



A FLOOD OF BENEFITS

USING GREEN INFRASTRUCTURE
TO REDUCE FLOOD RISKS

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Using Green Infrastructure to Reduce Flood Risks

The Nature Conservancy 2014



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Cover photo credits: Top photo— by Jonathan Eisen at the Yolo Bypass; Bottom photo— Mark Godfrey, 2005, of the Mississippi River valley looking west toward Iowa.

1. Overview

“Green infrastructure” encompasses natural features, such as forests and wetlands, that provide similar or complementary flood-management benefits as engineered infrastructure. While engineered infrastructure can degrade rivers and the values they provide, green infrastructure tends to support a diverse array of other benefits. A sustainable and resilient approach to flood-risk management will deploy a mix of green and engineered infrastructure solutions, tailored to specific challenges and objectives.

Flooding is the most damaging natural disaster in the world, with average annual losses exceeding \$40 billion (Cooley 2006). These damages have been increasing through time and flood risk will continue to rise due to population growth in flood-prone areas, climate change contributing to more intense storms, and the aging of flood-management infrastructure.

This infrastructure—including dams, levees and floodwalls—has been the traditional response to managing flood risk. However, the successful performance of this infrastructure necessarily eliminates one of the most important ecological processes on Earth: the connection between rivers and floodplains. This connection is what makes river-floodplain systems among the most productive and diverse ecosystems on the planet (Bayley 1995). Throughout Africa, Asia and Latin America, river-floodplain systems support productive fisheries and



Highlights

- ◆ The Mississippi Flood of 2011 had the greatest volume of floodwater ever recorded for that river. The flood-management system was able to safely convey that flood in large part because, in multiple locations, floodwaters were allowed to spread out onto the historic floodplain, relieving pressure on levees and sparing cities like Baton Rouge and New Orleans.
- ◆ In several locations in California, flood managers have concluded that setting levees back from the river provided the most effective method of reducing local flood risk. While driven by flood-risk reduction, these projects will restore thousands of acres of floodplain habitat
- ◆ During major floods, the Yolo Bypass—a 60,000 acre portion of the floodplain that was reconnected to the river in the 1930s—carries 80% of the volume of floods of the Sacramento River and is the key feature protecting the city of Sacramento during floods. The Bypass also supports productive agriculture and, though built for flood management, it is the best remaining floodplain habitat in California’s Central Valley for native fish and birds.
- ◆ The US Army Corps of Engineers found that acquiring and protecting floodplain wetlands could reduce Boston’s flood risk from the Charles River for 1/10 the cost of a plan that included new engineered infrastructure.

agriculture, providing a primary food source for hundreds of millions of people in rural communities (UNEP 2010).

River basins with extensive flood-management infrastructure have lost this essential connection between rivers and floodplains, resulting in dramatic declines in river productivity and biodiversity. In fact, freshwater species are endangered at higher rates than either terrestrial or marine species, in large part to the fragmentation and changes in flow from infrastructure (Richter et al. 1997, Ricciardi and Rasmussen 1999).

Thus, river floodplains present two great challenges to those seeking sustainable management of the world's rivers: the need for actions to reduce flood risk and the need to maintain or restore the connections between rivers and floodplains. At first glance, those objectives seem incompatible. In this report we describe how a "green infrastructure" approach to flood-risk management can address both objectives. This approach incorporates natural features and processes into flood-management projects. The techniques and approaches described here are intended to reduce flood risk for people. However, unlike engineered infrastructure, green infrastructure approaches can also include restoration or conservation of forests, wetlands, rivers and floodplains. When implemented as part of an overall strategy for sustainable river and watershed management, these approaches provide not just the primary benefit of flood-risk reduction, but also support a diverse array of other benefits.

2. Floods and flood-risk management

Rivers have always attracted people because they provide abundant benefits: fish, transportation, water for drinking and, because the river continuously flows away from a community, a convenient place to dump waste. For much of their length, most rivers are located within valleys that provide flat, fertile land for farming. Thus river valleys have served as important places for settlement, with the first civilizations arising along the Nile, the Yangtze, and the Tigris and Euphrates rivers.

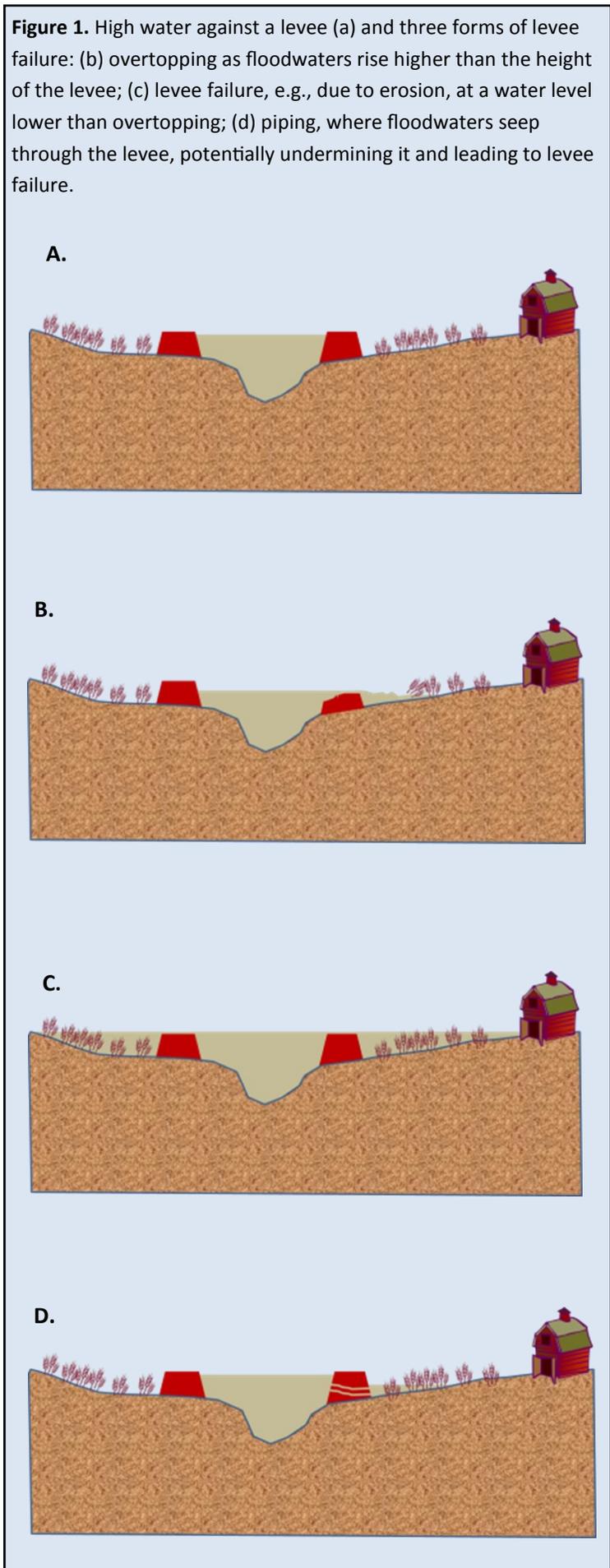
The cornucopia of river benefits have always been twinned with a risk: periodic flooding. (In fact, that flooding is directly responsible for one of the advantages of floodplain settlement because floods, over centuries, are responsible for depositing layers of nutrient-rich sediment, creating that flat, fertile valley land. Simple settlements could deal with flooding by moving seasonally or restricting buildings to the very highest ground. But as civilizations grew more dense, large populations with permanent buildings became vulnerable to floods. It is because of this intertwined fertility and danger that the Yellow River is known as both China's "cradle" and its "sorrow." In stories, folk tales and songs the Mississippi serves as a backdrop for romantic adventure, but also for inexorably rising floods.

The 1931 floods in China, along the Yellow, Yangtze, and Huai rivers, are estimated to be the deadliest natural disaster ever: official statistics report 145,000 deaths but external estimates place the death toll at nearly 4 million (Kundzewicz and Takeuchi 1999). Today, flooding remains the most damaging type of natural disaster. Since 1900, nearly 7 million people have been killed in floods and 3 billion people have been negatively affected, such as being displaced or suffering economic losses. While flooding is still a major source of mortality, the frequency of flood events causing massive mortalities appears to be decreasing, likely due to improved warning systems and improved delivery of medical care, food and water to flood refugees. Most (90%) of the 7 million fatalities since 1900 occurred in just 5 individual flood events in China, all before 1960. However, the number of people negatively affected by floods continues to increase and has been rising steadily since the 1970s, with currently approximately 100 million affected annually. Over the past 20 years, annual flood damages have averaged \$40 billion (Cooley 2006).

These rising damages have occurred even as massive investments have been made in flood-management infrastructure. Key types of flood-management infrastructure include:

1. **Flood-control dams and reservoirs.** Dams can be operated to reduce downstream flood levels. By maintaining empty reservoir space behind the dam, a flood-control dam and reservoir can capture incoming floodwaters and release a lower flow rate downstream. A dam can store floodwater, and thus reduce the downstream volume and height of the flood, up until the reservoir is full. After that the dam will “spill” water and the rate of water leaving the dam will be the same as the rate of water entering the reservoir. Thus the ability to manage a flood is a function of the empty storage space within the reservoir relative to the size of the floods the upstream watershed can produce. As described below, the need to maintain empty storage space can compete with other reservoir purposes that benefit from storing water, such as water supply and hydropower.

2. **Levees.** Levees are essentially walls that are constructed along one or both sides of a river . These walls prevent rising floodwaters from inundating land behind the levee. The Chinese began constructing levees along the Yangtze and Yellow Rivers over 4000 years ago and levees were constructed along major rivers in the US and Europe, such as the Rhine and Mississippi, in the 18th and 19th century (Sayers et al. in preparation). Levees can range from simple berms of earth pushed up along a river to highly engineered “super levees” intended to hold back even the largest floods. It is estimated that there are more than 100,000 km of levee in the United States alone (National Levee Safety Committee 2009). An area protected by levees can be flooded if the levee is overtopped (e.g., by a flood that exceeds the level that the levee was designed to protect against) or if it fails. Levee failure can occur due to erosion and water seeping under or “piping” through the levee (Figure 1).



3. **Floodwalls.** Floodwalls serve a similar function as levees—a barrier to prevent floodwater from rising into and entering the area behind the structure—but are vertical and constructed of material such as concrete (see Figure 2). Levees, on the other hand, are generally made of soil and are sloping on both sides. Thus a floodwall takes up much less space than a levee and so floodwalls are used to protect very dense or valuable real estate, such as the downtown of a city.
4. **Channel modifications.** Flood-management projects often modify river channels. Modifications can include “armoring” of banks to prevent rivers from changing course (e.g., meandering) and to reduce the erosion of stream banks. Other modifications can include dredging and straightening of channels to increase the speed at which a flood travels down the channel.

Developed countries have made massive investments in flood-management infrastructure, and this infrastructure has certainly saved lives and reduced damages in many places. However, as described below, flood damages continue to rise, suggesting the need for more innovative and resilient approaches. Further, to work, structural approaches necessarily break the connection between rivers and floodplains. But it is this connection between rivers and floodplains that drives a diverse array of benefits (see Box “Diverse benefits from river floodplains”). Clearly, structures play an essential role in preventing floodwaters from inundating cities, towns and flood-vulnerable crops. However, structural approaches can be a blunt tool that, while striving to prevent flood damage, eliminates most of the beneficial connections between rivers and floodplains. In large part due to the extensive proliferation of dams and levees, rivers are among the most converted and degraded ecosystem types on earth and freshwater species are endangered at far higher rates than terrestrial or marine species (Richter et al. 1997, Tockner and Stanford 2002).

The decline and endangerment of freshwater species is a strong indicator of how structural modifications to river systems can cause significant harm to the other values and benefits that people derive from rivers. Due to widespread floodplain disconnection and flow alteration, freshwater fish populations have declined dramatically in many rivers. For example, the Missouri River commercial fish harvest declined 80% from the 1880s to the 1990s due to flow regulation and levee construction (Galat et al. 1998). These declines in floodplain extent and function have had negative impacts on millions of river-dependent people worldwide (Richter, Postel et al. 2010). For example, the loss of the flood pulse due to flow regulation from dams has negatively impacted the agricultural livelihoods of people in rivers such as the Tana, Senegal, and Niger (Opperman et al. 2013).



Figure 2. A floodwall in New Orleans, Louisiana © Kate Rosok



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Watersheds and floodplains

A flood in a river is generated by heavy rainfall, snowmelt or a combination of these sources of runoff in the upstream **watershed**—all the land that eventually drains into that river. Characteristics of a watershed, including geology, topography, and land cover, all influence how rainfall and/or snowmelt become runoff that generates a flood. For example, certain features—such as forests, deep soils, and wetlands—tend to retain water and slow runoff, resulting in lower flood peaks. Conversely, impermeable surfaces, such as pavement, prevent infiltration of water in the soil, producing rapid and high levels of runoff and thus higher flood peaks. Other features that hasten runoff include channel straightening and drainage systems for farm fields.

The **channel network** collects runoff from the land, conveying floodwater downstream into streams and, eventually, to a river. In addition to moving water, the channel network also transports sediment (such as soil that erodes from the land), wood and other biological material.

Floodplains convey water when floods exceed the ability of the river channel to transport the flood between its banks (the “channel capacity”). Although people often think of floods as rare events, the channel capacity of natural rivers is exceeded fairly frequently, from approximately every year to once every few years, depending on the river. Thus, water on the floodplain is not an unusual event but something that can be expected on a fairly regular basis. During floods, floodplains essentially increase the ability of a river to move or convey floodwaters. Initially during a flood, the flood height rises with increasing flood volume. When the flood exceeds the channel capacity and spills out onto the floodplain, flood height increases much more slowly with flood volume because the additional volume of water moves out onto

the floodplain. Floodwaters move much more slowly on floodplains, because they tend to be flat and vegetated, and so very extensive floodplains can act something like a reservoir that temporarily stores water, slowly releasing it back to the river as the flood recedes. Proliferation of levees, which prevent water from moving onto the floodplain, hastens the movement of water downstream and researchers have found that the levees throughout the channel network of rivers like the Mississippi have resulted in increased flood heights for a given volume because the floodplain is no longer holding and then slowly releasing floodwaters upstream (Criss and Shock 2001).

While most people view the river as “water” and the floodplain as “land,” in reality the river and floodplain are one integrated system for conveying water and sediment downstream, with the floodplain being the component that only carries water during floods. In fact, floodplains tend to be flat and fertile precisely because they are built up over time as centuries of floods deposit sequential layers of soil. So, during floods, the floodplain carries water from the river and the river “builds” land on the floodplain

Floodplain ecosystem services include:

- ⇒ Sequestration of nutrients and sediments to improve downstream water quality
- ⇒ Groundwater recharge
- ⇒ Reduction of flood risk
- ⇒ Productive fisheries
- ⇒ Wildlife habitat
- ⇒ Open space and recreation

Diverse benefits from river floodplains

While this report emphasizes that floodplains can play a key role in reducing flood risk, they also provide a diverse range of other values and benefits. These benefits can be characterized as ecosystem services – products and processes generated by functioning ecosystems that economically benefit society (Brauman, Daily 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., non-marine) ecosystem service benefits. Other researchers have attempted to quantify the benefits provided by floodplains. For example, Sheaffer et al. (2002) estimated that replacing the services provided by functioning floodplains (e.g. through constructed features) would cost approximately \$150,000 per hectare.

During overbank flooding, floodwaters spread out on floodplains and, due to slower water velocities on the floodplain, much of the sediment in transport is deposited there. Because nutrients such as phosphorous are largely adsorbed to sediment particles, this deposition can reduce the loads of sediment and some nutrients in rivers and thus improve water quality for downstream water bodies, such as estuaries and near-shore marine habitats (Noe and Hupp 2005). Biogeochemical processes within floodplain wetlands, such as denitrification, can also reduce nitrogen loads in river water (Burt and Pinay 2005). Floodplain reconnection and restoration of floodplain wetlands is therefore recommended as a strategy to reduce nutrient pollution to important waterbodies such as the Chesapeake Bay (Noe and Hupp 2005) and the Gulf of Mexico (Mitsch, Day et al. 2001). Due to sediment deposition during recurrent overbank flooding, portions of floodplains can have deep, fertile soil which can support productive forests. Thus, in addition to nutrient sequestration, floodplains can also sequester carbon within rapidly growing trees.

During overbank flooding, floodwaters can percolate into the shallow groundwater. The Yolo Bypass, a managed floodplain in California’s Sacramento Valley, is frequently inundated for long periods of time, recharging the groundwater. The Bypass supported a valuable “groundwater bank” during a drought (Jercich 1997). Particularly in arid or semi-arid climates, groundwater recharge on floodplains can support higher plant productivity than the surrounding land. Groundwater recharge is often one of the most important ecosystem services provided by floodplains, supporting much of the agriculture in parts of Africa (Barbier 2003) and along major rivers in Asia and Latin America.

River systems that are still hydrologically connected to extensive floodplains support the most productive freshwater fisheries in the world, in large part because floodplain habitats often provide beneficial conditions for fish, including slow velocity water with extensive cover. Floodplain habitats also offer abundant food resources for fish, including terrestrial items such as insects, seeds, fruits and leaves, and high productivity of aquatic plants and algae which, in turn, supports concentrations of zooplankton and aquatic invertebrates that can be orders of magnitude greater than within the adjacent river (Grosholz and Gallo 2006).

Rivers that exhibit annual flood pulses onto extensive floodplains have significantly higher productivity of fish per unit area than water_bodies_that lack a dynamic flood pulse, including regulated rivers or reservoirs, a phenomenon characterized as the ‘flood-pulse advantage’ (Bayley 1995). The Mekong River supports the largest freshwater fishery in the world and its productivity is derived from the extensive floodplains and lakes inundated by the annual flood pulse; annual harvest averages 2 million tons and provides the primary source of protein to tens of millions of people in Southeast Asia. In developing countries, small-scale freshwater fish harvests total 14 million tons, with 66% from Asia, 25% from Africa and 4% from Latin America. These fisheries provide employment to 60 million people and are a primary source of cash income to rural families in Africa and southern Asia (UNEP 2010).

3. Challenges for traditional structural flood management

Although flood management based on engineered structures has saved lives and allowed greater economic utilization of floodplains in many areas (e.g., allowing flood-intolerant crops to be grown in rich floodplain soils), this path has also resulted in many unintended negative consequences, including the decline of freshwater ecosystems and the loss of productive floodplain fisheries and other values.

Further, dams and levees can create a false sense of security. Believing that all flood risk has been eliminated, people begin to move into and make investments within areas where these structures have eliminated frequent small floods (Mount 1995). However, dams and levees are generally not designed to stop *all* floods and, further, structures can fail during a flood below the level they were designed to contain (see Figure 2). When this happens, the new development behind the levees or below the dams is subject to flooding, and flooding from the failure of a structure can be rapid and catastrophic (Tobin 1995). Because of this “hidden” risk that remains after flood-management structures are built, the Association of State Floodplain Managers recommends that levees not be used as a method to facilitate new development (Association of State Floodplain Managers 2007). Because development has increased on land that is imperfectly protected by structures, flood damages in the U.S. have continued to rise over the past century, from less than \$1B US annually in the 1930s to over \$6B US currently (in constant dollars) (Pielke, Downton et al. 2002), even as billions have been spent to build and maintain dams and levees to manage floodwaters.

Structural approaches to flood management face a variety of new challenges:

Rising risk from changes in climate, population and structural integrity

Several trends suggest that flood risk will continue to increase in the U.S. and in other developed countries. First, development continues in places vulnerable to flooding while upstream land-use changes, such as an increase in impervious surfaces, continue to alter runoff and downstream flood dynamics (Pinter 2005). Further, forecasts indicate that climate change may lead to greater flood magnitudes and frequencies. Evaporation rates increase with air temperature and warmer air can hold more water vapor, increasing the intensity of heavy precipitation events (Kundzewicz, Mata et al. 2008). Beyond forecasts, scientists have already found a climate “fingerprint” on a rise in precipitation or flood frequency and magnitude (Min et al. 2011, Pall et al. 2011). For example, the frequency of intense rainfall events in the Midwestern US has approximately doubled over the past half century (Saunders et al. 2012). Based on both increased flood frequency and magnitude and growing populations in flood-prone areas, a 2011 study by the US Federal Emergency Management Agency (FEMA) predicted that the land area vulnerable to a “100-year flood” will increase by 45% (Lehmann 2011) (see Box: flood frequency and the “100-year flood”).

Many of the nation’s dams require extensive rehabilitation, with an estimated five-year price tag of \$12.5B US including 1,743 high hazard dams in need of repair. Levee maintenance is chronically underfunded (Leavenworth 2004b), requiring an estimated five-year investment of \$50B US (American Society of Civil Engineers 2009).

Due to all of these trends—changing land use, population increases in flood-prone areas, a warmer climate generating bigger floods, and aging infrastructure—flood risks are greater than commonly perceived and are growing.

Managing flood risk while conserving, or restoring, rivers’ diverse environmental values

In developed countries, social values and environmental legislation are challenging river managers to meet traditional objectives, such as flood management or hydropower, while also restoring river ecosystems and their environmental, cultural, and recreational values (Warner et al. 2011). For example, the US Endangered Species Act requires that those charged with flood management, such as the US Army Corps of Engineers and the Federal Emergency Management Agency (FEMA), consider the needs of endangered aquatic species, as reflected in a 2008 decision by the US National

Marine Fisheries Service that FEMA's flood insurance program was negatively impacting the habitat of endangered salmon (Le 2012).

In later-developing countries, river managers face the challenge of increasing outputs from rivers, such as hydropower or flood-risk reduction, without compromising other values. In these countries, large rural populations may still depend directly on the productivity of river-floodplain ecosystems, and so finding solutions that allow rivers to continue to provide the broadest range of resources are urgently needed.

Conflicts with other water-management objectives

Reservoirs that provide flood control often also provide multiple purposes, such as water supply, hydropower and recreation and these various objectives can compete with each other. Flood control is maximized by maintaining low reservoir levels during periods of flood risk whereas hydropower generation is maximized by high reservoir levels. Water supply risk can increase when reservoirs are lowered for flood control; for example if the basin enters a period of drought after reservoir drawdown. These conflicts may be exacerbated by climate change, which is forecasted to increase the "flashiness" of precipitation and runoff and thus may increase both flood and drought risk in many parts of the world (Kundzewicz et al. 2008). Thus, providing flood management within reservoirs can come at the expense of other reservoir benefits, including water supply and hydropower which are coming under increasing demand due to growth and climate change.

4. Incorporating green infrastructure in flood-risk management

As described above, river and flood managers faced a broad range of challenges, from changing climate to aging infrastructure to the growing imperative to reduce flood risk without degrading rivers' many other values and resources. One key way to address all of these challenges is through better integration of "green" and "grey" infrastructure. Grey infrastructure refers to engineered structures such as dams and levees whereas green infrastructure refers to the ability of natural features—including forests, wetlands and floodplains—to replace or complement the services provided by engineered infrastructure.

The integration of green infrastructure into flood management is a key thread of a larger trend. The way that people deal with floods has been evolving, encompassing diversification of the approaches used to changes to the very name of the discipline: the term "flood control" has gradually been replaced with terms such as "flood-risk management" or "flood-risk reduction." Flood control suggests mastery over rivers and the capacity to stop flooding, whereas the latter terms acknowledge that risks can never be completely eliminated, although they can be managed and reduced.

Whereas flood control relies primarily on structures that attempt to determine where water should go, flood management draws upon a broader range of tools, interweaving structural with nonstructural approaches. Nonstructural approaches encompass a broad range of tools, including zoning that avoids development in flood-prone areas, elevating or flood proofing structures, insurance, forecasting and evacuation systems, and using natural features to manage floodwaters (Freitag et al. 2009). Flood management generally draws upon a mix of structural and nonstructural approaches and, thus, a mix of keeping floods away from people *and* keeping people away from floods.

The integration of green infrastructure into flood management is an extension of this evolution of flood management philosophies and tools. Integrating green infrastructure in flood management should be part of an overall comprehensive and integrated approach to flood management predicated upon three basic principles:

1. **To the extent possible, work *with*, not against natural processes.** Green infrastructure methods rely on the natural processes of how natural systems produce, store, and convey floodwaters (see box: watersheds and floodplains).

Flood frequency and the “100-year flood”

The term “100-year flood” commonly appears in the media in the United States. The term causes much confusion because many people expect that a 100-year flood should occur just once in a century; once such a flood has occurred then people do not expect to see it again in their lifetime. However, a 100-year flood is simply the result of a statistical method called **flood frequency analysis**, which uses existing data to predict the frequency with which various sized floods will occur. Based on flood frequency analysis, over a period of a thousand years you’d expect approximately ten 100-year floods. However that expectation is not the same thing as the regular occurrence of this flood on a once-in-a-century schedule – several 100-year floods could be clustered within one century.

The “100-year floodplain” corresponds to the land that is inundated by a 100-year flood. The designation of the hundred year floodplain strongly influences patterns of development in the United States. In order to receive a federally backed mortgage, owners of property within a mapped hundred year floodplain are required to hold a policy with the National Flood Insurance Program (NFIP), administered by the Federal Emergency Management Agency (FEMA) (Sheaffer et al. 2002, Pinter 2005).

For calculating real risk statistics, a 100-year floodplain simply means that a piece of land has a 1 in 100 chance of flooding in *any given year*. Each year is a new, independent roll of the dice and, with unlucky rolls, “hundred-year floods” could arrive in consecutive years. The term “100-year floodplain” has led to widespread confusion among citizens, who may assume that, following such an event, they are safe for the next century. Because of the potential for misunderstanding, the U. S. Army Corps of Engineers has begun to use the terminology of ‘percent exceedance’ (Hickey et al. 2002). Statistically, the ‘100-year flood’ is equivalent to 1% exceedance probability. However, the term ‘100-year flood’ is well established in planning and the popular media and thus remains in common usage.

However, even expressing flood risk in terms of a percent chance of annual flooding can seem somewhat abstract. A 1% annual chance of flooding may seem very small be-

cause most people find it hard to envision the *cumulative* probability of flooding represented by this level of risk. To make it more tangible, consider this: a house in a 100-year floodplain has 26% chance of flooding during a 30-year period (i.e., the common period for a mortgage), **or more than one-in-four**.

Further, flood frequency analysis can provide numbers and maps that are misleadingly precise. The estimate of a 100-year flood is often based on a relatively short record of floods and thus the number given to the 100-year flood is a statistical result, not necessarily reality. In fact, the statistics of Flood Frequency Analysis can change considerably after a large flood event; after the frequencies are recalculated based on the additional information provided by the big flood, the statistical estimate of the 100-year flood, and thus the size of the 100-year floodplain, can grow.

Finally, the actual probability of a flood of a given size occurring is not fixed, but can change as precipitation patterns change. Over the past 7000 years, relatively small changes in annual precipitation resulted in dramatically different flood frequencies in the Upper Mississippi. What is today considered to be a “500-year flood” was relatively common during a period when annual precipitation was only 10-20% higher than today (Knox 1993). Climate change may already be shifting the frequency of extremely large floods in the upper Midwest as the frequency of intense precipitation events has increased (Saunders et al. 2012). Portions of the Midwest have now experienced several 100 to 500-year flood events in the past twenty years (Skopec 2010). While this is statistically possible, it may be more likely that the true flood frequencies have shifted, emphasizing the importance of building greater resiliency into flood-management systems.

Traditional flood management methods often seek to contain or reverse natural processes, such as confining floodwaters between narrow levees and modifying channels to maximize the speed that floods travel downstream. Working against natural processes requires continuous vigilance (e.g., against levee failures) and invites constant maintenance (e.g., to repair erosion sites). Working with natural processes can allow nature to do some of the work and reduce long-term maintenance. Further, these natural processes are responsible for other diverse benefits and resources from river-floodplain systems (see Box Diverse benefits from river floodplains), and so flood-management methods that *promote* these natural processes can produce a much broader array of benefits than can methods that *prevent* natural processes.

2. **Plan and implement flood management within a river-basin perspective.** Flood management is most effective when implemented at the scale of the entire river basin. Flooding at a given site along a river is due to floodwaters that are generated throughout the upstream watershed and that have moved along the entire upstream channel network (see Box: watersheds and floodplains). Thus, the condition of the land and stream channels across the whole river basin contribute to the flood risk at a given point: is upstream the land mostly forested or mostly paved? Are streams flanked by wetlands and floodplains or have they been channelized and straightened to maximize the speed of drainage? Flood-management projects that do not consider these river-basin conditions and processes are vulnerable to being overwhelmed by them. Although not all flood projects can be implemented at the scale of an entire river basin (e.g. due to economic cost or institutional complexity), projects can at least ensure that they fully understand how the specific site is influenced by basin-scale conditions.
3. **Deploy a diverse portfolio of methods.** Green infrastructure is not *the* solution for flood-risk management, rather it can be a key part of an overall solution that draws upon diverse approaches. Because green infrastructure methods can produce diverse benefits and work with, not against, natural processes, flood managers should seek to maximize their use. However, nature-based solutions will not be appropriate in all situations and their effectiveness will vary with location and the size of the river or watershed: a method that may reduce flood risk for a small watershed in New England will not necessarily be equally effective for the Mississippi River. Similar to an investment portfolio, a diversity of approaches to flood management can increase resiliency (Aerts et al. 2008, Dawson et al. 2011). A sustainable and resilient approach to flood-risk management will deploy diverse approaches throughout the river basin, with methods varying by local conditions while still reflecting the overall basin conditions. These approaches can include a mix of structural (e.g., secure floodwalls protecting the downtown of a city, levees protecting farmland) and non-structural tools (e.g., early-warning systems, insurance) and relying as much as possible on green infrastructure, such as forests and wetlands to retain runoff and using some floodplains as “relief valves” to convey water during large floods.

Within the comprehensive approach to flood management described above, potential green infrastructure methods include:

Managing the land to retain runoff and floodwaters

Floodwaters are generated by rain falling on the land, and/or snow melting, and becoming runoff at a sufficient rate to produce a marked rise in the level of water in streams and rivers that receive the runoff. A key “green infrastructure” principle is that land can be managed so that it retains, or slows down, that runoff as much as possible. In other words, manage the floodwaters where they are generated, which is on the land surface throughout the watershed. Specific methods to do this vary by the setting:

- **Reforestation of watersheds** can help to reduce peak flows produced from those watersheds. Forests have numerous features that help retain water, beginning with the interception and storage of precipitation on the leafy canopy. Forests generally have a thick layer of organic matter on the ground, such as leaves and wood, and this layer serves as a sponge to hold water and also protects the soil from the direct impact of raindrops, reducing erosion. Finally, forests tend to have soils that allow water to infiltrate and much of the precipitation moves into the shallow groundwater, a much slower path to the stream than via surface runoff. In contrast a deforested or overgrazed watershed is characterized by a limited or absent organic layer and more compacted soils. Lacking the water-retaining features of the organic layer and permeable soils, much of the precipitation that hits the ground is rapidly converted to surface runoff. In fact, any feature that tends to retain and slow water down, including wetlands, wood in streams, or beaver dams (essentially a combination of wood and wetlands) can reduce peak flows (Nyssen et al. 2011).
- **Various best practices in agriculture**, such as the addition of wetlands and small detention ponds—particularly wetlands that can retain the rapid runoff from fields with tile drains—can also re-

Figure 3. (Top) An abandoned lot in the Slavic Village neighborhood of Cleveland and an artist’s rendition **(Middle)** of a proposed park-like stormwater detention area for the site to reduce rates of runoff into the stormwater system. **(Bottom)** The photo below them shows a “curb extension” or “green street” – vegetative features that capture, filter, and slow down stormwater runoff from roads. These photos illustrate how green infrastructure projects for flood management in cities contribute to vibrant, livable neighborhoods.



duce the magnitude of runoff produced from farm fields. These features have the added benefits of improving water quality by processing and removing excess nutrients from the farm runoff (Fiener et al. 2005, Mitsch and Day 2006, Magner and Alexander 2008) (Figure 4).



Figure 4. Green infrastructure features can produce multiple benefits beyond flood management, such as these wetlands in an agricultural landscape that can help reduce nutrient loading in rivers.

- Because **cities** are characterized by impervious surfaces, such as roads, parking lots and rooftops, a high proportion of rainfall swiftly becomes surface runoff, with a five-fold increase over an undeveloped watershed (Freitag et al. 2009). In urban settings various methods can be used to retain stormwater and prevent floods from overwhelming storm drain systems and causing urban flooding. These methods can range from those deployed at the scale of individual buildings, including porous pavement, “green” (vegetated) roofs, rain gardens and rain barrels, to features that can attenuate runoff for larger areas, including grassy swales, wetlands and detention basins (Freitag et al. 2009). Fortuitously, most methods for slowing runoff also help make cities greener, healthier, and cooler in the summer with improved aesthetics and recreational value. Parks, greenways, daylighted creeks, and urban gardens all contribute to a more vibrant city that also happens to slow and retain stormwater (Figure 3).

The ability of these methods to reduce peak flood levels varies by the size of the watershed and the magnitude of the flood. Generally, techniques to retain water within forests and wetlands of a watershed are most effective at reducing moderate floods of short duration and within small watersheds (Bathurst et al. 2011). During very large or very long floods, the capacity of soils and wetlands to hold water is exceeded—they become full of water—and thereafter have limited or no further influence on the flood (Pitlick 1997). While broad patterns suggest that more forested regions experience lower flood damages (Bradshaw et al. 2007), land management to retain and slow floodwaters will be most effective in small watersheds and/or to reduce vulnerability to short-duration floods. Because urban drainage systems are characterized by small watersheds that can be overwhelmed by intense but very short storm events, these techniques show promise in addressing urban flood challenges.

Large-scale preservation of floodplains

In addition to land management that aims to hold the rain where it falls, large-scale preservation of floodplains along a river can reduce flood levels and risk in certain types of watersheds. The US Army Corps of Engineers has studied and implemented this approach in Massachusetts, focused on “natural valley storage” which they define as wetlands or floodplains along a river or stream that can temporarily store overflow from rising rivers and release it slowly back into the river, thus reducing the flood peak (US Army Corps of Engineers 1993). In the 1970s, the Corps of Engineers studied alternatives for reducing flood risk for Boston from the Charles River and concluded that acquisition and protection of floodplain wetlands could provide similar protection as new levees and a flood-control reservoir - for approximately 1/10 the cost. The Corps acquired 3440 ha in the Charles River floodplain for approximately \$10 million (Postel 2005). The Corps reports that the “total annual cost” of the project is \$477,000 and estimates that annual benefits are \$722,000, with \$125,000 of those benefits derived from recreational and environmental benefits (e.g., open space, habitat, recreation) (US Army Corps of Engineers 1993). The Corps cautions that natural valley storage is most effective at reducing flood peaks for floods of short duration, noting that during long-duration flooding the “storage capacity (of floodplain wetlands) is maximized and inflow equals outflow.”



Figure 5: Aerial view of the Savannah River below J. Strom Thurmond dam looking south towards Augusta, Georgia, during a period of extra water release by the U.S. Army Corps of Engineers. © Mark Godfrey/TNC.

Connected floodplains (i.e., natural valley storage) can be maintained through real-estate transactions such as acquisition, easements or government funding programs, such as the Wetland Reserve Program. For example, to maintain the potential for floodplains to be inundated along the Savannah River (Georgia/South Carolina, USA), The Nature Conservancy is working with willing landowners to acquire or place under easements floodplain land to maintain it in low-intensity land uses (Figure 5; Opperman et al. 2010). In addition to acquisition or easements, emerging markets for ecosystem services, including carbon and nutrient sequestration, floodwater storage, and recreation may be able to provide revenue to landowners that maintain floodplains connected to rivers (Opperman et al. 2009, Opperman et al. 2010).

In addition to retaining and slowing floodwater, the protection of floodplains provides another important benefit: minimizing economic damages from floods. Land that remains in forest, wetland, or other flood-tolerant land uses is gen-

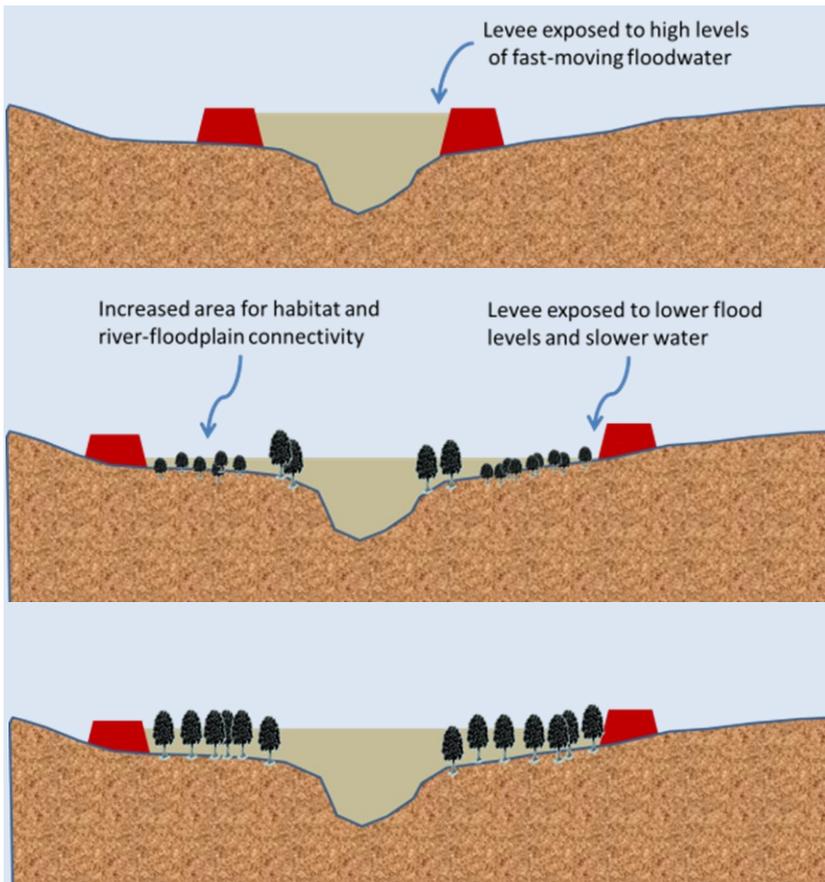


Figure 6. The **top image (a)** shows levees that are located relatively close to the channel. During a flood (pictured here), the levees are exposed to high levels of fast-moving water, increasing the risk of erosion and the need for maintenance. Further, there is limited area for natural river-floodplain habitats and processes between the levees. The **second image (b)** shows setback levees. For the same flood, the levees are exposed to lower water levels and velocities, reducing erosion risks and maintenance costs. The area that can support other floodplain benefits is greatly expanded. The **third image (c)** shows how the type of vegetation within a setback levee can influence flood levels. A mature forest (c) can have greater hydraulic roughness (resistance to flow) than grasses, shrubs or crops (b). Management of vegetation within levees can be influenced by the need to maintain hydraulic roughness below a certain threshold.

erally not vulnerable to damage during floods. The conversion and development of these lands, conversely, transitions them into land uses that become vulnerable to flood damages. Preventing floodplains from becoming developed, and thus vulnerable to future damages, can be a cost-effective approach for flood-risk reduction, particularly when the multiple benefits of floodplains are included, such as open space and improved water quality. Using models that incorporate potential flood risk, damage and land values, communities can target the protection of those parcels that will provide the most reduction in future flood damages for the lowest cost of acquisition or easement (Kousky et al. 2011).

The benefits of maintaining floodplain in land uses compatible with flooding (i.e. limiting development of houses and other structures) can be substantial. A comparison of the damages experienced by adjacent portions of Michigan and Ontario, including urban areas, during a series of storms and floods in the late summer of 1986 provides a clear illustration. While the floods were actually more severe in Ontario, total damage to property was only \$500,000 while damages in Michigan exceeded \$200 million. The factor most responsible for this dramatic difference in flood damages was that Ontario had far fewer structures in the floodplain due to a regulatory policy that discouraged such development (Brown et al. 1997).

Settling levees back from the river

Along many major rivers, such as California’s Sacramento, levees were constructed very close to the edge of the river channel. This alignment of levees maximizes the amount of land protected by the levee. By placing levees close to the channel, river managers were hoping to convert rivers into more effective conduits for drainage that could rapidly flush floodwater and sediment through the system.

However, levees close to the channel can create a set of problems and challenges. Because they greatly narrow the area available to transport floods, they do work to rapidly flush floodwaters through the system – but this means that the levees are exposed to high-velocity water along their “wet” side (Figure 6). This can result in erosion and high maintenance costs. In many places, the growing list of sites needing repair has outstripped the maintenance budget, resulting in levees that are more likely to fail during a flood (Leavenworth 2004, American Society of Civil Engineers 2009). Levees close to a river also dramatically restrict the area of floodplain that benefits from periodic connections with the river and constricts the ability of the river to meander and create new river-floodplain habitat. Because of the

vulnerability to erosion mentioned above, these levees often require armoring to prevent erosion and meandering, further diminishing the natural habitat values of the river’s edge, which is generally the most biologically valuable habitat.

Moving levees back away from the channel—often called “setback levees”—can address these problems. Setback levees increase channel capacity for carrying floodwaters, which is often the primary objective of moving or setting levees back from the channel. However, setting levees back promotes several other benefits. The area exposed to periodic inundation from the river increases thus increasing the variety of benefits from river-floodplain connectivity, such as water-quality improvements. The expanded area on the “wet side” of the levee provides greater room for the channel to meander and create floodplain habitat features, such as wetlands and forests. While levees close to the channel are exposed to deep, high-velocity water during floods, setback levees are less frequently exposed to floodwaters because of the increased channel capacity. Further, because flow over floodplains is generally much shallower and slower than rivers, when setback levees are exposed to floodwaters they are less vulnerable to erosion (Figure 6).

By increasing conveyance through a section of river, setback levees can relieve “bottleneck” points on a river where floodwaters would tend to back up and potentially cause flooding. For example, the Bear River (Central Valley, California) once had narrow levees along the channel, including at its confluence with the Feather River. When both rivers were flooding, floodwaters would back up on the Bear. Engineers determined that the best solution to reduce this backwater flooding was a levee setback project (Figure 7). The new setback levee is two miles long and restores hundreds of acres of floodplain habitat. The increased conveyance provided by the setback levee is projected to lower flood stages by 3 feet during major floods, reducing flood risk along the lower Bear River.

While levee setbacks can allow restoration of floodplain forests, flood managers must evaluate how different vegetation types will affect flood levels. Vegetation is a form of *hydraulic roughness*, or resistance to flow, and different types of land cover can have very different values for hydraulic roughness. Bare ground has very low roughness whereas a



Figure 7. A setback levee project on the Bear River at its confluence with the Feather River (Central Valley, California, USA). To increase conveyance and reduce backwater flooding, the north levee of the Bear and a section of levee along the Feather River were removed (white dashed line) and two-mile long setback levee was built (green line). The project lowers flood risk along the Bear and restored hundreds of acres of floodplain habitat. Figure adapted from Williams et al 2009

mature forest can have high roughness. Because roughness slows down floodwaters, it can contribute to higher flood elevations for a given sized flood (see Figure 6). Hydraulic models can be used to understand the effect of different vegetation types on roughness, and thus flood stage, and can guide how much forest restoration is possible and in which locations forest will have greater or lesser effects on flood stage (Leyer et al. 2012). The Bear River levee setback project was aligned such that the lower portion of the reconnected floodplain could be planted with floodplain forest and the upper portion will be maintained as a grassland. Because long duration and frequent flooding can be particularly important for river-floodplain ecosystems and native fish, a low wetland feature was added to ensure that portions of the reconnected floodplain experienced this type of flooding (Figure 7; Williams et al. 2009).

Initial flood management on both the Mississippi and Sacramento rivers relied almost entirely on levees constructed quite close to the channel. Both rivers experienced floods that overwhelmed those levees, exposing the vulnerability of narrowly confining a river between levees, and both rivers have subsequently moved toward a more diverse flood-management system, with flood bypasses and some levees set back further from the river. However, along these rivers and throughout the world, much of the length of existing levees, or those planned, are quite close to the channel. Thus there is great potential to reduce vulnerability and increase other benefits by setting levees back.

Floodways and flood bypasses: large-scale storage and conveyance of floodwater

Major lowland rivers, such as the Mississippi, Yangtze and Rhine, were once flanked by vast areas of floodplain that annually flooded and drained. While the extent of inundation varied between years, these river channels never carried the floods on their own, but rather the river and floodplain were an integrated system for moving water from the continental interiors to the ocean.

Along these great rivers, leaders attempted to control the flood to allow land to be settled and farmed with greater certainty and security. The Chinese began building levees along the Yangtze and Yellow rivers thousands of years ago, but floods continued to overwhelm these defenses, occasionally killing hundreds of thousands to millions of people. In the late 19th century, both the Mississippi and Sacramento rivers became arenas in which engineers debated about how best to manage flood risk. Both rivers had advocates for a “levees only” approach and both had advocates for an approach that would allow the river to continue to access portions of its floodplain during major floods. The “levees



Figure 8. The Morganza Spillway (long line in center) during the 2011 Mississippi Flood. The Morganza Spillway was opened during this flood, allowing the Mississippi River, on right, to begin to flow into the Morganza Floodway (fields and forests on the left).

© NASA

only” side won the debate in both rivers, in large part because that approach maximized the amount of land that could be “reclaimed” from the river. However, great floods provided the final counter-argument for both rivers as extensive levee failures exposed the vulnerabilities of a levees only approach.

For both rivers, the US Army Corps of Engineers responded to the levee failures by redesigning the flood-management system to include areas designated as “**floodways**” or “**flood bypasses.**” These were portions of the historic floodplain that, during major flood events, are reconnected to the river and become inundated. The Yangtze too has portions of the historic floodplain, known as Flood Detention Areas, that can be reconnected during floods. Along the Rhine River in the Netherlands, flood managers are pursuing a program called “Room for the River” which will include features that allow the floodwaters to move into portions of the historic floodplains (Vis et al. 2003, Forster et al. 2005).

These connected portions of the floodplain are very large. For example, the Yolo Bypass encompasses 24,000 hectares while the Birds Point-New Madrid Floodway is 130,000 acres. Because bypasses or floodways are only inundated during floods, they serve as “relief valves” for the system, relieving pressure on levees. They act as relief valves in two ways:

1. **Conveyance.** Bypasses can provide conveyance: they increase the cross-sectional area available to move floodwaters safely through a particular stretch of river. This is analogous to opening up more lanes at a bridge toll crossing during rush hour to manage intense traffic. For example, the Yolo Bypass conveys approximately 80% of the volume of major floods safely around the city of Sacramento. By increasing conveyance, strategically placed bypasses or floodways can also reduce “backwater flooding,” which is caused by the “piling up” of floodwaters at and behind a bottleneck, such as where bluffs constrict the river. Similar to levee setbacks, the vegetation within a bypass can influence its hydraulic roughness and affect the ability to convey floodwaters. Thus, some bypasses are managed for vegetation with low roughness.
2. **Storage.** These features can also detain and store water, functioning similarly to a flood-control reservoir. While conveyance is analogous to adding lanes, a floodway providing storage can be viewed as a parking lot alongside a major freeway. During a particularly heavy period of traffic, a large number of cars exit the highway and park in the lot, staying there until traffic ebbs. The highway “downstream” of the parking lot will experience lower peak traffic because of the cars parked in the lot. In flood management using a floodway for storage, this effect is known as “peak shaving” — reducing the height of the flood peak experienced at some downstream point. The Jianjiang Flood Detention Area along the Yangtze is intended to function in this manner with the capacity to hold 5 billion cubic meters of water, reducing the height of the peak against the levees that protect cities with millions of people.

Flood bypasses can provide a mix of conveyance and storage benefits that vary with the size of the feature, its location in the river system, and the characteristics of the flood. Bypasses also vary in the frequency with which they are used. The Yolo Bypass is inundated relatively frequently—almost every year—while some of the floodways on the Mississippi have been used only a few times in 80 years.

Because the floodways are only inundated during floods they can be used for a variety of economic activities, with land use varying with the frequency of inundation. For example, the New Madrid Floodway has been used rarely (twice since the 1930s) and is almost entirely farmed and includes 200 homes whereas the Bonnet Carre Spillway has been used 10 times in that period and is uninhabited with land managed for fishing, hunting and recreation. Because in California the flood season (winter to early spring) and the growing season (spring to fall) have little overlap, much of the Yolo Bypass is in productive agriculture despite the fact that it is flooded nearly every year. The agriculture in the Bypass is in annual crops that are not jeopardized by up to months of inundation (See Figure 9).

Bypasses can provide significant environmental benefits. Approximately 1/3 of the Yolo Bypass is in wildlife refuges,

including managed wetlands, and much of the land within the three Mississippi River floodways that are in Louisiana are in natural vegetation and support abundant fish and wildlife. Even floodways that are in agricultural land use can provide environmental benefits, particularly during periods of inundation. The Yolo Bypass is now recognized as the most valuable remaining floodplain habitat in the Central Valley, and native fish and birds are abundant on the flooded farm fields (Sommer et al. 2001). The agricultural land of the New Madrid Floodway also likely provided favorable conditions for fish during the several weeks it was inundated during the flood 2011, based on observations that fish species capable of exploiting floodplain resources had very high growth during the 1993 flood on the Mississippi River, in which much of the flooded land was in agriculture (Gutreuter et al. 1999, Jones and Noltie 2007).

The examples of flood bypasses described previously were planned and implemented 50 to 80 years ago, during a time when scientific understanding of river-floodplain systems was limited and society expected a much narrower range of benefits from rivers. Scientists now understand that connectivity between rivers and floodplains drives processes that produce a broad range of resources and benefits, and now society expects these benefits—including fish and wildlife habitat, improved water quality, and recreation—from rivers. Thus the design of future flood bypasses can more fully incorporate these scientific advances and expanded expectations to create features that can produce a broader set of benefits. A portion of a bypass could specifically be managed for frequent, long-duration inundation, similar to the “fish wetland” in the Bear River setback levee (Figure 7).

Further, existing bypasses can be modified or managed to increase their output of benefits beyond flood-risk management. For example, the Yolo Bypass provides important floodplain habitat and, although it is inundated in most years, it is not always inundated during the most important time of the year for native fish (the early to mid-spring with warmer temperatures that drive productivity). River managers and conservation organizations have been exploring options for a control structure on the weir that shunts water from the Sacramento River to the Bypass. This control structure would allow for managed flooding of portions of the Bypass to maximize benefits to native fish while still avoiding negative impacts to agricultural management.

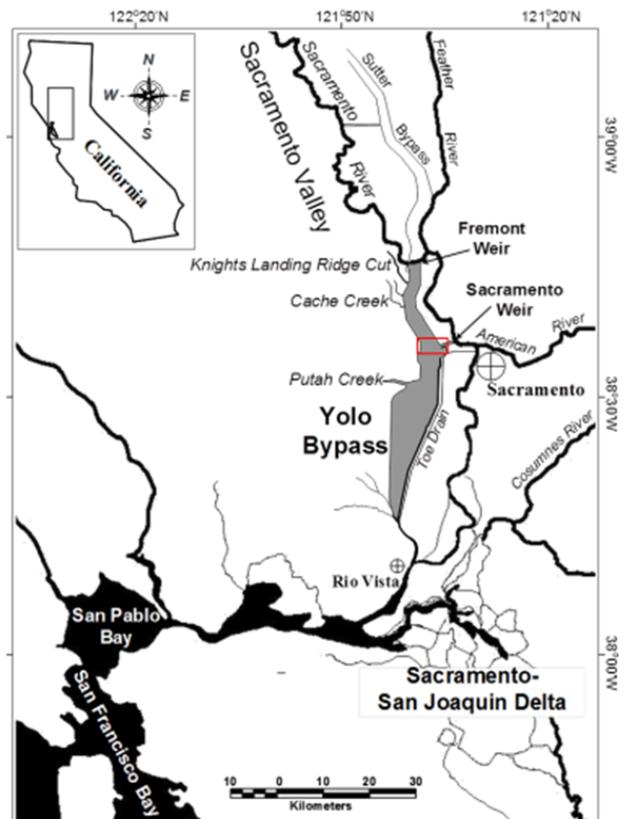


Figure 9. (Top) Location of the Yolo Bypass (shaded gray), within the lower Sacramento Valley, California. Adapted with permission from Sommer et al. (2001). **(Middle)** The red rectangle on the map corresponds to the photo showing a mosaic of land uses in the Bypass, including both agriculture and wetlands and other natural habitats. In the photo, the levees on the boundaries of the Bypass are highlighted in red. **(Bottom)** The same area while flooded. Map used with permission from T. Sommer.

5. The case for green infrastructure: multiple benefits and overcoming constraints

Grey infrastructure generally provides a single benefit, such as a levee that prevents floodwaters from inundating crops. Moreover, grey infrastructure often causes impacts to other benefits, such as a levee that moves water quickly through a reach of river, increasing flood height and velocity downstream and negating the water-quality improvements that arise from floodplain processes. Conversely, green infrastructure solutions often provide a broad range of benefits beyond their primary purpose. For example, the Yolo Bypass was built in the 1930s strictly to reduce flood risk for Sacramento. Without realizing it, river managers had created a feature that would later be recognized as providing the best remaining floodplain habitat in the Central Valley, and one that also provided recreation, open space in a rapidly growing region, and a groundwater bank that proved important during a drought (Jercich 1997, Sommer et al. 2001). Similarly, levee setbacks increase the area available for habitat and recreation. Green infrastructure features within a city double as parks, greenways, and recreational areas that make a city a more appealing place to live.

As described below, understanding and quantifying the multiple benefits of green infrastructure are key to overcoming several of the constraints that have limited the adoption of these approaches.

Although green infrastructure approaches to flood management have numerous benefits, due to a variety of constraints they have been implemented far less frequently than traditional engineering approaches. First, green infrastructure approaches are much less known among engineers and decision makers and this limits the extent to which these approaches are even considered. Second, green infrastructure solutions, such as levee setbacks and flood bypasses, require more land than structural approaches such as building (or rebuilding) levees close to the channel. Because land can be expensive, this can make green infrastructure solutions more expensive in the short run. Further, taking land out of agricultural production can have negative economic consequences for rural communities, and thus solutions that change floodplain land use can be controversial and require consideration of these economic impacts. Finally, the diverse services that river-floodplain systems provide—such as improving water quality and supporting fisheries—can be difficult to quantify. The inability to quantify these services results in benefit-cost analyses that don't fully consider the negative impacts on these benefits from traditional approaches nor the secondary benefits resulting from green infrastructure approaches. Finally, even if these services could be quantified, mechanisms, such as markets, may not exist to link the beneficiaries of the service with those whose land provides the service.

Below are potential solutions for overcoming these constraints.

1. **Combining multiple sources of funding.** Although, levee setbacks can lower flood risk and reduce long-term maintenance costs, acquiring the necessary land can be expensive. Simultaneously, agencies and conservation organizations are trying to increase the amount of ecologically functional floodplains because of their multiple environmental benefits. Because levee setbacks can also create new ecologically functional floodplain, this flood-management tool can draw on sources of funding for flood-risk reduction *and* environmental restoration. Along the rivers that drain to Puget Sound (Washington, USA), The Nature Conservancy is currently working with several state and federal agencies, including US Fish and Wildlife and the Federal Emergency Management Agency, to identify areas of floodplain that if reconnected, such as through a levee setback, will produce significant benefits for both flood-risk management and salmon restoration. By combining these objectives into their prioritization processes, the agencies can identify areas that provide multiple benefits and can combine funding sources (e.g. flood risk and restoration) to achieve floodplain reconnection. Tapping into restoration funding can potentially allow flood-risk projects to go forward that would otherwise be unable to secure sufficient funding, as illustrated by Hamilton City along the Sacramento River.

2. Flood compatible agriculture. Land exposed to periodic flooding, such as the land on the “wet side” of a levee set-back or within a flood bypass, do not necessarily need to be in natural habitat. These areas can be in traditional crops (e.g., intolerant of flooding) if they are in “relief valve” areas that will very rarely be flooded (such as the New Madrid Floodway) or if floods rarely or never occur during the growing season. Areas that are flooded more frequently (during the growing season) can be maintained with flood-tolerant forms of agricultural land use, including pasture, timber, or flood-tolerant crops. Potential flood-tolerant crops include feedstocks for cellulosic ethanol biofuels, such as willow, switchgrass, or diverse native prairie grasses (Volk et al. 2004, Tilman et al. 2006). Flood compatible agriculture can thus allow green infrastructure solutions that do not take agricultural land out of production and can be consistent with vibrant agricultural economies and rural communities (Donath et al. 2004). For projects where hydraulic roughness is a concern, agriculture can provide a land cover with much lower hydraulic roughness than forest (see Figure 6).



Figure 10. Green infrastructure features can produce multiple benefits beyond flood management, such as these wetlands in an agricultural landscape that can help reduce nutrient loading in rivers. © Mark Godfrey.

3. “Stacking” multiple ecosystem services. While some portions of land within green-infrastructure flood projects could be maintained in flood-compatible agriculture, other projects, or portions of land within a project, may be most appropriately managed as natural floodplain vegetation due to the frequency of inundation. Because floodplains provide a range of valuable ecosystem services, natural floodplain habitats can still potentially provide revenue to landowners. Potential services include groundwater recharge, recreation, open space, habitat, sequestration of carbon in rapidly growing floodplain forests and removal of sediment and nutrients from floodwaters, improving the water quality for downstream rivers, estuaries and oceans. Some of these services have existing markets or other mechanisms that can provide revenue to floodplain landowners who provide the service. For example, the Yolo Bypass includes land that is leased to duck hunting clubs and, during a drought, the high groundwater table of the Bypass contributed to a groundwater bank (Jercich 1997, Sommer et al. 2001). Habitat “banks” also exist for wetlands and endangered species, providing compensation for landowners that maintain land providing these values. Other services, such as habitat and open space, can be promoted by public sources of funding, such as the Wetland Reserve Program. Carbon sequestration has potential markets for climate change mitigation (Joyce 2011) and markets may emerge for removing nutrients from rivers, for example to reduce nutrient inputs that cause the “dead zone” in the Gulf of Mexico (Mitsch

et al. 2001) (Figure 9). Revenue from the services described above may allow agricultural landowners to continue to receive income from land in natural floodplain vegetation, *particularly if revenue from multiple services can be “stacked” together*. In other words, while carbon sequestration revenue may not be competitive with crops, that service plus recreation and nutrient sequestration may be comparable, particularly for marginal agricultural land—such as land that is frequently too wet for successful cropping. With the Mollicy Farms project, The Nature Conservancy reconnected 18,000 acres of marginal farmland on the floodplain to the Ouachita River and is now implementing a research program to better understand the potential for “stacked” ecosystem services to provide comparable revenue to agriculture on these marginal croplands (Opperman et al. 2010)

4.Improve valuation of floodplains’ ecosystem services. Methods to value floodplains’ ecosystem services are still being developed. Further, policies to evaluate the benefits and costs of alternate projects (e.g., green infrastructure versus traditional engineering) often focus on a narrow set of benefits and do not incorporate the diverse values provided by floodplains. Additionally, structural projects’ long-term costs for maintenance, rehabilitation and replacement are often underestimated, while green infrastructure projects tend to have lower long-term maintenance costs. Because of these limitations of science and policy, processes to select among flood-management options generally fail to capture the full value of benefits supported by green infrastructure projects and, similarly, do not reflect the full costs and impacts from traditional engineering projects. Improvements in both the science of measuring services and policies can thus “level the playing field” for green infrastructure projects. Improvements in valuation and policies governing cost-benefit analysis will advance the strategies above, including the “stacking” ecosystem services and combining multiple funding sources.



A flock of swans finds refuge in floodplain wetlands along the Cosumnes River, CA. Located on the western slope of the Sierra Nevada, the Cosumnes River and its floodplain habitats support large populations of birds and native fish as well as unique valley oak streamside ecosystems. © Timothy Wolcott

6. Conclusions

Green infrastructure projects have great potential to reduce flood risks for people while maintaining or restoring the diverse benefits that river-floodplain systems provide. With climate change, population growth and aging dams and levees contributing to rising flood risk, green infrastructure solutions can play a key role in increasing communities' safety and resilience to floods.

Green infrastructure cannot replace traditional infrastructure. Dams and levees will of course continue to play a pivotal role in keeping people safe. However, within already developed river basins, green infrastructure projects can increase the flexibility and resiliency of current water-management systems and should be given full consideration as flood-management systems are retrofitted, rehabilitated, rebuilt or re-operated. For example, in the wake of flood damages to levees, managers should consider alternate alignments of levees that include setting them back from the river. Within river basins that are just beginning to be developed for flood and water management, agencies should explore alternatives that fully incorporate green infrastructure methods. This will allow these river basins to "get it right" the first time, rather than pursuing strictly structural approaches and later seeking to retrofit the system, either because of structural failures or the desire to restore broader river-floodplain benefits, or both.

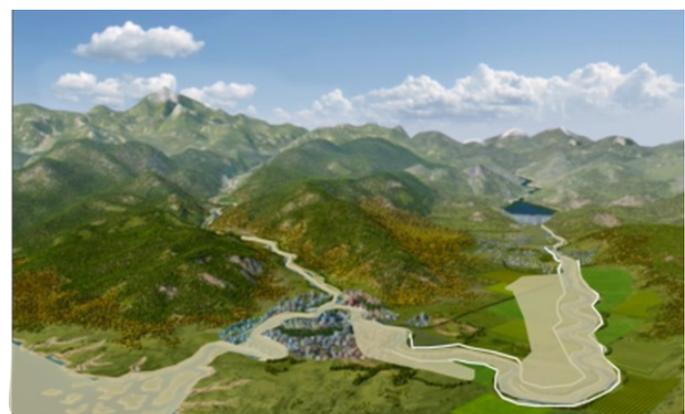
Green infrastructure approaches, and flood management generally, are most effective when implemented as part of a diverse portfolio of tools that are deployed within a river-basin perspective. This perspective allows green infrastructure approaches to be targeted to where they can be most effective. Specific approaches are more or less appropriate depending on the river system – and the location within that river system. Natural valley storage may be an effective approach for reducing flood risk in a small watershed, but the utility of this approach may diminish within larger watersheds. Flood bypasses may provide either storage or conveyance benefits, and the same feature may provide storage benefits for small floods but not for large floods. In some locations, levee setbacks may reduce flood risks for areas up or downstream while, in other locations, the primary benefit of levee setbacks may be the flood damages



Figure 11: Traditional flood management with levees close to river.



Traditional flood management during a moderate flood (e.g., 1 in 10 year frequency) with high velocity water against levees; limited extent of inundated floodplain habitat.



Traditional flood management during a large flood (e.g., 1 in 100 year frequency), levee breaches lead to urban flooding and unplanned flooding of agricultural land.

Case studies

Case studies referenced throughout the report can be found on the web at: <http://nature.ly/floodofbenefits>

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avoided in the area reconnected to the river (e.g., a previously cropped area now in natural vegetation), lower maintenance because the levee is less frequently exposed to high-velocity floodwaters, and natural resource benefits.

Through a river basin perspective, green infrastructure approaches can be effectively integrated with traditional flood management—and water management more broadly. This integrated approach strives to create a mosaic of land uses in the floodplain that provide the most benefits for society (see figures 11-13).



Figure 12: Flood management emphasizing green infrastructure. In some locations, levees are set back from the river; additional levees added to create a flood bypass and a flood detention area, with weir or gates (yellow rectangles) to control flooding of these features.



Flood management with green infrastructure during a moderate flood (e.g., 1 in 10 year frequency). In many locations floodwaters are not directly adjacent to levees. The bypass is in use; greater extent of inundated floodplain habitat.



Flood management with green infrastructure during a large flood (e.g., 1 in 100 year frequency). Both bypass and flood detention area are in use. Agricultural land is flooded but primarily land planned to flood; either in flood-compatible crops or with compensation mechanism.



Figure 13. Mosaic of land use within the floodplain: Within specific portions of the floodplain, land uses are matched to the inundation frequency of that portion. Basin image from Natural Heritage Institute.

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