Setting Goals in River Restoration: When and Where Can the River “Heal Itself”?

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Ecological research demonstrates that the most diverse, ecologically valuable river habitats are those associated with dynamically migrating, flooding river channels. Thus, allowing the river channel to “heal itself” through setting aside a channel migration zone, or erodible corridor, is the most sustainable strategy for ecological restoration. The width and extent of channel can be set from historical channel migration and model predictions of future migration. However, the approach is not universally applicable because not all rivers have sufficient stream power and sediment load to reestablish channel complexity on a time scale of decades to years, and many are restricted by levees and infrastructure on floodplains that preclude allowing the river a wide corridor. A bivariate plot of stream power/sediment load (*y* axis) and degree of encroachment (urban, agricultural, etc.) (*x* axis) is proposed as a framework for evaluating the suitability of various restoration approaches. Erodible corridors are most appropriate where both the potential for channel dynamics and available space are high. In highly modified, urban channels, runoff patterns are altered, and bottomlands are usually encroached by development, making a wide corridor infeasible. There, restoration projects can still feature deliberately installed components such as riparian trees and trails with the social benefits of public education and providing recreation to underserved families. Intermediate approaches include partial restoration of flow and sediment load below dams and “anticipatory management”: sites of bank erosion are anticipated, and infrastructure is set back in advance of floods, to prevent “emergency” dumping of concrete rubble down eroding banks during high water.

1. INTRODUCTION

Ecological research demonstrates that the most diverse, ecologically valuable river habitats are those associated with dynamically migrating, flooding river channels [*Ward and Stanford*, 1995; *Ward et al.*, 1999, *Naiman et al.*, 2005]. Yet eroding banks may create conflicts with human uses, and there is a long tradition of measures to protect riverbanks from erosion. Ironically, many of the projects funded as “restoration” in North America have been oriented toward “stabilizing” banks, i.e., arresting bank erosion, which is implicitly assumed to be negative. The most common projects involve use of large logs, root wads, and boulders to stabilize eroding banks, along with planting of willow (*Salix* spp.) and other woody riparian plants to stabilize banks [*Bernhardt et al.*, 2005]. The underlying conflict with habitat needs for fish and other organisms is commonly ignored.

There is increasing recognition that the most effective and sustainable approach to restoring the ecological value of rivers is to let them “heal themselves” by facilitating or restoring the physical processes of flooding, sediment transport, erosion, deposition, and channel change that create and maintain complex river forms [*Beechie et al.*, 2010]. This requires both room for the river to move and flood and a

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sufficiently dynamic flow regime and sediment load to permit the channel to move and change in response to floods. In rivers whose flow regimes and sediment loads are still reasonably intact, self-healing by rivers can often be achieved by giving the river room to erode and flood, setting human infrastructure back to avoid conflicts with active channel movement [*Piégay et al.*, 2005]. This approach usually has the added virtue of reducing maintenance costs that result from conflicts between infrastructure and dynamic river processes.

Where the flow and sediment regimes have been substantially altered, simply setting back from the river will not suffice. In such cases, it may be possible to restore (at least partially) some of the natural processes, e.g., to adjust reservoir operations to restore a more natural flow regime (including seasonally appropriate high flows) and to add sediment below dams to compensate for loss of sediment load to trapping in the reservoir. Downstream of large, important reservoirs, it is usually possible to return the river flow regime only partially to its natural seasonal and interannual flow pattern. In highly urbanized settings, it may be impossible to restore process to any significant degree because space is lacking to expand the stream corridor, and the runoff patterns from the urbanized catchment have been so altered that scouring floods occur frequently, resulting in simplification of channel form.

Thus, the question is posed: When can we allow rivers to the freedom to move and develop their own complex habitats, and when is this approach impossible? This chapter provides an overview of the role of active channel migration and flooding in creating and maintaining aquatic and riparian habitat in rivers, and reviews a range of restoration approaches, from allowing the river a wide corridor in which to develop complex channel morphology to active channel reconstruction, as a function of stream power and sediment load, and availability of space for the river. The illustrations draw upon studies from many rivers and use the Sacramento River, California, as a recurring example.

2. ECOLOGICAL VALUE OF DYNAMIC RIVER CHANNELS

2.1. Channel Complexity

The process of bank erosion creates channel complexity in many river systems [*Florsheim et al.*, 2008] (Figure 1). As the outside bank erodes, the deep pools and undercut banks at its base provide cover, holding habitat for large fish, and thermal refugia during hot weather. Bank erosion also recruits large wood, as (often mature, late-successional stage species) trees fall into the channel, providing important complexity to many river systems [*Gurnell et al.*, 2002]. On many North American rivers, including the Sacramento, bare vertical banks of cohesive silt provide habitat for bank swallows (*Riparia riparia*) and other bird species, for which the banks offer a refuge inaccessible to land-based predators. Maintaining the verticality of the banks requires active bank erosion; no-longer actively eroding banks evolve from vertical to sloping profiles, along which predators can access nests.

As channels laterally migrate, scour and deposition produce bare sand and gravel bars, providing surfaces for colonization by pioneer woody riparian vegetation species. In the meantime, older established surfaces evolve through vegetative succession into later-successional-stage woodlands. The young plants of pioneer species that establish on newly deposited bars provide a marked contrast in vegetative structure to the mature, late-successional trees established on older, higher surfaces, and thus provide a range of habitats for birds and other riparian-dependent animals [*California State Lands Commission*, 1993]. The result is a palimpsest of diverse habitat types, a pattern that is constantly shifting from year to year, but which always retains a diverse mixture of vegetative structures and open bars, and which thus provides habitat for a wide range of faunal species and life stages [*Stanford et al.*, 2005].

Geomorphically produced channel complexity is also expressed, in part, as shallow water, seasonally inundated habitats on channel margins. These habitats form as a function of overbank flows (e.g., floodplains) and point bar dynamics (e.g., scour channels on point bars and edge habitat). Shallow water areas provide important rearing habitat for juvenile salmon [*Lister and Genoe*, 1970; *Bjornn and Reiser*, 1991] and have been documented to provide the best juvenile rearing habitat for Chinook salmon (*Oncorhynchus tshawytscha*) in the Sacramento River basin [*Sommer et al.*, 2001].

2.2. Former Channels and Other Floodplain Water Bodies

Oxbow lakes, sloughs, and side channels and other off-channel water bodies are created by channel cutoff or channel change and typically go through an evolutionary sequence in which sedimentation gradually converts them from aquatic to terrestrial environments [*Piégay et al.*, 2002]. The initial creation of an abandoned channel occurs through geomorphic processes such as development of tortuous meander bends leading to neck cutoff, overbank flood flows shortcutting bends and leading to chute cutoff, or avulsion caused by debris jams or by sedimentation and abandonment of braid channels. In one of many such examples, a meander bend along the Sacramento River near Hamilton City was cut off during a high flow in 1970 as a chute channel across the

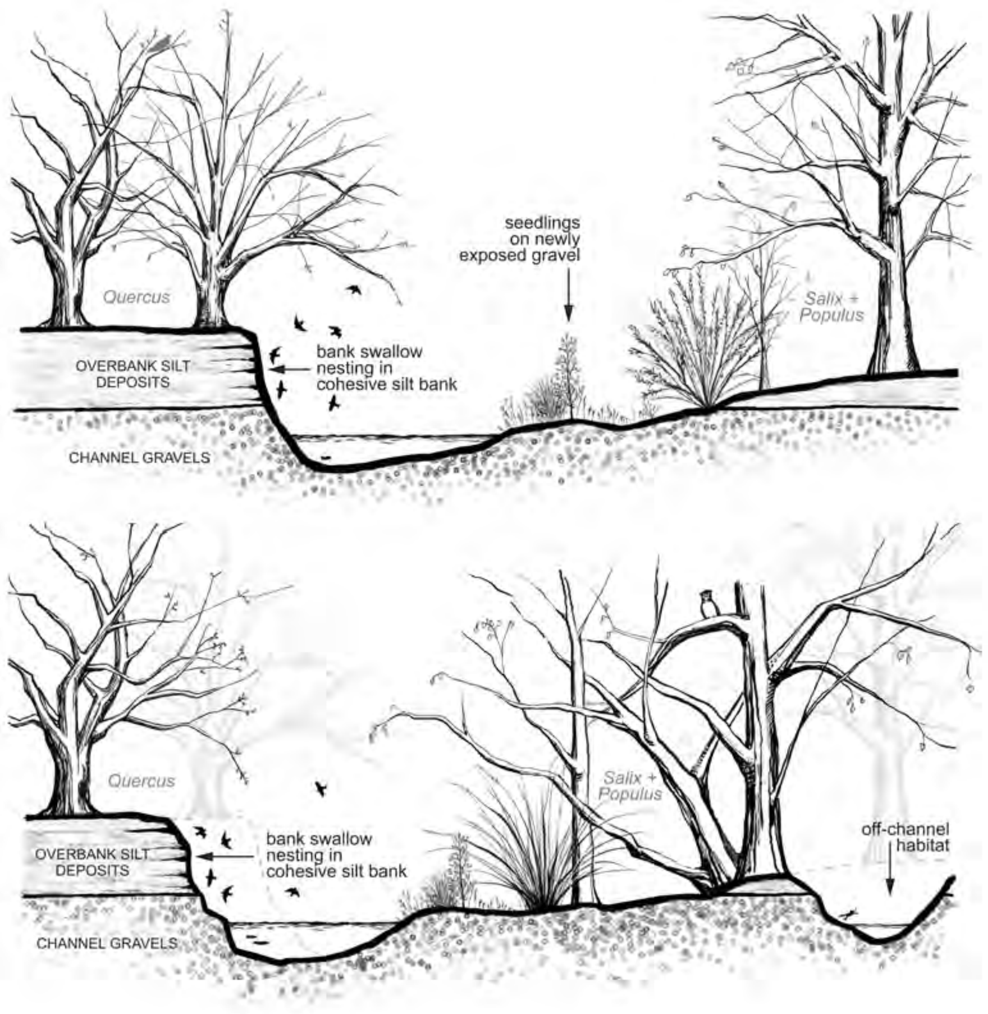

Figure 1. Lateral channel migration and its relation to riparian and aquatic habitats, Sacramento River (generalized relations).

floodplain grew in dimensions, and by the time the flood receded, the main flow of the river had been captured by this cutoff channel (Figure 2). Meander cutoffs on the Sacramento are dominantly chute cutoffs, probably owing to extensive clearing of riparian forests from floodplains, which has decreased hydraulic roughness and increased overbank flow velocities, accelerating erosion and expansion of chute channels [*Brice*, 1977]. The sinuosity of the Sacramento River has not measurably changed since the late nineteenth century, but the size of cutoffs after about 1962 was significantly smaller, probably reflecting changes in flow regime and sediment supply due to dam construction and extensive bank revetments [*Constantine and Dunne*, 2008; *Michalková et al.*, 2011].

Thus, abandoned channels owe their origins to dynamic channel migration and change. Once created, they evolve through sedimentation, vegetation colonization and succession, and the buildup of organic detritus from aquatic vegetation into progressively more terrestrial environments. The evolution of oxbow lakes is illustrated in Figure 3, which begins with the flowing river channel at the bottom of the diagram. During the initiation of a meander bend cutoff, the original main channel transitions to a side channel that is hydrologically connected at both ends. The upstream inlet to the side channel usually plugs with sediment first, creating an oxbow slough. When the downstream outlet of the side channel plugs as well, the feature becomes an oxbow lake, which begins as a fully aquatic feature. As the oxbow lake

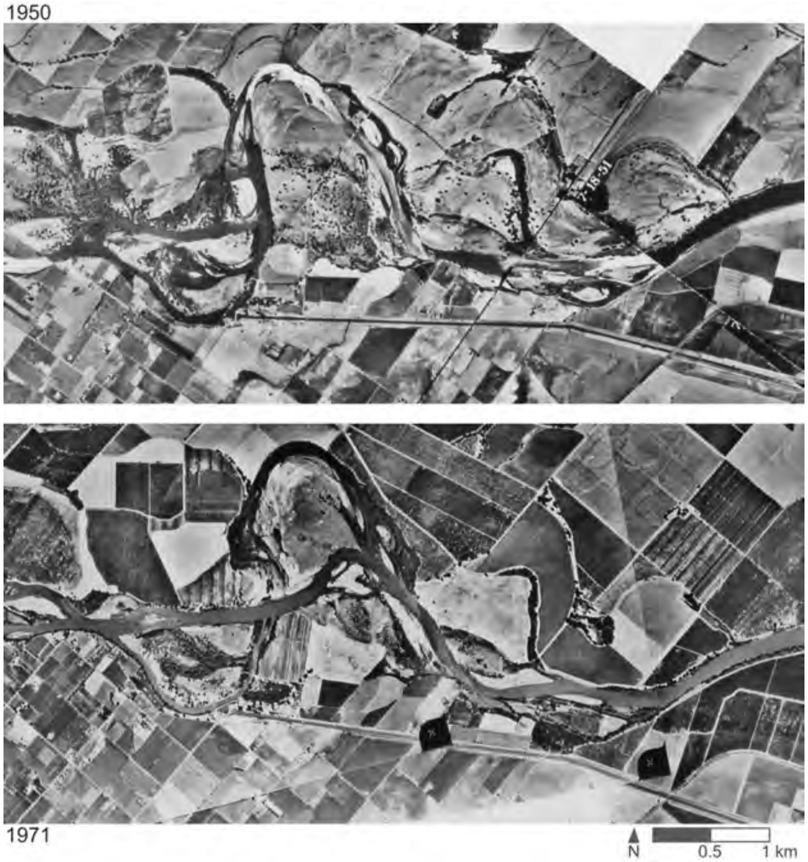

Figure 2. Meander cutoff on the Sacramento River near km 323–328, as shown on historical aerial photographs. The well-developed leftward (eastward) meander bend in the top (1951) aerial photograph cut off in the flood of 1970, leaving the former bend as an oxbow lake in the bottom (1970) photograph. The 1951 photography is by U.S. Bureau of Reclamation; 1970 photography is by U.S. Army Corps of Engineers.

fills with sediment and vegetation establishes and undergoes succession, the oxbow lake evolves from fully aquatic to progressively more terrestrial habitat, with each stage providing distinct habitats (e.g., in vegetative structure, soil conditions, frequency, and duration of inundation) that meet habitat needs for different faunal species and life stages.

The rate at which a former channel evolves from fully aquatic to terrestrial determines its persistence as aquatic habitat and its value to different species. Within the Sacramento River corridor, some oxbow lakes (such as Packer Lake) have persisted as open-water habitat for over a century, while others (such as Hartley Island) completely filled within decades. Oxbow lakes and other off-channel water bodies provide important (and diverse) habitats, and can be regarded as ecological "hot spots" on the landscape [*Amoros et al.*, 2005]. On the Sacramento River, California, off-channel water bodies provide critical habitat for a variety of native species, such as western pond turtle (*Clemmys marmorata*), Sacramento sucker (*Catostomus occidentalis*), Sacramento pikeminnow (*Ptychochelilus grandis*), California roach (*Hesperoleucus symmetricus*), and Chinook salmon (*O. tshawytscha*) [*Kondolf and Stillwater Sciences*, 2007].

2.3. Effects of Reduced Channel Dynamics on Habitat Complexity

The complex in-channel features and floodplain water bodies form, persist, and evolve as a function of flow and sediment dynamics. In many rivers, these have been altered dramatically by the emplacement of upstream reservoirs and rock revetment along the banks. Reservoir regulation typically reduces the frequency and magnitude of high flows that drive bank erosion and meander migration. Even more important are bank revetments, designed specifically to halt bank erosion and meander migration, which thus prevent creation of new cutoffs. However, other human actions may

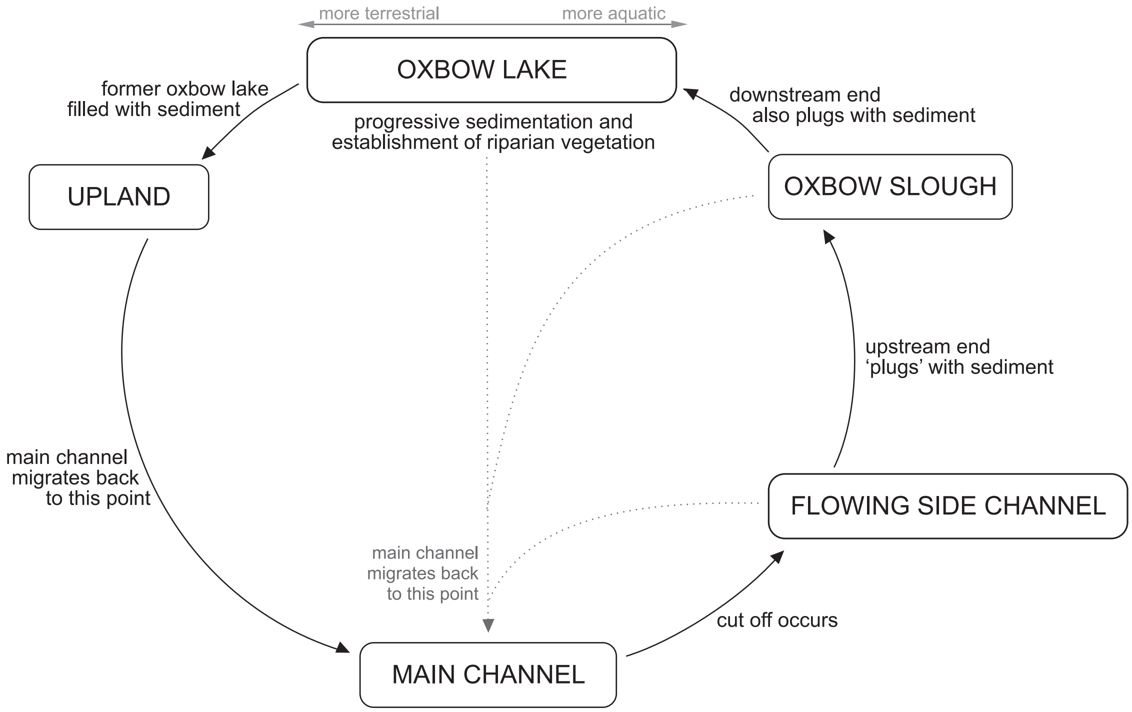

Figure 3. Conceptual model of oxbow lake evolution. A given reach of channel goes from being part of the main channel to a flowing side channel (when the new, shorter channel has been cut but some of the river water still flows through the meander bend). Because the slope is lower through the old channel than the new cutoff channel, velocities are lower, and the abandoned channel starts to fill with sediment. Usually the upstream end plugs with sediment first, creating an oxbow slough, whose downstream end is still connected hydrologically with the river. Next, the downstream end typically fills with sediment, producing an oxbow lake. Over time, the oxbow lake fills with (mostly fine-grained) sediment suspended in overbank flows, eventually reaching the elevation of the surrounding floodplain. As the oxbow lake silts up further with each overbank flow, its habitats transition from fully aquatic to more terrestrial. At any point in the cycle, the reach in question may transition abruptly back to "main channel" if the river channel erodes back to the point in question. Given that existing oxbow lakes are always undergoing the process of filling, to sustain the complex mix of habitats in river-floodplain systems requires that new oxbow lakes be frequently cut off by active channel migration.

promote meander migration and concomitant channel cutoff, such as clearing of riparian vegetation from the floodplain, which reduces hydraulic roughness of overbank flow and encourages formation of chute channels, which can lead to chute cutoffs [*Brice*, 1977].

The seasonal inundation of shallow water habitat is also affected, as flow regulation typically reduces the magnitude and frequency of flows large enough to produce overbank flooding, and levees have isolated channels from floodplains. Both factors reduce the frequency, extent, and duration of floodplain inundation.

When periodic flood scour is eliminated, as commonly occurs downstream of large storage reservoirs, riparian vegetation can encroach into the active channel, eliminating open sandbars. On the Platte River in Nebraska, these geomorphic features provide essential habitat for three species of threatened or endangered birds: whooping crane (*Grus americana*), piping plover (*Charadrius melodus*), and interior least tern (*Sterna antillarum athalassos*). Dam-induced reductions in flow regime (and artificially raised water tables) have resulted in encroachment of vegetation onto sandbars that would formerly have been scoured biannually [*Johnson*, 1994, 1997; *Murphy and Randle*, 2003]. To maintain some habitat for these important bird species, large areas of the channel are mechanically cleared of vegetation [*National Research Council (NRC)*, 2004].

On the Missouri River below Garrison Dam, reduced flood flows and sediment load have resulted in loss of open sandbar habitat and gradual conversion of young and early-successional-stage vegetation to late-successional-stage vegetation. *Johnson* [1992] documented the reduced rate of channel erosion and deposition after construction of

Garrison Dam in 1953 and the resultant loss of diversity in vegetative structure and habitat (Figure 4). Postdam, the ratio of different vegetation types changes, with the percentage of early-to-midsuccessional-stage vegetation decreasing, as later successional stages establish, and open sandbars disappear.

In sum, actively migrating meandering rivers create the greatest floodplain habitat diversity [*Ward and Stanford*, 1995], when meanders migrate across the bottomland, eroding outside banks, depositing fresh point bars, and cut off to create oxbow lakes (Figure 5). Rivers that are more dynamic, such as braided channels, have lower diversity because floods rework the bottomland so often that vegetative succession is arrested, and the landscape is dominated by bare bars and supports only early-successional-stage vegetation. Rivers, whose frequent floods have been eliminated by upstream regulation (or whose bank erosion is arrested by revetments), have lower diversity because migration is slowed or stopped, and the attendant habitat creation is thus eliminated [*Johnson*, 1992].

2.4. Implications for Restoration

The ecological literature suggests that actively migrating, flooding rivers support the greatest habitat diversity and that these habitats are constantly being renewed. They are not static features, but ever evolving in response to geomorphic processes. These insights suggest that restoration of the ecosystem is best accomplished by the geomorphic processes that create and renew habitats and thus, where processes have been impaired, by restoration of those processes [*Beechie et al.*, 2010; *Kondolf*, 2000]. While this is the preferred approach in most European countries (where restoration has become more widespread in response to requirements of the European Union (EU) Water Framework Directive), it is in stark contrast to the most common, conventional restoration approaches in North America, which have emphasized building of structural elements (or rebuilding entire channels) to create desired forms.

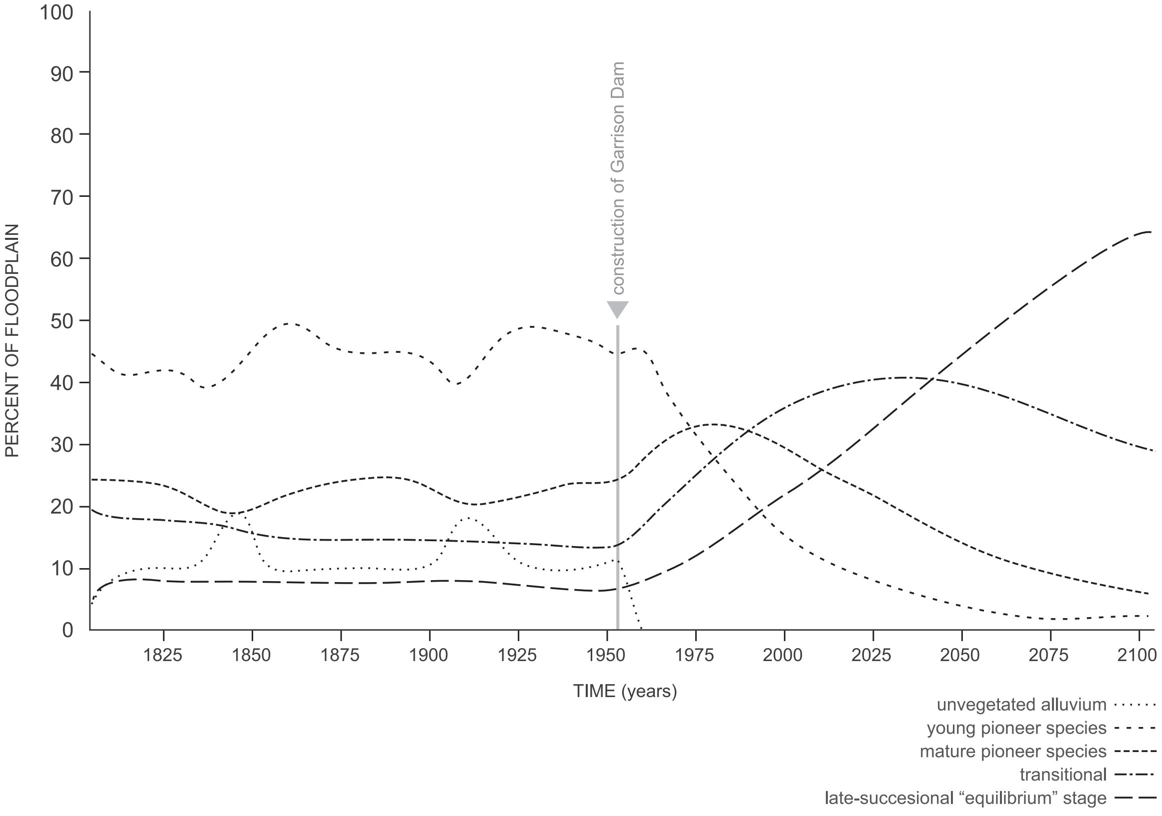

Figure 4. Floodplain habitat diversity over time for the Missouri River before and after construction of Garrison Dam in 1953, based on observations through the 1990s and model predictions thereafter by *Johnson* [1992]. The dynamic predam regime maintained a mosaic of diverse vegetative communities, dominated by juveniles of pioneer species such as *Salix* and *Populus*. After the dam cut off sediment supply and reduced flood peaks, the process of creating new surfaces for colonization by vegetation essentially stopped, but the process of vegetative succession continued, so there is a progressive shift to dominance by later successional stage vegetation. Adapted from *Johnson* [1992], reprinted with permission from S.E.L. & Associates.

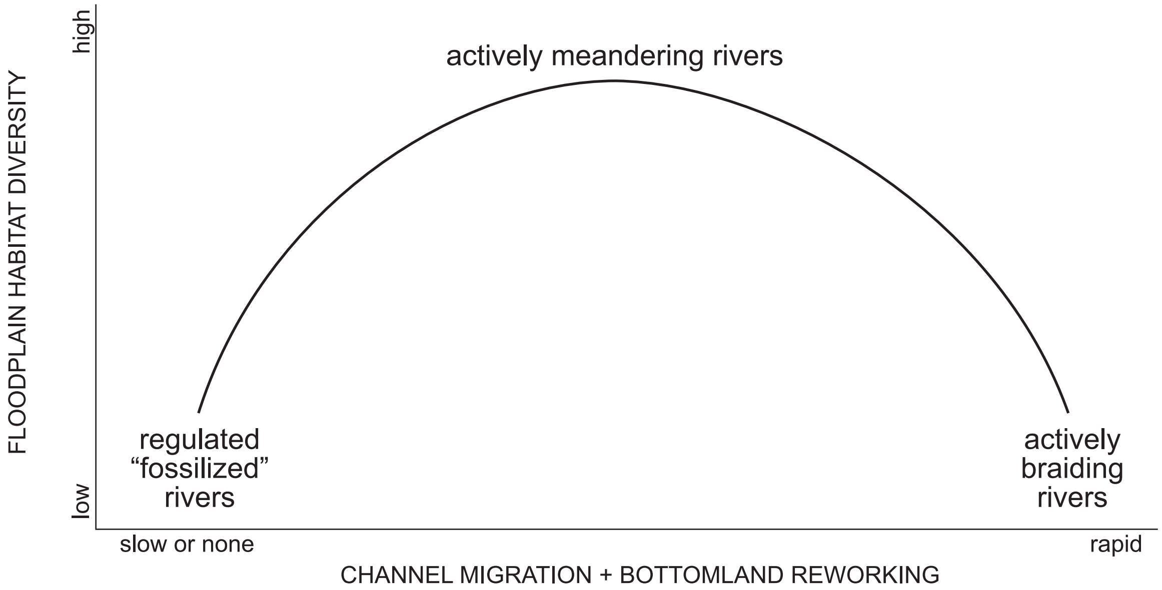

Figure 5. Floodplain habitat diversity as a function of channel migration rates. Habitat diversity is greatest when the river channel migrates actively. Braided channels are so active that they are able to support only juvenile and some adult pioneer plants, whose seedlings establish on freshly scoured or deposited bar surfaces. Formerly dynamic channels whose high flow regime and sediment supply has been reduced by upstream dams become less active, and in extreme cases, the bed forms are "fossilized." Later successional stage vegetation increasingly dominates. While there is nothing wrong with the mature later successional stages trees, the diverse mosaic is lacking. Adapted from *Ward and Stanford* [1995], reprinted with permission from John Wiley and Sons Ltd.

The form-based restoration projects so common in North America have mostly been based on templates derived from the popular Rosgen channel classification scheme and inevitably include revetment of outside banks with boulders, large logs, and basal root wads, designed to stabilize the channel (prevent migration and bank erosion) and also to provide some complexity to the static bank [*Kondolf*, 2006]. Well-documented examples of this kind of project include single-thread meandering channels built on Cuneo and Uvas creeks, California, in the mid-1990s. Despite the log and boulder revetments on their outside meander bends, both of these projects washed out, so they are widely seen as "failures" [*Kondolf*, 2006]. Consultants involved in the design of these projects have argued that they failed because the construction did not follow their specifications regarding length of revetments, etc., but these channels did not fail by erosion of revetments; rather, the streams simply cut down the middle, ignoring the revetments. In both cases, the appropriateness of attempting to build meandering channels in these high-energy, episodic streams can be questioned. But more fundamentally, what if the channels had not washed out, but remained stable. Would they have been "successful"? Perhaps they would have met their objectives of stabilizing the channels, but at a more fundamental level, would they have constituted real ecological restoration [*Palmer et al.*, 2005]? Would they have created diverse habitats for native species? Without the renewal of habitats by active migration, erosion, and deposition, the ecological value of such restoration projects that make static habitats is questionable, at least in the long term.

Ironically, one of the most significant barriers to letting rivers heal themselves is that "action agencies" need to be seen by the community (and especially those in power) to be "doing something," whether or not that something is the "right thing" in the long term. With the media saturation, short attention spans, and rapid feedback provided by new technology, there is an expectation of quick results, which tends to discount longer-term goals (sustainability and planning for future generations). Unfortunately, letting the river to do the work may be seen as "doing nothing" and may not be acceptable under these constraints, at least without significant public education.

3. THE ERODIBLE CORRIDOR OR CHANNEL MIGRATION ZONE

Setting infrastructure back from the active channel to give the river a zone in which to freely erode and deposit has been advocated by several authors in different countries, including France (the "erodible corridor" or "espace de liberté" [*Piégay* *et al.*, 2005]), Spain (the "fluvial territory" [*Ollero*, 2010]), the Netherlands ("Room for the River" [*Nijland*, 2005]), and the United States in the Pacific Northwest (the channel migration zone [*Rapp and Abbe*, 2003]), and in California (the "conservation area" of the Sacramento River). This approach has the virtues of reducing conflicts with human infrastructure and allows the river to accomplish the work of building habitats itself through dynamic channel processes [*Piégay et al.*, 1997].

Piégay et al. [2005] identified three scales at which the instability (or potential instability) of a river channel can be assessed: the river basin scale, the longitudinal reach scale (discrete reaches of 10–100 km in length), and the scale of the unstable reach, each with its own utility to management agencies and stakeholders (Table 1). *Piégay et al.* [2005] reviewed various approaches to delimit the erodible corridor width, noting that attempts to develop simple rules of thumb (such as 10 times the active channel width) had not been easily exported to other river systems. A historical overlay of past channels can be based on mapping from historical maps (typically going back about a century for accurate topographic maps, longer for manuscript maps) and aerial photographs (typically back to the 1940s). Simulation modeling can be used to predict future directions of channel erosion, but "models are frequently restricted to artificial morphologies tied to idealized representations of the river planform, such as uniform width. . . . Meander models do not account for all the degrees of freedom involved in planform adjustment" [*Piégay et al.*, 2005, p. 784].

Along the Sacramento River, mapping of historical channel courses was supplanted by predictions of channel erosion over the coming 50 years to develop the limits of the "inner river zone" [*Larsen et al.*, 2007; *Greco et al.*, 2007], in which the river was (eventually) to be allowed to migrate freely (Figure 6).

Rapp and Abbe [2003] identified four components of the channel migration zone: (1) The "historical migration zone" was the collective area occupied by the channel in the historical record, which for the Pacific Northwest of the United States encompassed roughly a century; this zone is essentially the same as the overlay of channel positions described by *Piégay et al.* [2005] and used along the Sacramento River (Figure 6) [*Larsen et al.*, 2007]. (2) The "avulsion hazard zone" is the area vulnerable to avulsion that lies outside the historical migration zone. (3) The "erosion hazard area" consists of additional areas at risk from future stream bank erosion or mass wasting of terraces. (4) The "disconnected migration area" is bottomland where channel migration is now physically prohibited by artificial structures. *Rapp and Abbe* [2003] therefore recommended the channel migration zone be delimited as the sum of the first three areas, with the fourth (artificially protected) area subtracted.

Given the advantages of the erodible corridor concept, why has the concept not been more widely applied? In part, the problem probably lies in a lack of understanding of fluvial systems by the general public and many decision makers. Rivers are commonly seen as permanent, static features, and when they flood or erode a bank, it is seen as a natural disaster, rather than an expected event linked to normal fluvial behavior. In the face of strong pressure to develop housing and other human uses, local jurisdictions with land use authority find it difficult to keep development away from the channel and off riverbanks. In addition, there are places where the concept is simply not appropriate because preexisting development restricts options, or the current flow and sediment transport regimes are inadequate for the river to rebuild its natural channel forms. *Piégay et al.* [2005, p. 775] observed that the erodible corridor concept "is perhaps most usefully applied to free-moving meandering and braided rivers in alluvial plains that can reasonably be expected to remain within a defined corridor on the time scale of interest (several decades). The [concept] therefore has most potential to be a helpful management tool in cases where there is generalized movement of the bank (e.g., a few meters of bank erosion a year along a significant length of river) and where human activities within the corridor are insufficiently developed to conflict strongly with other

Table 1. Nested Approach to Identify Potential Locations of Erodible Corridors[a]

Approach	Specific Steps	Application
River basin or network scale	At river basin scale, identify reaches with greatest divergence from reference state or with greatest mobility or potential for mobility.	Agencies responsible for meeting ecological goals can select reaches with potential to reactivate fluvial processes to restore habitat.
Longitudinal targeting (10–100 km long reaches)	Within given reach, identify locations of greater instability.	Agencies locating large-scale channel works can avoid zones of high mobility.
Unstable reach scale	Define erodible corridor width based on historical movements (from maps, air photos), vegetation patterns, sedimentology, modeling, etc.	Corridor is defined such that infrastructure is set back and channel permitted to migrate.

[a] Adapted from the work of *Piégay et al*. [2005].

Figure 6. The "inner river zone" of the Sacramento River Conservation Area from approximately km 215 to km 255. This zone (in which the river is proposed to be allowed to migrate freely except at infrastructure) was determined from channel migrations over the preceding century (based on analysis of historical maps back to the 1890s and aerial photographs) and projected channel migration for the coming 50 years (based on modeling). Unpublished GIS data layers courtesy of the California Department of Water Resources, Red Bluff.

management goals." These conditions are best met in rural areas on rivers with sufficient stream power and sediment load, as illustrated in Figure 7, a bivariate plot in which the erodible corridor approach appears as "Espace de Liberté" in the upper right, corresponding to a bottomland unencroached by urbanization (i.e., with space available adjacent to the channel), relatively undisturbed catchment conditions ("wilderness") (to the right along the *x* axis), and to high stream power and sediment supply (toward the top along the *y* axis).

4. RESTORING FLOW AND SEDIMENT LOAD

When flow or sediment load is inadequate to do the geomorphic work needed to create and maintain complex channel forms, as is frequently the case below dams, simply giving the river lateral room may not recreate the desired channel complexity. In such cases, it may be necessary to find ways to reoperate the reservoir to let out higher flows capable of supporting a dynamic meandering channel. Such reservoir reoperation schemes have successfully led to reestablishment of riparian vegetation through mimicking natural hydrographs, including postflood or wet season recession rates [*Rood et al.*, 2005]. Another specific goal of such deliberate reservoir releases is often mobilization of the channel bed, to flush fine sediment from spawning gravels or to prevent encroachment of riparian vegetation in the active channel [*Kondolf and Wilcock*, 1996].

Even if reservoirs have relatively small effects on flow regime, they still trap all of the coarser bed load sediment, and some fraction of the finer suspended load, with the effect of causing sediment starvation downstream. To compensate for this "hungry water," especially the lack of desirable sediment size fractions such as the gravels needed for salmonid spawning, sediment (commonly gravel) is added below many dams [*Kondolf*, 1997].

For this approach to work, the released high flows must be capable of mobilizing the bed, eroding banks, depositing point bars, etc. In some cases, adequate releases are not economically/politically possible, such as on the Platte River, where encroached vegetation is instead removed mechanically [*NRC*, 2004]. In the Central Valley of California, the idea of a scaled-down river is being explored, partly by adding smaller gravels than characterize the channel at present, as well as specifying flow releases that are high enough to move sediment, but considerably lower than floods that would naturally occur.

5. ANTICIPATORY MANAGEMENT

Occupying a similar position on the *x* axis of the bivariate plot (Figure 7) as "Flow + SedimentRestoration" is

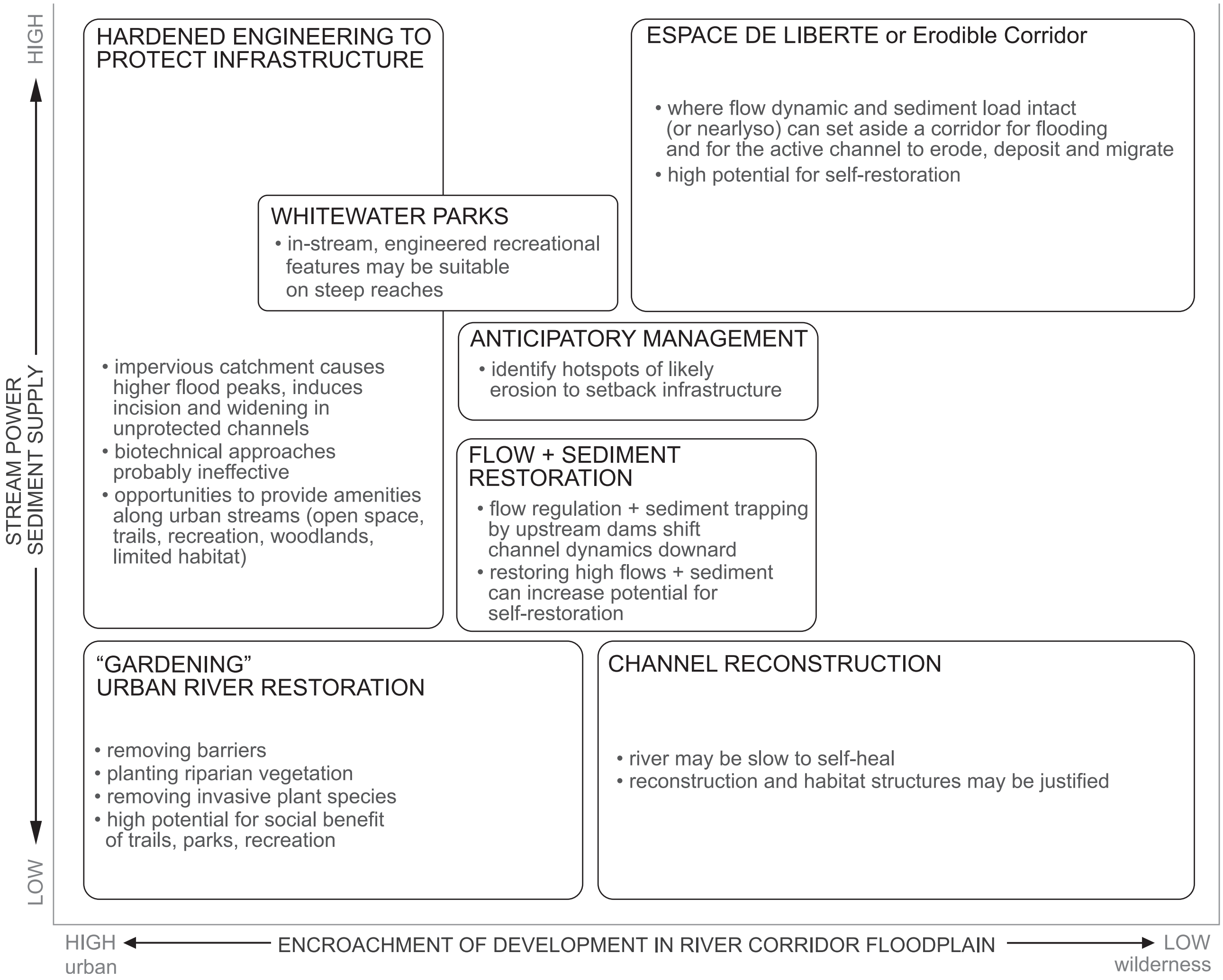

Figure 7. Suitability of self-healing approaches to restoration, such as the erodible corridor concept, depend upon the degree to which the river still retains its dynamic flow regime and sediment supply and the degree to which it is not constrained by land uses and infrastructure. The greatest potential is found in rivers with high stream power and whose sediment loads have not been reduced by upstream dams and which are located away from dense settlement or infrastructure constraints (upper right corner of diagram). Low stream power reaches are unlikely to restore themselves, so channel reconstruction is more justified (lower right). Below dams, it may be possible to partially restore flow dynamics and sediment loads through reservoir reoperation and sediment augmentation (center). Channels with adjacent high-value land uses, but which are not highly dynamic, are good candidates for anticipatory management, wherein the zones most vulnerable to bank erosion are identified, and infrastructure is set back from these banks in advance of high flows that would cause erosion. Where urban encroachment is severe, stream restoration can be likened to gardening, where individual elements are chosen for inclusion and where social benefits may outweigh ecological (left side diagram).

"Anticipatory Management." This is an approach suitable for rivers whose channels would (under current climatic and geological conditions) not migrate across the entire valley floor and where agriculture or urban developments encroach up to the channel edge so that a broad, uniform setback would entail significant economic impacts [*Beagle*, 2010]. Under anticipatory management, flood damage is treated as an inevitable, expected event, and landowners and agency staff work out a postflood response that meets the landowners' needs while protecting the integrity of aquatic habitat.

The approach is illustrated on Carneros Creek, a tributary to the Napa River, California. The catchment was largely cleared to harvest timber and create pasture in the late nineteenth century, and in the second half of the twentieth century, vineyards (and some rural residences) became the dominant land use in the catchment. The creek still supports native, anadromous steelhead trout (*Oncorhynchus mykiss*). Carneros Creek is deeply incised, and as a consequence, it experiences high shear stresses during floods. Much of the channel is simple in form and offers little habitat for fish. The best fish habitats (and most observed fish) occur at sites of active bank erosion, with undercut banks, large wood in the channel, and greater channel complexity than observed along most of the incised channel [*Beagle*, 2010]. However, the ecological functions of these eroding bank sites may be lost immediately after floods, when landowners commonly respond to bank erosion by dumping concrete rubble, boulders, even old automobiles onto the bank, under "emergency" authorities that allows them to bypass environmental permit requirements.

To protect complex habitats and prevent dumping of debris for bank protection, *Beagle* [2010] proposed an anticipatory management plan that identified where bank erosion was likely to occur (based on an analysis of bank height, bank material, channel orientation, and field evidence of recent active erosion). At sites most vulnerable to bank erosion, farmers would set back their vineyards, roads, and other infrastructure a distance equivalent to about three channel widths from the creek. They would also plant riparian trees along these setback areas, to potentially provide large wood to the channel in the future (Figure 8). Most of the large landowners along Carneros Creek already participate in the "Fish Friendly Farming" program, a voluntary program under which farmers develop a plan for their entire property and implement best management practices to reduce impacts of farming operations upon stream channels. The vineyards produce very high quality, expensive wines, so giving up

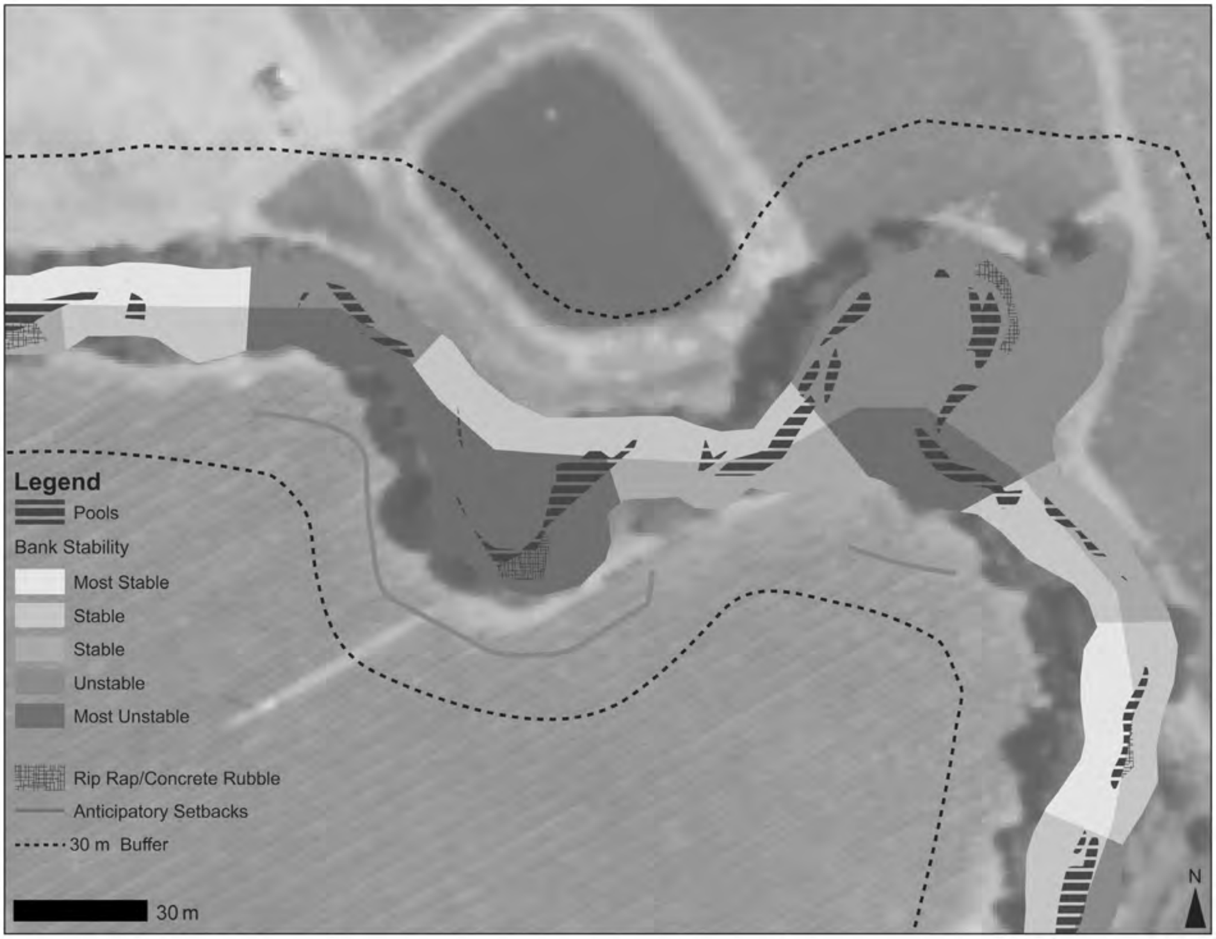

Figure 8. Map of current conditions and proposed anticipatory management for a 600 m long reach of Carneros Creek, California. At sites most likely to experience bank erosion, infrastructure is to be set back from the stream channel so that bank erosion will not create serious conflicts with farming operations. Adapted from *Beagle* [2010].

land to the creek is not a trivial matter. However, many of the landowners are environmentally aware, and largely thanks to their positive experiences with Fish Friendly Farming, initial reception to the anticipatory management approach has been positive.

6. CHANNEL RECONSTRUCTION IN LOWLAND RIVERS

Many formerly sinuous lowland rivers have been straightened to improve agricultural drainage, urban flood control, or to improve navigation. To reverse the loss of channel complexity in such rivers, reestablishing the meander beds (often termed renaturalization or remeandering) is an obvious restoration approach.

One could ask whether such rivers could reestablish their meander bends on their own, without the need for direct intervention in the form of channel reconstruction. Well-known examples of straightened rivers reasserting their former meandering nature include the Walla Walla River in southeastern Washington state, United States, which broke through its straightened channel levees in a flood in the 1960s, as captured in a well-known aerial view [*Kondolf*, 2009]. However, in low-energy, low-sediment-load rivers, it is unclear how long this kind of self-recovery from channelization might take. In some rivers, it may be centuries, if indeed it were to occur at all. However, on the River Idle in the United Kingdom, in-channel structures installed in the 1990s to encourage the channel to meander have increased channel complexity over a 15 year period, changes that are now being quantified (P. Downs, University of Plymouth, personal communication, September 2010), so at least on a decadal time scale, even low-energy channels may be capable of self-healing. Nonetheless, on the shorter-term time scales expected by the public, active intervention in the form of channel reconstruction may be justified in lowland streams. Well-known recent examples include the Kissimmee River, Florida [*Toth*, 1993; *Koebel*, 1995] and the Brede River, Denmark [*Neilsen*, 2002], both low-energy systems whose meander bends have been successfully restored, with measurable improvements in aquatic habitat and populations of valued species. In both cases, the restored channels are not fixed by hardened banks but are allowed to have natural banks, even if that means they experience some erosion.

As exemplified by the Kissimmee and Brede rivers, channel reconstruction is most appropriate on rivers with low stream power and sediment load but which have not been intensely encroached by development, so there is room to reestablish former meander patterns (illustrated by the lower right corner of Figure 7).

7. HIGHLY MODIFIED URBAN RIVERS

On urban rivers whose catchments have been rendered largely impermeable and whose bottomlands have been encroached by urban settlement, allowing the river to "heal itself" or even to restore fluvial processes, is unlikely to succeed unless there is sufficient land available to set aside a fluvial corridor. However, such a corridor would require the purchase of multiple properties, usually at high cost, and there are inevitably some property owners who resist being moved, so this approach is inevitably more difficult to implement in most already urbanized settings. The current, posturbanization flood regime is usually not well suited to restoring complex channel forms because the exaggerated peak flows tend to scour bars and vegetation from constricted urban channels, eliminating the features that could impart some complexity. Thus, urban channels must be constructed to withstand intense flows without failing. Viewed holistically at a catchment scale, restoration of urban streams should involve upstream storm water infiltration to address the underlying hydrologic distortions that cause the channel degradation. In the absence of solutions that address the underlying causes, restoration of urban channels can be seen as treating symptoms, a form of "gardening." In the design, one can include desired elements such as riparian trees, bicycle trails, picnic areas, swimming, and wading access points, but these elements are all artificially implemented and maintained, the opposite to the erodible corridor concept, in which we leave the river alone so that its natural processes can create the habitats on its own. This space is illustrated along the left side of Figure 7.

Moreover, the ecological potential of such urban streams will always be limited, so that in seeking a balance between ecological goals and human uses, the relative benefits of designing for human enjoyment will often outweigh the potential wildlife benefits of habitat creation [*Kondolf and Yang*, 2008]. Thus, restoration projects on highly urban streams in Oakland, California, have often pitted advocates for riparian habitat against local residents: the former seek to establish dense stands of willow (*Salix* spp.), while the latter oppose them because the thick vegetation may hide illicit activities.

This is not to say that we should reject outright the option of using the river to do the work or healing itself in urban settings. However, the potential benefits and limitations of each approach need to be evaluated carefully, so that preconceived ideas of "restoration" are not inappropriately applied.

8. WHITEWATER PARKS

A special case of active human use of rivers is whitewater parks, increasingly popular in cities in the United States and

EU (also often referred to as "slalom courses"). These are reaches of river designed with drop structures to create standing waves on which kayakers and boogie-boarders can surf, with shallow, protected marginal waters suitable for wading by toddlers, etc. During higher spring flows, many of these artificial courses are used for kayak competitions, while during the base flows of summer, they attract families with children. Wingfield Park on the Truckee River in Reno is a particularly successful example, attracting thousands of users on hot summer afternoons. User surveys indicate that over 80% of users come from the immediate urban area, and many are low-income families for whom escape to more distant and expensive recreational sites would be difficult (K. Podolak, University of California, Berkeley, unpublished data, 2010). Because they require sufficient slope to create multiple drops (typically 0.30–0.40 m), these features are most appropriate toward the higher end of the y axis in Figure 7 and, because the demand for these features is within urban areas, they would usually plot toward the left side of the x axis, although this is not always the case as some such parks have been built in rural areas.

9. CONCLUSION

Where possible, allowing the river channel to "heal itself" through setting aside a channel migration zone is the most sustainable strategy for ecological restoration. The width and extent of this zone can be set based on mapping of historical channel migration and model predictions of future migration. However, the approach is not universally applicable because not all rivers will naturally have sufficient stream power and sediment to reestablish channel complexity on the management time scale of years to decades. Some rivers have had their stream power and sediment load reduced by upstream dam regulation and have become inactive. For this approach to work, in addition to requiring stream power and sediment, rivers require space. Many rivers are restricted by levees and infrastructure on floodplains that preclude allowing the river a wide corridor in which to move. Thus, in a bivariate plot of stream power/sediment load (y axis) and degree of urban encroachment (x axis), the space in which such erodible corridors are most appropriate lies in the upper right, with both channel dynamics and space for the channel to move (Figure 7).

Highly modified, urban channels are typically unsuited to self-restoration by rivers because the fluvial processes that might accomplish this restoration would typically be so altered that they would no longer produce the desired channel complexity, but might instead "blow out" bars and other complex features. Moreover, urban encroachment has usually foreclosed opportunities to expand the width of the river corridor. In such cases, "gardening" may be an appropriate analogy because such urban projects can include many worthwhile features such as riparian woodlands, trails, and swimming access points, but these components are deliberately chosen and installed, rather than created by the river itself. Such projects plot along the left side of the bivariate plot (Figure 7). In such highly urban settings, the potential for real ecological restoration is limited, so the social benefits of providing recreation to disadvantaged families, and the increased potential for public education, may ultimately be more important.

Intermediate approaches include partial restoration of flow and sediment load below dams, and anticipatory management, in which sites of bank erosion are anticipated, and infrastructure is set back in advance of the erosion itself, to prevent the common "emergency" response of dumping concrete rubble down an eroding bank during high water.

River restoration can mean many things to different people. In North America, channel reconstruction and bank stabilization are among the most popular activities undertaken in the name of (and funded by) river restoration programs, but by any scientifically credible measure, they are not real ecological restoration. In urban areas and where infrastructure is threatened, active intervention and hardened bed and banks may be unavoidable given constraints of urban encroachments and altered hydrology. But wherever possible, river restoration should embrace channel dynamics and allow the river room to move and develop channel complexity through natural fluvial processes. Viewing the opportunities and potential actions along a bivariate plot can provide a framework within which to evaluate different options.

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