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ERRATA:

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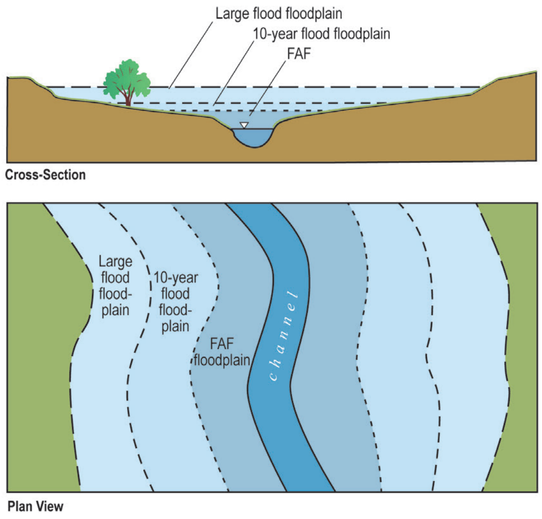
Page 3, third sentence of the caption of Figure 2: for "The years after regulation from Shasta Dam generally have much lower during the spring ... ", read "The years after regulation from Shasta Dam generally have much lower flow during the spring because the reservoir is refilling during this time."

Page 4, top of page: the first paragraph is a figure caption for Figure 2 and should not be repeated here. Sentence is omitted in corrected version.

Page 13, under Results: for "Discharge and stage elevation values for the floodplain activation flow, the average spring flow, and the two-year peak flood (Q2) are summarized in Table 2. We also present data for the two-year peak flood for comparison." read "Discharge and stage elevation values for the floodplain activation flow, the average spring flow, and the two-year peak flood (Q2) are summarized in Table 2."

Page 6, The illustration in Figure 4 is incorrect. Figure 4 is accurately represented by the illustration to the right:

(a) Unregulated Hydrologic Regime



(b) Regulated Hydrologic Regime

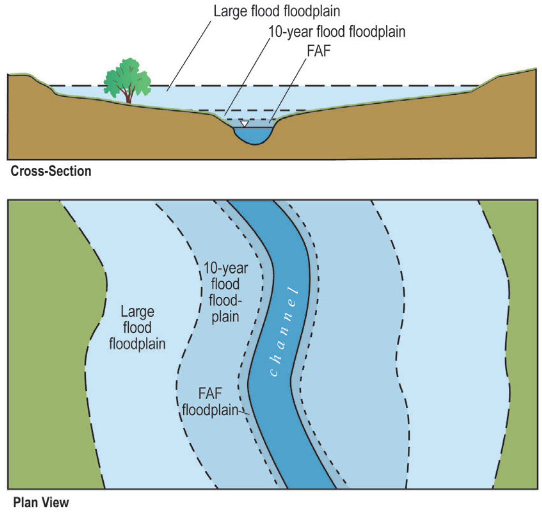


Figure 4 An illustration of how river regulation affects nested floodplains

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ABSTRACT

We describe a process and methodology for quantifying the extent of a type of historically prevalent but now relatively rare ecologically-valuable floodplain in the Sacramento lowland river system: frequently-activated floodplain. We define a specific metric, the "Floodplain Activation Flow" (FAF), which is the *smallest* flood pulse event that initiates substantial beneficial ecological processes when associated with floodplain inundation. The "Activated Floodplain" connected to the river is then determined by comparison of FAF stage with floodplain topography. This provides a simple definition of floodplain that can be used as a planning, goal setting, monitoring, and design tool by resource managers since the FAF event is the smallest flood and corresponding floodplain area with ecological functionality—and is necessarily also inundated in larger flood events, providing additional ecological functions. For the Sacramento River we selected a FAF definition to be the river stage that occurs in two out of three years for at least seven days in the mid-March to mid-May period and Activated Floodplains to be those lands inundated at that stage. We analyzed Activated Floodplain area for four representative reaches along the lower Sacramento River and the Yolo Bypass using stream gauge data. Some significant conclusions are: (1) The area of active functional floodplain is likely to be less than commonly assumed based on extent of riparian vegetation. (2) Levee setbacks may not increase the extent of this type of ecologically-productive floodplain without either hydrologic or topographic changes. (3) Within the Yolo Bypass, controlled releases through the Fremont Weir could maximize the benefits associated with Activated Floodplain without major reservoir re-operation or grading. This approach identifies a significant opportunity to integrate floodplain restoration with flood management by establishing a FAF stage metric as an engineering design criterion alongside the commonly-used 100-year flood stage for flood hazard reduction.

KEYWORDS

Floodplain restoration, functional floodplains, activated floodplains, floodplain activation flow, design criteria, regulated river, reservoir re-operation, Sacramento River, Yolo Bypass

SUGGESTED CITATION

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INTRODUCTION

For millennia humans used lowland river floodplains for hunting, recession agriculture and temporary settlement. While these uses altered floodplain ecological communities they did not affect the basic hydrologic and geomorphic processes that sustain floodplain ecosystems. Following the industrial revolution, major engineering projects—including those for navigation, flood control, and multipurpose reservoirs—transformed large river systems and their ecosystem processes from headwaters to estuaries (Dynesius and Nilsson 1994; Nilsson and others 2005; Postel and Richter 2003). These anthropogenic interventions also facilitated the disconnection and conversion of ecologically-vibrant lowland river floodplains, both directly, by the construction of flood control levees, and indirectly by the alteration of the hydrology and hydraulics of the river itself.

These anthropogenic changes of the riverine and floodplain landscape have been identified as a significant cause of the decline of key ecological functions in California's Central Valley and the Sacramento-San Joaquin Delta, including the loss of riparian biotic communities and the decline of native fishes. Accordingly, the CALFED program established by state and federal agencies to plan and execute restoration within the Central Valley watershed stated as one of its Ecosystem Restoration goals in 2001 to:

> "Re-establish active inundation of at least half of all remaining un-urbanized floodplains in the Central Valley, where feasible"
> – *CALFED ERPP p 92, 2001*

To implement this goal requires a definition of "active inundation" that is understandable and usable by resource managers. This definition needs to provide a rigorous way of quantifying the active inundated area, as well as a methodology for establishing the feasibility of restoration of biologically significant floodplains. This paper proposes a method for defining and quantifying the area inundated or "activated" by a particularly important type of flood—the frequent, long-duration period of inundation that supports the processes described by the Flood Pulse Concept (Junk and others 1989) and produces the biological productivity central to the Flood Pulse Advantage (Bayley 1991). Several of the beneficial outputs that CALFED seeks to promote from floodplains, including the production of biologically-available carbon and spawning and rearing habitat for native fish, are provided primarily during such flood pulses. Larger, less frequent floods and shorter duration floods will initiate other ecologic processes within the same floodplain area.

THE SETTING

The Sacramento Valley's lowland floodplains and flood basin wetlands have been dramatically reduced in the last 150 years due to levee construction for agriculture and flood control (Kelley 1998) to a tiny fraction of their original extent (TBI 1998). Only a remnant portion of the Sutter Basin at the lower end of the Sutter Bypass is still directly connected to the river system and regularly inundated by backwater stages.

In addition, the construction of large multipurpose reservoirs in the last 60 years, whose storage accounts for approximately 80% of annual watershed runoff, have drastically altered river hydrology (TBI 1998) (Figure 1). Relatively low magnitude and frequent spring snowmelt floods historically inundated the extensive flood basins along the lower reaches of the Sacramento River for extended periods. These small spring floods have been disproportionately reduced because they are now captured in upstream reservoirs (Figure 2). Conversely, very large infrequent winter floods still occur within the watershed, posing a significant risk to development and infrastructure in former floodplain areas.

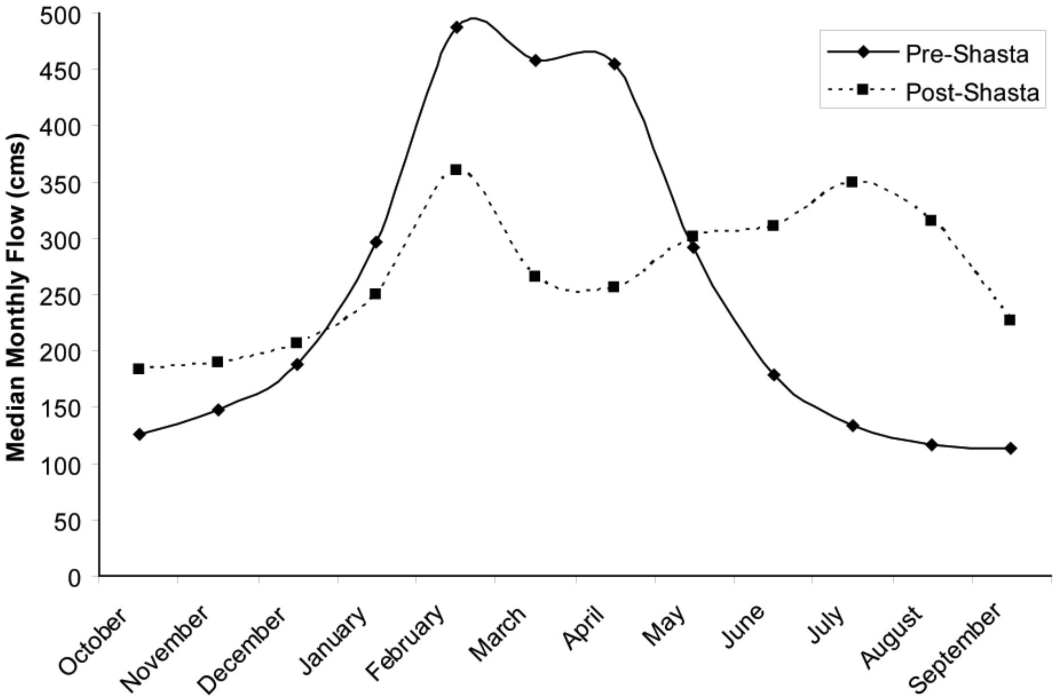


Figure 1 Monthly median flow values, pre-Shasta and post-Shasta, at the USGS gauge at Red Bluff. Median flows have been considerably reduced during winter and spring, due to reservoir storage and regulation, and increased during summer for irrigation and water supply deliveries.

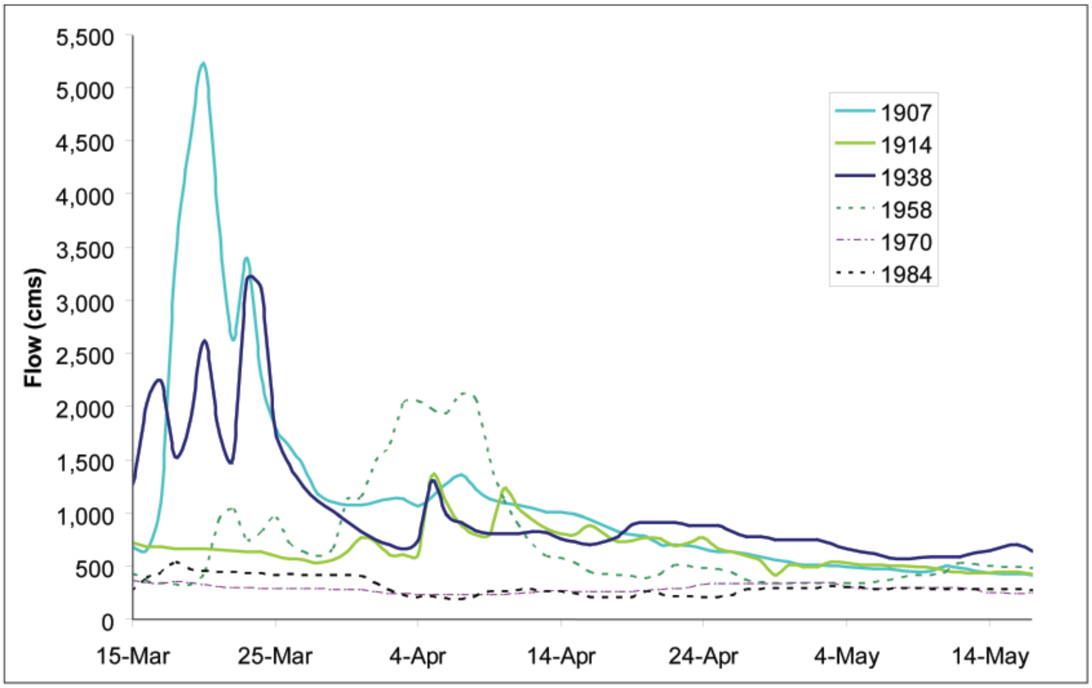


Figure 2 Spring flows for three pre-Shasta (solid) and three post-Shasta (dashed) years, at the USGS gauge at Red Bluff. These six years had similar total annual discharge. The years after regulation from Shasta Dam generally have much lower flow during the spring because the reservoir is refilling during this time.

Sacramento River hydraulics have also been altered by engineering modifications, vegetation removal, gravel mining, and upstream reservoir sediment capture (TBI 1998). These interventions cause channel bed lowering which leads to lower river stages for a given flow so that small floods can no longer inundate most of the original floodplain surface. Figure 3 illustrates long term channel bed lowering of approximately one to two meters on the lower Sacramento River between 1957 and 1997 (USACE 1957, 2002). These isolated floodplain surfaces may still support aging riparian woodland for many decades but they do not experience the dynamic connectivity with-high flows required for regeneration of riparian tree species (Rood and Mahoney 1990; Trush and others 2000). Thus, although these habitats appear to support natural floodplain communities, they should be viewed as relict landscapes with limited ecological function as floodplains because they do not support self-sustaining riparian forests or provide the ecological benefits associated with periods of routine springtime inundation.

THE PROBLEM: DEFINING FUNCTIONAL FLOODPLAINS

The main difficulty in developing a simple definition of an "active" or ecologically valuable floodplain—suitable for use in practical resource management decisions—is that the large array of different floodplain ecological processes relies on inundation by a continuum of various-sized floods of varying stage, duration, seasonality, and variability. In addition, the same flood pulse might influence different geomorphic and ecological processes in different river reaches of the same river. This complexity and the scientific uncertainty of linkages between hydrologic and geomorphic processes, and ecologic functions, can lead to paralysis in restoration decision making. In this event, management decisions implicitly favor the *status quo*, where ecologic needs in floodplain restoration are not systematically addressed in the same way, for example, as flood management and water supply needs are addressed. This tension between the need for simple, pragmatic and rigorous methods in

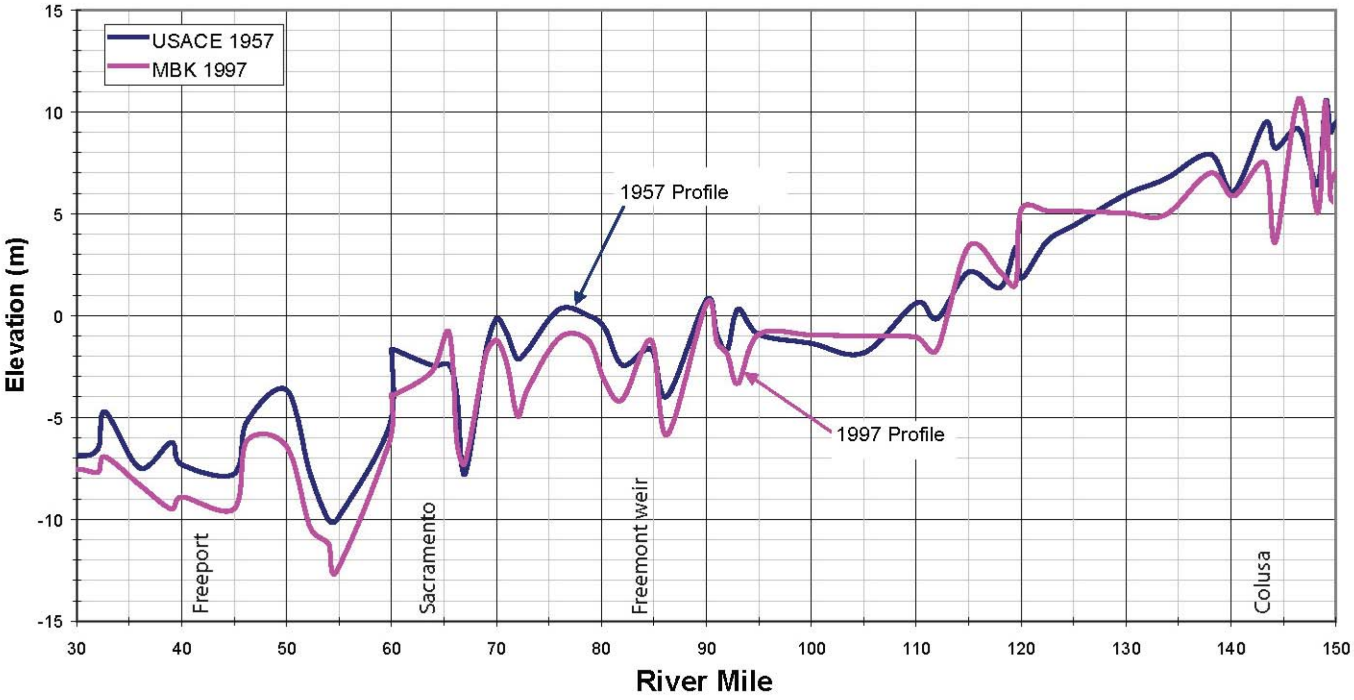


Figure 3 Historic and current longitudinal profiles of the middle and lower Sacramento River. Data by MBK 1997 is developed and reported in USACE 2002.

the applied science of restoration practice (recognizing what we know) and the need for objective skepticism and open-ended inquiry in scientific research (focusing on what we don't know) is not unique to floodplain restoration (Cabin 2007). "Scientific reticence" is seen by some to inhibit decision-making on major environmental questions (Hansen 2007).

There is a precedent for developing methods and criteria for managing floodplains in the face of uncertainty: those developed over the last 50 years in the U.S. for flood hazard assessment and the design of flood control works. There is a continuum in the relationship between flood damage potential and flood stage and duration that varies from river to river and reach to reach. Since 1973 a single metric—the 100-year recurrence interval instantaneous peak stage—has been adopted as a nationwide societal standard for flood hazard reduction. This crude approximation of an acceptable risk metric has proved extremely valuable in public policy.

Although intended for flood hazard delineation the widespread use of the hydraulically-defined 100-year floodplain has provided a default definition of the extent of a floodplain. However, for ecologic functions floodplain extent is defined by more complex river stage characteristics such as inundation frequency, period, seasonality, and connectivity with the river channel. While infrequent floods such as the 100-year instantaneous peak flood are important for some ecological processes—for example, those that benefit from large scale geomorphic disturbance—the 100-year flood stage will generally be much higher than the smaller more frequent flood pulses that provide a wide array of ecologic benefits. This means that within a given mapped 100-year floodplain, large areas may be dry and floodplain processes inactive for long periods of time. The areal extent of the 100-year floodplain is therefore not a good metric for defining the extent of an ecologically-functional floodplain.

Floodplains have been variously defined by other disciplines, each using its own set of floodplain identifiers. One definition of floodplains is derived from mapping geomorphic, sedimentary or soil features. This is useful in identifying historic flood-influenced landscapes, but in regulated river systems such as the Sacramento River, where hydrologic and geomorphic processes have been fundamentally altered, it provides little insight into the extent of current and potential future functional floodplains.

Biologists use ecologically-based identifiers such as wetland delineation maps or vegetation maps to identify floodplain areas. Although in some instances active floodplains can be identified using wetlands as indicators, there are situations where wetlands may be isolated from the river channel or where their association with flooding is debatable. Also in many areas, wetlands have been filled in or converted to farmland.

Earlier attempts to develop an easily definable metric in restoration planning that captures the importance of the smaller, more ecologically-significant frequent floods, have used the 1.5, two-year or 5-year flood instantaneous peak flow to determine floodplain stage (USACE and TRB 2004; Riley 2003; PWA 2002; Andrews 1999) This type of hydrologic definition is sometimes used for convenience because it can be readily determined using the same flood frequency and hydrodynamic models used to define the 100-year floodplain for flood management purposes. However, a two-year peak stage definition does not capture the ecologically significant variables of inundation period and seasonality (Booth and others 2006). The production of flood pulse benefits is controlled by multiple hydrological factors beyond peak flow magnitude, including the seasonality and duration of the flood event (Poff and others 1997). In river-floodplain systems with seasonally-predictable flood events, riverine organisms, such as fish, have adapted their life histories to take advantage of floodplain resources (King and others 2003; Moyle and others 2007). Key floodplain processes, such as production of floodplain-adapted fish and invertebrates and export of carbon to associated river and lakes, require floods of sufficient duration for the processes to occur (Junk and others 1989). The importance of duration and seasonality are recognized in hydrological analysis tools such as the "Indicators of Hydrologic Alteration" (Richter and others 1996; Booth and others 2006) and the "Range of Variability Approach" (Richter and others 1997);

however, by themselves, these tools do not identify the extent of floodplain areas inundated by specific flood types.

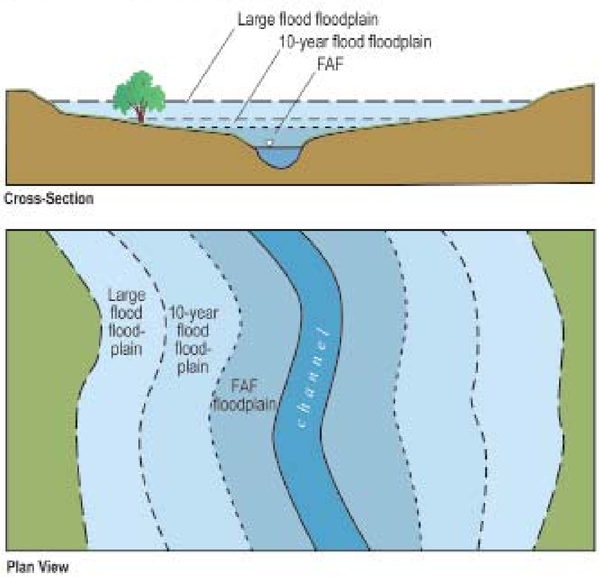
A SOLUTION: THE FLOODPLAIN ACTIVATION FLOW

In natural river systems, floodplains that flood frequently but shallowly are nested within spatially larger floodplains that are inundated more deeply and less frequently. Thus, the areas inundated by small, frequent floods that activate riverine and estuarine food web processes will also always be inundated by larger, less frequent floods that trigger different ecological processes. On regulated rivers like the Sacramento, flows have been considerably altered by reservoir storage upstream. The frequency, and inundated area of smaller flood pulses have been reduced. Nevertheless, a suite of nested floodplains still operate in modified form (Figure 4).

We have used the term "Floodplain Activation Flow," or FAF, to designate the smallest representative flood pulse capable of triggering or "activating" significant ecological processes on the floodplain during the period of inundation anywhere within an alluvial river system. Floodplain topography not inundated by this minimum flow is not considered activated. Floodplain topography inundated by this flow will also be inundated by larger, less frequent floods that initiate other ecologic processes, such as riparian woodland succession, floodplain erosion, and sedimentation or wildlife uses.

Floodplain restoration intended to support the entire continuum of ecologic processes that rely on different types of flooding has to be designed first to inundate significant areas by this minimum flood pulse. It is not the intention of this paper to provide a comprehensive set of flow prescriptions that link to each significant floodplain ecologic process. Instead, the simple practical approach proposed, that addresses the minimum flow required, insures that the whole suite of floodplain processes will be active in some fashion. This suite would include flows that initiate geomorphic processes such as sediment transfer (Florsheim and others 2006), meander migration (Larsen and Greco 2002), or disturbance flows. For highly regulated rivers whose natural flow variability has been "flat-lined" additional floodplain flow prescriptions are likely necessary (Richter and others 1997; McBain and Trush 1997).

(a) Unregulated Hydrologic Regime



(b) Regulated Hydrologic Regime

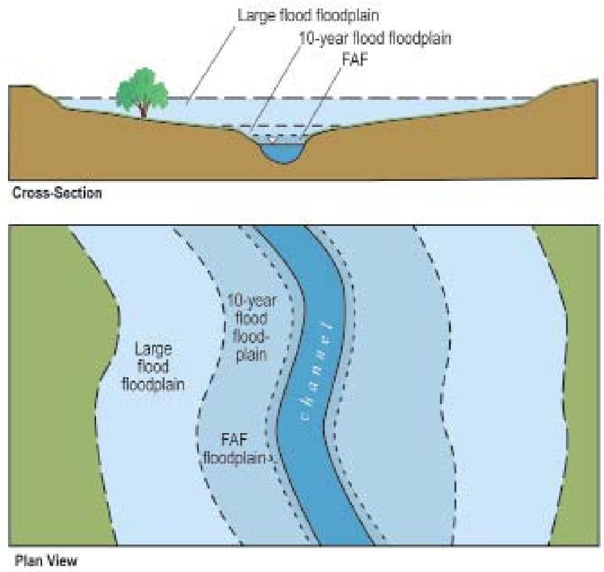


Figure 4 An illustration of how river regulation affects nested floodplains

The hydrologic definition of the Floodplain Activation Flow depends on understanding how key floodplain ecological processes respond to hydrologic variables. Fortunately, in the case of the lowland Sacramento River system recent research has established a number of these key linkages. These include the production of biologically-available carbon for downstream ecosystems, rearing habitat for juvenile Chinook salmon *(Oncorhynchus tshawytscha)* and spawning and rearing habitat for the Sacramento splittail *(Pogonichthys macrolepidotus)*, an endemic minnow. The year class strength of Sacramento splittail is highly correlated with the duration of spring flooding in the Sacramento River system (Sommer and others 1997). Splittail spawn on inundated terrestrial vegetation primarily between March and May. Eggs require three to five days to hatch, although inundation of longer duration will improve spawning success because adults gain energy by feeding within floodplains prior to spawning and floodplains provide optimal rearing conditions for larval fish and juveniles (Moyle and others 2004). Recent research has demonstrated that juvenile Chinook salmon also rear on inundated floodplains (Sommer and others 2001a, 2001b). Juvenile Chinook had faster growth rates within the Yolo Bypass, the primary floodplain of the Sacramento River, than within the Sacramento River itself, likely due to higher productivity on the floodplain. In the two years of this study, growth rates between the floodplain and river were similar during February and early March; the increased growth rate on the floodplain became apparent in mid-March and April as the water temperature of the floodplain increased relative to that of the river (Sommer and others 2001b). While salmon growth gains increase with increasing duration of inundation, increased growth can be observed in as short as one to two weeks on the floodplain (Jeffres and others 2008). Other fish species also have life histories that allow them to use floodplains for rearing and spawning when inundated for sufficient duration in late winter and early spring (Moyle and others 2007).

Floodplains can be sources of biologically-available carbon, primarily in the form of phytoplankton, to downstream food-limited ecosystems such as the Sacramento-San Joaquin Delta (Ahearn and others 2006). Phytoplankton productivity is positively correlated with the duration of draining of inundated floodplain area (Ahearn and others 2006; Schemel and others 2004; Sommer and others 2004) and temperature (Cushing and Allan 2001). The production of both phytoplankton and zooplankton generally peak during the draining phase of a flood event (i.e., after the cessation of floodwater inflow) as residence time increases (Ahearn and others 2006; Grosholz and Gallo 2006; Sommer and others 2004). A sufficient duration of flooding is required for both phytoplankton and zooplankton biomass to develop (Sommer and others 2004).

Based on these observations of the importance of duration and seasonality to fish utilization and food-web productivity, we propose a hydrological definition of the Floodplain Activation Flow (FAF), for Sacramento River lowland floodplains. The FAF must occur with a suitable duration and timing to produce identifiable ecological benefits, must allow hydraulic connectivity between the river and the floodplain during the period of flooding, and occur with sufficient frequency to make ecological benefits meaningful inter-annually. Accordingly we define the FAF as the river stage that is exceeded in at least two out of three years and sustained for at least seven days between March 15 and May 15.

We recognize there is considerable uncertainty over how long, how frequent, and in what time period floodplain inundation will be most ecologically-beneficial. For each of these variables we have selected what we consider to be minimal values and examined the sensitivity of our results to variations in these parameters.

We recognize that other floodplain characteristics, not considered in this definition, (e.g., land uses, topographic heterogeneity, depth of flooding, and the temporal sequence of flood events) might be additional criteria that refine our understanding of the potential ecological value of an Activated Floodplain. Some of these factors are discussed in Moyle and others (2007) and Ahearn and others (2006).

This simplified definition of the threshold for activation of floodplain processes in the regulated Sacramento River system is most applicable to low gradient lowland reaches with typology described by Nanson and Croke (1992, their Table 1) as “low energy cohesive floodplains." In the Sacramento River system these are the confined leveed reaches downstream of Colusa and are adjacent to the largest area of former and potentially restorable floodplain in the system.

Upstream of Colusa to Red Bluff the river is less confined, has a steeper gradient, and active geomorphic processes as well as floodplain inundation are important drivers to the floodplain ecosystem. The floodplains in this reach are similar to what Nanson and Croke describe as "meandering river lateral migration floodplains". Here, floodplain functionality relies on both frequent inundation and erosion and deposition processes to create heterogeneous topography and a continually changing mosaic of riparian plant communities and wetlands. Stillwater Sciences (2003) and The Nature Conservancy and others (2007) have recently evaluated the linkages between geomorphic processes such as channel bank and channel bed maintenance flows and ecosystem functions for the meander reaches, as well as floodplain inundation. These linkages are incorporated as a meander migration algorithm represented as a simplified single geomorphically-effective discharge in the Sacramento Ecological Flows Tool, a decision support computer model intended to inform water managers (http://www.delta.dfg.ca.gov/erp/sacriverecoflows.asp). Therefore, in the upstream meander reach, above Colusa, both the geomorphically-effective channel forming discharge and floodplain activation processes would be major determinants of floodplain functionality.

METHODS

We refer to the area of floodplain inundated by the Floodplain Activation Flow as the Activated Floodplain. The Activated Floodplain area is quantified by analyzing the intersection of two elevational surfaces, the three-dimensional floodplain topography, and the two-dimensional water surface profile of the FAF river stage. This area is then edited to eliminate areas that are floodable but disconnected from the river channel at the FAF stage. Floodplain topography is provided by LIDaR based detailed surveys. Flood profiles can be obtained from hydrodynamic models calibrated to recorded stage levels. However, small extended flood hydrographs such as the FAF have not been modeled. Instead, to test the application of this methodology, we used an interpolation of water surface slopes between sets of recorded water levels at paired gauging stations approximately 6 to 15 miles apart.

We analyzed four reaches of the Sacramento River system (Figure 5). The Vina to Hamilton City reach is located on the main-stem of the Sacramento in the moderate gradient [slope = 0.0004], meander zone, the Colusa to Meridian Pumps and the I-Street to Freeport reaches are located downstream on the main stem low gradient [slope = 0.00008] lowland river segment where flood control levees had been constructed on the channel banks approximately 152.4 m (500 ft) apart and floodplain terraces largely eliminated. The fourth reach is located on the Yolo Bypass [slope = 0.00012], the main flood bypass protecting the city of Sacramento that receives flood discharges from a few small tributaries, and intermittent large flood discharges from the Sacramento River over the Fremont weir and the Sacramento weir (Sommer and others 2001a). Figure 6 illustrates the typical floodplain landscape constrained by levees on the lower Sacramento at Colusa. Figure 7 illustrates the managed wetland and farmed landscape of the 3-km wide Yolo Bypass at Woodland.

For each reach we identified the FAF river stage by analyzing the stage-duration-frequency of paired gauge records for the period 1968–2003 as representative of contemporary reservoir management and river conditions. The gauging stations were categorized either as the "primary" station with a long hydrologic record or as the "paired" station, a nearby station with an overlapping period of record as illustrated in Table 1. We analyzed stage data for the period between March 15 and May 15 at the primary station (Figure 8a). Flow was converted to stage for some stations using recent rating curves. Within this period we recorded the minimum stages for each seven-day moving window, and for each year recorded the maximum value (Figure 8b). This maximum value is the highest stage that was sustained for seven days between March 15 and May 15 for that year. Each year's maximum stages were then ranked

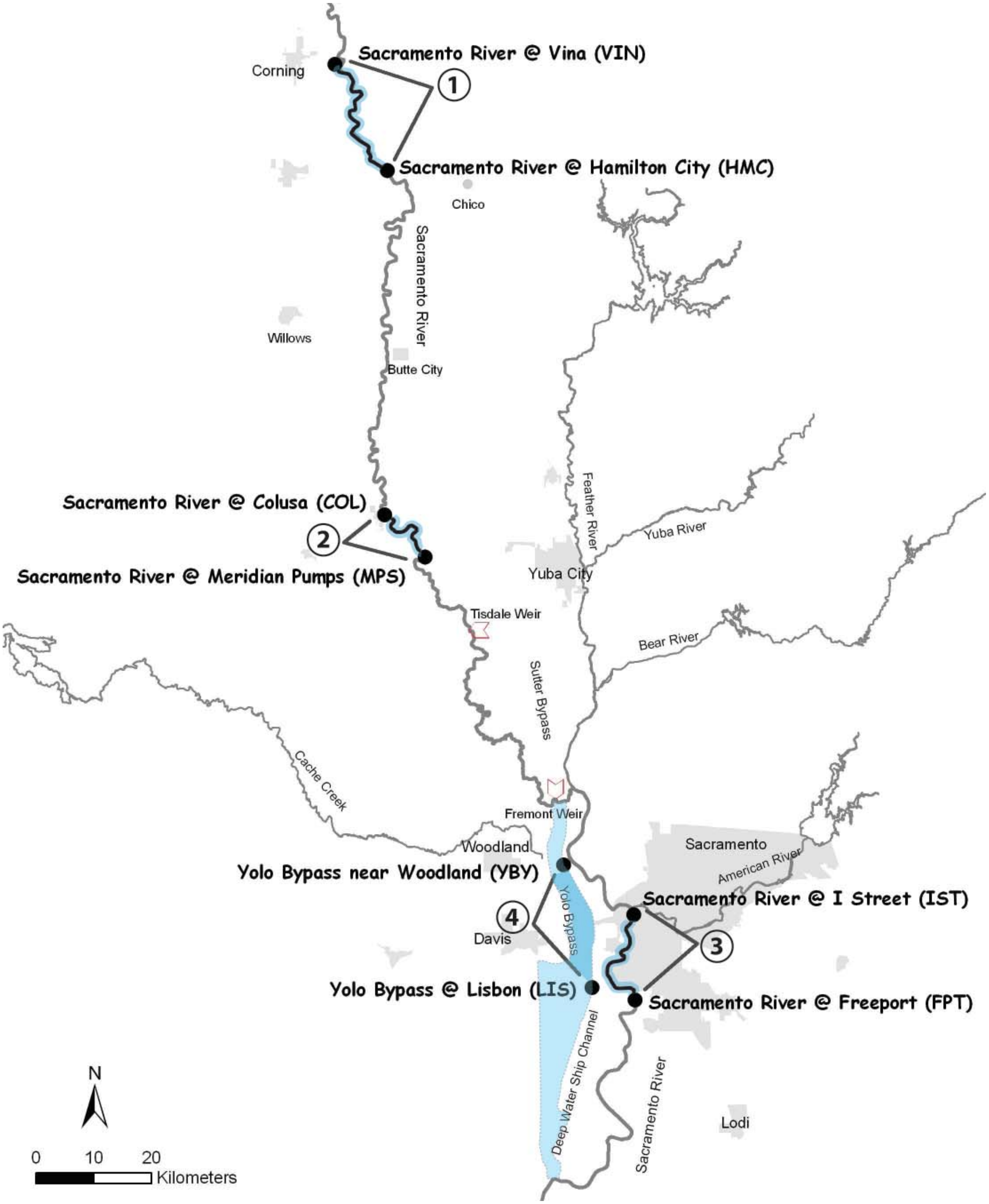


Figure 5 Study reaches and paired gauges along the Sacramento River and Yolo Bypass

Figure 6 Typical floodplain landscape along the Sacramento River at Colusa. Image source: Google™ Images.

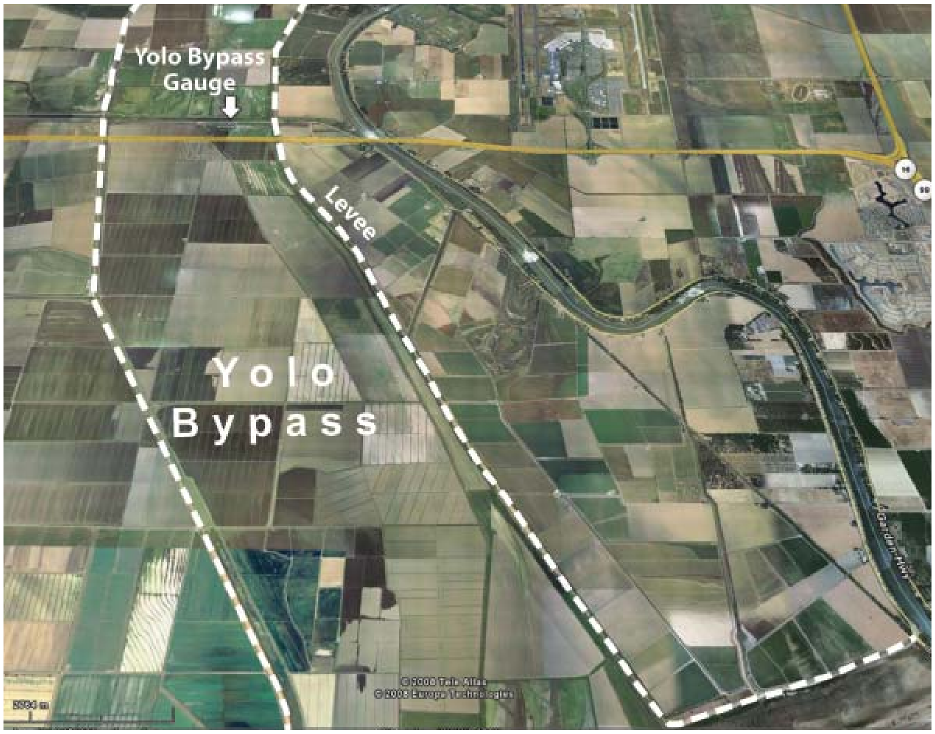


Figure 7 Farmed landscape of Yolo Bypass north of Interstate 80. Image source: Google™ Images.

Table 1 Information on the Sacramento River and Yolo Bypass paired gauges

Station Name	Pair	River Mile	Station Identifier	Description of Record	Period of Record
Primary Stations					
Sacramento River at Hamilton City	1	198.6	HMC	Hourly stage	06/19/1991 - 09/30/2004
Sacramento River at Colusa	2	143	COL	Daily discharge	10/01/1967 - 09/30/2004
				Hourly stage	01/01/1984 - 09/30/2004
Sacramento River at Freeport	3	46	FPT	Daily discharge	10/01/1967 - 09/30/2004
				Hourly stage	01/01/1984 - 09/30/2004
Yolo Bypass near Woodland	4	51.1	YBY	Daily discharge	10/01/1967 - 09/30/2004
				Hourly stage	03/17/1997 - 09/30/2004
Paired Stations					
Sacramento River at Vina-Woodson Bridge	1	214.8	VIN	Hourly stage	10/01/1984 - 09/30/2004
Sacramento River at Meridian Pumps	2	134	MPS	Hourly stage	10/17/1997 - 09/30/2004
Sacramento River at I-Street	3	59.7	IST	Hourly stage	01/01/1984 - 09/30/2004
Yolo Bypass at Lisbon	4	36.2	LIS	Hourly stage	01/01/1984 - 09/30/2004

and the stage that was exceeded in two-thirds of all years was identified to find the stage and flow that occurs in approximately two out of three years with a duration of seven days between March 15 to May 15 (Figure 8c).

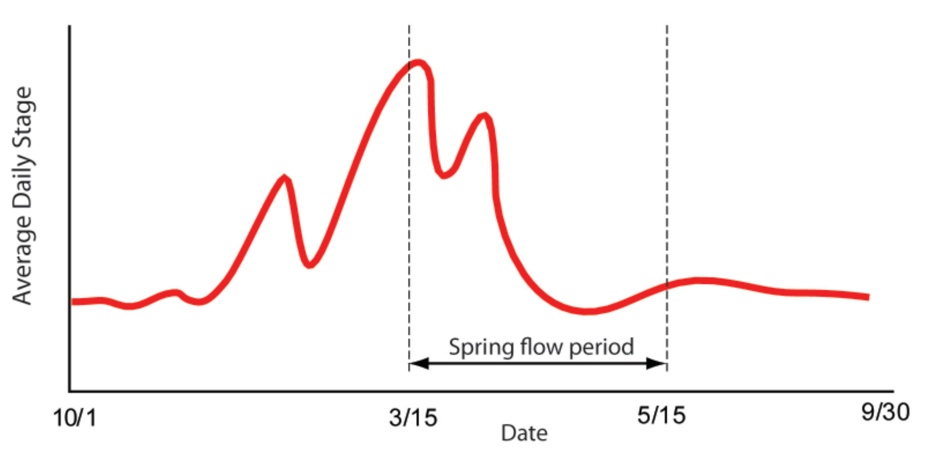
The FAF water surface plane between the two gauging stations was determined by sampling hourly stages, in particular spring flood events, to identify when FAF stage values were occurring at the primary station and correlating with the stage at the same time at the paired station.

For comparison we also analyzed the instantaneous two-year peak flood stage derived using the guidelines discussed in Bulletin 17B (Interagency Advisory Committee on Water Data 1982). We then used the method of moments to fit the Pearson Type III distribution to the logarithms of annual flood peaks. The Bulletin 17B skew was used for the analysis. Peak flow measurements for each station were downloaded from: http://nwis.waterdata.usgs.gov/usa/nwis/peak.

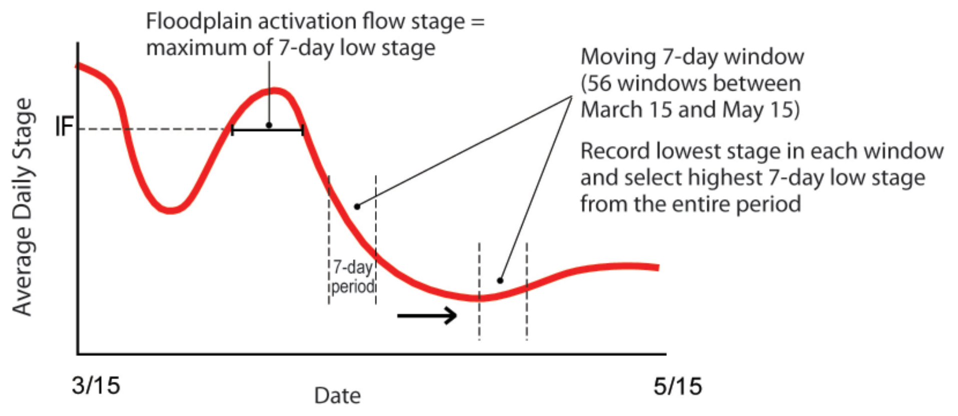
The extent of Activated Floodplain was mapped by superimposing the sloping water surface plane on the detailed floodplain topography mapped as a part of the Sacramento-San Joaquin Comprehensive Flood Study (USACE 2002). All of our study reaches, except the most upstream reach on the Sacramento River, were mapped to an accuracy suitable for development of 0.6 m (2 ft) contours above the waterline. Our most upstream reach was surveyed with accuracy suitable to produce 1.5 m (5 ft) contours. The mapping data for the Yolo Bypass was not complete at the time of this study and is missing an 8-km (5-mi) section in the middle part (approximately 2,150 ha (5,300 ac) between I Street and 2.7 km (1.7 mi) north of Lisbon.

Digital elevation models (DEMs) of the channel bed and water surface plane were constructed from contours using 3-D Analyst in ArcGIS. Ground surface DEMs were constructed using natural land surface features as well as artificial topographic features (e.g., levees and roads). Inundated floodplain area was derived by analyzing where the water surface DEM intersected the ground surface DEMs. To optimize computational time, a raster grid size of 6 m (20 ft) was used for differencing for each pair of gaug-

(a) Typical Daily Stage Hydrograph



(b) Selection of Activation Flow for a Particular Year



(c) Selection of Floodplain Activation Flow from Period of Record

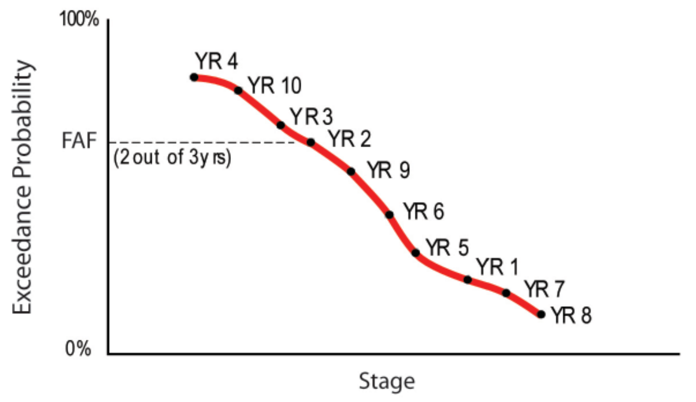


Figure 8 Hydrologic analysis methodology for the primary gauging stations

ing stations. Areas disconnected from the river were eliminated.

We conducted two historical analyses to compare how the FAF may have changed since flow regulation:

1. We calculated the pre-Shasta and post-Shasta FAF discharge upstream at Red Bluff using the same method described above. The pre-Shasta period encompassed water years 1900 to 1943 and the post-Shasta period encompassed water years 1944 to 2006.
2. We analyzed data recording flow over three weirs that regulate inundation of the Sacramento Valley's two major flood bypasses—Sutter Bypass (Tisdale Weir) and Yolo Bypass (Fremont Weir)—and the Butte Sinks (Colusa Weir) (DWR 2003). We calculated the mean number of days of overflow during the FAF interval (March 15 through May 15) and examined the proportion of years that contained at least one overflow event of seven days or greater for pre-Shasta (1935-1943) and post-Shasta (1944-1995) periods.

RESULTS

Discharge and stage elevation values for the floodplain activation flow, the average spring flow, and the two-year peak flood (Q2) are summarized in Table 2.

FAF and two-year flood stages are shown on typical cross sections at Colusa in Figure 9 and in the Yolo Bypass at Woodland in Figure 10. In addition the FAF area for the reach within the Yolo Bypass is shown in Figure 11.

To allow springtime floodplain inundation for more than seven days in two out of three years along the main stem of the Sacramento River, floodplain elevations have to be below the river stages of flows in the range of 340 to 680 $m^3 s^{-1}$ (12,000 to 24,000 $ft^3 s^{-1}$). As is illustrated in the Colusa channel cross section (Figure 9), these stages are substantially lower, by approximately 3.6 m (12 ft), than the diked historic floodplain, as well as the remnant floodplain terrace between the levees. Unsurprisingly, in the lower reaches of the Sacramento River there is a negligible area of Activated Floodplain because of the narrow floodway. Only in the furthest upstream reach at Vina is there a measurable amount of Activated Floodplain between the levees, exclusive of open water areas, of approximately 3.4 ha km^{-1} (14 ac mi^{-1}). In contrast, within the Yolo Bypass, the FAF of approximately 760 $m^3 s^{-1}$ (2,000 $ft^3 s^{-1}$) inundates large areas of the floodplain surface, approximately 144 ha km^{-1} (570 ac mi^{-1}) as is shown in Figures 10 and 11.

The two-year peak instantaneous flood elevation is substantially higher than the FAF elevation in all our study reaches and above the adjacent floodplain

Table 2 Discharge values, stage elevations, and unit FAF area at the paired gauges

Pair	Station	Discharge Values ($m^3 s^{-1}$)		Stage Elevations (m)		FAF Area (ha km^{-1})
		FAF	2-yr Flood	FAF	2-yr Flood	
1	Sacramento River at Vina	352	2,660	51.1	55.6	3.4
	Sacramento River at Hamilton City	495	2,564	40.1	42.3	
2	Sacramento River at Colusa	340	1,139	14.3	20.4	0
	Sacramento River at Meridian Pumps	---	---	13.4	---	
3	Sacramento River at I Street	---	---	2.1	---	0
	Sacramento River at Freeport	679	1,999	1.5	4.3	
4	Yolo Bypass near Woodland	57	757	5.3	7.9	144
	Yolo Bypass at Lisbon	---	---	2.9	---	

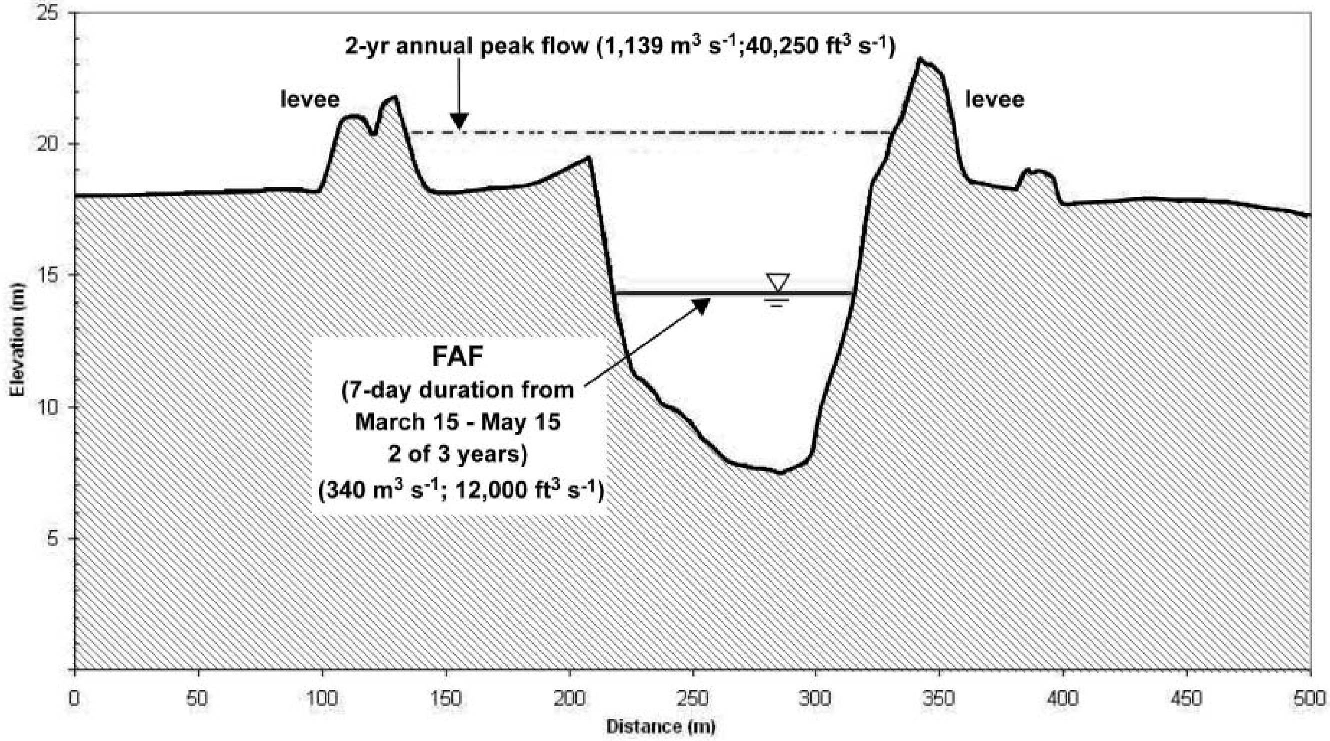


Figure 9 Sacramento River and floodplain cross section at Colusa

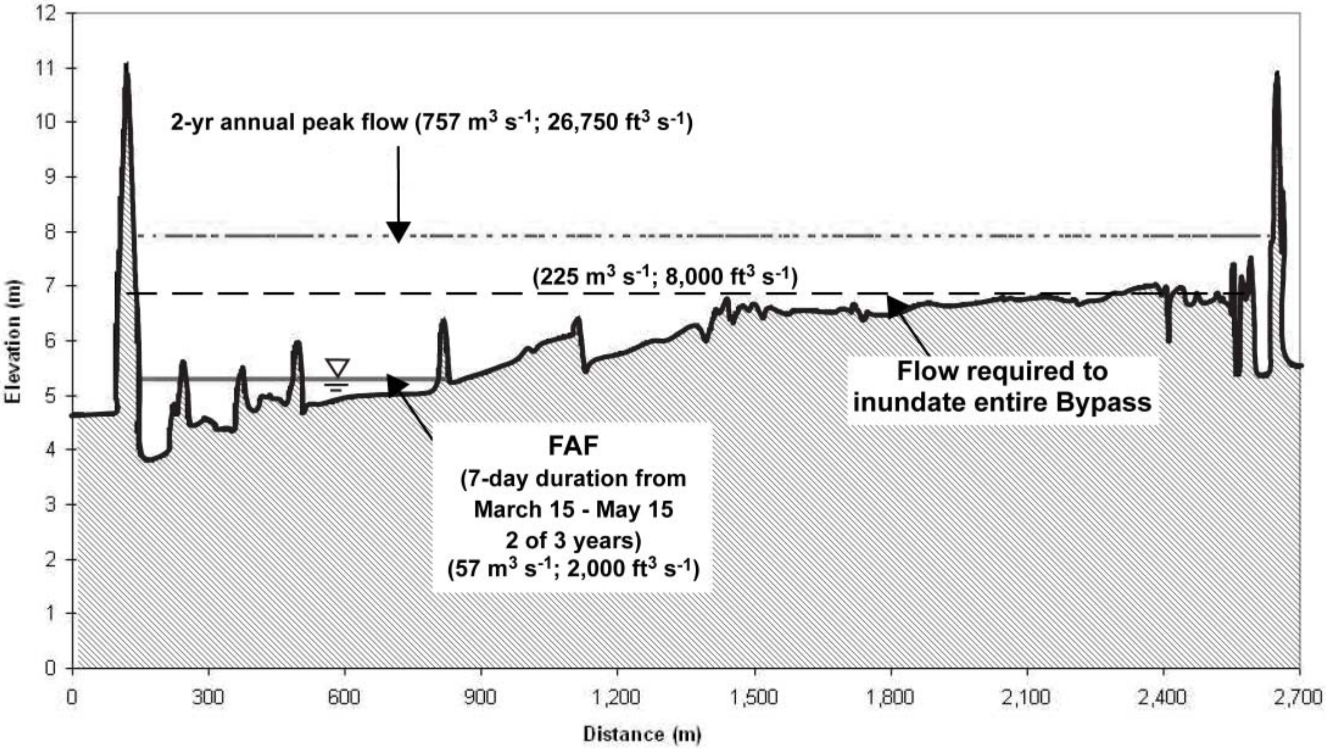


Figure 10 Cross section at Yolo Bypass at Woodland gauge

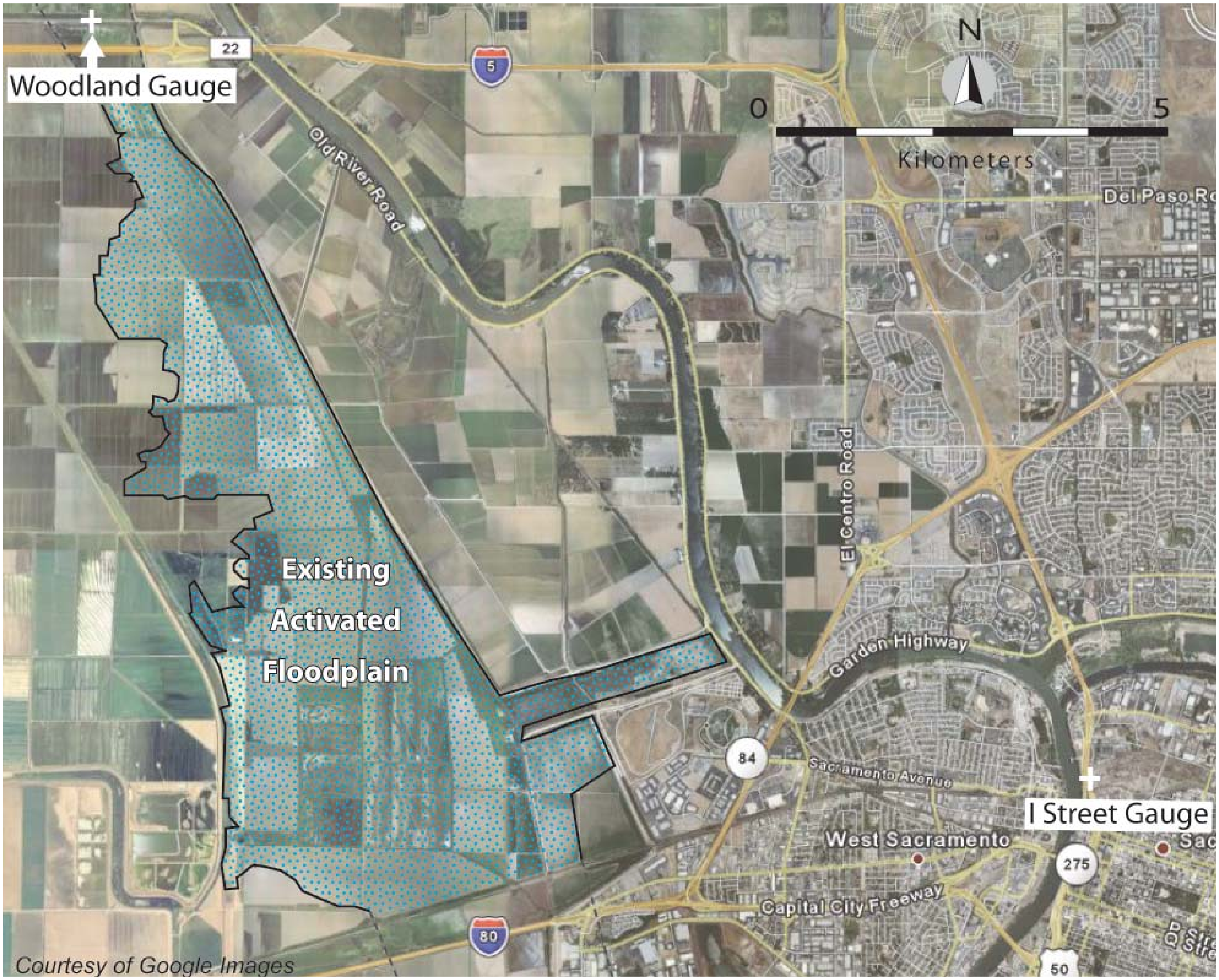


Figure 11 FAF area along the Yolo Bypass reach. Image source: Google™ Images.

elevation everywhere except the lowest Sacramento River reach examined, from I Street to Freeport.

The historical analysis indicates that the FAF discharge has been reduced by approximately half (Figure 12). At Red Bluff, the pre-Shasta FAF was 772 $m^3 s^{-1}$ (27,250 $ft^3 s^{-1}$) compared to a current value of 410 $m^3 s^{-1}$ (14,500 $ft^3 s^{-1}$), while at Butte City the pre-Shasta FAF was 1,056 $m^3 s^{-1}$ (37,000 $ft^3 s^{-1}$) compared to a current value of 521 $m^3 s^{-1}$ (18,400 $ft^3 s^{-1}$).

The average annual days of overflow into Sutter and Yolo Bypasses during the FAF interval, and the proportion of years with overflow events of seven days or longer during the FAF interval have also been greatly reduced. Before the Shasta Dam was put in operation, Tisdale Weir averaged 32 ± 7.5 days (mean ± standard error) of overflow during the FAF interval. During the post-Shasta period, Tisdale Weir overflowed 7.5 ± 1.9 days during that period. Before Shasta, overflow from Fremont Weir into the Yolo Bypass averaged 23 ± 6.9 days during the FAF interval compared to 6.5 ± 1.9 post-Shasta. The values for Colusa Weir, into the Butte Sinks, averaged 17.1 ± 6.5 days pre-Shasta compared to 4.6 ± 1.4 days post-Shasta. For both weirs, long-duration overflow events (≥ 7 days) during the FAF interval occurred in approximately three out of four years while today these events occur in approximately one out of four years (Figures 13 and 14).

DISCUSSION

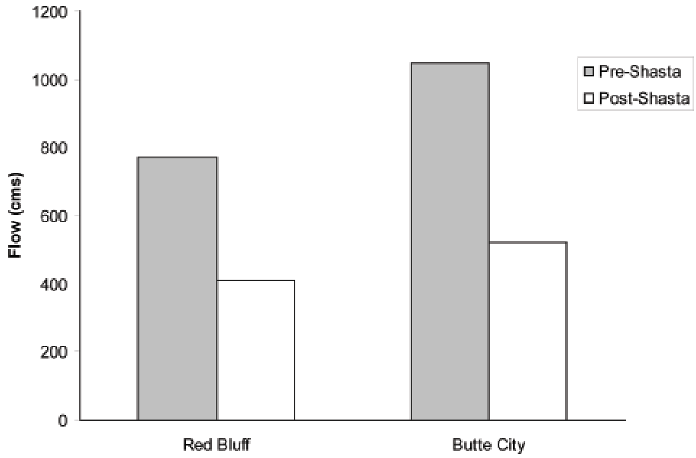


Figure 12 FAF values for pre-Shasta and post-Shasta for Red Bluff and Butte City

Using the FAF definition described above, our analysis indicates that much of the Sacramento River no longer has frequently inundated active floodplains and that the biggest opportunities for restoration lie in the bypasses. This reflects the fact that since the large multipurpose dams began operation in the Sacramento River watershed 40 to 60 years ago, the small, frequent and ecologically-important spring flood events have been significantly reduced. A trial application of the FAF to the lowland Sacramento Valley indicates that the few remnant floodplain terraces remaining between the levees of the Sacramento River are relict features inundated only for short periods during large, infrequent floods and are "inactive" with regard to the food web ecological processes identified as key functions activated by the FAF. Levee setbacks for improved flood conveyance in these areas would likely not result in increase in Activated Floodplain unless upstream reservoir operation was changed to allow the release of small spring flood pulses or unless the newly-established floodplains were graded down to intersect with the current FAF stage.

Although a historic reconstruction of Activated Floodplain area was outside the scope of our study, this analysis provides an indication of how storage of spring flow pulses in upstream reservoirs has changed

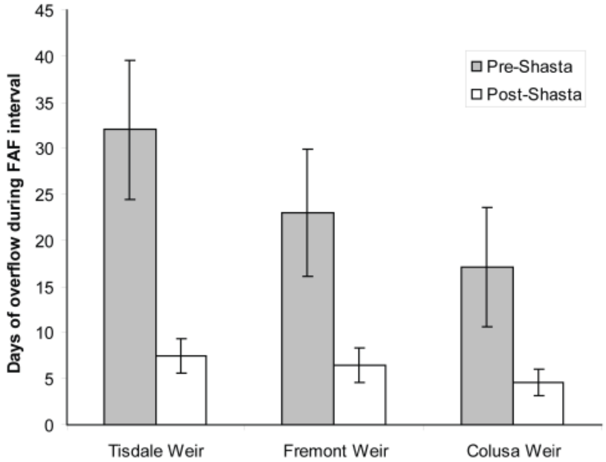


Figure 13 Days of overflow of Tisdale Weir into Sutter Bypass and Fremont Weir into Yolo Bypass, pre-Shasta and post-Shasta, within the FAF interval (March 15 – May 15)

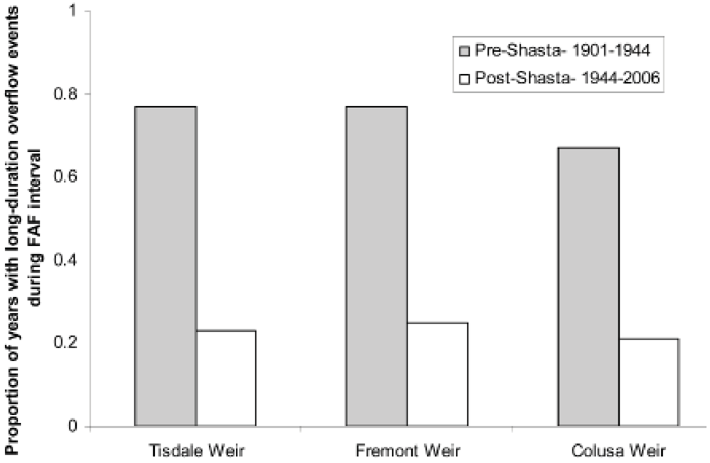


Figure 14 Proportion of years with overflow events of seven days or longer of Tisdale Weir into Sutter Bypass and Fremont Weir into Yolo Bypass, pre-Shasta and post-Shasta, within the FAF interval (March 15 – May 15)

floodplain inundation. Assuming the historic FAF for the Butte City gauge (1,056 $m^3 s^{-1}$ [37,000 $ft^3 s^{-1}$]) is representative of Colusa historic flows, and taking into account historic channel bed lowering, FAF stages used to be high enough to inundate adjacent floodplains, whereas now they are below floodplain elevations. This can be seen in Figure 9, which shows the stage at 1,139 $m^3 s^{-1}$ (40,250 $ft^3 s^{-1}$).

The trial application of the FAF area metric to a segment of the Yolo Bypass indicates that a substantial increase in area of Activated Floodplain could be accomplished with relatively small changes to the hydrology of the floodway.

Although the Yolo Bypass supports by far the largest area of Activated Floodplain (3,450 ha or 144 ha km^{-1}) in the lowland river system, the reach north of Hamilton City illustrates the linkages between geomorphically effective flows, channel complexity, and Activated Floodplain. This reach includes large sections that do not have levees and thus active geomorphic processes create a relatively complex channel, with oxbows, islands, bars, and secondary channels. In Figure 15 shading indicates portions of the channel and floodplain inundated by the FAF (495 $m^3 s^{-1}$ or 17,480 $ft^3 s^{-1}$) that are not inundated with lower flows (e.g., the flow in the photo is 208 $m^3 s^{-1}$ [7,345 $ft^3 s^{-1}$]). The shaded areas include an oxbow, bars, and secondary channels. In comparison, the reach south of Colusa has levees that are close to both sides of the channel, resulting in a simplified, straight channel, and therefore the FAF results in a negligible increase in high-quality rearing habitat. In the reach north of Hamilton City, the FAF inundates these complex channel features, representing a relatively large incremental increase in high-quality habitat for juvenile salmon. Further, the Activated Floodplain includes areas with high residence time, such as the oxbow in the upper right of Figure 15, that will contribute to food web productivity (Reckendorfer and others 1999; Schiemer and others 2001) that can contribute to higher growth rates of juvenile salmon (Limm and Marchetti 2003) as well as be exported back into the mainstem river. In contrast, south of Colusa the FAF results in a negligible increase in high-quality habitat for salmon or areas with higher residence time. Due to the simplified, straight channel, higher flows result in minimal incremental gains in shallow water, channel-margin habitat (Sommer and others 2004).

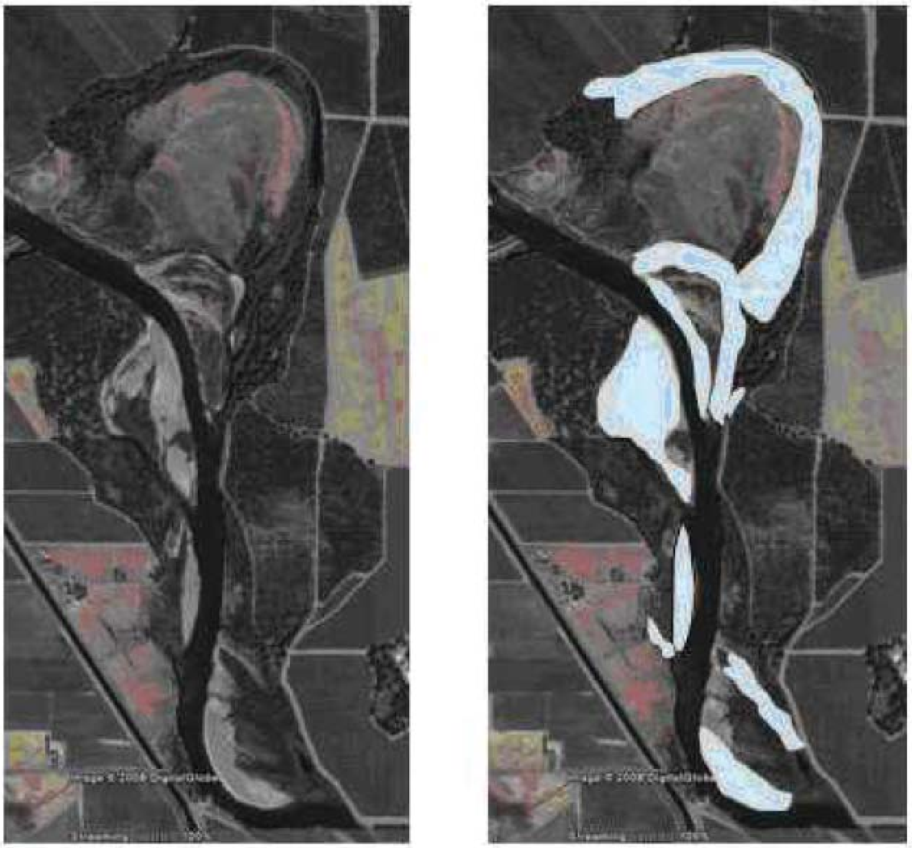


Figure 15 Typical complex channel and "Activated Floodplain" along the Sacramento River north of Hamilton City

Use of Activated Floodplain as a Planning Tool

Activated Floodplain area provides an easily quantifiable habitat metric that can be used as an “outcome” indicator to inform a landscape-scale adaptive restoration and management program as defined by CALFED. Using detailed floodplain topographic mapping and a hydrodynamic model to predict river stage (instead of interpolating between gauging stations), the current extent of Activated Floodplain within the entire lowland river system of the Central Valley under existing reservoir operation and hydrologic conditions can be quantified. This metric is applicable and adaptable to changing conditions over the planning horizons of 50 to 100 years required for implementing a landscape-scale adaptive restoration program. The future change in Activated Floodplain area can be analyzed under different planning scenarios. These could include change in hydrology due to climate change, construction of additional reservoirs, altered reservoir operation, long-term change in channel morphology due to long-term erosion, and change in floodplain topography due to levee setbacks and other flood control modifications. Using historic reconstruction of pre-dam or pre-colonization hydrology and river channel and floodplain morphology, it may also be possible to hind-cast an approximate value of historic extent of active floodplain for different river reaches. This information could be used to inform the selection of system-wide floodplain restoration goals.

Use of Activated Floodplain in a System-wide Adaptive Management Program

The intent of a system wide adaptive management is “learning by doing.” It requires an ability to test conceptual models and hypotheses efficiently and within a reasonable timeframe by monitoring linkages between restoration management actions and expected outcomes. In this instance the hypothesis to be tested is whether or not restoring areas of Activated Floodplain will initiate both important food-web processes and allow for other ecologic processes initiated by less frequent flood pulses. The Activated Floodplain area metric can be easily monitored using existing tools and data collection efforts. These are:

1. River stage gauge data analyzed to identify flood frequency, duration and timing.
2. Channel and floodplain topographic surveys that are periodically updated
3. Hydrodynamic model runs to identify Activated Floodplain area.

This analysis can be used to determine how well system-wide functional floodplain area restoration goals are being achieved.

Use of Activated Floodplain as a Design Tool

The FAF stage at a particular location on the river can be used as a design criterion for establishing floodplain elevations to maximize Activated Floodplain area in a similar way that a flood management design criterion, such as the 100-year instantaneous peak flood stage, is used to design appropriate flood control structures. When used as part of a multi-objective floodplain restoration project, use of a FAF stage criterion for floodplain design can provide long-term ecosystem benefits in conjunction with flood management. This can be illustrated by two hypothetical floodplain restoration projects:

1. For a hypothetical flood control levee setback intended to lower 100-year flood stages by widening the floodway, there are two possible complementary approaches to increase Activated Floodplain area (Figure 16): excavating a floodplain terrace to lower it below the FAF stage elevation; or changing upstream reservoir releases to allow a seven-day spring flood pulse to inundate the existing floodplain topography. Grading the floodplain surface to increase the extent of Activated Floodplain will increase channel cross-sectional area and conveyance; and also provide for flood storage that reduces peak flows downstream.
2. For floodplain enhancement on a flood bypass with a similar cross section as the Woodland gauge (Figure 10), Activated Floodplain area can be significantly increased by allowing for controlled spring flow diversions from the Sacramento River into the bypass floodway. For example, operation of a control structure at the Fremont Weir would permit more frequent or larger flows in the bypass. A 225 m^3 s^{-1} discharge (8,000 ft^3 s^{-1}) (the same discharge rate as the USACE Caernarvon structure on the Mississippi River, operated for wetland habitat enhancement (WaterMarks 2004), would allow for complete activation of the floodway width as shown on Figure 10.

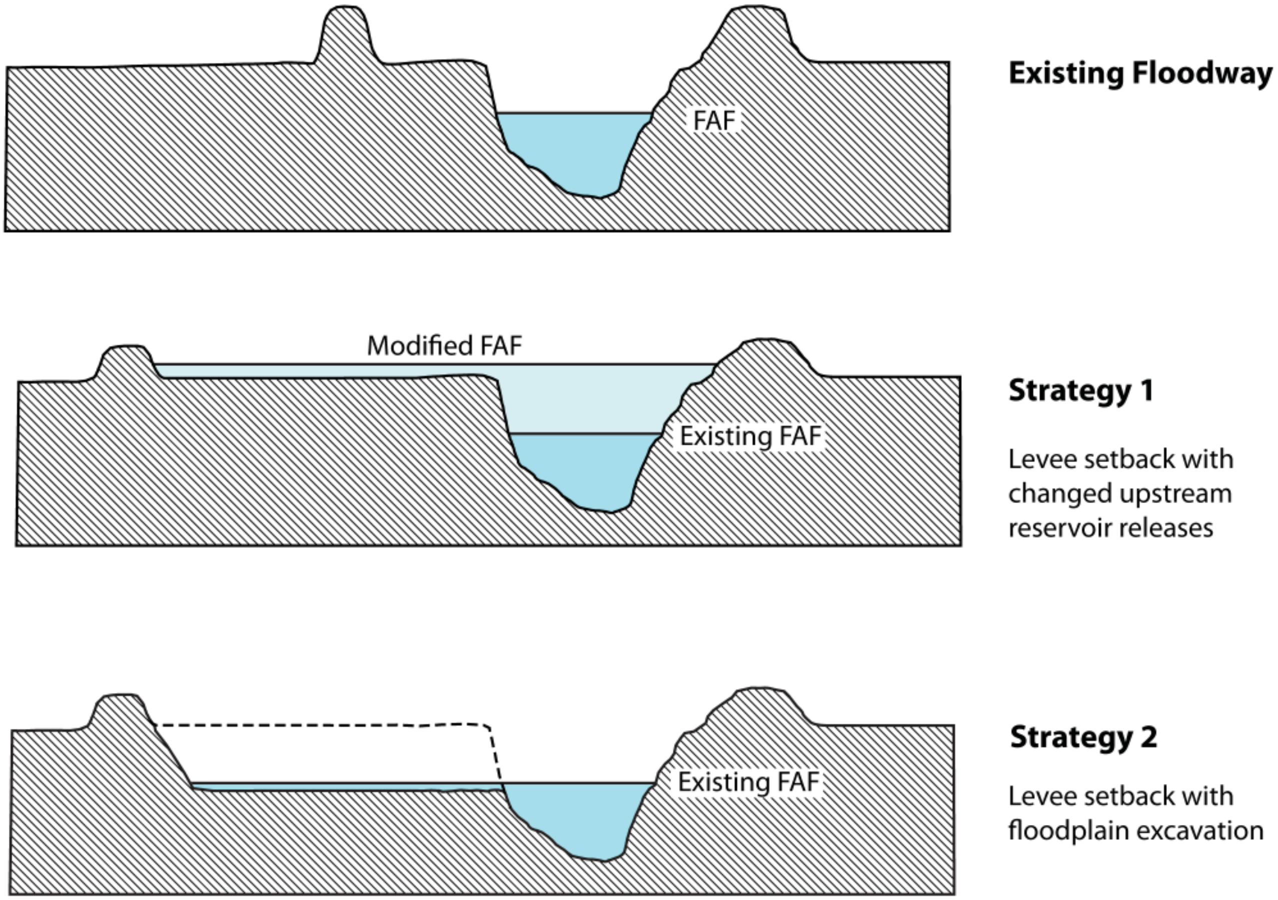


Figure 16 Two strategies for increasing "Activated Floodplain" area with levee setback

In 2006 the Three Rivers Levee Improvement Authority implemented a flood control levee setback at the mouth of the Bear River to improve flood conveyance (Figure 17). The additional 36 ha (90 ac) of potential floodplain created by the levee setback was isolated from the river channel by high elevation terraces formed of hydraulic mining debris between the levees. To increase the ecological benefits provided by the project, the design sought to increase Activated Floodplain area. To accomplish this goal, the Authority incorporated a connecting swale graded to connect the river channel to floodplain below the estimated FAF stage elevation of 22.1 m (72.5 ft) (PWA 2006). This swale excavation also supplied fill material for levee construction and reduced the risk that fish would become stranded on the floodplain during the floodplain draining phase.

Integrating Floodplain Restoration and Flood Protection Design

Using the FAF stage elevation as a floodplain design criterion together with peak flood criteria allows for development of a fully integrated river corridor design that has cumulative benefits for flood hazard reduction and ecosystem services, as opposed to a plan that designs a floodway first for flood control, and then attempts to include floodplain restoration features as add-on benefits. At least four cumulative benefits are describe, as follows:

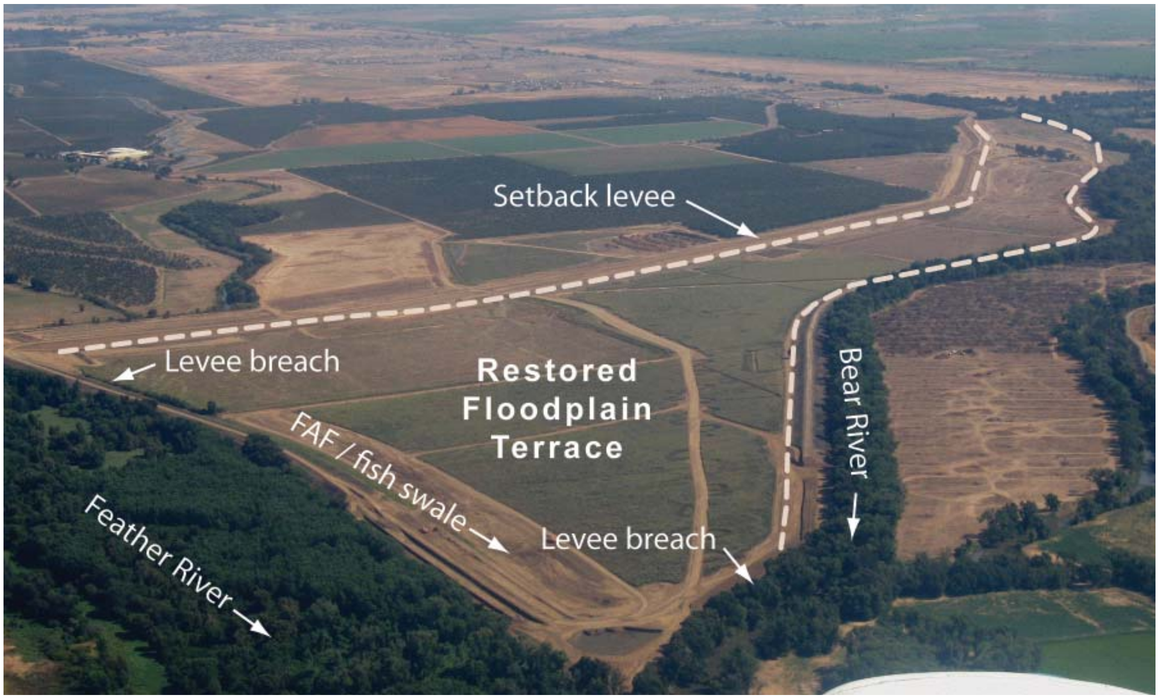


Figure 17 Bear River Levee Setback Project, design based on FAF approach

1. Provision of additional conveyance capacity by grading floodplain terraces lower to intersect with the FAF stage.
2. Provision of additional floodplain storage that can reduce peak flood stages downstream.
3. Reduction of scouring velocities close to the river bank.
4. Ability to develop a pre-planned performance based maintenance regime for the floodway. For example, increased conveyance can be designed to offset the increased hydraulic roughness that would occur if riparian trees become established in the floodplain. This would provide the dual benefits of increasing riparian habitat and reducing vegetation maintenance costs.

Integrating restoration and flood control design also allows for mitigating or accommodating between potential conflicts between ecologic and flood hazard reduction goals. Examples of potential conflicts follow:

1. *Increased hydraulic roughness of Activated Floodplain.* Riparian woodland and the more heterogeneous topography of active floodplain will likely have a higher hydraulic resistance than agricultural land uses on the floodplain. This may be compensated for in an integrated design by the lower floodplain elevations required for an Activated Floodplain; additional levee setbacks, or performance based channel maintenance criteria (see below).
2. *Loss of conveyance due to sedimentation on the floodplain.* The long term evolution of the floodways' topography and its effect on conveyance and peak flood stage can be anticipated in planning and design in the same way as potential increased hydraulic roughness.
3. *Expensive maintenance requirements.* At present many flood control channels are maintained on a prescriptive basis where ecologically-valuable riparian habitat is cleared on a fixed schedule. Integrating ecological design in the maintenance

plan allows for a performance based maintenance regime that anticipates the evolution of floodplain vegetation and morphology and so initiates maintenance actions only when hydraulic thresholds have been exceeded. These river stage thresholds for a particular river reach are evaluated from the same monitoring data as is used in the adaptive management program.

Limits and Uncertainties

Application of this approach necessarily—to make this a useful management tool—requires a major simplification of complex floodplain processes. By focusing the FAF criterion on the minimum ecologically-important flow, the criterion allows for, but may, or may not reflect the relative importance of larger less frequent flood events. For this reason its initial application should be limited to the low gradient lowland river reaches where the importance of initiating food web processes and providing splittail spawning habitat has been demonstrated. The FAF stage criterion Approach also relies on an implied linear relationship or simplification of the linkage between these ecological functions and floodplain wetted area, where other factors such as depth of flooding or vegetation cover may be important. Prediction of the Activated Floodplain area relies on the accuracy of surveys of floodplain topography and the resolution of predicted river stage elevations.

The hydrologic characteristics described above to establish the FAF criterion have been selected as a representation of the minimum ecologically-significant flow but is defined in a way that would allow for successive refinements with adaptive management monitoring. To explore uncertainty in the hydrologic characteristics used to define the FAF stage criterion, we performed a sensitivity analysis on flood stages at the Colusa gauge data varying the season, period, and frequency of the FAF (Table 3). These results show that the FAF stage at Colusa is approximately 1.8 to 4.6 m (6 to 15 ft) below the typical floodplain elevation for the range of hydrologic variables tested. The largest uncertainty in proposing the FAF for the lower Sacramento River was selecting the minimum period of inundation. This sensitivity analysis shows the three-day FAF stage to be 1.3 m higher than the seven-day stage, whereas the 14-day stage is only 0.4 m lower. This means that the Activated Floodplain area metric is not very sensitive to inundation periods greater than about seven days.

CONCLUSIONS

The application of the methodology as outlined and applied in this study to identify Activated Floodplain area is a simple but powerful approach based on recorded river stage and topographic data. It allows the delineation of a minimum ecologically-valuable Activated Floodplain using deterministic values of frequency, duration and seasonality. The area of connected Activated Floodplain inundated by the FAF can be used as a response indicator metric for planning, goal setting, adaptive management monitoring,

Table 3 Sensitivity analysis: FAF stages at the Colusa Station for different hydrologic criteria. Initially proposed values are indicatined in bold; modified values in italics.

	Period	Frequency	FAF Stage Elevation (m)
7-Day Duration	**March 15 - May 15**	**2 out of 3 years**	**14.3**
7-Day Duration	March 15 - May 15	*1 out of 3 years*	16.2
7-Day Duration	*January - June*	2 out of 3 years	16.5
3-Day Duration	March 15 - May 15	2 out of 3 years	15.6
14-Day Duration	March 15 - May 15	2 out of 3 years	13.9

and design of lowland river floodplain restoration projects. This metric can reflect the impact of potential future anthropogenic changes in the hydrology, geomorphology and hydraulics of the river system and is therefore adaptable to guide future long-term planning scenarios that incorporate climate change, altered reservoir operation, and the long-term effects of changes in sediment budget in the river system. Its application in "what-if" scenarios allows for an evaluation of the most cost-effective means of increasing the area of this particular type of ecologically-valuable floodplain by providing a method of quantitatively investigating the relative benefits of levee setbacks, floodplain grading, and changed reservoir operation. The recent application of FAF as a design criterion in the flood control levee setback project at the Bear and Feather River confluence illustrates how ecological and flood management objectives can be integrated to achieve cumulative benefits at relatively small additional cost.

We emphasize that the FAF stage approach applied here as an indicator represents a minimum criterion for restoring historic ecosystem values of floodplains. The seven-day flood evaluated here in reality represents a threshold criterion; longer periods of inundation punctuated with periodic disconnection will generally provide proportionally greater ecological benefits. Likewise the specific dates of inundation are somewhat arbitrary; the key is to have inundation occur at times when native plants and animals are likely to respond positively to it, and these benefits occur over a longer time period, though typically to a lesser degree at the extremes of that period. The FAF nevertheless provides good starting place for developing ecologically sensitive flood regimes that can adapt to changing local and regional conditions.

We also think the FAF concept has application beyond the Sacramento River watershed because it facilitates transparent and rigorous decision-making by resource managers. Definition of the FAF or FAF stage for a particular river, however, requires an ecologically-based conceptual model that links key floodplain functions to river stage, frequency, duration and seasonality. Its use in quantifying Activated Floodplain area requires a determination of river stage, frequency, and duration characteristics for that reach of river based on gauge records or hydrodynamic modeling, and floodplain topography detailed enough to establish connectivity with the river channel and inundated area with a reasonable degree of accuracy.

Since adoption of the CALFED restoration goal, the disastrous flooding from Hurricane Katrina has stimulated public support for large scale improvements in the flood management system in the Central Valley. In 2006 California voters approved up to $4 billion for evaluation, repair, and upkeep of flood control structures, as well as for flood management measures that include setback levees for improved flood conveyance (http://www.water.ca.gov/floodsafe/). This public support for flood protection creates an opportunity to integrate ecological benefits with public safety. Floodplain restoration projects can provide these benefits by both lowering the stages of large potentially damaging floods and by expanding areas that are inundated by ecologically-beneficial non-damaging floods. The Floodplain Activation Flow criterion offers a way to do this systematically in a way that allows us achieve significant ecologic benefits and also to learn how to improve our management of floodplains.

REFERENCES

Ahearn DS, Viers JH, Mount JF, Dahlgren RA. 2006. Priming the productivity pump: flood pulse driven trends in suspended algal biomass distribution across a restored floodplain. Freshwater Biology 51:1417-1433.

Andrews ES. 1999. Identification of an ecologically based floodway: the case of the Cosumnes River, California. In: Marriott SB, Alexander J, editors. Floodplains: interdisciplinary approaches. Geological Society Special Publication No. 163. London. p 99-110.

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

Booth E, Mount J, Viers J. 2006. Hydrologic variability of the Cosumnes River floodplain. San Francisco Estuary and Watershed Science [Internet]. Available from: http://repositories.cdlib.org/jmie/sfews/vol4/iss2/art2

Cabin RJ. 2007. Science-driven restoration: a square grid on a round Earth? Restoration Ecology 15(1):1-7.

[DWR] California Department of Water Resources. 2003. Sacramento River Flood Control Project weirs and flood relief structures. Sacramento (CA): Dept. of Water Resources.

Cushing CE, Allan JD. 2001. Streams: their ecology and life. New York: Academic Press.

Dynesius M, Nilsson C. 1994. Fragmentation and flow regulation of river systems in the northern third of the world. Science 266:753-762.

Florsheim JL, Mount JF, Constantine CR. 2006. A geomorphic monitoring and adaptive assessment framework to assess the effect of lowland floodplain river restoration on channel-floodplain sediment continuity. River Research and Applications 22(3):353-375.

Grosholz E, Gallo E. 2006. The influence of flood cycle and fish predation on invertebrate production on a restored California floodplain. Hydrobiologia 568:91-109.

Hansen JE. 2007. Scientific reticence and sea level rise. Environmental Restoration Letters 2(2): article 024004.

Jeffres CA, Opperman JJ, Moyle PB. 2008. Ephemeral floodplain habitats provide best growth conditions for juvenile Chinook salmon in a California river. Environmental Biology of Fishes 83:449-458.

Junk WJ, Bayley PB, Sparks RE. 1989. The flood pulse concept in river-floodplain systems. In: Dodge DP, editor. Proceedings of the International Large River Symposium. p 110-127.

Kelley R. 1998. Battling the Inland Sea: Floods, Public Policy, and the Sacramento Valley. University of California Press.

King JM, Brown C, Saber H. 2003. A scenario-based holistic approach to environmental flow assessment for rivers. River Research and Applications 19(5-6): 619-639.

Larsen EW, Greco SE. 2002. Modeling channel management impacts on river migration: a case study of Woodson Bride State Recreation Area, Sacramento River, California. Environmental Management 30(2):209-224.

Limm MP, Marchetti MP. 2003. Contrasting patterns of juvenile chinook salmon (*Oncorhynchus tshawytschaw*) growth, diet, and prey densities in off-channel and mainstem habitats on the Sacramento River. Chico, California: The Nature Conservancy.

McBain and Trush. 1997. Trinity River Maintenance Flow Study Final Report. Performed under contract to the Hoopa Tribe. 481 p.

Moyle PB, Baxter RD, Sommer TR, 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 [Internet]. Available from: http://repositories.cdlib.org/jmie/sfews/vol2/iss2/art3

Moyle PB, Crain PK, Whitener K. 2007. Patterns in the use of a restored California floodplain by native and alien fishes. San Francisco Estuary and Watershed Science [Internet]. Available from: http://repositories.cdlib.org/jmie/sfews/vol5/iss3/art1

Nanson GC, Croke JC. 1992. A genetic classification of floodplains. Geomorphology 4:459-486.

Nilsson C, Reidy CA, Dynesius M, Revenga C. 2005. Fragmentation and flow regulation of the world's large river systems. Science 308:405-408.

Poff NL, Allan JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime. BioScience 47:769-784.

Postel S, Richter B. 2003. Rivers for life: managing water for people and nature. Washington, DC: Island Press.

[PWA] Phillip Williams & Associates, Ltd. 2002. Lower Redwood Creek restoration project. Prepared for the National Park Service Golden Gate National Recreation Area. PWA Ref. No. 1502.

[PWA] Phillip Williams & Associates, Ltd. 2006. The Bear River levee setback design: opportunities and constraints for environmental enhancement. Prepared for South Yuba River Citizen's League and Yuba Feather Workgroup. PWA Ref. No. 1779.

Reckendorfer W, Keckeis H, Winkler G, Schiemer F. 1999. Zooplankton abundance in the River Danube, Austria: the significance of inshore retention. Freshwater Biology 41:583-591.

Richter BD, Baumgartner JV, Powell J, Braun DP. 1996. A method for assessing hydrologic alteration within ecosystems. Conservation Biology 10:1163-1174.

Richter BD, Baumgartner JV, Wigington R, Braun DP. 1997. How much water does a river need? Freshwater Biology 37:231-249.

Riley AL. 2003. A primer on stream and river protection for the regulator and program manager. CRWQCB San Francisco Bay Technical Reference Circular W.D. 02-#1. Oakland (CA): California Regional Water Quality Control Board, SF Bay Region. 111 p.

Rood SB, Mahoney JM. 1990. Collapse of riparian poplar forests downstream from dams in western Prairies: probable causes and prospects for mitigation. Environmental Management 14:451-464.

Schemel LE, Sommer TR, Muller-Solger AB, Harrell WC. 2004. Hydrological variability, water chemistry, and phytoplankton biomass in a large floodplain of the Sacramento River, CA, USA. Hydrobiologia 513:129-139.

Schiemer F, Keckeis S, Reckendorfer W, Winkler G. 2001. The "inshore retention concept" and its significance for large rivers. Algological Studies 135:509-516.

Sommer T, Baxter R, Herbold B. 1997. Resilience of splittail in the Sacramento-San Joaquin Estuary. Transactions of the American Fisheries Society 126:961-976.

Sommer T, Harrell B, Nobriga M, Brown R, Moyle P, Kimmerer W, Schemel L. 2001a. California's Yolo Bypass: evidence that flood control can be compatible with fisheries, wetlands, wildlife, and agriculture. Fisheries 26:6-16.

Sommer TR, Nobriga ML, Harrell WC, Batham W, Kimmerer WJ. 2001b. Floodplain rearing of juvenile Chinook salmon: evidence of enhanced growth and survival. Canadian Journal of Fisheries and Aquatic Sciences 58:325-333.

Sommer TR, Harrell WC, Solger AM, Tom B, Kimmerer W. 2004. Effects of flow variation on channel and floodplain biota and habitats of the Sacramento River, California, USA. Aquatic Conservation-Marine and Freshwater Ecosystems 14:247-261.

[TBI] The Bay Institute. 1998. From the Sierra to the sea: the ecological history of the San Francisco Bay-Delta watershed. San Francisco (CA): TBI. 275 p.

The Nature Conservancy, Stillwater Sciences, ESSA Technologies Ltd. 2008. Sacramento River ecological flows study: final report. Prepared for the California Bay-Delta Authority, Ecosystem Restoration Program. Sacramento (CA). 72 p. Available from: http://www.delta.dfg.ca.gov/erp/docs/sacriverecoflows/Sacramento_River_Ecological_Flows_Study_Revised_Final_Report.pdf

Trush WJ, McBain SM, Leopold LB. 2000. Attributes of an alluvial river and their relation to water policy and management. Proceedings of the National Academy of Sciences 97:11858-11863.

[USACE] U.S. Army Corps of Engineers. 1957. Sacramento River Flood Control Project levee and channel profiles. Available from: http://www.cvfpb.ca.gov/profiles/sactoriverbasin1of4.pdf

[USACE] U.S. Army Corps of Engineers. 2002. Sacramento and San Joaquin River Basins Comprehensive Study Technical Studies Documentation. Available from: http://www.compstudy.net/reports.html

[USACE and TRB] U.S. Army Corps of Engineers and The Reclamation Board. 2004. Hamilton City Flood Damage Reduction and Ecosystem Restoration, California. Final Feasibility Report and Environmental Impact Statement/Environmental Impact Report. Available from: http://www.compstudy.net/hamilton.html

WaterMarks. 2004. Caernarvon: a case study. Louisiana Coastal Wetlands Planning, Protection, and Restoration News. September 2004. Available from: http://lacoast.gov/watermarks/2004-09/4caernarvon/index.htm