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ECOLOGICALLY FUNCTIONAL FLOODPLAINS: CONNECTIVITY, FLOW REGIME, AND SCALE[1]

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ABSTRACT: This paper proposes a conceptual model that captures key attributes of ecologically functional floodplains, encompassing three basic elements: (1) hydrologic connectivity between the river and the floodplain, (2) a variable hydrograph that reflects seasonal precipitation patterns and retains a range of both high and low flow events, and (3) sufficient spatial scale to encompass dynamic processes and for floodplain benefits to accrue to a meaningful level. Although floodplains support high levels of biodiversity and some of the most productive ecosystems on Earth, they are also among the most converted and threatened ecosystems and therefore have recently become the focus of conservation and restoration programs across the United States and globally. These efforts seek to conserve or restore complex, highly variable ecosystems and often must simultaneously address both land and water management. Thus, such efforts must overcome considerable scientific, technical, and socioeconomic challenges. In addition to proposing a scientific conceptual model, this paper also includes three case studies that illustrate methods for addressing these technical and socioeconomic challenges within projects that seek to promote ecologically functional floodplains through river-floodplain reconnection and/or restoration of key components of hydrological variability.

(KEY TERMS: aquatic ecology; ecosystem services; flooding; fluvial processes; restoration; riparian ecology; wetlands.)

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INTRODUCTION

Riverine floodplains support high levels of biodiversity and some of the most productive ecosystems on Earth. They are also extremely valuable economically in terms of the services they provide to society, including reduction of flood risk and support for highly productive fisheries (Costanza *et al.*, 1997). Despite their considerable environmental and economic benefits, temperate-region floodplains have been extensively disconnected from rivers and converted to land uses such as agriculture. Although large expanses of hydrologically connected floodplains remain in late-developing regions of Africa, Asia, and Latin America, these systems face increasing

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pressure from land-use change and infrastructure development (Tockner and Stanford, 2002).

Recent research has highlighted both the values of floodplains and their loss and continued vulnerability (Tockner and Stanford, 2002). This increased attention has led to considerable expansion of efforts to restore and protect floodplains (Rohde *et al.*, 2006). Due to the complexity and variability of these ecosystems, and because floodplain conservation often requires addressing both land use and water management, the conservation of ecologically functional floodplains poses considerable scientific, technical, and socioeconomic challenges. This paper strives to distill the scientific complexities through a conceptual model and then provides case studies that illustrate approaches for addressing the technical and socioeconomic challenges.

The conceptual model emphasizes three primary elements necessary for the restoration or conservation of a functional floodplain ecosystem: hydrological connectivity between the river and floodplain, a variable flow regime that incorporates a range of flow levels, and sufficient geographic scale for key processes to occur and for benefits to accrue to a meaningful level. To illustrate how floodplain conservation must simultaneously address these primary scientific elements and overcome socioeconomic and technical constraints, we provide case studies of three projects where The Nature Conservancy (TNC) is restoring functional floodplain ecosystems. These projects address issues of connectivity, flow regime, and spatial scale with varying approaches including collaborations with water managers, the development of markets for ecosystem services, and linking floodplain restoration with flood-damage reduction.

FLOODPLAIN ECOSYSTEMS: PRODUCTIVITY, DIVERSITY, VALUES, AND THREATS

Although numerous definitions exist (Nanson and Croke, 1992), a floodplain can be broadly defined as a landscape feature that is periodically inundated by water from an adjacent river. In this paper, we focus primarily on lowland floodplains that are generally associated with low gradient rivers within broad alluvial valleys. Here, we emphasize floodplains as geomorphic features – formed and influenced by river flows and sediment – upon which ecosystems develop and operate.

Floodplain ecosystems support high levels of biodiversity and levels of primary productivity that generally exceed the production of either purely terrestrial or aquatic ecosystems (Tockner and Stanford, 2002). Floodplain diversity and productivity can both be attributed to dynamic and variable connectivity with river flows: the periodic inundation by flood waters is largely responsible for high floodplain productivity (Junk *et al.*, 1989) whereas high-energy flows induce erosion and deposition, resulting in habitat heterogeneity and, consequently, high levels of biodiversity (Salo *et al.*, 1986).

During periods of inundation, floodplains provide very different habitat conditions than found in the adjacent river channel. As flow moves from the river onto the floodplain water velocity generally slows considerably, allowing sediment to drop out of suspension. As a result, floodplain water is often less turbid than river water and can thus support greater rates of photosynthesis from aquatic vascular plants and algae (including both attached algae and phytoplankton) (Ahearn *et al.*, 2006). This primary productivity in turn supports high productivity of zooplankton and aquatic invertebrates (Junk *et al.*, 1989; Grosholz and Gallo, 2006).

River organisms such as fish can enter floodplains during high flows and gain access to the high productivity of floodplain habitats (Figure 1). Further, the low-velocity, shallow, and vegetated habitats of the floodplain serve as a refuge from the fast, turbid waters of the river during high flows (Sommer *et al.*, 2001b). Many fish species time their spawning to coincide with flooding so that their offspring can rear

FIGURE 1. Floodplain Productivity Benefits Fish. Juvenile Chinook salmon reared in experimental enclosures on the Cosumnes River (California) floodplain (on right) had significantly faster growth rates than those reared in enclosures on the main-stem river (on left). Photograph by Jeff Opperman; research described in Jeffres *et al.* (2008).

within food-rich and sheltered floodplain habitats (Welcomme, 1979). As a result of the increased productivity available to fish, rivers with connected floodplains and an unaltered flood pulse generally have a higher yield of fish per area than do rivers lacking a flood pulse, known as the "flood pulse advantage" (Bayley, 1991). Consequently, floodplain rivers support the largest freshwater fisheries in the world (discussed further below; Welcomme, 1979).

The floodplain aquatic productivity described above is driven by long-duration and frequent flood pulses (Junk *et al.*, 1989). Other key floodplain characteristics, such as riparian forests, are influenced by a different type of flooding: high magnitude, and thus less frequent, floods with sufficient energy to drive geomorphic processes (Whiting, 1998). Infrequent large floods build and rework floodplain surfaces, eroding sediment and vegetation in some areas and depositing sediment in other areas. Channels can shift during large floods, resulting in the creation of new features such as side channels and oxbow lakes created by meander cutoffs (Knighton, 1998). Floodplains that are connected to dynamic river regimes undergo periodic disturbance that creates topographic heterogeneity. Floodplain surfaces with small differences in elevation and soil type can have considerable differences in hydroperiod and disturbance regime (Naiman *et al.*, 2005). Thus, topographic heterogeneity and connectivity with dynamic flows result in a floodplain with a shifting mosaic of diverse habitat patches, in terms of species, age classes, and physical structure (Ward *et al.*, 2002). The development of floodplain (riparian) forest is strongly influenced by the availability of appropriate sediment substrate and hydrological conditions, driven by river flow patterns and geomorphic processes (Mahoney and Rood, 1998; Richter and Richter, 2000; Rood *et al.*, 2003).

Due to this productivity and habitat heterogeneity, floodplains support high levels of biodiversity (Salo *et al.*, 1986; Tockner and Stanford, 2002). Floodplains also support high levels of ecosystem services (Gren *et al.*, 1995; Opperman *et al.*, 2009) – products and processes produced by functioning ecosystems that economically benefit society (Brauman *et al.*, 2007). In their review of the value of the world's ecosystem services, Costanza *et al.* (1997) found that floodplains were the second ranked ecosystem type, behind only estuaries, in terms of their per-hectare value to society. Despite representing <2% of Earth's terrestrial land surface area, floodplains provided approximately 25% of all "terrestrial" (i.e., nonmarine) ecosystem service benefits, with regulation of disturbance (i.e., attenuation of flood flows) providing the most value (e.g., see Akanbi *et al.*, 1999). Other floodplain ecosystem services include filtration of surface water (Mitsch *et al.*, 2001; Noe and Hupp, 2005), groundwater recharge (Jolly, 1996), recreation (Gren *et al.*, 1995), and provision of protein (e.g., fish) and fiber (e.g., timber and other plant resources) (Welcomme, 1979). Fisheries supported by floodplain productivity provide one of the most tangible examples of an economically and socially valuable ecosystem service. The Mekong River, which retains an unregulated flood pulse and extensive hydrologically connected floodplains, supports the largest freshwater fishery in the world, providing a primary source of protein to 60-70 million people in Southeast Asia (Mekong River Commission, 2005; Baran *et al.*, 2007). The commercial fisheries of temperate river floodplains – such as those on the Illinois and Missouri Rivers – have disappeared or are greatly diminished, due in large part to the disconnection of rivers from productive floodplain habitats (Galat *et al.*, 1998).

Despite floodplains' immense ecological and economic values, they have been disconnected from river flows and converted to other land uses in much of the world. For example, <10% of historic floodplain habitat in California remains (Barbour *et al.*, 1991) and floodplain forests on the Mississippi River below the confluence of the Ohio River have declined by 80% from their historic extent (Llewellyn *et al.*, 1995). Levees prevent river flows from entering floodplains (Tobin, 1995), whereas dams can greatly alter the magnitude, frequency, and duration of floods and thus the interaction between rivers and floodplains (Magilligan and Nislow, 2005) (Figure 2). Intact floodplains remain along large rivers in late-developing regions of Africa, Asia, and Latin America. However, these floodplains are vulnerable to changing land-use patterns, such as the expansion of cities and agriculture, and by flow regulation from rapidly proliferating dams (Dudgeon, 2000). In their review of the current and future status of floodplains, Tockner and Stanford (2002) note that "in the near future, floodplains will remain among the most threatened (ecosystems), and they will disappear faster than any other wetland type."

A CONCEPTUAL MODEL FOR FLOODPLAIN RESTORATION AND CONSERVATION

The recent research summarized above highlights both the values of, and threats to, floodplains. Consequently, considerable resources are now being directed to floodplain conservation and restoration (Bernhardt *et al.*, 2005; Rohde *et al.*, 2006). Here, we describe a conceptual model that attempts to capture the complex interactions and processes that structure ecologically functional floodplains (Figure 3). The conceptual

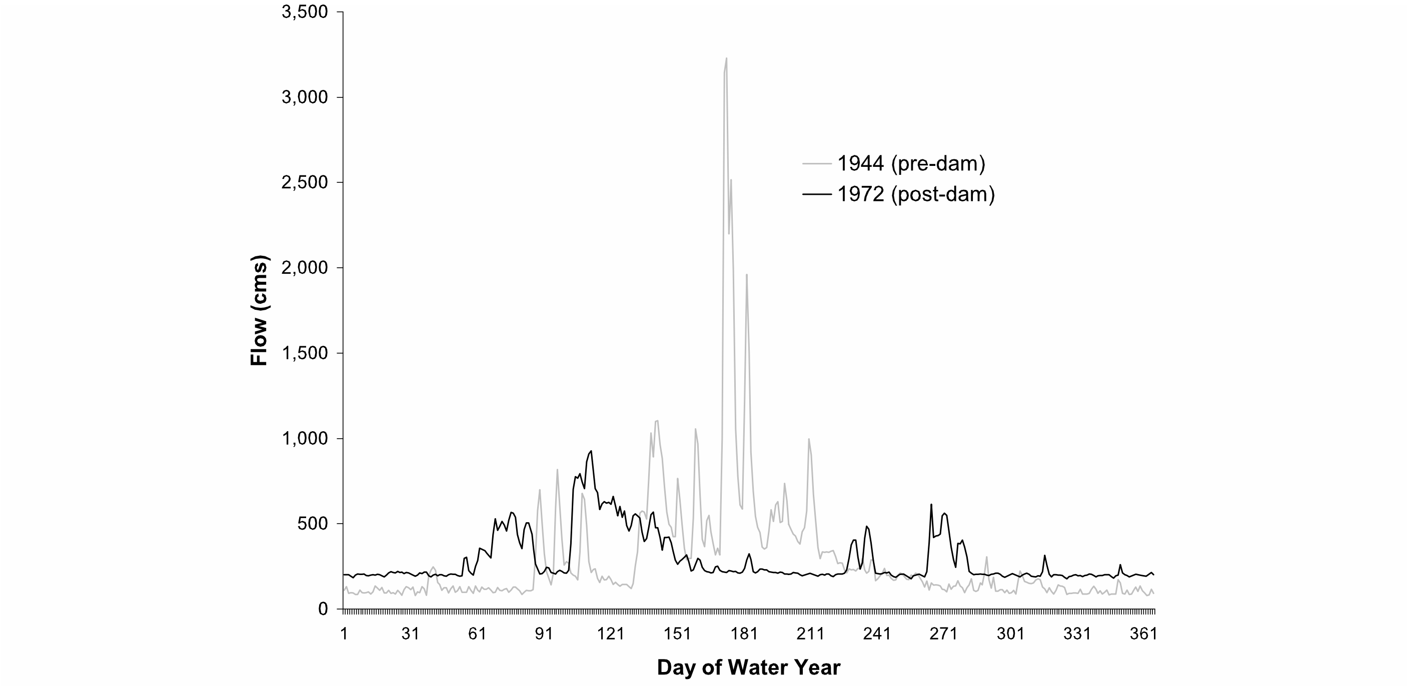

FIGURE 2. Pre-dam (1944; gray line) and Post-dam (1972; black line) Hydrographs for the Savannah River at Augusta, Georgia, Below Thurmond Dam. The two years had nearly identical mean annual flow.

model's basic premise is that ecologically functional floodplains require three primary elements.

1. *Connectivity*. A functional floodplain must be connected with its adjacent river to allow the exchange of flow, sediment, nutrients, and organisms (Amoros and Bornette, 2002).
2. *Flow regime*. Floodplain ecosystems are created, maintained, and influenced by a wide variety of flow levels and events, ranging from extreme low flows to infrequent high flows (Poff *et al.*, 1997; Whiting, 2002). Therefore, an ecologically functional floodplain requires interaction with a river that retains a flow regime with sufficient variability to encompass the flow levels and events that support important floodplain processes.
3. *Spatial scale*. A functional floodplain requires a minimum geographic extent for two reasons. First, the floodplain must encompass sufficient spatial scale to allow important dynamic processes to occur, such as erosion and deposition during large floods (Richards *et al.*, 2002; Rohde *et al.*, 2005). Second, the floodplain (by itself or with other associated floodplain sites) must encompass sufficient spatial scale for benefits to accrue to a meaningful level (e.g., for management purposes).

The primary elements of the model and Figure 3 are sufficiently general so as to apply to a broad range of lowland, low-gradient river floodplains, with the exception of the box "Extended inundation of various patch types." This box illustrates the linkages between the *timing* of flood events and biological processes and in this figure reflects floodplain processes within California's Central Valley; the specific timing of biological processes, such as fish spawning, will vary from system to system. This conceptual model synthesizes elements from a broad range of concepts and studies that describe various floodplain processes and functions. The most well-known conceptual model, the Flood Pulse Concept (FPC) (Junk *et al.*, 1989) posited that large rivers and floodplains should be viewed as interacting components of a single system. Although the FPC paper (Junk *et al.*, 1989) and its update (Junk and Wantzen, 2004) and extensions (e.g., Tockner *et al.*, 2000) acknowledge the role of erosive floods in creating floodplain topography, they focus primarily on processes and interactions that take place during periods of floodplain inundation and draining. A different set of studies and concepts – in the fields of geomorphology and riparian and landscape ecology – focus on the interactions between river flows and floodplain topography (Whiting, 1998; Florsheim and Mount, 2002; Larsen *et al.*, 2006) and how vegetative communities develop on heterogeneous floodplain topography, influenced by flow and disturbance regimes over time (Mahoney and Rood, 1998; Ward, 1998; Greco and Plant, 2003). These studies

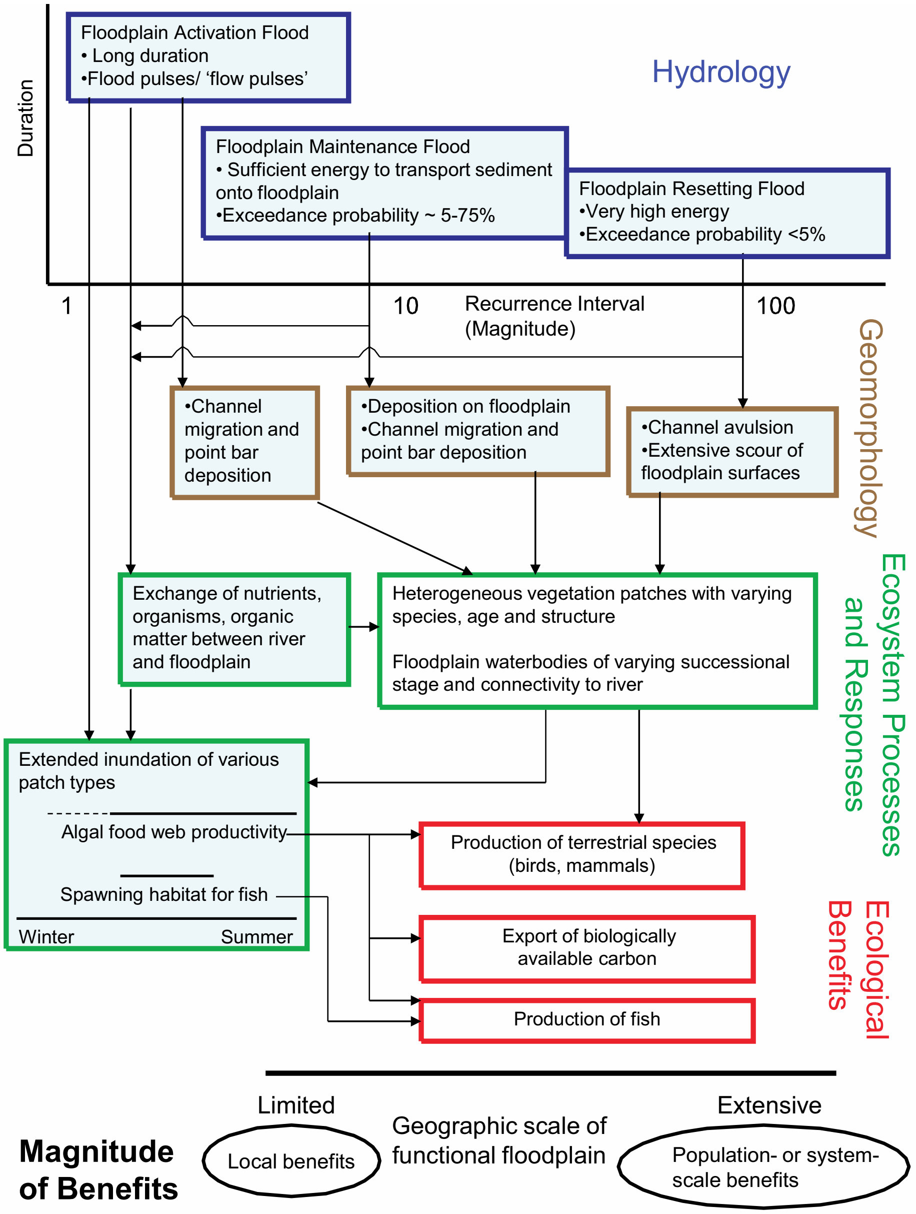

FIGURE 3. A Conceptual Model of Floodplain Processes in California's Central Valley. Blue-shaded boxes indicate processes that occur during the period of inundation. Note the temporal scale bar (Winter → Summer) in the box "Extended inundation of various patch types," which indicates that the occurrence and magnitude of ecosystem processes vary with the season of inundation.

generally do not examine the ecological processes that occur *during* periods of inundation.

In this conceptual model, we emphasize that floodplains are valued by society for both the processes that occur during periods of inundation, such as fisheries productivity, as well as those processes that occur over longer time periods, such as the development of riparian forest communities on floodplain landforms. Further, these various processes interact: short-term flood events shape and maintain floodplain topography and vegetation; the processes that occur during subsequent inundations, such as the development of aquatic food webs, occur within this evolving template of floodplain topography and ecosystems. Thus, this conceptual model seeks to encompass a broad range of flows, ranging from below bankfull flow pulses to very rare high-magnitude events, and various ecological processes that occur over time periods ranging from weeks to years to decades.

A diverse range of flows influence floodplain geomorphic and ecological processes (Trush *et al.*, 2000; Whiting, 2002) and numerous aspects of these flows have geomorphic and ecological significance, including magnitude, frequency, duration, rates of change, and seasonality (Poff *et al.*, 1997), as well as antecedent conditions on the floodplain. To simplify, this conceptual model focuses on three types of "representative floods," characterized by their frequency and magnitude (and, in the case of the floodplain activation flood, duration, and seasonality). These representative floods are simplifications of a much broader spectrum of flow types and events and can also be viewed as management targets that can be expressed as "building blocks" (*sensu* King and Louw, 1998) or Environmental Flow Components (EFC) (Richter *et al.*, 2006; Mathews and Richter, 2007; see also the Savannah River case study below).

The model (Figure 3) is organized into five main areas: at the top, the *Hydrology* portion of the model (blue-outlined boxes) depicts the representative floods, arrayed along axes for frequency/magnitude and duration. These floods perform geomorphic work, described in the brown-outline boxes in the *Geomorphology* portion of the model. Hydrologic and geomorphic processes create the conditions for *Ecosystem Processes and Responses* to occur (green-outlined boxes). In the model, blue-shaded boxes indicate processes that occur during the period of inundation. The non-shaded *Ecosystem* box encompasses ecological processes that occur over longer periods of time (e.g., decades), such as the development of riparian vegetation. This box necessarily simplifies these complex processes. The objective here is to simply depict the linkages between flows, geomorphic processes, and heterogeneous floodplain communities; numerous sources describe in detail the establishment and development of riparian vegetation (Mahoney and Rood, 1998; Rood *et al.*, 2003, 2005; Stella *et al.*, 2006). The Ecosystem Processes and Responses produce *Ecological Benefits* (red-outlined boxes), and the *Magnitude of Benefits* varies with the geographic scale of the functional floodplain (see scale bar along bottom of figure). Note that the *Ecological Benefits* listed in the figure are only a subset of those that could be identified. Three representative floods are described below.

Floodplain Activation Flood

The floodplain activation flood is a small-magnitude flood that occurs relatively frequently and can be further defined in terms of seasonality and duration (Figure 4) – for example, Williams *et al.* (2009) defined a floodplain activation flood for California's Central Valley as an inundation that lasts at least one week and occurs in the spring with a recurrence interval of two out of three years. A long-duration flood produces characteristic ecological benefits such as habitat for native fish spawning and rearing (Figure 1) and food-web productivity (Figure 4b). The duration of the flood is important as these processes cannot occur during a short event. The seasonality of the flood also influences which ecological processes occur and their magnitude [see the temporal scale bar (Winter → Summer) in one of the ecological process boxes]. For example, floodplain productivity is much greater when long-duration flooding occurs during periods of warmer temperatures and abundant sunshine (Schramm and Eggelton, 2006; Sheibley *et al.*, 2006). Note that floodplain activation floods can be temporally coincident with other representative floods. For example, a floodplain activation flood can occur during the recession limb of a higher-magnitude event such as a floodplain maintenance flood (Figure 4a). Floodplain activation floods support many of the processes ascribed to overbank flow pulses in the FPC (Junk *et al.*, 1989). Here, we suggest that the floodplain activation flood should be defined with greater specificity in terms of hydrological characteristics (e.g., duration, frequency, season) – linked to desired ecological outputs (e.g., food-web productivity) – than a more generic flood pulse. In complex channels, long-duration below-bankfull flow pulses (*sensu* Tockner *et al.*, 2000) that inundate bars, side channels, and other features of complex channels can also support many of the processes associated with a floodplain activation flood (Williams *et al.*, 2009).

Floodplain Maintenance Flood

The floodplain maintenance flood is a higher magnitude flood (Figure 4a) capable of performing geomorphic work including bank erosion and deposition on the floodplain that creates and maintains floodplain surfaces and contributes to heterogeneous floodplain topography (Whiting, 1998; Florsheim and Mount, 2002) (Figure 3). In turn, this heterogeneous topography results in vegetation patches of varying age, species composition, and structure (Figures 4c and 4d), and floodplain waterbodies of varying successional stage and connectivity to the river (Ward *et al.*, 2002). As expressed by flow-duration curves, floodplain maintenance floods occur relatively infrequently. However, the recurrence interval of this flood type varies based on river gradient, elevation difference between the channel and floodplain, sediment supply, and connectivity (Florsheim and Mount, 2002) and can range from every year to less frequently. A floodplain maintenance flood can be estimated by an analysis of the dominant processes that are responsible for creating floodplain surfaces (Whiting, 1998), such as vertical accretion (overbank deposition) or lateral accretion (meander migration

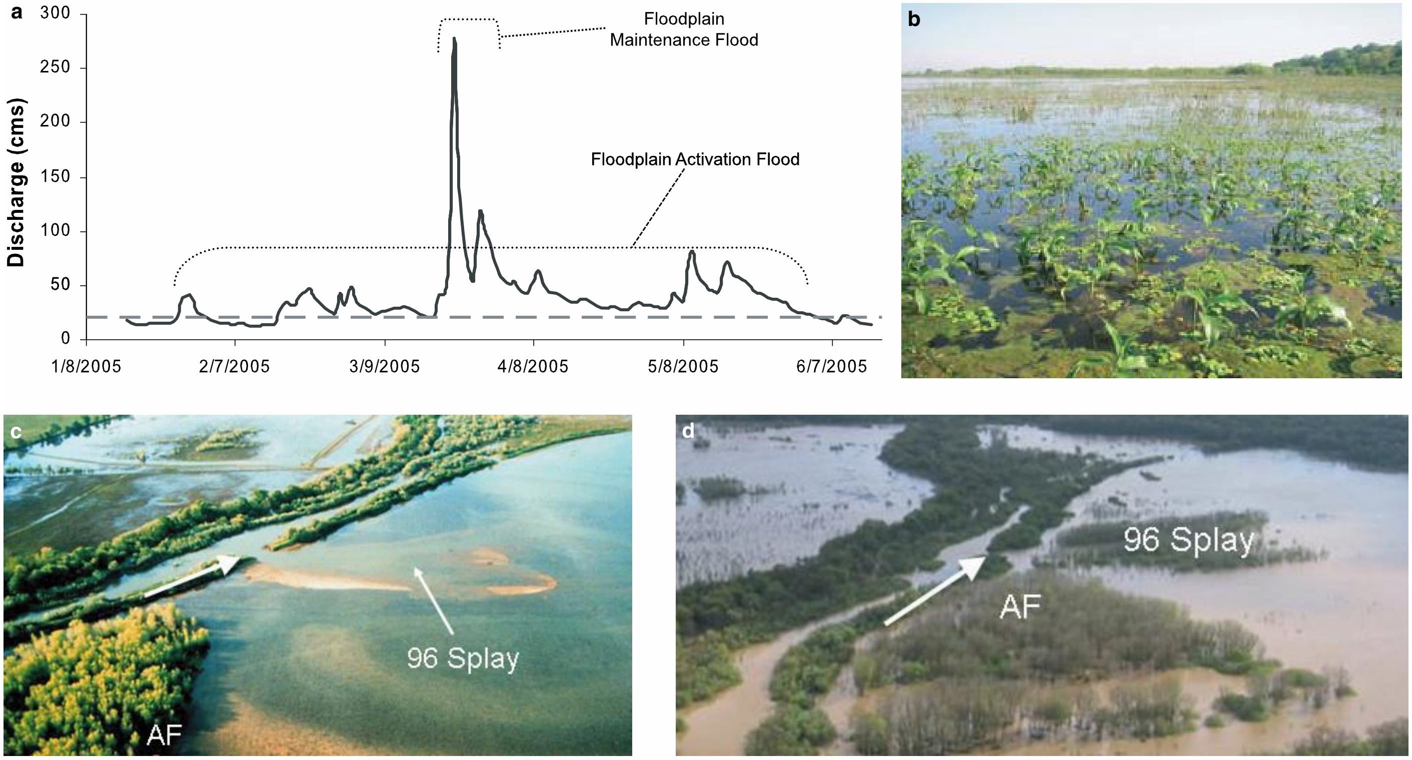

FIGURE 4. Representative Floods on the Cosumnes River Floodplain. (a) Hydrograph from the Cosumnes River (California), winter and spring 2005. The horizontal dashed line indicates the approximate discharge (20 cms) at which the river and floodplain are connected. (b) A floodplain activation flood on the Cosumnes River floodplain, April 2005. Note the relative clarity of the water (i.e., low turbidity) and the development of algal mats in the water and on the emergent vegetation (Photo by Jeff Opperman) (c) A crevasse sand splay was formed due to sediment transport and deposition during a floodplain maintenance flood in 1996 following an intentional levee breach in 1995 (described in detail in Florsheim and Mount, 2002). The white arrow indicates the direction of flow in the channel and points to the levee breach. "AF" indicates the "accidental forest," a stand of riparian trees that regenerated on a sand splay deposited during an unintentional levee breach in 1985 (Photo by Mike Eaton). (d) The inundated floodplain in 2006 (the white arrow again indicates the direction of flow and points to the 1995 levee breach). Riparian trees have preferentially established on the sediment deposits of the 1996 sand splay (shown after initial formation in c). "AF" again indicates the accidental forest (Photo by Mike Eaton).

and point bar deposition) (Nanson and Croke, 1992; Knighton, 1998). Whiting (1998) reported that the floodplain maintenance flood for the East Branch of the Chagrin River (Ohio) – a flood with sufficient depth and energy to deposit fine sediment onto the floodplain – had a recurrence interval of four years. At the Cosumnes River floodplain (California), flows capable of depositing sand on the floodplain corresponded to a 1.5-year recurrence interval (Booth *et al.*, 2006; Florsheim *et al.*, 2006). Richter and Richter (2000) estimated that the mosaic of floodplain forest along the Yampa River (Colorado) could be maintained provided that sufficient meander migration occurred over time to rework floodplain surfaces and initiate vegetative succession. They suggested that flows with a magnitude ≥125% of bankfull discharge, maintained for at least 15 days, were critical for maintaining sufficient meander migration and lateral accretion to support healthy floodplain forests over time. This observation emphasizes that duration, in addition to magnitude, can also be important for the geomorphic processes associated with a floodplain maintenance flood.

Floodplain Resetting Floods

Floodplain resetting floods are very high-magnitude and relatively rare events (e.g., exceedance probability <5%) that result in extensive geomorphic changes, including scouring of floodplain surfaces and changes in channel location due to avulsion (Nanson, 1986; Wohl, 2000). Although there is no clear-cut distinction between floodplain maintenance floods and resetting floods, the key feature of floodplain resetting flows is that they produce sufficient shear stresses to cause extensive scour of floodplain surfaces and can potentially result in abrupt changes in channel location (Trush *et al.*, 2000). The ecosystem processes associated with a floodplain activation flood occur within the mosaic of habitat features created during floodplain maintenance floods and floodplain resetting floods.

Application of model to Central Valley

To expand on these basic concepts and illustrate the conceptual model, we provide an example of floodplain processes from California's Central Valley. The conceptual model could be similarly elaborated and refined for other lowland, low-gradient river-floodplain systems.

Floodplains in the Central Valley have been reduced dramatically from their historical extent due to flow regulation from dams, levees and rip-rap, and channelization and channel incision (Katibah, 1984). This loss of floodplains has contributed to the decline of numerous species in the Valley's rivers and riparian forests as well as in the downstream Sacramento-San Joaquin Delta ("the Delta"). State and federal agencies have numerous policies and programs dedicated to reversing these declines. In the following, we describe three important ecological benefits that the restoration actions seek to promote. Note that here (Figure 3) the primary outputs of the model are "ecological benefits" – by which we mean desired outcomes of environmental management and restoration programs – and the model does not reflect broader ecosystem services such as flood attenuation or groundwater recharge. The conceptual model could be adapted to include such ecosystem services as outputs.

Food-Web Productivity. Central Valley floodplains can produce high levels of phytoplankton and other algae, particularly during long-duration flooding that occurs in the spring (Sommer *et al.*, 2004; Ahearn *et al.*, 2006). Downstream of Central Valley floodplains, the Delta contains several fish species with declining populations, such as the Delta smelt (*Hypomesus transpacificus*), and food limitation is likely one of the factors contributing to these declines (Jassby and Cloern, 2000). Algae provide the most important food source for zooplankton in the Delta (Muller-Solger *et al.*, 2002) and these zooplankton are a primary food source for numerous Delta fish species. Consequently, a potential benefit of floodplain restoration is an increase in the productivity of food webs that support Delta fish species (Ahearn *et al.*, 2006).

Spawning and Rearing Habitat for Native Fish. Recent research has demonstrated that floodplains provide the necessary spawning habitat for the Sacramento splittail (*Pogonichthys macrolepidotus*), an endemic minnow. Splittail can be considered "obligate floodplain spawners," meaning they require inundated floodplain habitat to spawn. Recruitment of splittail is strongly correlated with the duration of floodplain inundation (Sommer *et al.*, 1997). Recent studies have also revealed that juvenile Chinook salmon (*Oncorhynchus tshawytscha*) have faster growth rates on floodplains than in main-stem river channels (Sommer *et al.*, 2001b; Jeffres *et al.*, 2008). Juvenile Chinook can enter and rear on floodplains during their downstream migrations in the winter and early to mid-spring. The juveniles have access to a diverse and dense prey base on floodplains – zooplankton density can be 10-100 times greater in a floodplain compared with the river (Grosholz and Gallo, 2006) – along with generally more favorable habitat conditions (warmer, slower water, fewer predators). These conditions translate to faster growth compared with juveniles rearing in rivers (Figure 1). Faster growth rates allow juveniles to attain larger sizes when they enter the estuary and ocean, and body size has been found to be positively associated with survival to adulthood for salmonids (Unwin, 1997).

Riparian Habitat Structure. Floodplain maintenance and floodplain resetting floods erode banks and deposit sediment, creating the necessary conditions for the regeneration of riparian tree species (Richter and Richter, 2000; Trush *et al.*, 2000). In the Central Valley, tree species such as cottonwood (*Populus fremontii*) time their seed release to coincide with the historic peak of snowmelt runoff because these high flows create the necessary conditions – such as the deposition of alluvial soil – for successful germination, growth, and survival of seedlings (Stella *et al.*, 2006). Riparian forests support high levels of biodiversity and provide essential habitat to a number of endangered species, including the Valley elderberry longhorn beetle (*Desmocerus californicus dimorphus*), the yellow-billed cuckoo (*Coccyzus americanus*), and many other birds (Golet *et al.*, 2008).

The model illustrates the importance of hydrological variability and connectivity for an ecologically functional floodplain. For example, a floodplain that rarely is inundated by a floodplain activation flood will not produce the ecological benefits of food-web productivity or spawning and rearing habitat for native fish. A floodplain that is not subject to floodplain maintenance floods or floodplain resetting floods will not maintain the mosaic of habitats (e.g., vegetation and water bodies of varying successional stages) that help support floodplain biodiversity (Amoros, 1991; Tockner and Schiemer, 1997; Ward *et al.*, 2001). Along the bottom of the Figure 3, the scale bar indicates that a small floodplain site will only produce local benefits, whereas extensive floodplains will produce benefits that are measurable at a population or system scale.

Recent research in the Central Valley illuminates how issues of connectivity, flow regime, and scale influence the functionality of Central Valley floodplains. For example, the Cosumnes River is the only major river entering the Central Valley that lacks major dams and flow regulation. Consequently, the Cosumnes River retains a natural hydrograph encompassing a broad range of flow levels (Figure 4). TNC acquired lowland floodplain habitat along the Cosumnes River and began planting riparian trees on former agricultural land. However, the floodplain was still disconnected from the river by a remnant levee and widespread natural regeneration of riparian trees did not occur until an accidental breach in the levee reinitiated dynamic connectivity between river and floodplain. High-energy flows through the breach deposited sediment and created topographic heterogeneity, which lead to the regeneration of a stand of riparian trees, named the "accidental forest" (Figures 4c and 4d) (Swenson *et al.*, 2003).

Due to the successful riparian regeneration from the accidental breach, TNC intentionally breached the levee in several additional locations. With the increased connectivity, floodplain maintenance floods occur relatively frequently, with flows with a recurrence interval of one to two years capable of inducing heterogenous topography on the floodplain (Florsheim and Mount, 2002). In addition to promoting geomorphic processes and riparian regeneration, the restored connectivity allows floodplain activation floods to occur, with the associated key processes of splittail spawning, juvenile Chinook rearing (Figure 1), and food-web productivity (Figure 4b) (Ahearn *et al.*, 2006; Moyle *et al.*, 2007).

Williams *et al.* (2009) recently explored the effect of altered flow regimes on the functionality of floodplains along the Sacramento River. They found that due to channel incision and regulation from upstream reservoirs, floodplain activation floods (defined in their study as floods that last at least one week in the spring) have been greatly reduced compared with pre-dam conditions. Currently, the production of benefits associated with these floods – food-web productivity and native-fish habitat – are mostly restricted to the Yolo Bypass, a large (24,000 ha) engineered flood bypass that conveys overflow from the Sacramento River (Sommer *et al.*, 2001a). Thus, due to the alteration of the flow regime, even areas that are hydrologically connected to the Sacramento River during larger magnitude floods have a much lower frequency of inundation by long duration spring floods than occurred historically, limiting their ability to provide this important component of a functional floodplain.

Finally, the two floodplain areas described above – the Cosumnes River floodplain and the Yolo Bypass – differ dramatically in scale, with the Cosumnes encompassing approximately 40 ha of frequently inundated floodplain compared with the bypass's 24,000 ha. Although the Cosumnes can provide local benefits for splittail and Chinook salmon, the Yolo Bypass can influence fish at the population scale. For example, the duration of inundation of the Yolo Bypass is a strong predictor of year-class strength for splittail for the entire system (Central Valley and Delta; Sommer *et al.*, 1997).

ADDRESSING CONNECTIVITY, FLOW REGIME, AND SCALE THROUGH RESTORATION PROJECTS

The conceptual model presented here outlines the challenges confronting floodplain conservation: to protect or restore a functional floodplain, the project must encompass both flow regime and connectivity and thus must address both land use and water management. Further, for the project or program to produce meaningful benefits, it must achieve its results at a sufficiently large spatial scale. Therefore, beyond addressing the scientific complexities of conserving a functional floodplain, floodplain restoration confronts significant technical and socioeconomic challenges (Opperman *et al.*, 2009).

In the following, we provide three case studies where TNC and its partners are working to restore flow regimes and/or connectivity with strategies that can affect a large spatial scale. These case studies also illustrate approaches to overcoming socioeconomic constraints to floodplain restoration through the use of a variety of strategies including collaboration with water management agencies (Savannah River), developing markets for ecosystem services (Mollicy Farms), and linking floodplain restoration with a flood-damage reduction project (Hamilton City). Thus, even though the environmental outcomes of these projects may not be apparent for years, the cases represent important advances in overcoming institutional and socioeconomic challenges to large-scale floodplain restoration.

The Savannah River (Georgia)

The Savannah River watershed contains extremely high species biodiversity, including the greatest number of native fish species (approximately 100) of any United States (U.S.) river draining into the Atlantic (Meyer *et al.*, 2003). However, the river's flow regime and longitudinal connectivity are heavily impacted by dams. The U.S. Army Corps of Engineers (the Corps) maintains three large dams on the upper Savannah

River, creating Hartwell, Russell, and Thurmond reservoirs. Thurmond Dam (1954) was the first built and is located the furthest downstream, just upstream of the city of Augusta. The dams are operated for multiple purposes, including flood control, water supply (for over 1.5 million people), hydropower, and recreation. The river forms the border of Georgia and South Carolina and empties into the Atlantic through an extensive estuary surrounding the city of Savannah.

Regulation from the dams has greatly altered the flow regime of the Savannah River (Figure 2). For example, the current estimate for the 100-year flow is roughly equivalent to the pre-dam 2-year flow [2,550 cubic meters per second (cms)]. The current two-year flow (approximately 991 cms) is one-third the size of the pre-dam two-year flow. Because of this flow regulation, interactions between the river and floodplain have changed greatly. Although the flow regime has been altered, the potential to restore high magnitude events (such as floodplain maintenance and floodplain resetting flows) persists because more than 68,000 ha of floodplain forest between the dams and the estuary remain undeveloped and unleveed (Meadows *et al.*, 2007).

Numerous fish species of southeastern rivers use lowland floodplains during periods of inundation (Ross and Baker, 1983) and the reproductive success of many species within the piscine families cyprinidae (e.g., common carps and various shiners), centrarchidae (e.g., sunfish and bass), and percidae (e.g., various darters) have been correlated with the extent, timing, and duration of floodplain inundation along southeastern rivers (Killgore and Baker, 1996). A literature review conducted in support of the restoration process described below concluded that between ¼ and ½ of the fish species found in the Savannah River likely use inundated floodplain habitats for spawning and approximately 85% of all the river's fish species likely use floodplain habitats for refuge and foraging (Meyer *et al.*, 2003). Thus, scientists hypothesized that restoring portions of the historic hydrograph to promote river-floodplain connectivity will benefit a high proportion of the Savannah River's fish species.

In 2002, TNC and the Corps began a collaborative effort to investigate the potential to release environmental flows from Thurmond Dam, as part of a national partnership (the Sustainable Rivers Project) to restore ecological integrity to rivers affected by Corps dams (Warner, 2007). Within a workshop setting, teams of scientists and water managers developed environmental flow recommendations for the river, floodplain, and estuary ecosystems. Flow recommendations were framed as the EFC of low flows, high-flow pulses, and floods (*sensu* Mathews and Richter, 2007) and defined in terms of magnitude, frequency, duration, season, and rates of change. Each EFC was expressed in the form of a hypothesis describing the expected linkages between flow and specific biological or physical processes (e.g., fish migration or river-floodplain connectivity). These hypotheses lay the foundation for monitoring and adaptive management to refine the flow recommendations (Richter *et al.*, 2006; Warner, 2007).

Following the workshop, the Corps has begun to implement portions of the flow recommendation, with four experimental high-flow pulses released over three years. Scientific staff from resources agencies, TNC, and academia are now monitoring the river to investigate the effects of the experimental flow releases. The monitoring program includes long-term response variables to measure ecosystem response (e.g., tree regeneration), and "trigger" variables that can give more immediate guidance to flow implementation (e.g., spawning movements of fish).

The Savannah River case (and the Sustainable Rivers Project more broadly) illustrates the potential gains in flow regime restoration that can be accomplished through collaboration with water managers (Warner, 2007). The monitoring program is building a foundation for scientists to refine flow recommendations and reduce uncertainties. The experimental flow releases provide an opportunity for scientists and water managers to communicate and for both to gain experience with implementing and studying environmental flows. Initial monitoring results were used to inform subsequent high-flow pulse releases.

Although large areas of the Savannah River floodplain are within public ownership such as wildlife refuges (16,000 ha in Georgia; 33,000 ha in South Carolina), future flow releases to inundate the floodplain could be constrained by even relatively small changes in floodplain land use that are incompatible with flooding (e.g., agriculture or residential development). To ensure that river-floodplain connectivity remains possible, TNC has organized a consortium of resource agencies, conservation organizations, and private landowners to create The Savannah River Preserve, a corridor of protected lands along both sides of the river encompassing a range of habitats – wetland forests, estuaries, streams, and adjacent uplands. To date, 66 private landowners – representing 100,000 ha of rural lands – have agreed in principle to sell their development rights at a discount value to help create the preserve. Maintaining this large, landscape-scale floodplain intact will remain a challenge but, if successful, The Savannah River Preserve will allow the Corps to release sufficiently high flows to connect the river to its biologically rich floodplain.

Mollicy Farms (Ouachita River, Louisiana)

Covering about 10 million ha (25 million acres), the Lower Mississippi River Alluvial Valley was once one of the great floodplain forests on Earth. But from the mid-1800s to late-1900s, most of the forest was cleared for timber and replaced by intensive row-crop agriculture. Today <3 million ha of bottomland forest remain (King and Keeland, 1999). Initially, clearing occurred on lands at higher elevations with well-drained soils but, with time, farmers began to clear and cultivate lower elevation lands that were prone to flooding and thus had lower potential agricultural productivity. Despite flood engineering structures, these low-lying agricultural lands are inundated every few years and major floods still threaten the region.

The Nature Conservancy is exploring an ecosystem services strategy for restoring bottomland hardwood forests to these lands as a viable alternative to marginal row-crop agriculture. The foundation for this strategy expands beyond the biodiversity benefits of floodplains and includes the full portfolio of ecosystem services they deliver. These services include carbon sequestration to mitigate climate change, recreation such as duck hunting and fishing, flood attenuation to reduce downstream flood risks, and nutrient removal to improve water quality and reduce contributions to the Gulf of Mexico's "dead zone" (Mitsch *et al.*, 2001). In some cases, floodplain reconnection may also reduce future levee maintenance costs.

To investigate the feasibility of this strategy, TNC is working with the U.S. Fish and Wildlife Service, U.S. Geological Survey, and other partners to implement floodplain reconnection and restoration at Mollicy Farms, a 6,400 ha site that was cleared for soybean agriculture in the 1960s. Located within the Upper Ouachita National Wildlife Refuge along the Ouachita River in Morehouse Parish, Louisiana, Mollicy Farms and the surrounding area already attract hundreds of thousands of migrating waterfowl each fall and winter. The restoration project will include reconnecting the floodplain to the river through levee breaches and restoring former agricultural land to wetland and forest. Scientists predict that these actions will greatly increase the diversity of habitat types and range of ecosystem services provided by the site.

As the site of the largest floodplain reconnection and bottomland afforestation project in the U.S., Mollicy Farms provides a valuable opportunity to study large-scale floodplain restoration and the associated ecosystem service benefits. A research program will examine the site's ecosystem services, with the following primary research questions: How much does floodplain restoration change the production of services? From the time of project initiation, how does the generation of these service benefits increase/change over time? How does scale affect benefits such as flood attenuation? What is the value of service improvements to society (social welfare value), and what is the potential private market value if a landowner were to sell services?

To support market development for these services, TNC will be conducting long-term monitoring at Mollicy Farms, as well as at control sites, to understand how services of restored floodplains change over time. For services, the focus is on carbon sequestration, nutrient removal and water quality, recreation, and flood attenuation. A study of ecosystem service values in the Mississippi Alluvial Valley indicates significant wetland service values, and the potential for future market values of services to exceed net income from agriculture (Table 1) (Murray *et al.*, 2009). Much will depend on how existing voluntary carbon markets (e.g., Chicago Climate Exchange) evolve under expected future regulation, and the extent to which markets for other services such as nutrient removal emerge.

Because it may be many years before the extent of service improvements at the site are fully understood, TNC plans to develop preliminary estimates of service benefits that can be refined over time based on monitoring data and changes in markets. By increasing the understanding about floodplain service benefits through a large-scale demonstration project, TNC seeks to inform and strengthen strategies for advancing floodplain restoration at meaningful spatial scales.

Hamilton City (Sacramento River, California)

The Nature Conservancy and several conservation partners formed the Sacramento River Project in 1988 to pursue large-scale, process-based restoration of riparian and floodplain habitats of the Sacramento River (Golet *et al.*, 2006, 2008). To date, the project has conserved approximately 5,400 ha of riparian habitat along the Sacramento River, between the towns of Colusa and Red Bluff (Figure 5). Primary strategies include the conservation of flood-prone land through acquisition or easement, active riparian restoration (i.e., planting), and the restoration of natural river processes (Golet *et al.*, 2008). Initial results suggested that, due to the altered hydrology of the Sacramento River, irrigation was necessary for successful riparian restoration (Alpert *et al.*, 1999). Golet *et al.* (2008) reported that restored riparian sites supported a broad range of fauna, including birds, bats, and insects.

TABLE 1. Ecosystem Service Values of Restoring Agricultural Lands to Bottomland Hardwood Forest Wetlands in the Lower Mississippi Alluvial Valley, Compared With the Net Income From Agriculture ($/hectare/year).

Ecosystem Services	Social Welfare Value	Private Market Value	
		Current	Potential
Greenhouse gas mitigation	$162-$213	$59	$419
Nitrogen mitigation	$1,268	$0	$634
Wildlife recreation	$16	$15	$15
Flood attenuation and other services	?	?	?
Total	$1,446-$1,497+	$74+	$1,068+
Agricultural net income		$368	

Notes: Question marks in the row for "flood attenuation" indicate that Murray *et al.* (2009) did not attempt to quantify these values as they are strongly influenced by location and total size of a floodplain site. The flood attenuation values of connected floodplains can be quite high (Akanbi *et al.*, 1999; Opperman *et al.*, 2009). Source: Murray *et al.* (2009).

Within this context of large-scale riparian restoration, the Sacramento River Project's scope expanded to encompass the integration of floodplain reconnection and flood risk management. The Hamilton City Ecosystem Restoration and Flood Damage Reduction Project was one of the first projects to utilize new Army Corps policy guidelines intended to promote multipurpose projects (e.g., projects that combine ecosystem restoration with flood-damage reduction). This case study examines the partnership and policy components that were keys to advancing a multipurpose project at Hamilton City. Because the multipurpose guidelines were new, this project confronted numerous policy challenges. Although some policy hurdles remain (discussed below), the project has provided a forum for resolving policy constraints that will benefit future multipurpose projects.

Hamilton City is located on the Sacramento River approximately 130 km north of Sacramento in Glenn County, California (Figure 5). The population of 2,500 and the surrounding agricultural lands receive marginal flood protection by an old (circa 1904) degraded private levee called the "J" levee. The J levee only offers protection against a 10-year flood and, as a result, Hamilton City has been evacuated due to flooding concerns six times in the last 25 years.

Over that time period, citizens of Hamilton City made several attempts to secure a project that would reduce flood risk. Although the Army Corps conducted various project feasibility studies, none produced a project alternative capable of meeting a positive cost-benefit ratio. In 2001, the Corps introduced new planning policies that created an opportunity for the town. These new policies facilitate a combination of project goals such as flood damage reduction and ecosystem restoration. Hamilton City formed a collaborative partnership to study a combined project alternative. The collaboration included a broad range of stakeholders, including Reclamation District 2140, the Hamilton City Community Services District, Citizens in Action, Glenn County, local agricultural interests, the Corps, the State Reclamation Board, the California Department of Water Resources, the California Bay-Delta Authority, and TNC (Golet *et al.*, 2006). The studies resulted in the first project alternative in over 20 years that met requirements for federal participation and funding.

A key to reaching this first successful project alternative was the inclusion of ecosystem benefits, specifically those benefits arising from river-floodplain connectivity. The project benefits arising from only riparian revegetation (e.g., through planting and irrigation and without reconnection) would have been insufficient to justify the project. Instead, the successful project formulation featured the removal of the degraded "J" levee and building 11 km of setback levee up to 1.6 km away from the river channel, thus creating 600 ha of reconnected habitat (Figure 5). The setback levee will provide the critical environmental benefits of river-floodplain connection across a range of flow levels, including high-energy flows capable of reworking floodplain sediment and creating diverse habitat patches (i.e., floodplain maintenance flows). The reconnected area will be sufficiently large to allow these dynamic processes to occur.

Flood protection for both Hamilton City and the surrounding agricultural lands are greatly increased by the recommended plan. The setback levee will provide the town with protection from a 75-year recurrence interval flood (compared with the town's current level of protection from a 10-year flood) and surrounding agricultural lands, which previously flooded very frequently (<5 year protection), will benefit from a training dike that will both reduce the frequency of inundation and, when flooding occurs, prevent harmful scouring.

The Hamilton City case study illustrates the potential for large-scale floodplain restoration to occur through multipurpose flood-damage reduction projects. More broadly, the case study highlights the need for continued policy reforms to encourage and facilitate such multipurpose projects. The initial policy changes allowing Corps projects to combine project purposes resulted in a plan for Hamilton City that received broad support, met multiple objectives, and therefore utilized a variety of funding sources (e.g., federal flood-damage reduction and state-federal ecosystem restoration funding). However, securing additional funding for the project has posed challenges, highlighting the need for additional policy changes. Current policy for ranking and prioritizing

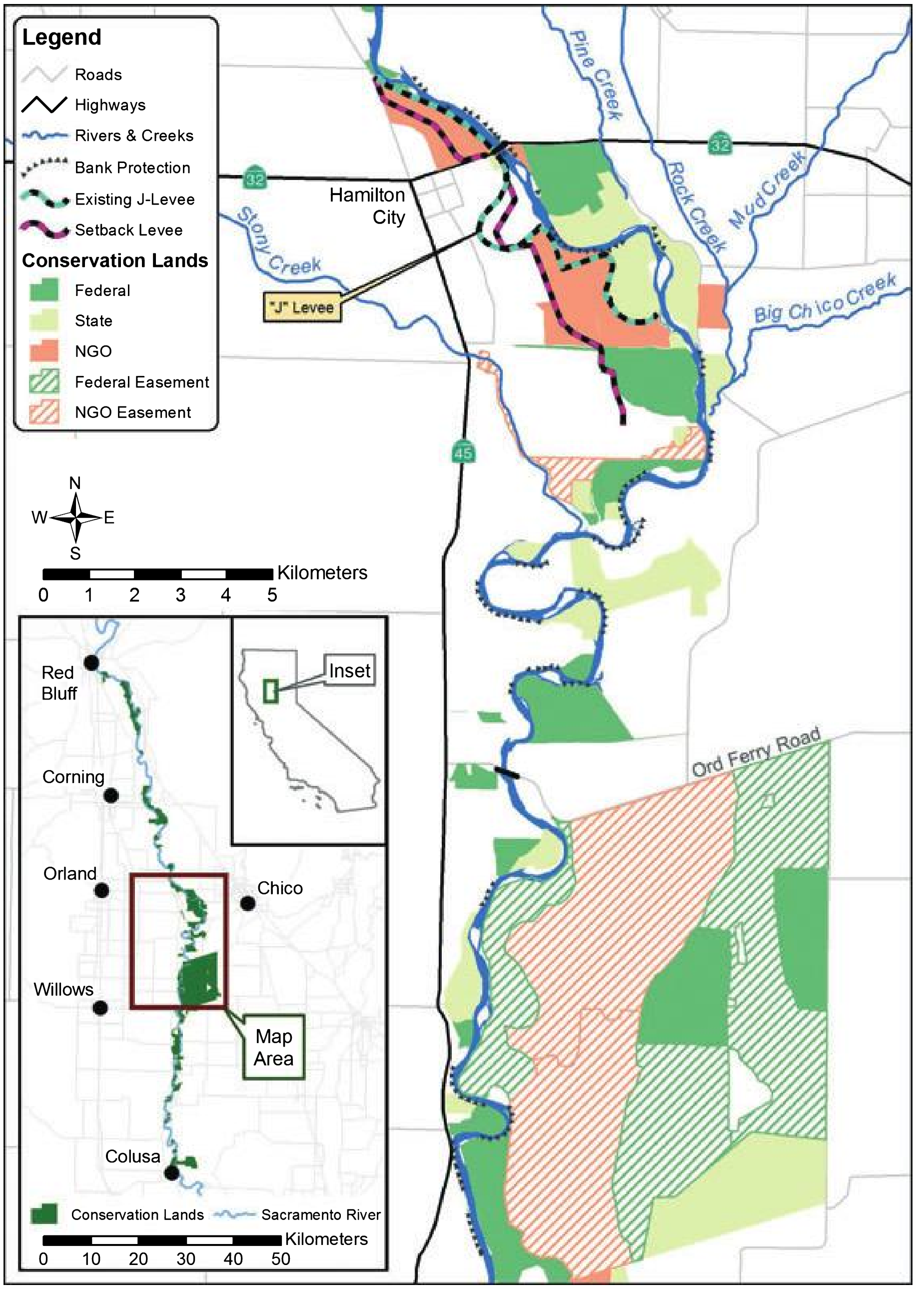

FIGURE 5. Location of the Hamilton City Ecosystem Restoration and Flood Damage Reduction Project. The project features the construction of a setback levee to replace the degraded "J" levee and to reconnect 600 ha of floodplain with the Sacramento River. The inset map shows the full spatial scale of riparian and floodplain conservation sites as part of the Sacramento River Project.

Corps projects for funding requires projects to be evaluated based on a single purpose and thus multipurpose projects must be evaluated on the strength of one of their purposes. Multipurpose projects such as Hamilton City would greatly benefit from a new system that ranked projects based on their full range of benefits.

Lastly, projects at the scale of the Hamilton City Project, embedded within the larger Sacramento River Project (thousands of hectares and >1 km in floodplain width), create the opportunity to implement flow regime management strategies. TNC is currently exploring opportunities to restore key components of the natural hydrograph to the Sacramento River. As a first step, TNC developed the Sacramento River Ecological Flows Project that reviewed existing information, integrated numerous models and field data, and created a software-based decision analysis framework. The analysis framework can compare life-history responses of several species – including cottonwood and Chinook salmon – to alternative flow management strategies.

CONCLUSIONS

Floodplains are complex, productive ecosystems that support high levels of biodiversity and provide important ecosystem services to society. An ecologically functional floodplain requires connectivity to a river with a flow regime with sufficient variability to include a range of flow levels and events, such as the floodplain activation flood and floodplain maintenance flood described in this conceptual model.

This conceptual model is intended to guide restoration projects so that they consider the broad range of flows required to support functional floodplains. For example, using hydraulic models, a proposed floodplain reconnection project can be evaluated in terms of which types of floods will inundate various portions of the project site. For a levee setback project on the Bear River (California), planners determined that none of the project area would be inundated by floodplain activation floods (as defined by Williams *et al.*, 2009) and thus a portion of the project area was graded to an elevation that would allow inundation by this type of flood (Williams *et al.* 2009).

The specific representative floods described in this model can provide preliminary examples for "building blocks" or EFCs for restoring or maintaining floodplain functions (see the Savannah case study). The representative floods described in this model must be refined – in terms of duration, frequency, magnitude, season – for the specific system as well as the specific functions and processes that managers seek to support. For example, floodplain maintenance floods will vary based on the dominant process for building floodplain surfaces (e.g., lateral versus vertical accretion). Finally, the representative floods described here are not an exhaustive description of important characteristics of the flow regime. Specific sequences of flood events can influence floodplain processes (Ahearn *et al.*, 2006) and groundwater levels beneath the floodplain are influenced by river stage, with important implications for riparian vegetation (Mahoney and Rood, 1998).

Conserving floodplains across large geographic areas remains a primary challenge for floodplain restoration projects and programs. The case studies in this paper illustrate various approaches for achieving floodplain restoration at large spatial scales, ranging from hundreds of hectares (Hamilton City) to tens of thousands of hectares (Savannah). The Savannah River Project demonstrates that environmental flow releases for floodplain inundation can be achieved through collaboration between conservation organizations, water managers, and other stakeholders. Additionally, the Savannah River Project highlights the linkages between flow regime and land use for floodplain conservation as the Savannah River Preserve strives to maintain land uses compatible with floodplain inundation. The significant ecosystem services associated with floodplains may provide a financial mechanism for implementing floodplain conservation at large spatial scales, as is being explored at Mollicy Farms. Finally, Hamilton City demonstrates that multipurpose flood-damage reduction projects can achieve large-scale floodplain restoration. Projects that integrate floodplain restoration and a primary floodplain ecosystem service – reduction of flood risk – will likely become increasingly important in a future where changes in climate and land-use patterns lead to increased flood risk.

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