



# Reconnecting Rivers to Floodplains

---

Returning natural functions to restore rivers and benefit communities

River Restoration Program

Spring 2016



**American Rivers**  
*Rivers Connect Us®*

## About American Rivers

American Rivers protects wild rivers, restores damaged rivers, and conserves clean water for people and nature. Since 1973, American Rivers has protected and restored more than 150,000 miles of rivers through advocacy efforts, on-the-ground projects, and an annual *America's Most Endangered Rivers*® campaign. Headquartered in Washington, DC, American Rivers has offices across the country and more than 200,000 members, supporters, and volunteers.

Rivers connect us to each other, nature, and future generations. Find your connections at [www.AmericanRivers.org](http://www.AmericanRivers.org), [www.facebook.com/americanrivers](https://www.facebook.com/americanrivers), and [www.twitter.com/americanrivers](https://www.twitter.com/americanrivers).



Flooding on commercial parking lots built along Ribary creek in North Bend, WA.  
Photo credit Jonathon Loos.

## Acknowledgments

Written by Jonathon Loos and Eileen Shader

This work is generously supported by the Lapham Family whose financial contributions provide the Anthony A. Lapham Fellowship, an opportunity to carry out a research-based project to advance the mission and objectives of American Rivers.

This document is owed to the guidance of Eileen Shader, and detailed review by herself and other members of the American Rivers Restoration team; John Cain, Laura Craig and Brian Graber. We would like to thank our Science and Technical Advisory Committee and external reviewers for their time and thoughtful review of this work. This document truly reflects knowledge and expertise of individuals from across the spectrum of floodplain practitioners and scientists.

## **Executive Summary**

Riverine floodplains are dynamic systems that play an important role in the function and ecology of rivers. Where floodplains are connected to a river and periodically inundated, interactions of land, water, and biology support natural functions that benefit river ecosystems and people. In this paper we explore the hydrologic and ecological functions that floodplains provide, and how those functions are lost through floodplain disconnection and modification. We synthesize current river-floodplain science to develop an understanding of the biophysical and river flow attributes that underpin floodplain functions. We characterize four attributes that create and sustain functional floodplains; connectivity, variable flow, spatial scale, and habitat and structural diversity. To best restore floodplain systems, restoration practitioners should look beyond habitat features and focus on restoring floodplain functions. We propose a framework from which to consider process-based floodplain restoration using the four attributes of functional floodplains. Well-targeted restoration can return natural floodplain functions to rejuvenate rivers and benefit people.

### **Purpose:**

1. To define riverine floodplains and the natural functions they support that benefit people and ecosystems
2. To examine how people have disconnected and modified floodplains, highlighting the need for floodplain restoration
3. To identify the biophysical and flow attributes that create ecologically functional floodplains
4. To propose a framework for considering process-based floodplain restoration, and actions for restoring floodplain functions

## Table of Contents

<b>I. Floodplains in the Landscape</b> .....	4
Ecological functions and long-term processes.....	5
<b>II. Floodplain Disconnection and Modification</b> .....	7
Floodplain disconnection.....	8
Altered flow.....	9
<b>III. Defining Attributes of Functional Floodplains</b> .....	11
Attributes 1 and 2: Connectivity and variable flow.....	12
Attribute 3: Spatial Scale.....	14
Attribute 4: Floodplain habitat and structural diversity.....	15
A scaled model of floodplain function.....	16
<b>IV. Restoring Floodplain Function</b> .....	18
1. Identify how a floodplain is not functional.....	18
2. Define restoration objectives.....	19
3. Acknowledge limitations inherent to the project location.....	20
4. Assess potential actions for advancing the floodplain to a functional state and meeting restoration objectives.....	21
<b>V. Conclusions</b> .....	29
<b>VII. Works Cited</b> .....	30

## **I. Floodplains in the Landscape**

Riverine floodplains are the relatively flat lands adjacent to a river that become inundated during periods of high flow, or flood. As a result of periodic inundation, floodplains are some of the most biodiverse and productive lands on the planet. Periodic flooding creates unique habitats and provides an exchange of water, sediment and organisms that drive the productivity of ecosystems in-stream and on the floodplain (Tockner and Stanford 2002, Opperman et al. 2010). A floodplain is part of a river, making up the transition zone between the river channel and upland areas. As such, defining floodplains from a landscape perspective is useful for understanding them. While floodplains are by definition dynamic lands that differ dramatically even along the same river, some general identifying features of floodplains can help frame discussion of them.

A river's floodplains are the result of its geomorphic setting and hydrology. Generally, floodplains are low-gradient lands comprised of material deposited by moving water, termed alluvium. Alluvial materials can range from fine silt and sand in lowland areas to coarse gravel and cobbles in mountainous headwater regions. A floodplain can vary from just a few meters wide on small rivers to many kilometers wide on the largest of rivers. Floodplains occur sequentially along the course of a river, expanding and contracting as a river moves through various degrees of bedrock confinement, with modified stream power and sediment size (Nanson and Croke 1992, Tockner and Stanford 2002, Ward et al. 2002).

A river's floodplain is less often covered in water than the channel. When a river's discharge exceeds the channel capacity, water overflows onto the floodplain. While floodplains are primarily inundated by river water, they also receive water from groundwater, precipitation and overland flow from upland sources. Ecosystems within the floodplain are uniquely adapted to live with inundation. Many riparian plants have life histories dependent on floods, and exploit the energy and nutritional benefits of such events. Floodplains host bird and fish species specially tuned to floodplain conditions and annual inundation.

Riparian ecosystems emerge within floodplains. Riparian species are semi-terrestrial plants and animals that are influenced regularly by freshwater. Riparian areas extend from the edge of a river and upwards to the edges of upland habitats. Riparian ecosystems are themselves dynamic, and interact with both aquatic and terrestrial components of the landscape. Riparian plant communities array along the same longitudinal, lateral, and vertical spatial gradients that define the physical attributes of floodplains (Naiman, Decamps and McClain 2005).

As a river moves across the landscape its floodplains arise as the result of complex factors of land, water, and ecology that interact over scales of space and time. Riverine floodplains are by nature complex systems, and our identification of them here is certainly an oversimplification. However, we use this general understanding of the floodplain landform to discuss the ecological and hydrologic value of riverine floodplains and to expand on the conceptual model of ecologically functioning floodplains in a way that informs efforts to restore them.

### **Distinguishing the landscape: Floodplains, riparian zones and wetlands**

Rivers flow through many landscapes and often have other bodies of water associated with them. It can be difficult to distinguish how a river's floodplains differ from or overlap with other components of the landscape, such as riparian areas and wetlands.

**Floodplain** – In the simplest terms, a floodplain is the land area adjacent to a stream or river that is inundated during high flow, or flood. Floodplains are dynamic landforms usually composed of alluvial material, and experience inundation at varying frequencies and magnitudes.

**Riparian zone** – Riparian zones comprise transitional semi-terrestrial areas regularly influenced by freshwater that extend from the edges of a water body to the edges of upland communities. Riparian ecosystems are characterized as having plants and animals uniquely adapted to living with flood disturbance, and create biotic assemblages that array along gradients in soil wetness and local hydrology within the floodplain (Naiman, Decamps and McClain 2005).

**Wetlands** –As defined by the United States Environmental Protection Agency (U.S. EPA), wetlands are areas where water covers the soil, or is present at or near the surface of the soil all year or for periods of time, and where conditions favor growth of specially adapted plants and support development of hydric soils. Riparian wetlands emerge along rivers and streams in isolated depressions surrounded by dry land where groundwater intercepts the soil surface, or where surface water flow or precipitation sufficiently saturates the soil (U.S. EPA).

Classifications for floodplains, riparian zones and wetlands are broad and not always distinct. For conceptualizing purposes, it may be easiest to consider floodplains as land areas along a river that become covered by water during overbank flow, and this area may encompass both riparian areas and wetlands.

### **Ecological functions and long-term processes**

Interactions among land, water, and biology occur within floodplains that support an array of functions that benefit a river and larger landscape. Floodplain managers often refer to these as natural and beneficial functions (Kusler 2011). These benefits accrue from intermittent periods of floodplain inundation, and as a result of processes that occur over longer periods to maintain riparian ecosystems and shape floodplain landforms (Tockner and Stanford 2002, Opperman et al. 2010).

When high flows move outside the river channel they slow down, disperse energy and deposit sediment. By providing room for floodwaters to spread out, floodplains lower flood levels and regulate the amount of sediment transported by a river. Unique side channels, ponds and wetlands form within the floodplain (Rhode et al. 2006, Opperman et al. 2010). As a result of consistent disturbance, floodplains are shaped into habitat mosaics that are characterized by a diversity of successional stages and uniquely adapted biota (Ward et al. 1999).



During inundation, floodplains support river ecosystems by providing habitat for fish and wildlife, maintaining water quality, and supplying nutrients and shelter that enhance fish reproductive success and growth rates. The flood pulse concept (Junk et al. 1989) illustrates the ecological value of floods, describing them as periodic pulses of nutrient and sediment rich water that spur productivity and connects riverine and floodplain habitats. Flooding underpins the processes that create and sustain the ecological functions of floodplains. Where those natural processes remain intact, and floodplain form and ecological processes are sustained, a floodplain is considered to be ecologically functional.

Natural floodplain functions also benefit human communities. We refer to the benefits that ecosystems provide to people as ecosystem services. Floodplain ecosystem services often include; regulating and reducing flood, maintaining water quality, storing carbon in wetlands and floodplain forests, providing habitat for the plants and animals we value, and supporting recreational areas and cultural identity (Seavy et al. 2009).

Ecologically functional floodplains are difficult to find in today's increasingly developed and engineered landscape, and this is to the detriment of people and rivers. Where a floodplain has been disconnected from a waterway and converted to other uses, its ability to provide an array of

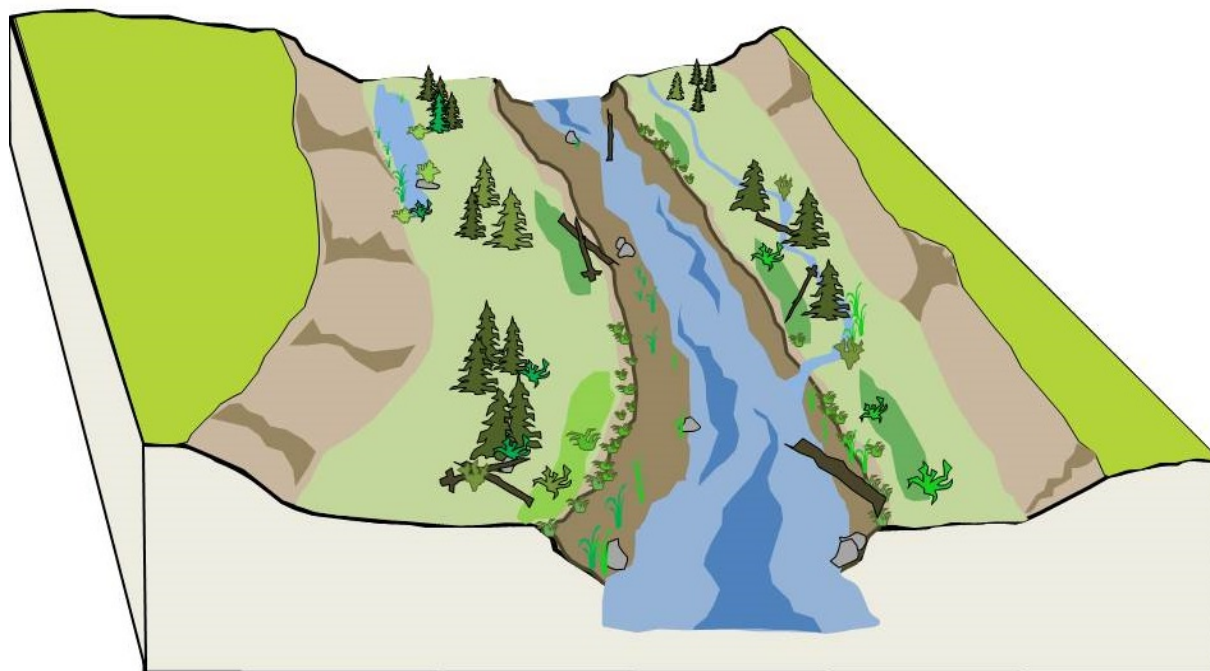


Figure 1 – A floodplain is part of a river, comprised of the lands adjacent to a river that become inundated by water during high flows. Floodplains are dynamic land areas that experience regular disturbance. Floodplain form and ecology are shaped overtime in response to natural processes that are driven by periodic flooding.

natural and beneficial functions is inhibited, curtailing benefits to both human and ecological communities (Opperman et al 2010).

## Natural Functions of Floodplains

### Driven by Periodic Inundation

- **Connecting organisms:** Fish, wildlife and riparian vegetation depend on floods to connect aquatic and riparian habitats, and to create lateral corridors along a river. Many species of fish depend on inundated floodplains to spawn and support growth of newly hatched fish.
- **Moving materials:** High waters exchange sediment and nutrients between the river channel and floodplain, driving productivity in both.
- **Maintaining water quality:** Riparian vegetation and soil biota filter pollutants and excess sediment and nutrients from river water.
- **Mitigating flood stage:** Floodplain ecosystems absorb and slow high waters, reducing flood stage.
- **Dispersing energy:** The erosive energy of moving water is dissipated when it's able to spread across floodplains, protecting downstream reaches from erosion.

### Driven by Long Term Processes

- **Stabilizing riverbanks:** Riparian plant communities hold onto soils and resist erosion.
- **Groundwater exchange:** Floodplains provide pervious space for floodwaters to recharge groundwater flows, and hyporheic exchange to occur that keep stream temperatures cool.
- **Accommodating movement:** Riverbank and floodplain landforms shift overtime in response to the transportation and deposition of sediment, naturally reshaping channel form to accommodate high flows.
- **Habitat mosaics:** Point bars, meander belts, side channels, oxbows, wetlands, and other landforms arise over time that support unique habitats and hold flood waters.

## II. Floodplain Disconnection and Modification

Offering rich resources and proximity to waterways, floodplains have served as thriving centers of agriculture, trade, industry, and residential development for centuries. To live within floodplains, people have had to become very good at dealing with the risk of flood. Even today, large, infrequent floods can take lives and destroy property, which is why communities have tried so hard to “control” them with levees and dams.

Unfortunately, most people don't realize how harmful engineered structures can be. Large floods can still overwhelm flood-control structures. When structures fail they release massive amounts of water all at once, endangering lives, destroying homes and businesses and costing millions of dollars. The National Weather Service estimates the 30 year flood loss average in the



United States in 2016 to be \$7.96 billion annually, causing 82 fatalities a year. In addition to creating an artificially high sense of security and encouraging risky development, dams and levees often disconnect rivers from their floodplains, allowing them to be converted to other uses.

Floodplains have been disconnected from waterways on a massive scale across the United States. It's estimated that floodplains covered 7% (700,000 km<sup>2</sup>) of the North American continent prior to colonization. Since then, over 50% of North American wetlands have been drained, with the largest loss from forested riverine wetlands. Today 46% of continental U.S. river riparian areas are classified as intensively cultivated (Tockner and Stanford 2002). This scenario has crippled the ability of floodplains to function naturally, masking floodplains' ability to provide many benefits they once did.

When not periodically inundated, floodplains support less functions and provide fewer benefits for rivers and people (Tockner and Stanford 2002). This occurs where a floodplain becomes physically disconnected from a river, or where a river's hydrology has been altered to the point that flows great enough to inundate the floodplain no longer happen.

### Floodplain disconnection

Across the United States, rivers have been engineered to enhance navigability and control flooding. Engineered river channels are the most common source of disconnection between rivers and floodplains, and structures can take multiple forms.

Levees are walls or earthen berms built along a river intended to contain high flows within the river channel and protect lands behind them from flood. To improve navigation, river channels are often straightened, dredged, and cleared of snags and obstructions. These engineering practices turn rivers into simplified pipes that move water downstream more quickly and with more energy. As a result of these projects, large areas of once functional floodplain become disconnected from rivers. The Mississippi River is one of the best examples of this. Today the Mississippi has more than 2,200 miles of levees and a net river length around 150 miles shorter than it did in 1929 as a result of straightening (Alexander et al. 2012).

In smaller rivers, channel straightening can lead to floodplain disconnection through incision. In channelized reaches, sediment is transported downstream faster than new sediment is deposited, leading a river bed to erode downwards overtime (Shields et al. 1994). This scenario is often exacerbated where river flow is impeded by dams upstream that alter sediment supply (Dixon et al. 2015). Dams catch sediment in their reservoirs rather than passing it downstream, so energy once used to transport sediment is instead expended to erode river beds and banks. Overtime, incision can leave a channel bed so deep that floodwaters no longer overtop river banks to disperse onto floodplain lands. Whether through engineering practices or worsened through incision, once a river and floodplain become disconnected the exchange of nutrients, sediment and organisms is eliminated and habitat corridors are severed (O'Hanley 2011, Tochner et al. 1998).

## Altered flow

Floodplains can become hydrologically disconnected where river flow is altered, even where they remain physically accessible to water. In the United States, it's estimated that 90% of river discharge is hydrologically altered by damming or water withdrawal (Jackson et al. 2001). As rivers flow across the landscape, significant volumes of water are withdrawn for people, industry and agriculture. Dams are constructed to create reservoirs for water supply, to generate energy, or to control floods for public safety. Dams and withdrawals alter the timing, magnitude, duration and frequency of flows that inundate and nourish floodplains (Rood et al. 2005). In the United States, dams have enough combined capacity to store a volume of water almost equal to an entire year's worth of river runoff (Graf 1999).

Flow regulated rivers commonly have lower high-flows, modified seasonal flow cycles and impaired sediment transport. Over time these effects reduce the complexity of river and floodplain landforms. Where floodplain-inundating flows no longer occur, a floodplain is considered hydrologically disconnected (Dixon et al. 2015). An analysis of 72 reaches of large American rivers showed that those with upstream large dams had 70 percent less active floodplains compared to those reaches without large dams upstream (Graf 20006).

Floodplains need floods to support their natural functions, but river floods are often made smaller and less frequent as a result of dams. In an analysis of the impacts of 21 dams in the U.S., Magilligan et al. (2003) found that even the most frequently occurring 2-year flood is significantly reduced, if not eliminated, in dam-altered rivers. Often, river flows are controlled to the point of removing all semblances of a natural flow regime and annual flood pulse downstream (Galat et al. 1998). Where this is the case, the dynamic processes that maintain floodplain form and support biota in-stream and on the floodplain are jeopardized (Poff et al. 1997, Ward et al. 1999, Ward et al. 2002, Nilsson et al. 2005, Rood et al. 2005, O'Hanley 2011). Behind dams, floodplains become permanently inundated, shifting a riverine system to a lake (McCartney 2009).

Floodplains can become disconnected from rivers as a result of engineering and flow regulation. Without regular inundation, floodplain functions cease and a floodplain transitions from ecologically functioning to impaired.



**Floodplain Disconnection:** Where high flows cannot inundate the floodplain

- No exchange of surface water, nutrients, sediment, or organisms
- Reduced riparian habitat
- Diminished side channels, ponds and wetlands
- Faster and higher, "flashier" floods
- Declines in native plant species, increased opportunity for invasive species
- Impaired water quality, stream temperature, and sediment transport dynamics
- Can exacerbate erosion and cause incision

**Flow Alteration:** When the timing, magnitude, duration, and frequency of river flows are altered

- Reduced occurrence of floodplain inundating flows
- Disrupted seasonal flow cycles
- Altered sediment supply patterns
- Reduced complexity of in-stream and floodplain landforms
- Loss of life-history supporting flows for plants, fish and wildlife
- Can lead to hydrologic floodplain disconnection

## **Floodplains and Public Benefits**

In a policy context, floodplains are more often defined as a risk zone rather than a complex and beneficial component of the environment. For instance, federal floodplain management requirements are dictated by the National Flood Insurance Program (NFIP) which defines the regulatory floodplain according to the frequency at which an area may flood. Floodplain management policies have allowed many communities to develop in floodplains, and in response, infrastructure to control and mitigate floods has been implemented on a vast scale across the country. These actions have contributed to increasing flood risk and disconnected floodplains.

Disconnecting a floodplain eliminates its ability to mitigate floods, and replaces natural functions with flood-prone development. This is especially problematic where floodplain development occurs behind infrastructure like levees because the consequences of infrastructure failure are catastrophic.

Climate change has and will continue to impact inland water resources. Shifts in the timing and volume of river-flow have been observed across the country, and these changes are predicted to continue (Georgakakos et al. 2014). Droughts are likely to become more severe in many regions, and impacts are exacerbated where disconnected floodplains lose their capacity to store groundwater. Similarly, the occurrence of very heavy precipitation events is projected to increase nationally, even where overall precipitation levels are in decline. These conditions are likely to lead to an intensification of flooding in most regions, alongside impaired water quality as sediment, nutrients and pollutants more quickly make their way into streams, rivers and other waterbodies.

We need to ensure that our streams and rivers can maintain their hydrologic and ecological functions under uncertain future conditions, and we need to better live with and avoid flood risk across the country. Reconnecting floodplains in geographically strategic locations can increase a river's capacity to contain floodwaters, reducing flood risk and reliance on expensive infrastructure in communities downstream. Managing and restoring floodplains to better contain flood waters, improve water quality, and restore ecosystem function can complement climate adaptation efforts in river basins nationally (Seavy et al. 2009).

### **III. Defining Attributes of Functional Floodplains**

Floodplain restoration is a means to restore a floodplain to an ecologically functioning status, and return benefits to rivers and people. Because floodplain systems are complex, restoration efforts need to look beyond surface features and focus on restoring underlying processes that create and sustain floodplains and their functions (Rhode et al. 2006, Matella and Jagt 2014, Matella and Merenlender 2014). By first identifying the biophysical and flow attributes that underpin functional floodplains, restoration efforts can be guided towards more impactful and self-sustaining outcomes.

A model organizing the complex interactions that generate ecologically functional floodplains is described by Opperman et al. (2010) as depending on three essential elements;

- Hydrologic connectivity between a river and floodplain
- A variable flow regime that produces high and low flows
- Sufficient spatial scale for floods to occur and benefits to accrue to an ecologically meaningful level

These elements offer a succinct way of communicating the physical and flow components of a river-floodplain system that drive natural processes and sustain floodplain ecosystems.

In this report we build upon this model of ecologically functional floodplains in three ways. First, we elaborate on the flow regime element to include temporal characteristics of flow such as seasonal timing, duration, and frequency that are key to many species' success. Secondly, we present "habitat and structural diversity" as a final emergent property of ecologically functional floodplains. We define it as the high-resolution details that arise in floodplain habitats and surface features driven by disturbance, ecological succession, and hydrologic connectivity gradients. Lastly, we offer a conceptual model of functional floodplains to more easily inform design of floodplain restoration projects.

To discuss a conceptual model of functional floodplains, we first need to define its parameters. We consider the river-floodplain as a single system, composed of flowing water and the landscape it moves through. The river-floodplain system hosts dynamic interactions of land, water and biology that carry out natural functions, and those functions produce benefits to ecosystems and people (hence, the "natural and beneficial functions of floodplains" often used in policy language). River-floodplain systems do not support functions on an all or nothing scenario, but instead on a graded scale. The extent to which a floodplain is ecologically functional depends on the presence and condition of four attributes; connectivity, variable flow, spatial scale, and habitat and structural diversity. We refer to these as the attributes of functional floodplains. What follows is a more detailed description of those attributes, and the justification of their importance in floodplain functions as discussed in previous research (Table 1).

### Attributes 1 and 2: Connectivity and variable flow

Flooding is the foundation of floodplain function. Flooding occurs where a floodplain is both accessible to and periodically inundated by high water. The importance of floods to floodplain ecosystem has been demonstrated by many researchers (eg., Rohde et al. 2006, William et al. 2009, Opperman et al. 2010, Matella and Merenlender 2014). Taken together, they describe floodplain ecosystem functions as dependent upon a connection to streams or rivers that are capable of periodic floods, or supportive of a hydrologic regime that produces flows of varying magnitudes.

Without the influence of flow regulation by dams or engineered works, the hydrology of most rivers is characterized by seasonal flow changes driven by wetter and drier months, occasional large storms, and/or snowmelt. Most natural river flow regimes include small, predictable floods that happen annually or every few years (Poff et al. 1997). These floods are pulses of high water that connect in-channel and floodplain habitats and drive an exchange of nutrients and sediment (Junk et al. 1998). Flows that are able reach the floodplain and initiate floodplain functions are characterized as "floodplain activating flows" (William et al. 2009).

The attributes of connectivity and variable flow are intact where a river-floodplain system periodically floods and where floodwaters are able to overtop riverbanks and dissipate onto the floodplain.

Floodplain ecosystems need more than just the occasional flood to support a full range of ecological functions. Not only must a floodplain experience high flows, it must receive those flows at ecologically beneficial times of the year, for adequate spans of time, and at appropriate return frequencies. Temporal characteristics of a river's flow regime are critical to meeting species-specific needs such as access to spawning and rearing habitat, or inundation intervals supportive of riparia (Galat et al. 1998, Naiman, Decamps and McClain 2005, Cain et al. 2010, Matella and Merenlender 2014). A hydrograph describes a river's flow regime by tracing its discharge as it changes through time (Figure 2).

Riverine and riparian species are typically adapted to flood disturbance, and are dependent upon the local temporal signature of flooding (Rood et al. 2005, Matella and Merenlender 2014). California's San Joaquin River Valley provides an example of species-specific requirements in river flow. The Sacramento Splittail (*Pogonichthys macrolepidotus*) is a fish endemic to the San Joaquin-Sacramento region that depends on access to floodplain-like habitat areas. Floodplains provide the preferred substrate for adult spawning, and conditions supportive of vulnerable and hungry newly-hatched fish (Cain et al. 2010). Research (Feyrer et al. 2006, Moyle et al. 2004) has shown that Splittail most frequently spawn in March. Their eggs require 3-5 days to hatch, and young fish remain within flooded habitats often until May. From this information, biologists are able to pinpoint the ideal duration and seasonal timing of inundation for ensuring Splittail success, in this case from the beginning of March through May. A similar three month inundation at other times of the will not benefit Splittail reproduction.

Ecological information can define when and for how long inundation is needed to support floodplain-dependent species. Species-specific needs can also dictate how often flooding needs to occur. Again using the example of Sacramento Splittail, biologists have shown that flooding from March-May only every fourth year supports healthy Splittail populations (Cain et al. 2010). This differs from Chinook salmon (*O. tshawytscha*), another floodplain-dependent fish species also native to the San Joaquin River. Unlike Splittail, juvenile Chinook need shorter periods of inundation to thrive; just two weeks can support robust growth (Jeffres et al. 2008). However, Chinook need access to floodplains annually or biennially to support healthy population levels. Taken together, Splittail and Chinook life histories illustrate that rivers must be capable of a diversity of floods, from infrequent and long-lasting to shorter more frequent floods, as defined by the specific needs of regional species.

We use the term variable flow to express the need for rivers to produce flows of varying magnitudes at ecologically beneficial times, durations and frequencies. To capture ecological and landscape flow function in regulated rivers, "functional flows" controlled by engineering works are designed to mimic the historic natural flow regime of flow regulated river systems (Yarnell et al. 2015). They suggest that functional flows should be an objective in regulated river systems because they sustain geomorphic and ecologic processes alongside varied human needs in regulated rivers.



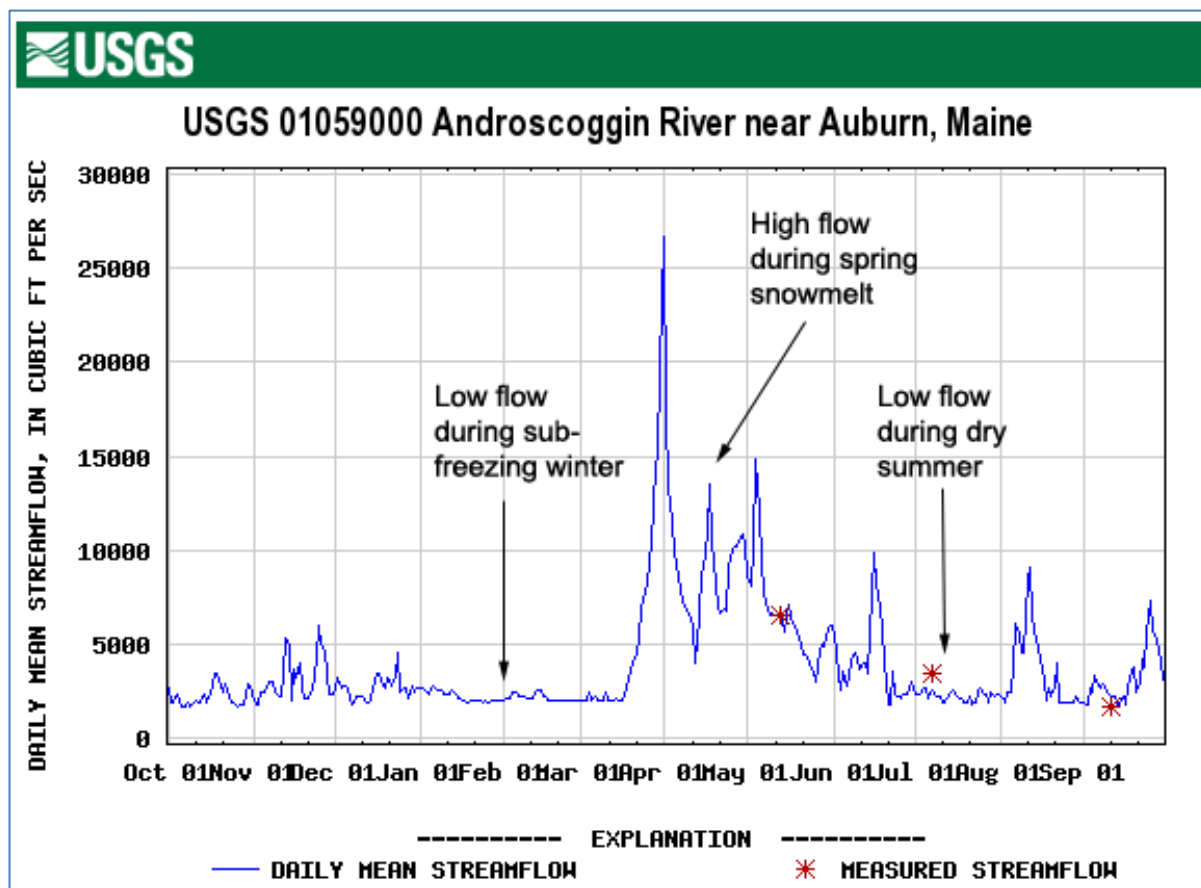


Figure 2 – A hydrograph from the Androscoggin River in Maine. A hydrograph is made from measurements of a river’s daily average flow (often in cubic feet per second) over an entire year at a single location. This figure illustrates the variety of flows, or discharge levels, that occurred throughout the year ranging from extremely high (27,000 c.f.s. in April), to very low (less than 3,000 c.f.s. in August). Despite being impounded by multiple dams, the Androscoggin River at Auburn, ME still produces flows with seasonal variations in magnitude and duration. Hydrograph figure obtained from the United States Geological Survey’s streamgauge data network (<http://waterdata.usgs.gov/nwis/rt>).

### Attribute 3: Spatial Scale

Floodplains that are connected to rivers with variable flow characteristics supportive of functional ecosystems need geographic space to accommodate their form and processes. During inundation floodplains are the setting for sediment deposition and erosion, and unique habitat forming processes. Generally, larger rivers need larger floodplains. This attribute has been referred to as both dynamic area (Tockner and Stanford 2002) and spatial scale (Opperman et al. 2010), and describes the need for floodplains to have a minimum area accessible to inundation to enable a full range of biotic and geomorphic processes to occur.

#### Attribute 4: Floodplain habitat and structural diversity

Ecologically functional floodplains arise where they remain open and connected to a river, and where a variety of flows occur throughout the year. Unique ecosystems emerge where these attributes occur together in a river-floodplain system. The shifting habitat mosaic concept (SHM) (Stanford et al. 2005) describes how gradients in hydrologic connectivity (water availability) and disturbance (flooding) create variability in habitat conditions across a floodplain. Physical and biotic processes interact along these gradients to create a pattern of continually shifting habitats. Overtime, flood disturbance, sediment erosion and deposition, succession and turn-over of vegetation, and debris recruitment shape floodplain habitats into uniquely distributed patches, or a habitat mosaic (Ward et al. 1999, Whited et al. 2007, Tockner et al. 2010). We refer to this as habitat and structural diversity, and treat it as a final attribute of ecologically functional floodplains that emerges where attributes of connectivity, variable flow and spatial scale are working in unison (Table 1). Habitat and structural diversity enhances ecosystems and maximizes the functional value of a river-floodplain system.

Floodplain habitat mosaics can support a diversity of organisms. Disturbance gradients drive differences in vegetation succession, producing patchworks of habitat that support high biodiversity. These patchworks lead to various thermal conditions within the floodplain (thermal mosaics) that create refuge for biota and regulate chemical respiration and decomposition processes (Tonolla et al. 2010). At the larger scale, variability of floodplain topography, soil properties, debris recruitment and vegetation create erosional heterogeneity across a floodplain, and influence river channel form over many decades (Gunerlap and Rhoades 2011). During inundation these features also influence water turbidity and temperature conditions, and can enhance a floodplain's capacity to store and slow floodwater, mitigating flood peaks in downstream reaches (Dixon et al. 2016).

Floodplain processes create unique ecosystems across watersheds, making a universally standardized description of habitat and structural diversity impossible. However, we know that routine inundation creates unique floodplain habitat mosaics and topographies, and this diversity supports an array of functions that benefit the larger riverine landscape.

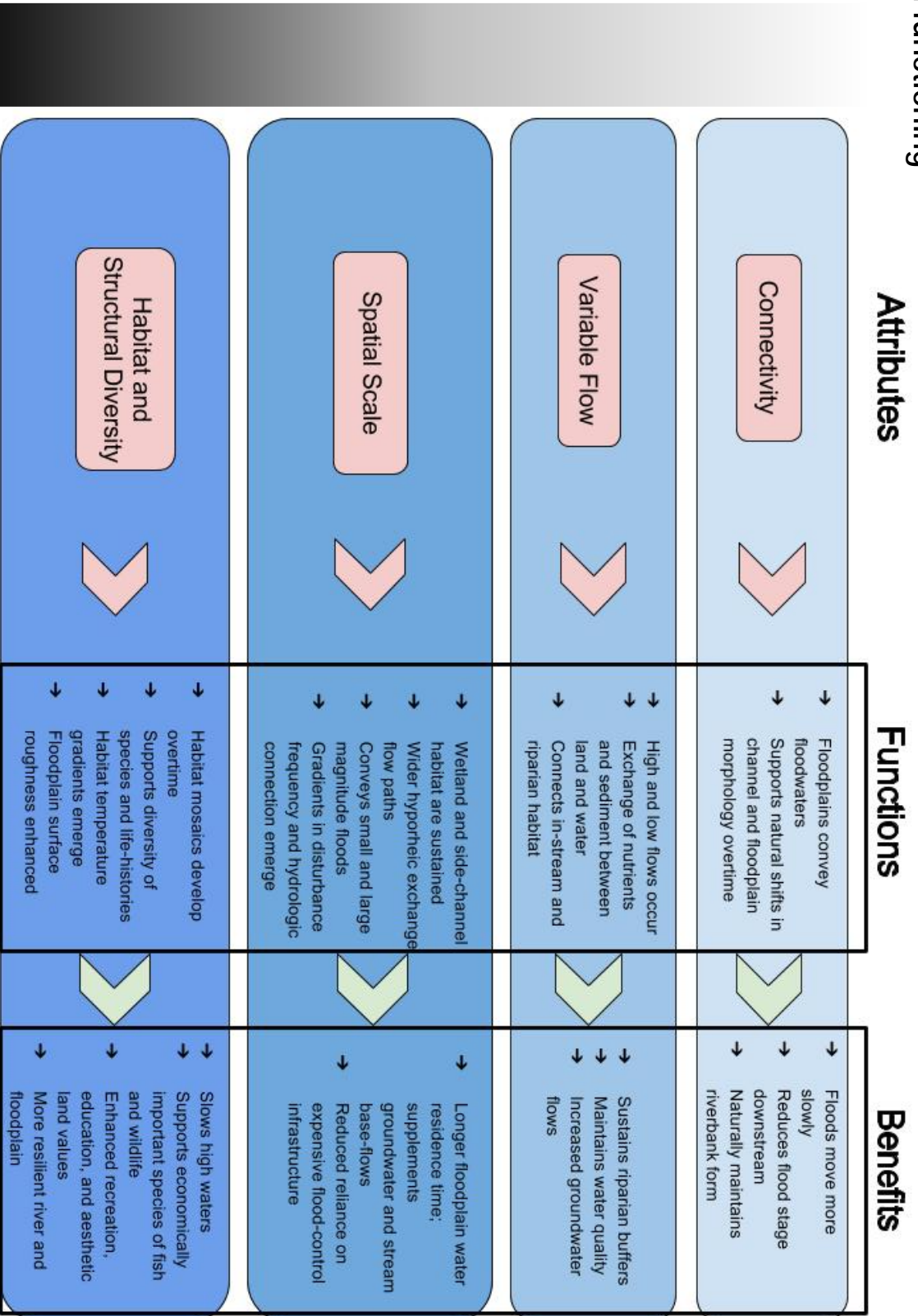
**Table 1 – The attributes of river-floodplain system that create and sustain ecologically functional floodplains. These attributes include both biophysical and flow characteristics that support natural functions of floodplains that in turn provide benefits to ecosystems and people.**

<b>Functional Attribute</b>	<b>Justification</b>	<b>References</b>
Connectivity	A functional floodplain is physically accessible by water from its adjacent river or stream to allow an exchange of water, nutrients, sediment and organisms.	Ward et al. 1999, Rohde et al. 2006, Opperman et al. 2010, Matella and Merenlender 2014
Variable Flow	A functional floodplain is connected to a river capable of producing flows with magnitudes large enough to inundate the floodplain. Additionally, a river must produce such flows at specific times of the year, for adequate spans of time, and at variable return frequencies to maximize a full range of ecological functions. Together, variable flow describes the necessary timing, duration, magnitude, and frequency (TMDF) of flows that support local biota.	Poff et al. 1997, Galat et al. 1998, Rohde et al. 2006, William et al. 2009, Cain et al. 2010, Opperman et al. 2010, Matella and Merenlender 2014, Dixon et al. 2015, Yarnell et al. 2015
Spatial Scale	A floodplain must have the space to accommodate inundation and the resulting habitat and landscape forming processes that occur.	Tockner and Stanford 2002, Opperman et al. 2010
Habitat and structural diversity	A diversity of sediment erosion and deposition conditions, gradients of hydrologic connectivity, ecological succession and naturally accumulated debris generate habitat supportive of terrestrial and aquatic organisms. Ideally, these features emerge from co-occurrence of the previous three attributes.	Galat et al. 1998, Ward et al. 1999, Stanford et al. 2005, Whited et al. 2007, Jeffres et al. 2008, Opperman et al. 2010, Tockner et al. 2010, Gunerlap and Rhoades 2011

### **A scaled model of floodplain function**

We know that river-floodplain systems need specific biophysical and flow attributes to produce natural functions (Table 1). These attributes build upon one another, each supporting a subset of functions that together form a fully functioning floodplain system. A useful conceptual model that assembles the interworking biotic and abiotic components, and dynamic process, of floodplain systems relies in part on the prior research of others (Table 1). We use this body of work to assemble Figure 3, which depicts the four attributes of functional floodplains, the functions and benefits each supports. This model portrays river-floodplain systems on a graded scale of ecological functioning, from non-functioning to fully functioning, depending on which attributes are intact.

Non-functioning



Fully functioning

Figure 3 –Within river-floodplain systems, the condition of four attributes is key to creating and sustaining ecologically functional floodplains. Where those attributes are intact, natural processes are enabled that support ecological functions and produce human benefits. Floodplains produce functions on a graded scale depending on the occurrence of each attribute.

## IV. Restoring Floodplain Function

Where a floodplain is no longer inundated or its natural cover degraded, the ecological functions it provides are diminished. Floodplain restoration is a means to recover the benefits floodplains provide to rivers and people. The inherent complexity of river-floodplain systems can make the task of restoring them seem daunting. By focusing on the attributes that underpin floodplain processes and functions, we offer a solution by proposing a coherent process-based approach to floodplain restoration.

Process-based restoration can be thought of as a bottom-up approach to fixing an ecosystem. Instead of restoring surface features, process-based restoration returns the natural processes that create and sustain an ecosystem, allowing it to restore at a natural rate. In this way, process-based restoration corrects the underlying causes of ecosystem degradation (Beechie et al. 2008, 2010, Roni et al. 2008).

We develop our floodplain restoration philosophy from a process-based perspective using the four attributes of functional floodplains. Through this approach, a river-floodplain system can be shifted towards a trajectory of recovery with minimal human intervention.

Although restoration uses a similar philosophy for most floodplains, no two river-floodplain systems are the same. As such, restoration objectives will be unique among rivers, and often among reaches of the same river. A way to identify restoration objectives and prioritize actions on a project specific basis is needed. Various strategies for prioritization have been discussed in restoration literature (Beechie et al. 2008, 2010, DiGennaro et al. 2012, Opperman 2012, Rood et al. 2005), and guide the process we develop here. We do not pose a method for identifying potential floodplain restoration locations. Instead, we develop an adaptive framework to guide project design at an already selected restoration location. The four steps to that framework are as follows:

1. Identify how the floodplain is currently not functional. (ie: Which functional attributes are missing from the river-floodplain system?)
2. Define restoration objectives.
3. Acknowledge the limits inherent to the project location.
4. Identify the minimum actions needed to return floodplain functions to a level that meets restoration objectives.

Instead of designating an ideal state to restore to, this framework aims to restore underlying processes that support floodplain functions. These steps ensure that a restoration project is designed to correct the causes of floodplain disconnection and degradation, not just the symptoms. We describe these steps in detail below.

### 1. Identify how a floodplain is not functional

In the first step, restoration managers think from a landscape perspective and gather the information needed to identify which functional attributes are present and those that are missing within a river-floodplain system. They might use basic observation-based and historical data, or more technical results from hydrologic modelling. Data gathered to assess each

functional attribute in a floodplain system guides decision-making and investment in the restoration effort.

Figure 3 presents a sequence of steps to check for floodplain functional attributes, and potential methods for assessing each. Going through these steps can serve as a rapid assessment of floodplain functionality, and indicate which functions need to be returned to the river-floodplain system through restoration actions.

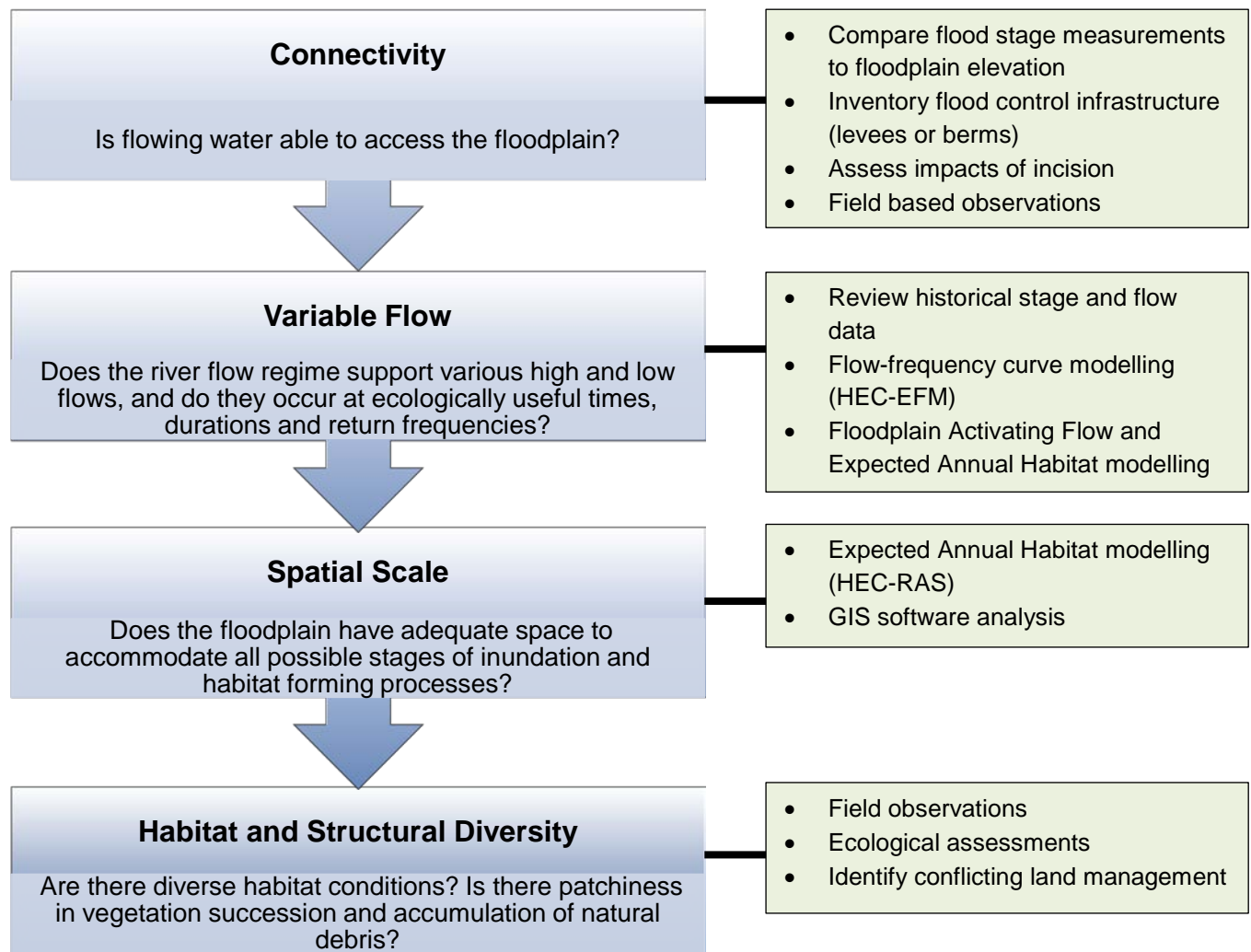


Figure 4 – A suggested method for assessing the functionality of a floodplain system. A check for each attribute can be done by answering the questions in the left boxes, using the methods listed on the right.

## 2. Define restoration objectives

Having identified the condition of each floodplain functional attribute, the basic objectives for restoration will be clear: restore the functional attributes missing from a floodplain system. Projects are likely to have other site-specific ecosystem or hydrology driven goals; enhance conditions for floodplain dependent species of fish, return hydrologic conditions supportive of floodplain forests, enhance water quality and sediment conditions.



The next question becomes, to what extent does each floodplain attribute need to be returned to meet specific ecosystem objectives? Various methods exist for assessing this by integrating geospatial, topographic and hydrologic data. Application of these methods help us understand how changes to floodplain attributes will influence flow regime, inundation, and floodplain ecosystems. The floodplain activation flow concept and expected annual habitat assessment are representative methods for doing so.

- **The floodplain activation flow (FAF)** concept was developed to identify the minimum flow level needed to inundate a floodplain and initiate a significant response in ecological processes, termed the activation flow (Williams et al. 2009). A river's activation flow is great enough to inundate the floodplain, occurs with suitable duration and timing to initiate ecological benefits, and reoccurs frequently enough to support those benefits inter-annually. The FAF is uniquely defined by the life-history needs of biota within a river-floodplain system. Williams et al. (2009) present in detail the methodology for defining the FAF for the Sacramento River. Defining the FAF requires four sets of data from a river-floodplain system: floodplain topography profiles (such as LIDaR aerial imagery surveys), river flood stage (depth of flow) profiles from hydrologic models, river gauge data (stage and temporal data), and ecosystem information detailing inundation thresholds for specific species needs and ecological processes (fish spawning needs and juvenile growth periods, for example).
- **The Expected Annual Habitat (EAH)** method is an integrative tool for quantifying acres of floodplain habitat that are supported by a flow of specific duration and stage (Matella and Jagt 2014). By merging flow-frequency relationships with inundated-area curves, an area-duration frequency curve is acquired that measures the amount of land inundated by a flow level lasting for a specific period of time. When used in a GIS program, the EAH method can predict the acres of floodplain habitat that will be newly inundated as a result of changes to river flow regime or river channel area.

Methods such as the FAF and EAH can identify the unique connection, flow and spatial conditions needed to support floodplain ecological processes, and inform the design of restoration actions.

### 3. Acknowledge limitations inherent to the project location

Rarely will a restoration practitioner have the ability to change all attributes within a river-floodplain system. Instead, restoration projects must work within the parameters set by the river, floodplain, or built infrastructure. Are parts of the floodplain not able to be reconnected? Can the flow regime be altered upstream? Are there areas within the floodplain that are not conducive to inundation? Factors that cannot be altered limit the actions available for restoration, and should be understood when assessing restoration actions. Examples of limitations might include:

- Floodplain disconnection by infrastructure that cannot be considered for setback, breaching or removal because of engineering problems or flood safety

- Regulated flow that cannot be changed because of water rights or legal considerations
- Floodplain areas constrained by infrastructure or with land use that is not conducive to inundation
- Riverbed incision where the channel and/or floodplain is too sensitive to be regraded or excavated, such as sensitive habitat or water supply areas

By laying out the limitations to a floodplain restoration project at a specific river reach, the objectives must be realistic and achievable. At this step in the restoration framework, a restoration manager knows which attributes need to be returned to a floodplain system, and what factors within the system they are able to work with to do so.

#### 4. Assess potential actions for advancing the floodplain to a functional state and meeting restoration objectives

Having identified how a floodplain is not fully functioning (Step 1), defined restoration objectives in returning those functions (Step 2), and acknowledged what can and cannot be changed within the system (Step 3), restoration actions can then be assessed. Restoring ecosystem processes through the minimum amount of human intervention required is an important principle of process-based restoration. This minimalist approach should be considered when designing projects. Actions often used to reconnect and restore floodplains are discussed below, organized by the four functional floodplain attributes.

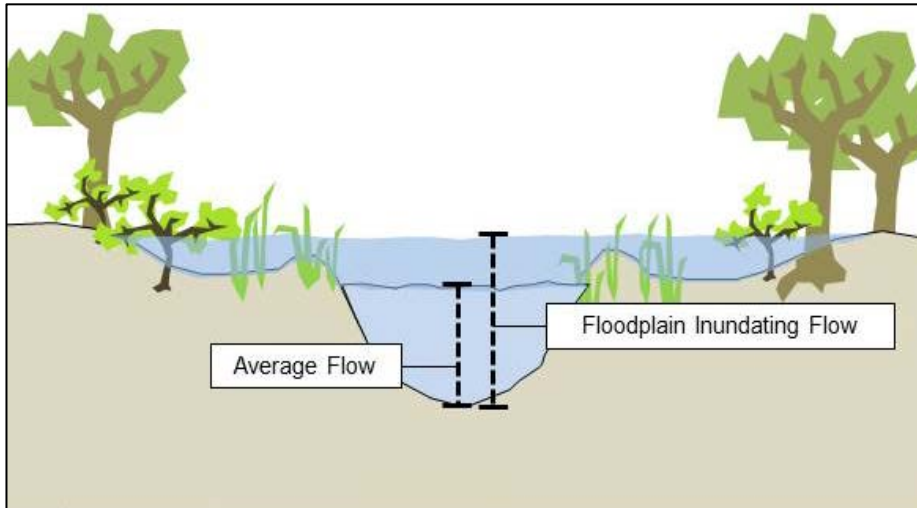
**Connectivity** – The methods used to reconnect a river and floodplain depend on the cause of disconnection. Physical disconnection results where high flows occur in a river but are unable to reach or inundate the floodplain area. Where physically disconnected, restoration actions will aim to increase the floodplain area inundated by flows that are already able to occur in the river system. There are two common types of physical disconnection; built disconnection and vertical disconnection.

- Built disconnection occurs where infrastructure, such as levees and berms, has been built to keep floodwaters from entering the floodplain. Correcting this arrangement involves setting structures farther back from the river channel, breaching them, installing weirs to allow controlled flooding, or completely removing them.
- Vertical disconnection results where hydrologic processes have lowered, or incised, a river channel to the point that floods no longer overflow from the channel onto the floodplain. This scenario may require intensive corrective action. Where in-stream habitat is not extremely sensitive, an inset floodplain terrace can be installed within the incised channel to create a smaller but accessible floodplain area. However, addressing the upstream causes of altered flow and sediment transport dynamics will likely be the most effective and least impactful action.

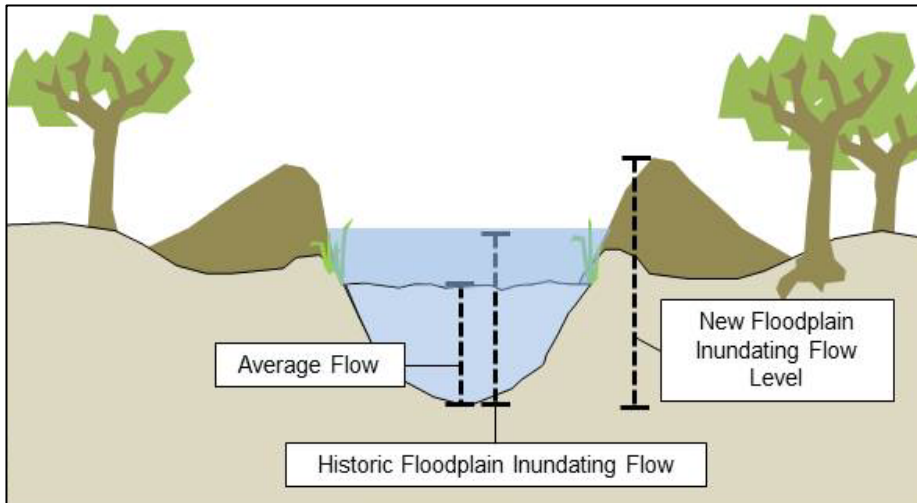
Hydrologic disconnection occurs where a river's flow is altered to the point that it no longer produces floodplain activating flows. Returning floodplain activating flows to a hydrologically disconnected system should be the priority restoration action where they are absent, and require

coordination with upstream flow regulators (See Variable Flow section below). Flow regulators might be federal, state, tribal or private actors depending on the source of flow alteration.

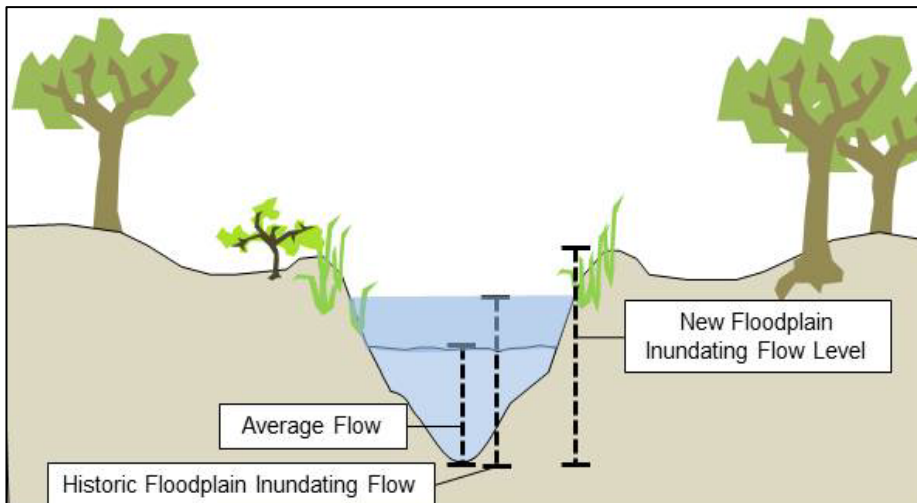
Where restoring some degree of natural flow is infeasible, restoration actions become more limited. In such instances restoration managers may consider working with existing flow regimes by regrading the floodplain area or excavating a floodplain terrace below the floodplain activating flow level. In some cases restored floodplains must be significantly smaller than the original floodplains.



**Connected Floodplain**



**Floodplain Disconnected by Levees**



**Vertically Disconnected Floodplain**

Figure 5 – Where rivers and floodplains are connected, high flows will inundate the floodplain (top figure). Floodplains can become physically disconnected from a river as the result of built infrastructure such as levees (middle figure), or vertical difference as a result of impaired sediment transport processes (bottom figure). When disconnected, floodplains are no longer inundated, even where high flows occur. Reconnecting floodplains is central to restoring them.

Table 2 – Actions for reconnecting floodplains.

<b>Action</b>	<b>Justification</b>	<b>Details</b>
Setback levees	Moving levees back from the river channel can reconnect rivers to floodplains and still provide flood protection to areas behind them.	<ul style="list-style-type: none"> <li>• Relocate levees further from the river.</li> </ul>
Remove or breach levees	Where levees are no longer needed to protect floodplain lands from inundation, they should be breached in segments or removed entirely.	<ul style="list-style-type: none"> <li>• Breach or open up holes in existing levee structures to allow floodwaters to reach the floodplain.</li> <li>• Remove levees entirely.</li> </ul>
Flood bypass	Where levees cannot be setback, breached or removed they can be managed as floodways to accommodate floodwaters during wetter seasons and support other uses in drier seasons. A bypass provides protection but can still support floodplain ecosystems.	<ul style="list-style-type: none"> <li>• Install flood bypasses that allow controlled flooding.</li> <li>• Install weirs or floodgates on existing levees.</li> <li>• Explore bypass land uses that are conducive to inundation, such as certain types of agriculture or wildlife reserves.</li> </ul>
Install a floodplain terrace	Where floodplain activating flows cannot reach the floodplain, a lower floodplain can be excavated to offset the vertical difference between floodplain and a flow levels.	<ul style="list-style-type: none"> <li>• Where a river is incised, a floodplain terrace can be excavated to a lower level</li> <li>• Where flow regulation limits high flows, a floodplain terrace can be excavated to a level that can be activated.</li> </ul>
Address causes of flow alteration	Where a river's flow is regulated to the point that floodplains are no longer inundated, restoring minimum floodplain activating flows should be a priority reconnection action.	<ul style="list-style-type: none"> <li>• Work with upstream flow managers to negotiate controlled water releases that mimic natural flood pulses. (Discussed in more detail below)</li> </ul>

**Variable Flow**— Restoring flows with the appropriate timing, magnitude, duration and frequency attributes is required to restore an ecologically functional floodplain. These flow adjustments require the cooperation of upstream regulators who may control releases of flow from dams according to specific schedules. Sometimes balancing restoration needs with other demands on regulated flows requires extensive consultations.

Where it exists, hydrologic and ecological data should be used (through methods such as FAF and EAH) to characterize the changes to flow regulation needed to restore and sustain floodplain systems. Many regulated rivers no longer produce the more frequent and smaller floodplain activating flows that naturally occur every 2 – 5 years. Returning these smaller and less dangerous flows to a river system can be done without jeopardizing a dam’s ability to protect human communities from larger floods. Dam operations in these rivers could be negotiated to allow functional flows that reflect natural flood pulses and restore floodplain supporting processes to the system (Yarnell et al. 2015). Future flow and land use conditions should be used where available to inform flow regulation and ensure that outcomes support floodplain functions for the long-term.

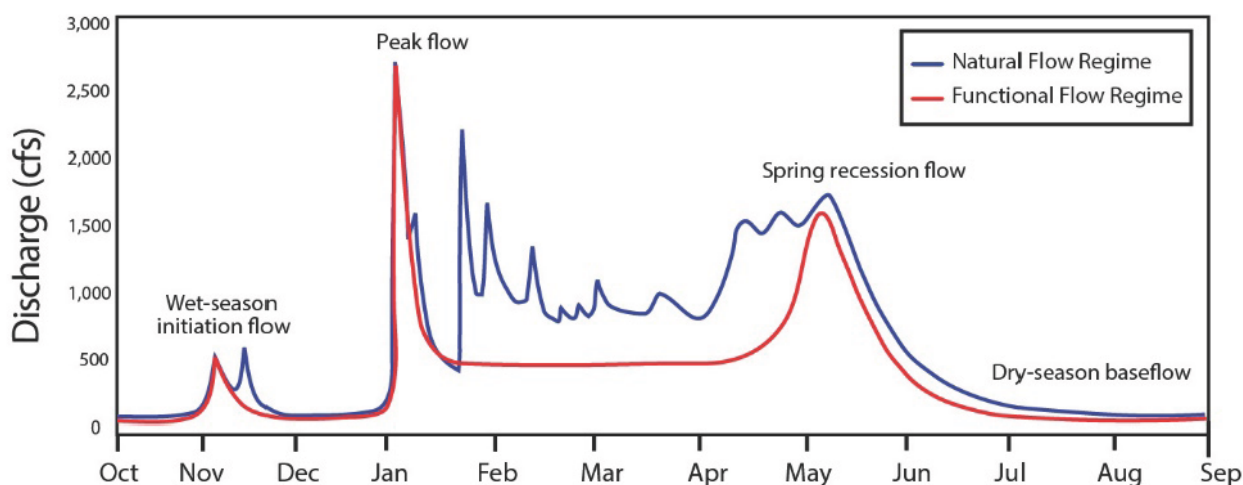


Figure 6 – In flow regulated river systems, a “functional flow” mimics the magnitude, timing, duration and frequency characteristics that support ecosystem processes and geomorphic functions, while still meeting human needs. Implementing a functional flow management plan can contribute to floodplain restoration. Figure borrowed from Yellen et al. 2015.



Table 3 – Actions for returning variable flow to a river-floodplain system.

<b>Action</b>	<b>Justification</b>	<b>Details</b>
Return floodplain activating flows	At the very minimum, a river must produce floodplain activating flows to sustain ecologically functional floodplains.	<ul style="list-style-type: none"> <li>• Engage with upstream flow regulators to negotiate controlled water releases that meet floodplain activating flow criteria.</li> <li>• Flows may also be managed to reflect seasonal changes in river discharge (functional flows)</li> </ul>
Address water withdrawals	Where flows are altered as a result of water withdrawals, returning variable flow may require addressing water use upstream.	<ul style="list-style-type: none"> <li>• Explore avenues for working with upstream users to secure greater water flow levels.</li> </ul>

**Spatial Scale** – A functional floodplain should have natural land cover that is conducive to inundation, and a setting for ecological processes. Determining what amount of land area is ‘adequate’ to support floodplain functions can be a challenge and is location specific. At the very least, enough floodplain area should be secured to contain the minimum floodplain activating flow for a river-floodplain system. The EAH and FAF concepts can provide a basis for estimating how much land area is needed to accommodate various flow levels and ecological processes. Conservation easements, regulatory tools, and land management practices can be used to open up floodplain lands and maintain them as functioning floodplains. These actions can be facilitated through relevant public agencies, flood control districts and coordination with private landowners.

Table 4 – Actions for securing the necessary space for floodplain processes to occur and benefits to accrue to a meaningful level.

Action	Justification	Details
<b>Conservation easement</b>	Undeveloped floodplain lands can be placed into conservation easement to protect their natural functions and limit their financial burden on landowners.	<ul style="list-style-type: none"> <li>• Work with local land owners and land management agencies to put lands into conservation easement.</li> <li>• An array of federal programs exist to support the natural use of floodplain lands such as; the Conservation Stewardship Program, Land and Water Conservation Fund, and the Flood Mitigation Assistance Program.</li> </ul>
<b>Land acquisition</b>	Maintaining or recovering floodplain natural and beneficial functions may require acquiring and compensating for those lands. State, county and municipal planning offices, land and resource agencies, or flood control districts, may offer various ways to secure flood prone lands for restoration.	<ul style="list-style-type: none"> <li>• Floodplain lands can be acquired through the buyout of repetitive loss properties.</li> <li>• Shorelines and floodplains are often under jurisdiction of the state or local governments that can manage them for restoration.</li> </ul>
<b>Federal land transfer</b>	Flood control infrastructure is sometimes federally owned, and there may be opportunity to have lands turned over to local authorities.	<ul style="list-style-type: none"> <li>• When working on federal flood control infrastructure, those lands may be turned over to local control following setback or removal.</li> </ul>

**Habitat and Structural Diversity** –Varying conditions of disturbance, hydrologic connectivity and surface features provide the template from which floodplain ecosystems

develop. Where appropriate conditions of connectivity, flow regime and spatial scale are present dynamic river-floodplain processes generate habitat and structural diversity overtime. Restoration actions are only needed where land management practices exist that interfere with natural development of floodplain mosaics, or floodplain areas are degraded to a point that intervention is needed to stimulate natural processes.

Table 5 – Actions that support the emergence of diverse floodplain surface features and habitats that define ecologically functional floodplains.

<b>Action</b>	<b>Justification</b>	<b>Details</b>
<b>Allow passive restoration</b>	Landscaping, mowing or clearing of vegetation in the floodplain interferes with natural ecosystem succession and reduces floodplain surface diversity.	<ul style="list-style-type: none"> <li>• Work with local land managers to ensure restored floodplain areas are managed to support natural ecosystem functions.</li> </ul>
<b>Secure sediment supply</b>	Flow regulated rivers are often starved of sediment that is trapped behind dams in reservoirs. A continual sediment supply is needed to establish new features in stream and on the floodplain, promote recruitment of riparian vegetation and to prevent channel incision.	<ul style="list-style-type: none"> <li>• Work with flow regulators to organize flushing of sediment behind dams, through infrastructure upgrades or other measures.</li> </ul>
<b>Enhance woody debris recruitment</b>	Log jams and root wads create complex habitat in-stream, on the floodplain, and in side channels. Woody debris can also increase sediment storage in stream and aggrade streambeds. Installing log jams can help initiate the process of debris recruitment in a reconnected floodplain environment.	<ul style="list-style-type: none"> <li>• Install log jams using local timber material</li> <li>• In some regions, beaver reintroduction can lead to more complex stream and floodplain habitat.</li> </ul>
<b>Riparian planting</b>	Moving flood control structures and earth moving projects can disrupt the delicate riparian ecosystems directly adjacent to rivers. It may be necessary to supplement passive ecosystem restoration.	<ul style="list-style-type: none"> <li>• Replant native riparian plants to support a natural vegetation community.</li> </ul>
<b>Manage non-native and invasive species</b>	Non-native and invasive plants may be present on impaired riparian and floodplain areas and can inhibit restoration of natural floodplain ecosystems.	<ul style="list-style-type: none"> <li>• Manage against or remove non-native and invasive plant species.</li> </ul>
<b>Minimize land use impacts</b>	Functional floodplains are often touted for their multiple uses, but these uses should not interfere with floodplain ecosystem	<ul style="list-style-type: none"> <li>• Paved paths, trails, structures, etc. should be carefully planned to not conflict with inundation</li> </ul>

	functions.	related processes or habitat development.
--	------------	---

There is no uniform template for floodplain restoration, though some broad guiding statements can be made. Necessary means for reconnecting a floodplain and restoring natural functions will be different from river to river, and reach to reach. However, we know that functional floodplains almost always depend on four attributes, and those attributes can guide efforts to restore them.

Restoring a floodplain can benefit more than just a river and riparian ecosystems. Human communities gain from restoration projects that result in greater public safety, reduced flood risk, water quality improvements, resilience of socio-economically valued fish and wildlife, and enhanced recreation opportunities. Reconnecting and restoring floodplains is a wise use of land that enhances public well-being and safety.

## V. Conclusions

When floodplains are allowed to be inundated and naturally function, they provide a suite of benefits that support terrestrial and aquatic ecosystems, maintain river form, and benefit human communities. Riverine floodplains have been disconnected and modified on a massive scale across the United States. Where a floodplain is disconnected it becomes converted and impaired, eliminating the natural processes it supports and benefits it provides. Floodplain restoration is a means to return a river-floodplain system to a healthy functioning state. Four floodplain attributes have been identified that together orchestrate the ecological functions of a floodplain; connectivity, variable flow, spatial scale, and structural and habitat diversity. These attributes can guide restoration projects to better focus on the bio-physical and flow characteristics that underpin floodplain function. Successful floodplain restoration is a result of active efforts, such as securing land and removing a levee, and the passive processes that naturally ensue. Plans for restoring each attribute should be catered to local ecological requirements, such as seasonal spawning needs of fish, to ensure that outcomes are maximally beneficial to native ecosystems. Well-targeted restoration can rejuvenate a river-floodplain system to deliver a stream of benefits to people and ecosystems, and enhance the resilience of river-resources into the future.

## VII. Works Cited

- Alexander, J.S., Wilson, R.C., and Green, W.R., 2012, A brief history and summary of the effects of river engineering and dams on the Mississippi River system and delta: U.S. Geological Survey Circular 1375, 43 p.
- Beechie, T.J., D.A. Sear, J.D. Olden, G.R. Pess, J.M. Buffington, H. Moir, P. Roni, M.M. Pollock. 2010. Process-based principles for restoring river ecosystems. *BioScience* 60(3): 209-222.
- Cain, J., J. Opperman, M. Tompkins. *Sacramento and San Joaquin Flows, Floodplains, Other Stressors, and Adaptive Management*, Exhibit AR-1; Informational Proceeding to Develop Flow Criteria for the Delta Ecosystem Necessary to Protect Public Trust Resources, 2010.
- Dixon, M.D., C.J. Boever, V.L. Danzeisen, C.L. Merkord, E.C. Munes, M.L. Scott, W.C. Johnson, T.C. Cowman. 2015. Effects of a 'natural' flood event on the riparian ecosystem of a regulated large-river system: the 2011 flood on the Missouri River, USA. *Ecohydrology* DOI: 10.1002/eco.1613.
- Dixon, S.J., D.A. Sear, N.A. Odoni, T. Sykes, S.N. Lane. 2016. The effects of river restoration on catchment scale flood risk and flood hydrology. *Earth Surface Processes and Landforms*. doi: 10.1002/esp.3919
- Feyrer, F., T. Sommer, W. Harrel. 2006. Managing floodplain inundation for native fish: production dynamics of age-0 splittail (*Pogonichthys macrolepidotus*) in California's Yolo Bypass. *Hydrobiologia* 573: 213-226.
- Galat, D., L. Fredrickson, D. Humburg, K. Bataille, J. Bodie, J. Dohrenwend, G. Gelwicks, J. Havel, D. Helmers, J. Hooker, J. Jones, M. Knowlton, J. Kubisiak, J. Mazourek, A. McColpin, R. Renken, R. Semlitsch. 1998. Flooding to Restore Connectivity of Regulated, Large-River Wetlands: Natural and controlled flooding as complementary processes along the lower Missouri River. *BioScience* 48(9) 721-733.
- Georgakakos, A., P. Fleming, M. Dettinger, C. Peters-Lidard, Terese (T.C.) Richmond, K. Reckhow, K. White, and D. Yates, 2014: Ch. 3: Water Resources. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 69-112. doi:10.7930/JOG44N6T. Available online: <http://nca2014.globalchange.gov/report/sectors/water>
- Graf, W. L. 1999. Dam NationL A geographic census of large American dams and their hydrologic impacts. *Water Resources Research*, 35: 1305-1311.
- Graf, W. L. 2006. Downstream hydrologic and geomorphic effects of large dams on American rivers. *Geomorphology*, 79: 336-361.

- Guneralp, I., B.L. Rhoades. 2011. Influence of floodplain erosional heterogeneity on planform complexity of meandering rivers. *Geophysical Research Letters* 38: L14401.
- Jackson, R. B., Carpenter, S. R., Dahm, C. N., McKnight, D. M., Naiman, R. J., Postel, S. L., & Running, S. W. 2001. Water in a changing world. *Ecological applications*, 11(4), 1027-1045.
- Jeffres, C., J. Opperman, P. Moyle. 2008. Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. *Environmental Biology of Fishes* 83(4): 449-464.
- Junk, W.J., P.B. Bayley, and R.E. Sparks. 1989. The flood pulse concept in river-floodplain systems. P. 110-127. In D.P. Dodge [ed.] Proceedings of the International Large River Symposium. Can. Spec. Publ. Fish. Aquat. Sci. 106.
- Kusler, Jon. 2011. Assessing the Natural and Beneficial Functions of Floodplains: Issues and Approaches; Future Directions. *The Association of State Wetland Managers, Inc.* Berne, NY.
- Magilligan, F., K. Nislow, B. Graber. 2003. Scale-independent assessment of discharge reduction and riparian disconnectivity following flow regulation by dams. *Geology* 31(7): 569-572.
- Matella, M. and K. Jagt. 2014. Integrative Method for Quantifying Floodplain Habitat. *Journal of Water Resource Planning and Management* 140 (06014003):1-4.
- Matella, M.K. and A.M. Merenlender. 2014. Scenarios for Restoring Floodplain Ecology Given Changes to River Flows Under Climate Change: Case from the San Joaquin River, California. *River Research and Applications* 31: 280-290, doi: [10.1002/rra.2750](https://doi.org/10.1002/rra.2750)
- McCartney, M. 2009. Living with dams: managing the environmental impacts. *Water Policy* 11(1): 121-139.
- Moyle PB, Baxter RD, Sommer T, Foin TC, Matern SA. 2004. Biology and population dynamics of Sacramento splittail (*Pogonichthys macrolepidotus*) in the San Francisco Estuary: a Review. *San Francisco Estuary and Watershed Science* [online serial]. Vol. 2, Issue 2 (May 2004), Article 3. <http://repositories.cdlib.org/jmie/sfews/vol2/iss2/art3>
- Naiman, R.J., Decamps, H., McClain, M.E. (2005). *Riparia: Ecology, conservation, and management of streamside communities*. Burlington, MA: Elsevier Academic Press.
- Nilsson, C. C. Reidy, M. Dynesius, C. Revenga. 2005. Fragmentation and Flow Regulation of the World's Large River Systems. *Science* 308: 405-408.
- O'Hanley, J. 2011. Open rivers: Barrier removal planning and the restoration of free-flowing rivers. *Journal of Environmental Management* 92: 3112-3120.



- Opperman, J. R. Luster, B. McKenney, M. Roberts, A. Wrona Meadows. 2010. Ecologically functional floodplains: Connectivity, flow regime, and scale. *Journal of the American Water Resources Association* 46(2):211-226.
- Poff, N.L., J.D. Allan, M.B. Bain, J.R. Karr, K.L. Prestegard, B.D. Richter, R.E. Sparks, J.C. Stromberg. 1997. The Natural Flow Regime: A paradigm for river conservation and restoration. *BioScience* 47(11): 769-784.
- Rood, S. B., S.M. Samuelson, J.H. Braatne, C.R. Gourley, F.M.R. Hughes, J.M. Mahoney. 2005. Managing river flows to restore floodplain forests. *Frontiers in Ecology and the Environment* 3(4): 193-201.
- Rohde, S., M. Hostmann, A. Peter, K.C. Ewald. 2005. Room for rivers: An integrative search strategy for floodplain restoration. *Journal of Landscape and Urban Planning* 78: 50-70.
- Seavy, N., T. Gardali, G. Golet, S.T. Griggs, C. Howell, R. Kelsey, S.L. Small, J.H. Viers, J.F. Weigand. 2009. Why Climate Change Makes Riparian Restoration More Important than Ever: Recommendations for Practice and Research. *Ecological Restoration* 27(3) 330-338.
- Shields, F.D., S.S. Knight, C.M. Cooper. 1994. Effects of Channel Incision on Base Flow Stream Habitats and Fishes. *Environmental Management* 18(1): 43-57.
- Stanford, J.A., M.S. Lorang, F.R. Hauer. 2005. The shifting habitat mosaic of river ecosystems. *Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie* 29: 123-136.
- Tockner, K. and J.A. Stanford. 2002. Review of: Riverine Flood Plains: Present State and Future Trends". *Biological Sciences Faculty Publications*. Paper 166.
- Tockner, K., M.S. Lorang, J.A. Stanford. 2010. River flood plains are model ecosystems to test general hydrogeomorphic and ecological concepts. *River Research and Applications* 26: 76-86.
- Tonolla, D., V. Acuna, U. Uehlinger, T. Frank, K. Tockner. 2010. Thermal heterogeneity in river floodplains. *Ecosystems* 13: 727-740
- Yarnell, S.M., G. Petts, J. Schmidt, A. Whipple, E. Beller, C. Dahm, P. Goodwin, J.H. Viers. 2015. Functional Flows in Modified Riverscapes: Hydrographs, Habitats and Opportunities. *BioScience* 65(9): 963-972. DOI: 10.1093/biosci/biv102.
- Ward, J.V., K. Tockner, F. Schiemer. 1999. Biodiversity of Floodplain River Ecosystem: Ecotones and Connectivity. *Regulated Rivers: Restoration Management* 15: 125-139.
- Ward, J.V., K. Tockner, D.B. Arscott, C. Claret. 2002. Riverine landscape diversity. *Freshwater Biology* 47: 517-539.

Whited, D.C., M.S. Lorang, M.J. Harner, F.R. Hauer, J.S. Kimball, J.A. Stanford. 2007. Climate, hydrologic disturbance, and succession: Drivers of floodplain pattern. *Ecology* 88(4): 940-953.

William, P.B., E. Andrews, J.J. Opperman, S. Bozkurt, P.B. Moyle. 2009. Quantifying activated floodplains on a lowland regulated river: Its application to floodplain restoration in the Sacramento Valley. *San Francisco Estuary and Watershed Science* 7(1). Available online at: <http://escholarship.org/uc/item/1sn8r310>