981, NRC 2002, Harding 1997). Snakes hunt in biologically rich riparian ecotones (NRC 2002). Riparian lizards (*Sceloporus occidentalis*) eat river-derived insects, which highlights the energy flux between rivers and surrounding

Table 1. Effects of channel bank infrastructure to control bank erosion.

Geomorphic and ecological attribute	Habitat or ecosystem service influenced	Examples of organisms affected
Loss of sediment source		
Supply	Downstream sandbars as resting habitat for migrating birds	Whooping crane (*Grus americana*)
Grain size	Coarse-grained substrate for attachment and interstitial space for hiding from predators	Macroinvertebrates (e.g., mayflies [*Ephemeroptera*], caddisflies [*Trichoptera*], and stoneflies [*Plecoptera*])
Loss of geomorphic processes		
Migration	Newly scoured or deposited surfaces	Riparian trees (e.g., cottonwood [*Populus*], willow [*Salix*], alder [*Alnus*])
Widening	Adjustment necessary for incised channel to evolve toward equilibrium with floodplain at elevation to support riparian plants	Riparian trees (see above)
Loss of bank substrate		
Unconsolidated sediment	Vertical banks for wildlife burrowing and nesting Filter and retention of nutrients, pollutants, water quality	Bank swallow (*Riparia riparia*) Macroinvetebrates (see above)
Natural biotic and abiotic components of land-water margin	Shoreline microhabitat: soft sediment or burrows, emergent vegetation to cling to; underwater plants, snags, roots protruding from bank	Shore-dwelling insects (e.g., *Neocurtilla*); macroinvertebrates
Roughness and irregularity in land-water margin	Variation in near-bank flow velocity, refugia during storm flows	Overwintering fish, macroinvetebrates (see above)
Undercut banks	Protection from predators	California shrimp (*Syncaris pacifica*), juvenile fish (e.g., Coho salmon [*Oncorhynchus kisutch*])
Loss of riparian forest		
Stream-side riparian ecosystem Willow and cottonwood forests	Complex riparian vegetation, areas for wildlife: bird breeding, nesting, safety from predators; probing for insects under tree bark; wildlife: food, migration corridor, and/or dispersal route; plants: structure for vines	Birds (e.g., willow flycatcher [*Empidonax traillii extimus*], Gila woodpecker [*Melanerpes uropygialis*], western yellow-billed cuckoo [*Coccyzus americanus occidentalis*]), reptiles (e.g., riparian lizard [*Sceloporus occidentalis*]), semiaquatic mammals (e.g., river otter [*Lontra canadensis*]), macroinvertebratres, climbing vines (e.g., river-bank grape [*Vitis riparia*])
Overhanging branches, leaves	Shade, organic material, fish food	Fish, macroinvetebrates (nymph and adult stages)
Large woody debris	Reduction in pool complexity and depth, loss of attachment sites	Fish, macroinvertebrates (see above)

terrestrial areas (Sabo and Power 2002). Semiaquatic mammals such as the water shrew (*Neomys fodiens*), star-nosed mole (*Condylura cristata*), beaver (*Castor*), river otter (*Lontra Canadensis*), and mink (*Mustela*) find food and shelter resources in riparian habitats (NRC 2002). Natural banks and associated vegetation offer cover for these animals while they move back and forth between water and land.

Riparian vegetation promotes bank stability and contributes large woody debris. Riparian vegetation influences bank stability (Simon and Collinson 2002) because the type and density of vegetation cover and the roots that stabilize banks minimize bank erosion (Pizzuto and Mecklenburg 1989, Abernethy and Rutherfurd 1998, 2000). Riparian forests generally maintain bank stability, but flow that scours around individual pieces of large wood derived from riparian forests may accelerate bank erosion rates locally—this contrast highlights the importance of considering scale in assessing bank erosion (Montgomery 1997). During floods, bank erosion delivers large woody debris to channels (Piegay et al. 1999, Wyzga and Zawiejska 2005, Sudduth and Meyer 2006). The large woody debris changes bed and bank morphology and increases channel complexity (Ralph et al. 1994). Pool formation in forested ecosystems is controlled in part by the size and abundance of large woody debris, but other factors are also important (e.g., sediment supply; Buffington et al. 2002). In rivers with fine substrate, large woody debris provides a stable substrate for organisms in channels otherwise dominated by highly mobile, fine-grained bed sediment (Junk et al. 1989).

Bank erosion modulates changes in channel morphology and pattern. Bank erosion includes two main processes that are often interrelated: mass wasting processes and fluvial erosion (Hooke 1979, Thorne 1982, Odgaard 1987, Osman and Thorne 1988, Thorne and Osman 1988, Hasegawa 1989, Lawler 1993, Darby and Thorne 1996, Lawler et al. 1997, ASCE 1998, Simon and Curini 1998, Casagli et al. 1999). Mass wasting processes on riverbanks include various types of slides (e.g., shallow or deep slides) and slab failure characterized by linear or rotational failure planes. Slides occur when the driving force exceeds the resisting force during floods or shortly after storm flows recede. Subsequent floods may erode sediment deposited in the channel from a slide. However, while the sediment remains at the base of the bank, it may locally increase the physical heterogeneity of the channel through the addition of large woody debris and cobbles, and the creation of microtopography and bare surfaces at various elevations above the channel bed.

Fluvial erosion occurs during floods when the near-bank flow velocity and acceleration exert shear stress on the banks that is greater than the critical shear stress needed to entrain bank sediment. Fluvial erosion frequently scours the toe of the bank, causing the upper portion to collapse (Thorne and Tovey 1981). The relation between the rate of sediment supply from bank erosion and the rate of fluvial transport of this material from the base of the bank controls the rate of bank retreat (Thorne 1982). Floods that cause erosion are stochastic, and local field conditions—as well as human modifications—are highly nonuniform. Thus, measurement and prediction of long-term erosion rates is complex; in practice, there are numerous challenges in extrapolating temporal and spatial scales of bank erosion (Couper 2004).

Fluvial erosion of bank sediment may expose tree roots or undercut and destabilize bank vegetation. Alternatively, if bank sediment bound by a root network resists erosion, flow may undercut banks below the roots, forming new niches for crustaceans, mollusks, or juvenile fish to hide from predators and find low velocity refugia during floods. For example, the California freshwater shrimp (*Syncaris pacifica*) prefers tree-lined banks with underwater vegetation, where it can rest on exposed roots in the summer and seek shelter by clinging to roots exposed in undercut banks during winter floods (Biosystems Analysis 1994). Additionally, fluvial erosion that scours sediment from the base of riverbanks maintains habitat for some avifauna, such as the bank swallow (*Riparia riparia*), which relies on unconsolidated bank sediment for nesting (Garrison et al. 1987). Erosion is a critical process in maintaining the vertical banks that preclude predators' access to bank swallow nests and prevent vegetation from covering the birds' habitat. Nesting colonies move to new sites along a river each year, taking advantage of new vertical banks that form following bank erosion.

Mass wasting and fluvial erosion at bends drives episodic or progressive channel migration and changes in channel pattern, which influence the establishment of riparian vegetation. Bank erosion is associated with long-term evolution of channel pattern and short-term geomorphic adjustments that alter morphology, including widening, migration, braiding, and avulsion and associated channel abandonment. Thus, the influence of bank vegetation on erosional resistance is a control that, along with other fluvial variables such as river slope and discharge, influences alluvial river patterns (Millar 2000). Bank erosion may occur on one or both banks in incising, aggrading, or in laterally migrating channels (ASCE 1998)—adjustments that lead to the formation of new scoured surfaces. Thus, bank erosion provides new niches for vegetation requiring sunlight and lack of competition. Recruitment of woody plant species such as cottonwood and willow occur on such alluvial surfaces (NRC 2002).

Bank erosion is especially prevalent, and erosion rates are highest, on the outside of river bends, where fluvial processes, mass wasting, and undercutting of riparian vegetation leads to meandering (e.g., Leopold and Wolman 1957, Johannesson and Parker 1989, Hupp and Osterkamp 1996). Bank erosion that facilitates meandering and creation of abandoned channels is important because it leads to vegetation succession, which is necessary for riparian diversity (Salo et al. 1986). Riparian plant succession is initiated with the establishment of patches of seedlings that favor bare substrate created during floods (Friedman and Auble 2000). As point bars and vertically accreted sediment deposits extend, and younger vegetation becomes established after subsequent floods, vegetation patches increase in age in a direction opposite to the migrating channel (Everitt 1968, Naiman et al. 2005).

Bank erosion also occurs in relatively straight, braided, or multiple-channel systems, and is often associated with changes in water and sediment supply that lead to incision (Simon et al. 1999, Thorne 1999). Channel adjustments that increase bank height and instability in incised channels ultimately lead to widening and deposition of sediment surfaces at elevations that support the establishment of riparian trees (Simon 1989). In braided channels, bar accretion may lead to local bank erosion when the flow is diverted around a bar toward the bank. In multiple channel systems, bank erosion facilitates avulsion, which creates new channel habitat patches within the floodplain and leaves others abandoned. Thus, bank erosion is one component of an array of geomorphic processes that govern channel evolution and lead to the morphologic diversity in habitat needed to sustain riparian biodiversity.

Effects of channel bank infrastructure

Channel bank infrastructure such as riprap, gabions, or concrete lining is increasingly common in agricultural, rural, and urbanizing areas, where its usual purpose is to limit land loss and associated hazards and damages. Many types of hard material are used (figure 2). Structures vary in extent from the scale of the individual bank erosion feature to longer reaches associated with urbanization or flood control projects that are kilometers long. Table 1 identifies and summarizes the main geomorphic and ecological effects of channel bank infrastructure, the potential habitat or ecosystem services lost, and examples of organisms affected.

Hard bank structures increase flood velocities along banks, preventing the establishment or survival of many riparian plant species (NRC 2002); thus, bank stabilization can have negative effects on riparian areas (Sedell and Beschta 1991, Fischenich 1997). Channel complexity tends to be reduced by the changes that channel bank infrastructure produces: elimination of bank irregularity and channel-width variations, homogenization of near-bank flow velocity, loss of access to side channels, loss of natural bank substrate, and limitation of geomorphic adjustments. Moreover, complex riparian areas offer a greater variety of food sources and physical habitats than do simple plant communities of uniform age and species, which are characteristic of stabilized banks (Gregory et al. 1991). Completely arresting bank erosion disrupts the lateral channel-bank sediment exchanges that are necessary to sustain an array of aquatic habitats (table 1).

Figure 2. Examples of channel bank structures. Some bank erosion-control structures are not designed or engineered; rather, they are ad hoc attempts to prevent local land loss or damage. (a) Car bodies; (b) riprap; (c) sacrete on left bank, riprap on right bank; and (d) rock-filled gabions along banks of concrete-lined channel. Photographs: Joan L. Florsheim (2a and 2c) and Anne Chin (2b and 2d).

Land-use changes that remove riparian vegetation have a significant influence on channel banks (Allan 2004). Hard erosion-control structures eliminate substrate for and microhabitats of plant species that grow on banks. They also impede the movement of species that use riparian zones for migration corridors, reduce structural integrity offered by roots, destroy reptile nesting areas, and diminish habitat for avifauna (NRC 2002). For example, willow habitat for the southwestern willow fly catcher (*Empidonax traillii extimus*) is threatened on the heavily modified Rio Grande in Colorado and on other southwestern rivers in the United States (Graf et al. 2002). Similarly, unconsolidated bank substrate habitat for the bank swallow is destroyed by riprap.

Removal of riparian vegetation reduces shade and energy input from fallen leaves, and can raise stream water temperature and primary production (Quinn 2000). Loss of riparian vegetation also reduces the volume of wood in channels (Johnson et al. 2003). Habitat created by large wood in channels once provided essential overwintering habitat, but is now considered a key limiting factor for coho salmon and other fishes in the Pacific Northwest (Moyle 2002). Similarly, deforestation of tropical ecosystems limits wood availability to pools, which plays a role in structuring fish communities and increases aquatic diversity (Wright and Flecker 2004).

In streams where riparian vegetation is removed from banks to make way for erosion control structures, it follows that macroinvertebrate production, essential for aquatic food webs, is often diminished. The diversity and density of aquatic macroinvertebrates are higher in streams with wider riparian areas (Newbold et al. 1980). Roy and colleagues (2003) found the strongest relationships between various macroinvertebrate indices and forest cover within a 100-meter-wide riparian buffer zone. The ecological consequences of erosion control infrastructure in urbanizing rivers include the removal of vegetation and the loss of habitat for macroinvertebrates (Sudduth and Meyer 2006).

The use of erosion control structures that reduce deleterious effects on biota has advanced in the past few decades (Downs and Gregory 2004, Chin and Gregory 2005). Recent engineering approaches often incorporate vegetation in the structure design to reduce habitat degradation. Despite inclusion of large woody debris or living vegetation in some channel bank infrastructure, however, two important geomorphic issues arise: (1) channel bank infrastructure fundamentally alters geomorphic processes, and (2) structures may be ineffective, especially over the long term. Gilvear (2000) noted that bank erosion-control structures might fail when flood magnitudes exceed the discharges for which the structures are designed, or when processes such as channel migration are ignored. Because hard structures, even when they incorporate vegetation, impede geomorphic adjustment processes, they can lead to more damaging erosion events locally or in downstream reaches (Henderson 1986, Arnaud-Fassetta et al. 2005). Nevertheless, bank erosion-control structures can be effective in minimizing land loss over decadal timescales (Shields et al. 1995), although some evidence suggests that they are ineffective over multidecadal timescales and potentially have secondary effects (Larsen and Greco 2002, Thompson 2002). Thus, the geomorphic and ecological effects of channel bank infrastructure may be severe, although generally little monitoring is done to assess the effects or the effectiveness of projects that use channel bank infrastructure (Kondolf and Micheli 1995, Harris et al. 2005). As a management strategy, construction of channel bank infrastructure addresses only one component (bank erosion) of the full spectrum of habitat degradation and environmental problems found in developing watersheds—problems such as channel incision, removal of riparian vegetation, changes in hydrology, and pollution (Booth 2005, Meyer et al. 2005).

Shortcomings of current riverbank management

The causes of bank erosion are complex and often combine disparate geomorphic processes, such as fluvial erosion and mass wasting. However, riverbank stabilization structures often are designed to address only fluvial erosion, and thus fail on banks where mass wasting processes are predominant (figure 3).

Failure to understand bank erosion processes and functions. Fluvial erosion and mass wasting processes both lead to channel migration, a mechanism that maintains the ecological structure of riparian ecosystems (Bravard and Gilvear 1996) and the width adjustments necessary for river morphology to adapt to incision and episodic or variable sediment loads. Thus, bank erosion is integral to sediment transfer, river evolution, and ecosystem sustainability. In fact, bank erosion is a necessary process that may bring about eventual channel stability in urbanizing systems (Chin 2006). Henshaw and Booth (2000) suggested that construction of channel bank infrastructure should not be an immediate response in watersheds with a low level of urban development or where development is in progress, because hard structures may prevent the adjustments required for a channel to stabilize on its own. Further, Sudduth and Meyer (2006) suggested that total elimination of bank erosion should not be a goal of habitat restoration because limiting bank erosion simplifies complex natural channel morphology. Thus, the short-term benefits of bank erosion-control infrastructure on geomorphic processes and ecological function may come with relatively high long-term environmental costs.

Failure to consider bank erosion management at the appropriate scale. Channel bank infrastructure constructed at the local scale is often implemented structure by structure over the short term by individual landowners or by government or public agencies. Such practices do not consider bank erosion in the geomorphic or ecological context of the appropriate temporal and spatial scales—namely, long-term and system-wide scales.

Couper (2004) pointed out the importance of defining and linking scales because rates of erosion measured over the course of long-term river evolution contrast with rates documented for a short period of time within a channel reach. Various river resource and regulatory agency management guidelines (Flosi et al. 1998, McCullah and Gray 2005, EPA 2007) address bank erosion processes at the scale of an identified erosion site even though channel bank erosion is a river management issue best addressed at the watershed or ecosystem scale. Rarely is the spatial extent or temporal frequency of bank erosion processes documented in the comprehensive manner necessary for long-term, watershed system–scale analyses. Moreover, the potential effects of global warming on geomorphic processes (Tucker and Slingerland 1997, Goudie 2006) are rarely considered in bank erosion management. Failure to consider the spatial distribution, extent, and temporal frequency of both bank erosion and bank erosion-control infrastructure at the scale of the watershed over the long term precludes understanding of the influence of bank erosion processes on both geomorphic and ecological functions. Without considering these scales, understanding the secondary and cumulative effects of bank infrastructure is not possible.

For example, bank erosion is a critical concern within California's Sacramento River system because eroding stream banks threaten levee integrity. The US Fish and Wildlife Service (USFWS 2000) estimates that more than half of the river's banks on the lower 310 kilometers of the Sacramento River were riprapped during the past 40 years as part of the Sacramento River Bank Protection Project. Governor Schwarzenegger brought the erosion issue to the policy forefront in the 2006 declaration of a state of emergency for California's levee system. The emergency declaration directed the California Department of Water Resources (DWR) to identify and repair erosion sites in the state-federal project levee system "in order to prevent catastrophic flooding and loss of life." More than 100 erosion sites were documented along the main stem (excluding tributaries) of the Sacramento River in 2005, and more than 20 were reported as critical, with bank erosion progressively threatening levee integrity. In 2006, DWR and the US Army Corps of Engineers undertook 21 levee repairs on the river's main stem (DWR 2006). Maintaining the dynamic Sacramento River in response to episodic erosion mechanisms carries a great economic and environmental cost—in particular to the bank swallow—and as a river management approach, it is not currently sustainable. Nor will the system be sustainable in the future, should flood discharges in the Central Valley increase, as they are predicted to do as a result of climate change (Dettinger et al. 2004).

Failure to consider secondary effects. Channel bank infrastructure that limits the geomorphic processes that transfer sediment through dynamic natural systems may lead to undesirable secondary effects. For example, such structures may reduce sediment supply to channels. In addition, such structures can shift the locus of erosion as the river adjusts to the hardened area that the structure presents. Bank structures can narrow channel width, leading to higher flow strength and thus

Figure 3. Failure of sacrete bank erosion control structure because of high pore-water pressure in the bank behind the structure. Photograph: Joan L. Florsheim.

initiating a cycle in which the increased flow strength, in combination with reduced sediment supply, leads to channel deepening. The deepening may in turn increase bank height and accelerate bank erosion. Thus, in deepening channels, bank structures may become ineffective and may be destabilized by continuing erosion.

Failure to consider long-term and cumulative effects. In many fluvial systems, hard bank erosion-control structures already exist, products of previous erosion control efforts. Over time, these structures are joined by new ones erected to armor new erosion sites, producing assorted generations and styles of channel bank infrastructure, all within short reaches of the same channel. As each new structure interacts with geomorphic processes, bank erosion may shift to a new location, creating a chain reaction in which each new section of eroded bank is armored with new erosion control structures. One consequence of channel bank infrastructure that has long-term effects (beyond the design life of the structure) is that a structure may preclude future restoration attempts designed to incorporate self-design and self-sustaining habitats (figure 4). If cumulative long-term effects are not taken into consideration, the result could be progressive construction of channel bank infrastructure that, although intended to limit local bank erosion, tends toward eventual channelization of entire river systems.

Alternatives to channel bank infrastructure

Alternatives to channel bank infrastructure that provide a vision for sustainable river management must accommodate dynamic geomorphic processes that sustain ecological functions and habitat on channel banks. Figure 5 identifies management actions and alternatives necessary to accommodate bank erosion processes. These actions are intended to reverse past and current failures in riverbank management. First, it is imperative to understand bank erosion processes and functions in diverse riparian systems. This requires the identification and assessment of geomorphic

Figure 4. Bank erosion processes continuing behind large rock riprap originally placed at the base of the bank. If left isolated in the channel, riprap may become an impediment to future restoration. Photograph: Joan L. Florsheim.

processes, ecological functions, and the likely effects of channel bank infrastructure. Second, it is imperative to consider bank erosion management at the appropriate temporal and spatial scales—that is, at the watershed scale over the long term, even if the extent of local erosion is small. Doing so will help avoid treating the symptom rather than the cause of erosion. Third, the secondary effects of any approach to modulate erosion must not interfere with the potential for future restoration initiatives or with the natural river adjustments needed to maintain equilibrium. Finally, to conserve aquatic and terrestrial riparian habitat, long-term and cumulative ecological and geomorphic effects must be considered in the context of the legacy of past and potential future projects.The four alternative approaches discussed below provide a conceptual framework to help planners and policymakers address bank erosion issues (figure 5).

Dynamic-process conservation areas are defined here as zones with sufficient area to accommodate bank erosion along with other dynamic processes, such as flooding. This approach accommodates geomorphic processes active within a watershed's sediment transport system over the long-term instead of focusing on the local scale, at which processes are episodic and erosion is transient. Designation of the appropriate extent of dynamic-process conservation areas could be accomplished through integrated ecological and geomorphic scenarios for restoration. Process-based restoration (Wohl et al. 2005) promotes floodplain functions, such as flooding, and inclusion of secondary channels, floodplain lakes, or marshes that rely on connectivity (Buijse et al. 2002). Dynamic-process conservation areas support connectivity and conservation of habitat and services needed by organisms that utilize riparian areas (see table 1). This alternative could be achieved through the development of long-term strategies to acquire riparian and adjacent land, land-use planning within riparian-centric governance structures, and multiagency and private or nongovernmental organization partnerships.

An *erosion easement* is a legally binding restriction placed on private or public riparian land to allow bank erosion processes to operate. Easements to accommodate geomorphic processes and ecological functions could be a component of a riparian buffer that promotes habitat or ecosystem services (see table 1). Designating the appropriate extent of an erosion easement depends on a thorough assessment of bank erosion processes and fluvial system evolution at the watershed scale; Piegay and colleagues (2005) addressed methods of quantifying appropriate widths on the basis of geomorphic processes. As with strategies to develop dynamic-process conservation areas, implementation of this alternative would require long-term land-use planning in order to purchase land and obtain landowner agreements along both riverbanks within riparian corridors.

Elimination of direct stressors, the impacts caused by human activities or land uses that directly cause or accelerate bank erosion processes, is a relatively simple way to enhance bank stability. For example, grazing is a stressor that leads to riparian vegetation denudation; however, the impact may be eliminated through exclusionary fencing, which keeps cattle from damaging stream banks and riparian vegetation in rangeland. This option could be implemented in concert with all the other alternatives to decelerate bank erosion through land-use planning, best-management practice guidelines, or ordinances.

Nonstructural approaches are those that do not contain hard elements such as large rocks, concrete blocks, root wads, or large woody debris as construction materials. Such approaches

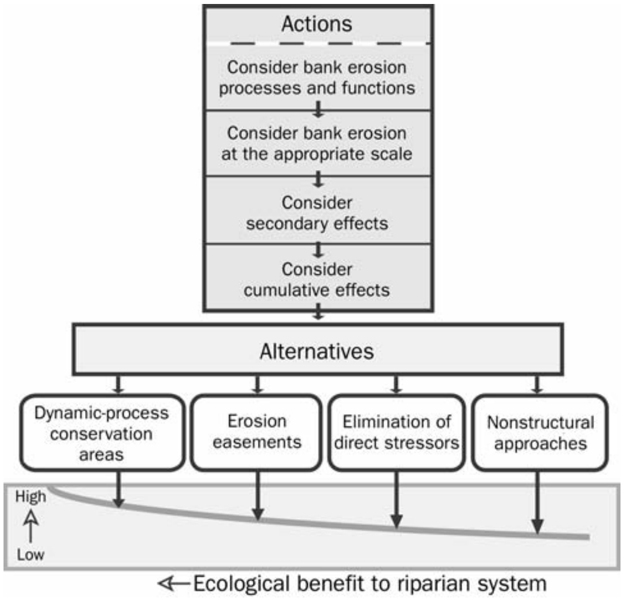

Figure 5. Framework for alternatives to channel bank infrastructure. Dynamic-process conservation areas protect the linkage between river channels and adjacent landscapes, and provide the highest ecological benefit to riparian ecosystems. The other alternatives provide ecological benefits to the degree that they accommodate the geomorphic processes that sustain them.

include planting native vegetation without inclusion of hard elements. In particular, willow sprigs are commonly planted to promote root networks that bolster bank strength. Fences are sometimes constructed of willow branches, which later take root and sprout. Such alternatives may not completely arrest bank erosion, but they may be beneficial when the management aim is short-term moderation of erosion processes that does not inhibit the potential for future restoration or preclude the long-term benefits of alternative management approaches such as dynamic-process conservation areas or erosion easements.

Transcending traditional notions of bank erosion management

Pervasive construction of infrastructure to control bank erosion—a product of the notion that bank erosion is deleterious—has greatly diminished natural channel banks, geomorphic processes, and ecology. Management approaches that aim to arrest bank erosion at the scale of the transient erosion site are spatially constricted and consider only the short term. Hard structures may include vegetation, but they cannot sustain or restore riparian functions in urban or rural areas. Thus, the challenge is to develop sustainable bank management alternatives that preserve aquatic organisms and riparian plants, birds, and other wildlife (see table 1).

Differentiating between extensive or chronic bank erosion caused by human activities and land uses versus those caused by natural geomorphic processes and river evolution warrants attention in current science and management efforts. In order to protect riparian functions, river management and policy decisionmakers must determine when channel bank infrastructure is warranted on the basis of societal needs. Management decisions to implement channel bank infrastructure may be necessary in some cases to protect public safety; however, an appropriate starting point for discussion is science-based policy that promotes conservation and restoration of river processes and channel bank habitat and functions. Policy based on alternatives illustrated in figure 5 stems from a growing understanding that bank erosion is one geomorphic process inexorably linked with ecological functions. Global river management efforts (Brookes 1995, Kauffman et al. 1997, Piegay et al. 1997, Cals et al. 1998, Gilvear 2000, Golet et al. 2003, Palmer et al. 2005, F. Nakamura et al. 2006, K. Nakamura et al. 2006) and research that promotes conservation and restoration of natural processes support the alternatives presented in this article.

Conclusions

Bank erosion is one component of the natural disturbance regime of river systems and is integral to long-term geomorphic evolution of fluvial systems and to ecological sustainability. Bank erosion is therefore a desirable attribute of rivers. Four shortcomings in current river management are the (1) failure to understand and accommodate bank erosion processes and functions, (2) failure to consider bank erosion management at the appropriate scale, (3) failure to consider secondary effects of bank erosion-control infrastructure, and (4) failure to consider long-term and cumulative effects of bank erosion-control infrastructure. These failures are often synergetic. For example, rarely is the spatial extent or temporal frequency of bank erosion processes documented comprehensively enough to allow for long-term watershed-scale analyses that could illuminate the cumulative effects of channel bank infrastructure. Such analysis is necessary to avoid the progressive channelization of rivers. To address current and past management failures, we identify and discuss broad alternatives to accommodate geomorphic processes that promote riparian functions: (a) dynamic-process conservation areas, (b) erosion easements, (c) elimination of direct stressors, and (d) nonstructural approaches, such as those that include live vegetation that may moderate bank erosion processes without limiting long-term geomorphic evolution. Combining bank management goals that conserve diverse natural bank habitat and riparian vegetation with policies that accommodate erosion processes and watershed-scale sediment cycling and river evolution contributes to a strong basis for sustainable river management.

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References cited

Abernethy B, Rutherfurd ID. 1998. Where along a river's length will vegetation most effectively stabilize stream banks? Geomorphology 23: 55–75.

———. 2000. The effect of riparian tree roots on the mass-stability of riverbanks. Earth Surface Processes and Landforms 25: 921–937.

Allan JD. 2004. Landscapes and riverscapes: The influence of land use on stream ecosystems. Annual Review of Ecology, Evolution, and Systematics 35: 257–284.

Arnaud-Fassetta G, Cossart E, Fort M. 2005. Hydro-geomorphic hazards and impact of man-made structures during the catastrophic flood of June 2000 in the Upper Guil catchment (Queyras, Southern French Alps). Geomorphology 66: 41–67.

[ASCE] American Society of Civil Engineers Task Committee on River Width Adjustment. 1998. River width adjustment, I: Processes and mechanisms. Journal of Hydraulic Engineering 124: 881–902.

Bayley PB. 1991. The flood pulse advantage and the restoration of river-floodplain systems. Regulated Rivers: Research and Management 6: 75–86.

———. 1995. Understanding large river–floodplain ecosystems. BioScience 45: 153–158.

Benda L, Poff NL, Miller D, Dunne T, Reeves G, Pess G, Pollock M. 2004. The network dynamics hypothesis: How channel networks structure riverine habitats. BioScience 54: 413–427.

Benke AC, Wallace JB. 1990. Wood dynamics in coastal plain blackwater streams. Canadian Journal of Fisheries and Aquatic Sciences 47: 92–99.

Biosystems Analysis. 1994. Life on the Edge. Santa Cruz (CA): Biosystems Books.

Booth DB. 2005. Challenges and prospects for restoring urban streams: A perspective from the Pacific Northwest of North America. Journal of the North American Benthological Society 24: 724–737.

Bravard JP, Gilvear D. 1996. Hydrological and geomorphological structure of hydrosystems. Pages 98–116 in Petts GE, Amoros C, eds. Fluvial Hydrosystems. London: Chapman and Hall.

Brookes A. 1995. Challenges and objectives for geomorphology in UK river management. Earth Surface Processes and Landforms 20: 593–610.

Buffington JM, Lisle TE, Woodsmith RD, Hilton S. 2002. Controls on the size and occurrence of pools in coarse-grained forest rivers. River Research and Applications 18: 507–531.

Buijse AD, Coops H, Staras M, Jans LH, Van Geest GJ, Grifts RE, Ibelings BW, Oosterberg W, Roozen FCJM. 2002. Restoration strategies for river floodplains along large lowland rivers in Europe. Freshwater Biology 47: 889–907.

Cals MGR, Postma R, Buijse AD, Martejin ECL. 1998. Habitat restoration along the river Rhine in the Netherlands: Putting ideas into practice. Aquatic Conservation: Marine and Freshwater Ecosystems 8: 61–70.

Casagli N, Rinaldi M, Gargini A, Curini A. 1999. Pore water pressure and stream bank stability: Results from a monitoring site on the Sieve River, Italy. Earth Surface Processes and Landforms 24: 1095–1114.

Chin A. 2006. Urban transformation of river landscapes in a global context. Geomorphology 79: 460–487.

Chin A, Gregory KJ. 2005. Managing urban river channel adjustments. Geomorphology 69: 28–45.

Church M. 2000. Geomorphic thresholds in riverine landscapes. Freshwater Biology 47: 541–557.

Couper PR. 2004. Space and time in river bank erosion research: A review. Area 36: 387–403.

Darby SE, Thorne CR. 1996. Numerical simulation of widening and bed deformation of straight sand-bed rivers, I: Model development. Journal of Hydraulic Engineering 122: 184–193.

Dettinger MD, Cayan DR, Meyer MK, Jeton AE. 2004. Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American river basins, Sierra Nevada, California, 1900–2099. Climate Change 62: 283–317.

Downs PW, Gregory KJ. 2004. River Channel Management. London: Arnold.

[DWR] Department of Water Resources, State of California. 2006. Fact Sheet: 2006 Emergency Levee Repairs. (21 April 2008; *www.nwp.nl/showdownload.cfm?objecttype=mark.hive.contentobjects.download.pdf&objectid=311B7845-9BA3-ECE8-1F2BA2C0BE16E6B7*)

[EPA] Environmental Protection Agency. 2007. National Management Measures to Control Nonpoint Source Pollution from Hydromodification. (21 April 2008; *www.epa.gov/owow/nps/hydromod/index.htm*)

Everitt BL. 1968. Use of cottonwood in an investigation of the recent history of a flood plain. American Journal of Science 266: 417–439.

Fischenich JC. 1997. Hydraulic Impacts of Riparian Vegetation, Summary of the Literature. Vicksburg (MS): US Army Engineer Waterways Experiment Station. Technical Report EL-97-9.

Florsheim JL, Mount JF. 2002. Restoration of floodplain topography by sand splay complex formation in response to intentional levee breaches, lower Cosumnes River, California. Geomorphology 44: 67–94.

Flosi G, Downie S, Hopelain J, Bird M, Coey R, Collins B. 1998. California Salmonid Stream Habitat Restoration Manual. 3rd edition. Sacramento: California Department of Fish and Game Inland Fisheries Division. (21 April 2008; *https://nrmsecure.dfg.ca.gov/FileHandler.ashx?DocumentID=3600*)

Friedman JM, Auble GT. 2000. Floods, flood control, and bottomland vegetation. Pages 219–237 in Wohl E, ed. Inland Flood Hazards: Human, Riparian, and Aquatic Communities. Cambridge (United Kingdom): Cambridge University Press.

Garrison BA, Humphrey JM, Laymon SA. 1987. Bank swallow distribution and nesting ecology on the Sacramento River, California. Western Birds 18: 71–76.

Gilvear DJ. 2000. Fluvial geomorphology and river engineering: Future roles utilizing a fluvial hydrosystems framework. Geomorphology 31: 229–245.

Golet GH, et al. 2003. Using science to evaluate restoration efforts and ecosystem health on the Sacramento River Project, California. Pages 368–385 in Faber PM, ed. California Riparian Systems: Processes and Floodplain Management, Ecology, and Restoration. Proceedings of the Riparian Habitat and Floodplains Conference; 12–15 March 2001, Sacramento, California.

Gomi T, Sidel RC, Richardson JS. 2002. Understanding processes and downstream linkages of headwater systems. BioScience 52: 905–916.

Goudie AS. 2006. Global warming and fluvial geomorphology. Geomorphology 79: 384–394.

Graf WL. 2005. Platte River: Water for people and wildlife. Pages 45–453 in Stewart BA, Howell TA, eds. Encyclopedia of Water Science. New York: Marcel Dekker. (16 April 2008; *www.dekker.com/sdek/abstract~db=enc~content=a713595874*)

Graf WL, Stromberg J, Valentine B. 2002. The fluvial hydrologic and geomorphic context for the recovery of the endangered southwestern willow flycatcher. Geomorphology 47: 169–188.

Gregory SV, Swanson FJ, McKee A, Cummins KW. 1991. An ecosystem perspective of riparian zones. BioScience 41: 540–551.

Harding JH. 1997. Amphibians and Reptiles of the Great Lakes Region. Ann Arbor: University of Michigan Press.

Harris RR, Kocher SD, Gerstein JM, Olson C. 2005. Monitoring the Effectiveness of Riparian Vegetation Restoration. Berkeley: University of California Center for Forestry. (21 April 2008; *www.cnr.berkeley.edu/.../DFG/Monitoring%20the%20Effectiveness%20of%20Riparian%20Vegetation%20Restorat.pdf*)

Hasegawa K. 1989. Studies on qualitative and quantitative prediction of meander channel shift. Pages 215–235 in Ikeda S, Parker G, eds. River Meandering (Water Resources Monograph). Washington (DC): American Geophysical Union.

Henderson JE. 1986. Environmental designs for stream bank protection projects. Water Resources Bulletin 22: 549–558.

Henshaw PC, Booth DB. 2000. Natural restabilization of stream channels in urban watersheds. Journal of the American Water Resources Association 36: 1219–1236.

Hooke JM. 1979. An analysis of the processes of river bank erosion. Journal of Hydrology 42: 39–62.

Hupp CR, Osterkamp WR. 1996. Riparian vegetation and fluvial geomorphic processes. Geomorphology 14: 277–295.

Johannesson J, Parker G. 1989. Linear theory of river meanders. Pages 181–214 in Ikeda S, Parker G, eds. River Meandering (Water Resources Monograph). Washington (DC): American Geophysical Union.

Johnson LB, Breneman DH, Richards C. 2003. Macroinvertebrate community structure and function associated with large wood in low gradient streams. River Research and Applications 19: 199–218.

Junk WJ, Bayley PB, Sparks RE. 1989. The flood pulse concept in river-floodplain systems. Pages 110–127 in Dodge DP, ed. Proceedings of the International Large River Symposium. Ottawa (Canada): Canadian Special Publication of Fisheries and Aquatic Sciences 106.

Kauffman JB, Beschta RL, Otting N, Lytjen D. 1997. An ecological perspective of riparian and stream restoration in the western United States. Fisheries 22: 12–24.

Kondolf GM, Micheli ER. 1995. Evaluating stream restoration projects. Environmental Management 19: 1–15.

Kondolf GM, et al. 2006. Process-based ecological river restoration: Visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages. Ecology and Society 11: 5. (21 April 2008; *www.ecologyandsociety.org/vol11/iss2/art5*)

Larsen EW, Greco SE. 2002. Modeling channel management impacts on river migration: A case study of Woodson Bridge State Recreation Area, Sacramento River, California, USA. Environmental Management 30: 209–224.

Lawler DM. 1993. The measurement of bank erosion and lateral channel change: A review. Earth Surface Processes and Landforms 18: 777–821.

Lawler DM, Thorne CR, Hooke JM. 1997. Bank erosion and instability. Pages 137–172 in Thorne CR, Hey RD, Newson MD, eds. Applied Fluvial Geomorphology for River Engineering and Management. Chichester (United Kingdom): Wiley.

Leopold LB, Wolman MG. 1957. River Channel Patterns: Braided, Meandering and Straight. Washington (DC): US Government Printing Office. US Geological Survey Professional Paper 282-B.

Lisle TE. 1989. Sediment transport and resulting deposition in spawning gravels, north coastal California. Water Resources Research 25: 1303–1319.

McCullah J, Gray D. 2005. Environmentally Sensitive Channel- and Bank-Protection Measures. Washington (DC): Transportation Research Board. National Cooperative Highway Research Program NCHRP Report 544. (21 April 2008; *www.trb.org/news/blurb_Detail.asp?ID=5617*)

Meyer JL, Paul MJ, Taulbee WK. 2005. Stream ecosystem function in urbanizing landscapes. Journal of the North American Benthological Society 24: 602–612.

Millar RG. 2000. Influence of bank vegetation on alluvial channel patterns. Water Resources Research 36: 1109–1118.

Montgomery DR. 1997. What's best on banks? Nature 388: 328–329.

Moyle PB. 2002. Inland Fishes of California. Berkeley: University of California Press.

Naiman RJ, Bilby RE. 2001. River Ecology and Management. New York: Springer.

Naiman RJ, Decamps H, Pollock M. 1993. The role of riparian corridors in maintaining regional biodiversity. Ecological Applications 3: 209–212.

Naiman RJ, Decamps H, McClain ME. 2005. Riparia Ecology, Conservation, and Management of Streamside Communities. Amsterdam: Elsevier.

Nakamura F, Swanson FJ, Wondzill SM. 2006. Disturbance regime of stream and riparian systems, a disturbance-cascade perspective. Hydrological Processes 14: 2849–2860.

Nakamura K, Tockner LK, Amano K. 2006. River and wetland restoration: Lessons from Japan. BioScience 56: 419–429.

[NRC] National Resource Council. 2002. Riparian Areas: Functions and Strategies for Management. Washington (DC): National Academy Press.

Newbold JD, Erman DC, Roby KB. 1980. Effects of logging on macroinvertebrates in streams with and without buffer strips. Canadian Journal of Fisheries and Aquatic Science 37: 1077–1085.

Odgaard AJ. 1987. Stream bank erosion along two rivers in Iowa. Water Resources Research 23: 1225–1236.

Osman AM, Thorne CR. 1988. Riverbank stability analysis, I: Theory. Journal of Hydraulic Engineering 114: 134–150.

Palmer MA, et al. 2005. Standards for ecologically successful river restoration. Journal of Applied Ecology 42: 208–217.

Piegay H, Cuaz M, Javelle E, Mandier P. 1997. Bank erosion management based on geomorphological, ecological and economic criteria on the Galuare River, France. Regulated Rivers Research and Management 13: 433–448.

Piegay H, Thevenet A, Citterio A. 1999. Input, storage and distribution of large woody debris along a mountain river continuum, the Drome River, France. Catena 35: 19–39.

Piegay H, Darby SE, Mosselman E, Surian N. 2005. A review of techniques available for delimiting the erodible river corridor: A sustainable approach to managing bank erosion. River Research and Applications 21: 773–789.

Pizzuto JE, Mecklenburg TS. 1989. Evaluation of a linear bank erosion equation. Water Resources Research 25: 1005–1013.

Quinn JM. 2000. Effects of pastoral development. Pages 208–229 in Collier KJ, Winterbourn MJ, eds. New Zealand Stream Invertebrates: Ecology and Implications for Management. Christchurch (New Zealand): Caxon.

Ralph SC, Poole GC, Conquest LL, Naiman RJ. 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. Canadian Journal of Fisheries and Aquatic Science 51: 37–51.

Roy AH, Rosemond AD, Paul MJ, Leigh D, Wallace JB. 2003. Stream macroinvertebrate response to catchment urbanisation (Georgia, U.S.A.). Freshwater Biology 48: 329–346.

Sabo JL, Power ME. 2002. River-watershed exchange: Effects of riverine subsidies on riparian lizards and their terrestrial prey. Ecology 83: 1860–1869.

Salo J, Killiola R, Hakkinen I, Makinen Y, Niemela P, Puhakka M, Coley PD. 1986. River dynamics and the diversity of Amazon lowland forest. Nature 322: 254–258.

Sedell JR, Beschta RL. 1991. Bringing back the "bio" in bioengineering. American Fisheries Society Symposium 10: 160–175.

Shields FD, Bowie AJ, Cooper CM. 1995. Control of stream bank erosion due to bed degradation with vegetation and structure. Water Resources Bulletin 31: 475–489.

Simon A. 1989. A model of channel response in disturbed alluvial channels. Earth Surface Processes and Landforms 14: 11–26.

Simon A, Collinson A. 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on stream bank stability. Earth Surface Processes and Landforms 27: 527–546.

Simon A, Curini A. 1998. Pore pressure and bank stability: The influence of matric suction. Pages 358–363 in Abt SR, Young-Pezeshk J, Watson CC, eds. Water Resources Engineering '98, vol. 1. Reston (VA): American Society of Civil Engineers.

Simon A, Curini A, Darby SE, Langendoen EJ. 1999. Streambank mechanics and the role of bank and near-bank processes in incised channels. Pages 123–152 in Darby SE, Simon A, eds. Incised River Channels: Processes, Forms, Engineering and Management. London: Wiley.

Stanford JA, Ward JV, Liss WJ, Frissell CA, Williams RN, Lichatowich JA, Coutant CC. 1996. A general protocol for restoration of regulated rivers. Regulated Rivers: Research and Management 12: 391–413.

Sudduth EB, Meyer JL. 2006. Effects of bioengineered streambank stabilization on bank habitat and macroinvertebrates in urban streams. Environmental Management 38: 218–226.

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

Thorne CR. 1982. Processes and mechanisms of river bank erosion. Pages 227–221 in Hey RD, Bathurst JC, Thorne CR, eds. Gravel-Bed Rivers. Chichester (United Kingdom): Wiley.

———. 1999. Bank processes and channel evolution in the incised rivers of north-central Mississippi. Pages 97–121 in Darby SE, Simon A, eds. Incised River Channels: Processes, Forms, Engineering and Management. London: Wiley.

Thorne CR, Osman AM. 1988. Riverbank stability analysis. II: Application. Journal of Hydraulic Engineering 114: 151–172.

Thorne CR, Tovey NK. 1981. Stability of composite river banks. Earth Surface Processes and Landforms 6: 469–484.

Trimble SW. 1997. Contribution of stream channel erosion to sediment yield from an urbanizing watershed. Science 278: 1442–1444.

Tucker GE, Slingerland R. 1997. Drainage basin responses to climate change. Water Resources Research 33: 2031–2047.

[USFWS] United States Fish and Wildlife Service. 2000. Impacts of Riprapping to Ecosystem Functioning, Lower Sacramento River, California. Sacramento (CA): US Fish and Wildlife Service. (22 April 2008; *www.fws.gov/sacramento/hc/reports/sac_river_riprap.pdf*)

Vogt RC. 1981. Natural History of Amphibians and Reptiles of Wisconsin. Milwaukee (WI): Milwaukee Public Museum.

Ward JV, Stanford JA. 1995. Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. Regulated Rivers: Research and Management 11: 105–119.

Ward JV, Tockner K. 2001. Biodiversity: Towards a unifying theme for river ecology. Freshwater Biology 46: 807–819.

Wohl E, Angermeier PL, Bledsoe B, Kondolf GM, MacDonnell L, Merritt DM, Palmer MA, Poff NL, Tarboton D. 2005. River restoration. Water Resources Research 41: W10301.

Wood PJ, Armitage PD. 1997. Biological effects of fine sediment in the lotic environment. Environmental Management 21: 203–217.

Wright JP, Flecker AS. 2004. Deforesting the riverscape: The effects of wood on fish diversity in a Venezuelan piedmont stream. Biological Conservation 120: 439–447.

Wyzga B, Zawiejska J. 2005. Wood storage in a wide mountain river: Case study of the Czarny Dunajec, Polish Carpathians. Earth Surface Processes and Landforms 30: 1475–1494.

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