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Floodplain restoration planning for a changing climate:  
Coupling flow dynamics with ecosystem benefits

by

Mary Katherine Matella

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Environmental Science, Policy, and Management

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Adina M. Merenlender, Chair

Professor Maggi Kelly

Professor G. Mathias Kondolf

Spring 2013

Floodplain restoration planning for a changing climate:  
Coupling flow dynamics with ecosystem benefits

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Mary Katherine Matella

## ABSTRACT

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Coupling flow dynamics with ecosystem benefits

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Mary Katherine Matella

Doctor of Philosophy in Environmental Science, Policy, and Management

University of California, Berkeley

Professor Adina M. Merenlender, Chair

This dissertation addresses the role that dynamic flow characteristics play in shaping the potential for significant ecosystem benefits from floodplain restoration. Mediterranean-climate river systems present challenges for restoring healthy floodplains because of the inter and intra-annual variability in stream flow, which has been dramatically reduced in an effort to control flooding and to provide a more consistent year-round water supply for human use. Habitat restoration efforts require that this reduced stream flow be altered in order to recover more naturally dynamic flow patterns and reconnect floodplains. This thesis defines and takes advantage of an eco-hydrology modeling framework to reveal how the ecological returns of different hydrologic alterations or restoration scenarios—including changes to the physical landscape and flow dynamics—influence habitat connectivity for freshwater biota. A method for quantifying benefits of expanding floodplain connectivity can highlight actions that might simultaneously reduce flood risk and restore ecological functions, such as supporting fish habitat benefits, food web productivity, and riparian vegetation establishment.

Pending climate change increases the uncertainty of restoration treatment outcomes yet must be addressed as part of the restoration planning process. An ecologically-oriented assessment of the current and potential future stream flow characteristics of selected Central Valley rivers makes it clear that climate change will affect future floodplain habitat function. Findings show that the low emissions (warm-wet) climate change scenario allows for higher flows at longer durations compared to the historical post-dam record and the high emissions (hot-dry) scenario. In fact, the low-emissions scenario flows might be more similar to pre-dam flow regimes—peak magnitudes in particular—than to the current regulated flow regime. The high emissions scenario can serve as a measure for the lower bounds of functional floodplain area for ecological benefit. Planning for potential impacts of climate change on flow dynamics will be essential if restoration managers are to minimize negative consequences of climate change and maximize the potential benefits that it may offer for species recovery.

Efforts to plan and evaluate floodplain reconnection projects for ecological benefits have been hindered by a lack of metrics that allow for comparisons among alternative restoration sites with respect to the type and quality of dynamic habitat potential. This dissertation presents a framework for quantifying the benefits of floodplain restoration projects by coupling the spatial

and temporal characteristics of floodplains to express the functional habitat they create. First, habitat was quantified using Area-Duration-Frequency (ADF) curves for several durations and across multiple frequencies of flood occurrence. From these data, a value was then generated for expected annual habitat (EAH). The method has advantages in framing the potential restored area in terms of probabilities based on dynamics of flow timing, durations, and frequencies. The EAH metric captures a comprehensive picture of the likelihood of flooded areas appearing in any given year. This method can be used to design projects to meet specific and measurable habitat objectives. These methods and new metrics provide a transparent and replicable means to examine the effects and relative importance of policy decisions and river restoration projects.

To illustrate this modeling method, statistical flow characteristics needed to support floodplain benefit for species were coupled with topographic alteration scenarios for increasing beneficial habitat along the Vernalis to Mossdale corridor on the San Joaquin River, California. Findings for a suite of species that span a range of necessary flow requirements exemplify a wide array of impacts associated with flow scenarios for the San Joaquin River system. Most importantly, the modeled results predict significant declines in the availability of required flow related habitat conditions for splittail spawning and rearing and Chinook salmon rearing in the future under two climate change scenarios. Physical habitat restoration must be paired with additional in-stream flows to meet frequency, duration, and seasonal requirements for these species. Thus, restoration treatment considerations for floodplain habitat should not only include physical alterations for additional channel floodplain connectivity, but also restore a more natural flow regime to increase habitat area and frequency of inundation.

Restoration planning often fails to follow strategies based on assessments of ecological benefit outcomes and cost effectiveness. A hydro-ecological approach was applied to multiple modeled floodplain restoration sites along California's Sacramento River and was integrated with socio-economic considerations into a prioritization scheme. The new EAH and ADF metrics were used to assess probabilities for ecological outcomes for increased salmon rearing habitat and combined with land value cost for parcels in the restoration areas. The model was used to assess individual and cumulative benefits of 26 floodplain rehabilitation options involving levee setbacks and examine the consequences of changing topography and climate for floodplain habitat along a large expanse of the Sacramento River. Cumulative effects of projects implemented concurrently showed only small changes in functional floodplain habitat creation. Climate change flow scenarios for this section of the Sacramento River indicate that the functional EAH habitat under a low emissions (warm-wet) regime overlaps with that created for restoration sites under the current flow regime. However, the high emissions (hot-dry) regime will create less functional habitat and serves as a good lower bound of expectations for any restoration plan. By adding to ecological outcome measures and integrating environmental benefits into a cost effectiveness ratio, some projects' priority rankings shift. Thus, cost effectiveness is relevant for informing decisions about restoration site priorities and could improve the way funds are allocated to restoration options. This study advances mitigation planning at a local and regional scale by providing tools for quantitative estimates of potential habitat that could be restored, for assessing projects individually and cumulatively, and for comparing and prioritizing sites using an analytical cost effectiveness approach.

In sum, this dissertation presents a modeling framework and new quantitative metrics that can be used to plan and evaluate floodplain restoration projects that address connectivity and dynamic flows, whether they are the result of climate change or prescribed reservoir release flows. Restoration options for multiple locations in California's Central Valley were investigated to demonstrate the utility of this approach. The method has advantages in estimating the potential restored area in terms of probabilities based on dynamics of flow timing, durations, and frequencies. Ultimately, using integrative hydro-ecological models offers support for decision makers considering where to rehabilitate floodplain processes upon which biological and social benefits depend.

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## **CHAPTER 1**

### **INTRODUCTION: RESTORING FLOODPLAIN HABITAT FOR A CHANGING CLIMATE**

## **Introduction: Restoring floodplain habitat for a changing climate**

Many believe the natural world might now be experiencing the sixth major extinction event in its history and expected effects of climate change only increase the risk (Thomas et al. 2004). Freshwater biodiversity is particularly at risk due to stock overexploitation, water pollution, flow modification, habitat loss, and invasive species (Dudgeon et al. 2005). Floodplain connectivity loss acts in concert with these threats to magnify stresses on freshwater ecosystems. This loss of connectivity diminishes natural processes and reduces available habitat, significantly impacting fisheries and other species dependent on riverine systems (Freeman et al. 2007; Opperman et al. 2010). Ecosystem services to society, such as flood water storage, nutrient cycling and recharging aquifers, are also threatened by floodplain loss. Urban development and agricultural use of river floodplains have caused many freshwater bodies to lose adjacent periodically inundated floodplains; some estimate that up to 90% of floodplains in North America and Europe are functionally extinct (Tockner and Stanford 2002).

Addressing the freshwater biodiversity decline requires rehabilitation and reconnection of floodplains. Hydrologic connectivity—defined as water-mediated transport of matter, energy and organisms—shapes floodplains according to variation in the spatial and temporal dynamics of their flow regimes (Freeman et al. 2007). Maintaining natural patterns of hydrologic connectivity is vital for populations of many riverine species (Bunn and Arthington 2002). Water management for human needs has altered not only hydrologic connectivity in longitudinal, lateral, and vertical dimensions, but also changed flow regimes. Many restoration projects have repaired hydrologic connections (e.g., by removing fish passage barriers or setting back levees) but do not restore flow dynamics (Kondolf et al. 2006). Kondolf et al. (2012) point out that restoration of mediterranean-climate rivers is particularly challenging because restoring the dynamic flow regime of these already variable systems is difficult.

Mediterranean-river systems generally exhibit hot, dry summers and cool, wet winters and are characterized by significant temporal and spatial variability. Rainfall is concentrated in the winter season and often occurs in a few major storms that produce floods, but annual precipitation amounts might still vary 30% or more from multi-annual averages (Gasith and Resh 1999). Alterations to these flow regimes in turn affect the availability and suitability of aquatic habitat for species. Since few large freshwater lakes occur naturally in mediterranean-climate regions, and groundwater tends to either be far below the land surface or in thin bands along the stream corridor, people rely heavily on rivers for freshwater. In response to the intra-annual seasonality and inter-annual unpredictability of rainfall, human communities have generally relied on intensive water management infrastructure to improve water supply reliability, including large dams and conveyance projects. The resulting decline and reduced variability in stream flow and river-floodplain connections throughout mediterranean-river basins have caused a dramatic loss of hydrologic connectivity. Compounding the problems of hydrologic connectivity loss and flow regime alteration is the growing expectation of more extreme weather events under climate change that will affect the frequency and severity of river flooding and droughts (Cayan et al. 2010; Dettinger et al. 2009; Dettinger 2011).

Many challenges exist for researchers studying how climate change might affect species and ecosystems. While temperature and moisture regimes influence the distribution, productivity, and reproduction of biota, climate model predictions of temperature and precipitation changes are not always consistent or easily translated into biotic response. Changes in hydrology can influence species in many ways, but the most completely understood processes are those that link moisture availability with intrinsic thresholds that govern metabolic and reproductive processes (Burkett et al. 2005). Ecological responses to altered flows have frequently been reported as changes in macroinvertebrate or fish taxa abundance, population demographic parameters, or diversity of assemblages (Poff and Zimmerman 2010). Few studies have been published where ecological metrics have been quantified in response to various degrees of flow alteration and explained mechanistically. To fill these gaps in knowledge, a group of international scientists is now calling for a synthesis of flow alteration–ecological response relationships based on classifying rivers according to flow regimes and geomorphic features (Poff and Zimmerman 2010; Poff et al. 2010). However, confounding effects of hydrologic alteration with other important environmental determinants of river ecosystem condition contribute uncertainty to studies of flow-ecology relationships (Poff et al. 2010; Burkett et al. 2005).

Scenario planning is one of the best tools for environmental problem solving when a high level of uncertainty about the system exists and field experiments might be difficult (Peterson et al. 2003). Also, given that there are always multiple ecosystem services traded-off for any proposed ecosystem alteration, it is critical that scenarios take uncertainty into account, reducing the chances for unintended consequences. Trade-offs in mediterranean-climate regions are inevitable when rehabilitating natural flow regimes because water management for human uses has been so extensive. There are still other trade-offs that are less obvious, such as using reservoirs instead of natural floodplains to provide flood control for downstream communities. The inherent trade-offs associated with various policy options need to be made explicit to better inform local decision-makers of their consequences and identify the best options for habitat conservation.

Restoration treatments now proposed in many river basins might increase the amount of functional floodplain area for native species and might involve both physical reshaping of the river-floodplain and changes to river flows often controlled by upstream reservoirs. To restore self-sustaining floodplain habitat, efforts to rehabilitate ecologically significant floodplain should strive to recreate the function of the habitat rather than desired physical features alone. Most previous efforts to restore floodplain have not captured essential dynamics of the flows that once created the transient inundation characterizing these productive ecosystems (Buijse et al. 2002; Henry and Amoros 1995). In fact, many river restoration projects have been undertaken without information about duration, frequency, and intensity of floods (Henry and Amoros 1995). Though many recent efforts to categorize and describe floodplain have made technological advances, they often rely on static definitions related to instantaneous wetted land cover area (such as the 100-year floodplain). Baseline assessment and planning using traditional floodplain definitions employ area estimates as metaphorical currency, though they might incorporate a measure of change over time by comparing pre- and post-project habitat unit areas [e.g., Habitat Evaluation Procedures (U.S. Department of the Interior, 1980)]. Other recent advancements couple remotely acquired images with field based habitat assessments to improve the resolution of floodplain habitat in a watershed context, but do not make explicit the temporal nature of the water-land interactions at the sites (Konrad et al. 2008; Anderson et al. 2010). Ecologically



significant floodplain depends on dynamic flow components, and researchers are beginning to couple physical models with ecosystem response models (Poff et al. 1997; Shenton et al. 2012). This dissertation advances this approach by explicitly coupling flow dynamics and ecosystem benefit models and presenting analysis of current and potential future flow regimes. Estimations of potential ecosystem benefits associated with restoration treatment alternatives involving channel alterations are provided for several mediterranean-climate rivers in California.

Chapter 2 explores dynamic flow components to provide an ecologically-oriented assessment of the current and potential future stream flow characteristics of selected mediterranean-climate rivers in California's Central Valley. I include four major rivers in the Sacramento River system (American, Yuba, Feather and Sacramento), one major river in the San Joaquin River system (San Joaquin mainstem near Vernalis) and the largest flood bypass in the Central Valley (Yolo Bypass). Future flow scenarios were drawn from 2001-2099 data developed by the USGS CASCaDE: Computational Assessments of Scenarios of Change for the Delta Ecosystem project (Cloern et al. 2011). The most extreme high emissions climate change model reflects air temperature increases of 0.42 °C per decade (A2GFDL scenario) with a significant precipitation decline (28 mm per decade) (Cloern et al. 2011). The B1PCM reflects no significant trend in precipitation, but has a 0.14 °C warming trend per decade. The Bay-Delta Watershed Model (BDWM), a physically based model of hydrologic processes, was used by USGS to generate stream flow at a daily time step with primary inputs of precipitation and air temperature, simulating hydrologic variability throughout the watershed. I chose the low emissions warm/precipitation neutral (B1PCM) and the high emissions warmer/drier (A2GFDL) climate scenarios for which to evaluate daily hydrologic records to bound a wide range of possible impacts.

Chapter 3 introduces a method and suite of metrics for evaluating dynamic flow characteristics that shape the riparian-floodplain interface. Connecting the characteristics of flow and area of floodplain allowing ecological response involves hydraulic modeling, spatial analysis, and statistical measures of flow regime dynamics. Information on flow frequency, duration, seasonality, inundation, and habitat characteristics describing floodplain suitability based on the literature are essential for setting up ecological points of reference. For example, the splittail, a species of concern in California, does not reproduce well unless it has access to significant floodplain habitat in the spring in 1 of every 4 years (Sommer et al. 2002); the "spring" defines the seasonal requirement and the 1 in every 4 years defines the habitat frequency requirement. This chapter presents a method of correlating and combining disparate model results, habitat requirements, and hydrologic scenarios into singular, streamlined evaluation criteria. A combination of standard hydrologic and hydraulic analysis quantifies habitat using Area-Duration-Frequency (ADF) curves for several durations and across multiple frequencies of flood occurrence. From these data, a value for expected annual habitat (EAH) is derived. ADF and EAH can be used to create project screening metrics with minimal costs and basic knowledge of species needs. While not a fully informed decision making tool, these metrics provide a much needed currency for valuing ecosystem benefits associated with floodplain restoration alternatives.

Chapter 4 incorporates the method and metrics of Chapter 3 by expanding their application to multiple ecological benefits and evaluating different hydrologic alterations including changes to

the physical landscape and flow dynamics. I chose to model flow-ecological relationships related to splittail spawning and rearing, Chinook salmon rearing, phytoplankton production, and zooplankton production because at particular life stages these species benefit greatly from the availability of floodplain habitat. The utility of this modeling framework is demonstrated with a detailed floodplain reconnection case study of the Lower San Joaquin River, California, whereby changes in physical flow paths improve the available number of flooded habitat hectares. A levee setback is contrasted with a reconnected slough bypass as restoration options. The restoration options are evaluated using the current flow regime and climate change scenarios. In addition to physical restoration treatments, a prescribed flow scenario based on reservoir re-operation is also explored as a form of restoration for the project area.

Deciding where to rehabilitate hydrologic processes that shape characteristics of the physical floodplain habitat can be approached using the integrative hydro-ecological model framework presented in Chapter 4. Chapter 5 extends this approach to multiple modeled floodplain reconnection sites on California's Sacramento River and integrates socio-economic considerations into a prioritization strategy. Sixteen levee setback sites are ranked by applying ADF curves and EAH metrics relevant to juvenile salmonid rearing on floodplain. Social factors such as land value and erosion site proximity were included in the analysis of project rankings as well. Because the EAH presents an average metric for assessing inundated habitat, I used another approach to measure potential floodplain habitat variation inter-annually by applying a water year type analysis. To illustrate the vast differences in floodplain habitat likely to result during different water year types, four example year hydrographs representing wet, above normal, below normal, and dry water years were used to tally functional floodplain for juvenile salmonids rearing. Cumulative effects of multiple projects were also investigated by modeling select combinations of levee setbacks on the Sacramento River. Sensitivity of ecological metric results to potential future flow regimes was also tested using climate change flow scenarios described in Chapter 2.

In summary, there is a renewed worldwide effort to restore or rehabilitate floodplain habitats in order to promote species recovery, especially as freshwater ecosystem health is increasingly linked to floodplain connectivity (Dudgeon et al. 2006; Rohde et al. 2006). Understanding ecological responses to floodplain restoration requires a synthesis of information about species' life histories, expected stream flows, and geographic context. Examination of timing, magnitude, frequencies, and durations of ecological flows is vital for planning sustainable, successful floodplain restoration projects. The integration of functional habitat measures within the existing social context and evaluation of trade-offs is essential to reap the full benefits to management decision-making and improve the way funds are allocated to restoration. The research described here and the analysis tools developed support systematic restoration planning for species recovery and illustrate their application for floodplain restoration in California.

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## **CHAPTER 2**

### **SEASONALITY AND FLOW DYNAMICS OF CLIMATE CHANGE SCENARIOS AND IMPLICATIONS FOR FLOODPLAIN HABITAT IN THE CENTRAL VALLEY, CALIFORNIA**

Mary K. Matella

## **Seasonality and flow dynamics of climate change scenarios and implications for floodplain habitat in the Central Valley, CA**

### **INTRODUCTION**

Given recent advances in understanding how the loss of floodplain has damaged freshwater ecosystems, there is a renewed worldwide effort to restore or rehabilitate these habitats in order to promote species recovery (Dudgeon et al. 2006; Rohde et al. 2006; Shenton et al. 2012). Understanding ecological responses to floodplain restoration requires a synthesis of information about species' life histories, expected flows, and geographic context. Examination of timing, magnitude, frequencies, and durations of ecologically significant flows is vital for planning sustainable, successful floodplain restoration projects.

Climate changes poses additional challenges for restoration planning as water resources face competing demands from agricultural, environmental and urban users (Iglesias et al. 2007). Changes in the large-scale hydrological cycle that respond to a warming climate include increasing atmospheric water vapor content; changing precipitation patterns, intensity and extremes; reduced snow cover and widespread melting of ice; and changes in soil moisture and runoff (Bates et al. 2008). Climate change will have diverse effects on moisture availability, ranging from alterations in the timing and volume of stream flow to the lowering of water levels in many wetlands (Bates et al. 2008). Most climate change studies agree that decreases in mean annual flow, reduced snowpack, and more rapid snowmelt runoff can be expected in the future (Null et al. 2010; Vicuna et al. 2007). The purpose of this chapter is to provide an ecologically-oriented assessment of current and potential future stream flow characteristics and is applied to selected California Central Valley rivers.

California's Central Valley experiences a mediterranean-climate of generally hot, dry summers and cool, wet winters. Mediterranean streams have variable stream flow rates across space and time, and annual predictable floods historically shaped the dynamics of biotic and abiotic controls in riparian communities. Rainfall is concentrated in the winter season and often occurs in a few major storms that produce floods, but annual precipitation amounts might still vary 30% or more from multi-annual averages (Gasith and Resh 1999). In response to the intra-annual seasonality and inter-annual unpredictability of freshwater supply, in the last century Californians invested in intensive water management infrastructure to improve water supply reliability, including large dams and conveyance projects. The projects have lowered the variability in stream flow and in some cases greatly reduced the amount of flowing water (Figure 2-1).

Considering the natural variability of mediterranean-river flows and the extent to which they are currently impaired, California faces great challenges in managing the effects of climate change on stream flows. Many researchers have selected sets of climate change model simulations for which to evaluate impact scenarios in California (Cayan et al. 2007; Cloern et al. 2011). During the twenty-first century temperatures over California might increase approximately +1.5°C under a lower emissions scenario and increase +4.5°C in a higher emissions scenario model (Cayan et al. 2007). I chose low emission warm/precipitation neutral and high emission warmer/drier

climate scenarios for which to evaluate daily hydrologic records to bound a wide range of possible impacts.

Given the trajectories of climate change effects, I predict dynamic flow elements will exhibit certain trends. If snowmelt is occurring sooner due to warming, then timing of flow peaks should shift earlier in the season. I expect climate scenarios to also produce more extreme flow events, whether they be high flow floods or extreme low flows. Durations of floods might be shorter, as floods might exhibit flashy characteristics resulting from reduced snowpack and more rainfall driven events. How flood flows respond to the high and low emissions climate scenarios will identify the types of flow changes restoration managers will need to consider in designing projects for decades to come.

## METHODS

I evaluated stream flow records for gages in California’s Central Valley that had daily flow records for scenarios of climate change (USGS 2009) as well as significant historical records of observations. I include four major rivers in the Sacramento River system (American, Yuba, Feather and Sacramento), one major river in the San Joaquin River system (San Joaquin mainstem near Vernalis) and the largest flood bypass in the Central Valley (Yolo Bypass) (Figure 2-1). Table 2-1 relates basic characteristics of the watersheds. Below are descriptions of the watersheds, gage locations, and dates relevant to analysis of the hydrologic record (Table 2-2; Figures 2-1 and 2-2).

Table 2-1. Station information

Station name	USGS gage #	Drainage area (km <sup>2</sup> )	Max elev. (m)	Mean elev. (m)	Major Dam	Year completed	Storage capacity (10 <sup>6</sup> m <sup>3</sup> )
Sacramento River above Bend Bridge near Red Bluff (SAC)	11377100	23051	4303	1207	Shasta	1943	5472
Feather River near Gridley (FR)	11407150	9521	2783	1518	Oroville	1967	4364
Yuba River near Marysville (YUBA)	11421000	3468	2761	1287	Engle-bright	1941	86
American River at Fair Oaks (AMR)	11446500	4890	3162	933	Folsom	1956	1246
Yolo Bypass near Woodland (YOLO)	11453000						
San Joaquin River at Vernalis (SJR)*	11303500	35058	4214	963	Friant	1942	642

\*Dams on Tributaries to SJR: New Melones (Stanislaus R.) 1979; New Don Pedro (Tuolumne R.) 1971; New Exchequer (Merced R.) 1967

## Study Sites

The Central Valley is a basin spanning a swath of California, draining 42% of the state via the Sacramento and San Joaquin Rivers that flow into the Delta and out into the greater San Francisco Bay (Bay Institute 1998). The Central Valley is bounded by the Sierra Nevada and Cascade Ranges on the east, western Coast Ranges, northern Klamath Ranges and Tehachapi



Range to the south. The Sacramento and San Joaquin Basins differ in the amount of precipitation received as rain (dominant on the Sacramento) versus snow (dominant on the San Joaquin) and geological differences affect runoff and stream flow as well (Figure 2-2).

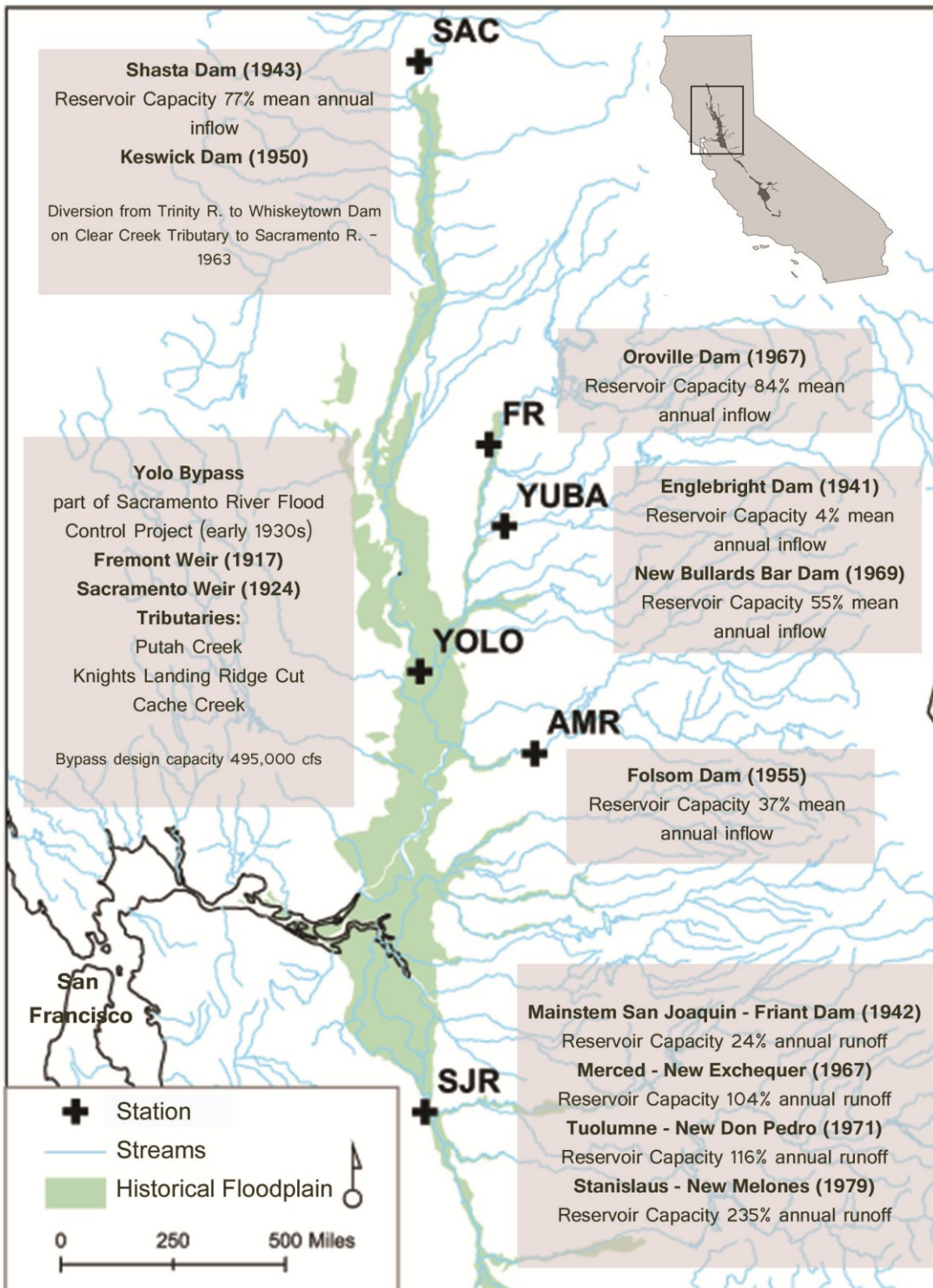


Figure 2-1. Map of Central Valley sites and associated historical events affecting flows

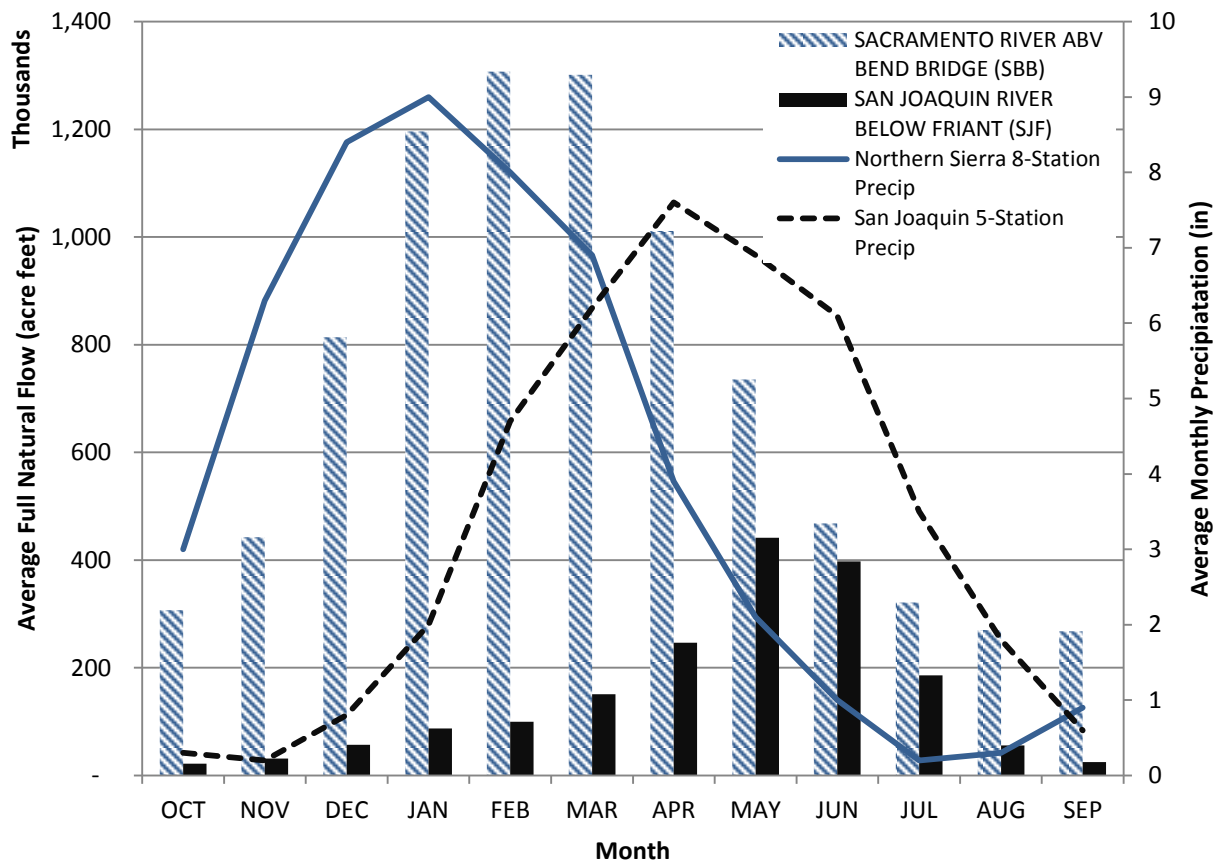


Figure 2-2. Full natural flow estimates (WY 1905-2012) overlaid with average precipitation

### *Sacramento River*

The Sacramento River is a major river in California, with the USGS gage above Bend Bridge near Red Bluff (#11377100) draining about a 23,000 km<sup>2</sup> (8,900 mi<sup>2</sup>) basin upstream, excluding Goose Lake Basin. Since 1943, Shasta Dam has regulated the majority of flows on the mainstem of the Sacramento River. Shasta Dam is 52 miles upstream of the Bend Bridge near Red Bluff gage, and in addition to the upstream storage, irrigation diversions have been in place for about 8910 ha between Keswick and above Bend Bridge. In April 1963, a trans basin diversion from the Trinity River to Whiskeytown Lake augmented Sacramento River flows. According to the USGS (2012a), annual runoff has declined from 8.55 million acre feet (MAF) (1892-1943) to 7.85 MAF (1946-1962) to 6.69 MAF (1964-2010). Before Shasta Dam was in operation monthly average flows for February-April were each over 142 cms greater than the 1964-2010 record reflects (USGS 2012a).

### *Feather River*

The Feather River is a tributary to the Sacramento River and drains the western slope of the Sierra Nevada, with 9,521 km<sup>2</sup> (3,676 mi<sup>2</sup>) upstream of the Feather River gage near Gridley (USGS station #11407150). Oroville dam, established in 1967, is about 16 miles upstream from

Gridley, managing water for flood control, hydropower generation, and irrigation. Precipitation at elevations above 1524 m in the watershed occurs primarily as snow. Infrequent summer thunderstorms can produce intense, short-lived rainfall events in small areas of the watershed (DWR 2007; NMFS 2009). The average annual runoff of the upstream Feather River Basin at Oroville is about 4.2-4.3 MAF (USGS 2012b). Annual flows are variable and depend upon precipitation. From 1979 to 1999, annual inflows ranged from a minimum of 1.7 MAF to as high as 10 MAF (DWR 2007).

#### *Yuba River*

The Yuba River is a tributary to the Feather River, draining approximately 3470 km<sup>2</sup> (1340 mi<sup>2</sup>) of upstream Sierra Nevada watershed area at the USGS gage at Marysville (#11421000). Three primary tributaries drain into the mainstem Lower Yuba River: the North, Middle and South Forks. Flow is regulated by reservoirs such as New Bullards Bar Reservoir on the North Fork, in operation by 1969. At Englebright Dam, created in 1941, the South Fork of the Yuba River joins the mainstem which then runs 24 miles to the confluence with the Feather River at Marysville. The Smartville gage (USGS #11418000) downstream of Englebright has annual runoff averages of 1.79 MAF (1941-2011), but has ranged from 0.37 to 4.93 MAF annual runoff (USGS 2012c; NMFS 2009). Runoff is rainfall generated during October through March and snowmelt related during April through September (NMFS 2009).

#### *American River*

The American River is a tributary to the Sacramento River and drains the western slope of the Sierra Nevada, with 4,890 km<sup>2</sup> (1,888 mi<sup>2</sup>) upstream of the American River at Fair Oaks gage (USGS station #11446500). Snowmelt is the source of approximately 40% of the American River flow (NMFS 2009). Folsom Dam began operation in 1956 and there are many diversions upstream from the station for irrigation, municipal, and domestic water supply. Average historical unimpaired runoff at Folsom Dam is 2.7 MAF, though the range is more variable at 0.3 to 6.4 MAF (USGS 2012d; NMFS 2009). Kondolf and Batalla (2005) note that the total reservoir storage capacity in the American River watershed is 67% of inflow (total reservoir capacity includes reservoirs with greater than 0.648 m<sup>3</sup> x 10<sup>6</sup> capacity).

#### *Yolo Bypass*

The Yolo Bypass is a 24,000 ha leveed floodplain that drains four western tributaries—Knights Landing Ridge Cut, Cache Creek, Willow Slough, and Putah Creek—in addition to floodwaters that enter the bypass via the Fremont and Sacramento Weirs. In winter and spring high-flow events, Sacramento River flows overtop the weirs and cause extensive flooding throughout the bypass (Benigno and Sommer 2008). The bypass can convey up to 80% of the flow of the Sacramento River basin during high water events (Sommer et al. 2001).

#### *San Joaquin River*

The San Joaquin River drains approximately 83,000 km<sup>2</sup>, running about 560 km, flowing northward to meet the Sacramento River in the Delta, which exhibits a network of islands and channels that feed into San Francisco Bay. Data on daily river flow exist since 1924, and continuously since 1929, at the San Joaquin River Near Vernalis gage (USGS station #11303500). The river has been impacted by development and water diversions and constrained

by levees that limit riparian and floodplain processes, although these levees sometimes fail under high flows (DWR 2005; Florsheim and Dettinger 2007). Over 80 dams on the San Joaquin River and its primary tributaries capture or store more than 135% of the average annual yield of the basin, such that the San Joaquin has experienced a 71% decrease in annual water yield (Cain et al. 2003).

Table 2-2. Periods of record for flow regimes

Location	Regime	Period of record (water years)	
		Bend Bridge	
SAC	Pre-dam	1879-1943*	
	Post-dam	1964-2010	
	Climate change	2011-2099	
		Gridley	Oroville
FR	Pre-dam		1902-1967
	Post-dam	1968-2010	1968-2010
	Climate change	2011-2099	
		Marysville	Smartville
YUBA	Pre-dam		1904-1941
	Post-dam	1970-2010	1970-2010
	Climate change	2011-2099	
		Fair Oaks	
AMR	Pre-dam	1904-1955	
	Post-dam	1956-2010	
	Climate change	2011-2099	
		Vernalis	
SJR	Pre-dam	1924-1942**	
	Post-dam	1980-2010	
	Climate change	2011-2099	
		Woodland	
YOLO	Pre-dam	1892-1944	
	Post-dam	1945-2010	
	Climate change	2011-2099	

\*SAC missing data for years 1890, 1891

\*\*SJR has low flows only for 1925-29

### Climate change scenarios

Climate change scenarios are generally based on the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment simulations of twenty-first century climate emission scenarios: B1 (low emissions) and A2 (a medium-high emissions). Climate models used to simulate the emissions include the Parallel Climate Model (PCM1) from the National Center for Atmospheric Research and the U.S. Department of Energy, and the National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory CM2.1 model (GFDL). Future flow scenarios were drawn from 2001-2099 data developed by the USGS CASCaDE: Computational Assessments of Scenarios of Change for the Delta Ecosystem project (USGS 2009). The most extreme climate change model reflects air temperature increases of 0.42 °C per decade (A2GFDL scenario) with a significant precipitation decline (28 mm per decade) (Cloern et al. 2011). The B1PCM scenario reflects no significant trend in precipitation, but has a 0.14 °C

warming trend per decade. USGS used the the Bay-Delta Watershed Model (BDWM), a physically based model of hydrologic processes, to generate stream flow at a daily time step with primary inputs of precipitation and air temperature, simulating hydrologic variability throughout the watershed. I chose the low emissions warm/precipitation neutral (B1PCM) and high emissions warmer/drier (A2GFDL) climate scenarios for which to evaluate daily hydrologic records to bound a wide range of possible impacts. The B1PCM model is now referred to as the B1 scenario and the A2GFDL model as the A2 scenario.

## **Statistical Methods**

I used the Index of Hydrologic Alterations (IHA) tool created by The Nature Conservancy (TNC) to analyze combined current flow regime and climate change records in a pre- and post-impact framework (TNC 2007). The IHA parameters have typically been used to examine the impacts of dams on rivers but are designed to reflect human-induced changes in flow regimes across a range of influences including dam operations, water diversions, and landscape modification and so the climate change record is applied as a hypothetical future (Richter et al. 1996; Richter and Thomas 2007). The IHA can generate over 100 statistical metrics for comparing hydrographs, but I focused on the environmental flow component (EFC) parameters using non-parametric statistics to deal with flow data not normally distributed. A small flood is defined as an event that begins when a pulse is over the 75th percentile and reaches a peak at or greater than the 2-year recurrence interval (Q2) flood (occurs with a probability of 50% of the years). A large flood reaches a peak that is at or greater than the 10-year recurrence interval (Q10) flood (occurs with a probability of 10% of the years). IHA also produces metrics that associate duration and timing of flows to the EFC event. Each metric has a deviation factor, which refers to the difference of the post-impact and pre-impact period, and is defined as  $(\text{post-impact value} - \text{pre-impact value}) / (\text{pre-impact value})$ . To place the potential climate change impacts in context of the historical pre-dam flow regime, I also calculated IHA statistics for the sites using the operation of major watershed dams to demarcate two flow records from the historical observations at the sites (Tables 2-1 and 2-2).

To aid evaluation of significance for the comparison of current flow regime and potential future scenario flow regime metrics, the IHA provides a non-parametric significance statistic similar to the parametric p-value. IHA randomly shuffles all years of input data and recalculates hypothetical pre-and post-impact medians 1000 times (TNC 2007). The significance count metric thus refers to the percentage of trials for which the deviation values for the medians were greater than for the actual result. A low value for significance count means the difference between current flow regime and climate change medians is highly significant.

Standard probability statistics were applied to the annual maxima flow data set at each location to create flow-frequency relationships. The U.S. Army Corps of Engineers Statistical Software Package (HEC-SSP) was used to create these frequency relationships and associated confidence intervals. This method uses a Log Pearson Type-3 (LPIII) distribution, and station skew statistics were set using updated regional skew parameters for California (Parrett et al. 2011). Using the Wilcoxon (Mann-Whitney) signed-rank test in STATA (v10), differences between frequency curves for the flow regimes were tested for significance.

To evaluate flood timing, seasonal identifiers were assigned to EFC flow events based on the start date of the event. The water year begins in October, but the fall season is defined as

September-November. December-February is winter; March-May is spring; and June-August is summer. Using flood event seasons, the peak flow magnitude was plotted against the duration of the event for each site and hydrologic regime (current flow regime, A2, and B1).

A duration analysis was conducted using the HEC Data Storage System Visual Utilization Engine (HEC-DSSVue) to compute the flow duration curve (FDC) for annual and seasonal periods, as defined above. FDCs were created by ranking all the data for the duration period and then extracting points along that curve. Using the standard duration analysis HEC-DSS technique, data values for each season and flow regime were ranked using Weibull plotting positions and ordered to provide the percent of time that each value is equaled or exceeded over the given time period.

One way to compare the FDCs is to create a dimensionless ratio based on any time frame (month, season, year) to explain the loss or gain in stream flow (Gao et al. 2009; Vogel et al. 2007). Vogel et al. (2007) define metrics of surplus and deficit ratios to refer to the gain and loss, respectively, that a hydrologic alteration produces when comparing the FDCs of two periods of record. Hydrologic alteration studies often compare an unregulated versus a post-dam hydrologic record, but in this case I refer to current flow regimes (post-dam) compared to climate change scenario flows. Surplus is the ratio of the area above the current flow duration curve that is below the climate change flow duration curve divided by the total area under the current curve. Deficit refers to the ratio of the area below the current flow duration curve and above the climate change curve divided by the total area under the current curve. This deficit ratio is the percentage of flow lacking from the river due to climate change.

## RESULTS

Across all locations, the periods of record for before and after major dams were constructed show reductions in maximum 7-day and 30-day flows (Table 2-3). Duration-magnitude parameters for the post-dam impact records generally show reduced 3-day, 7-day, and 30-day maximums and higher 3-day, 7-day, and 30 day minimum flows, except for the gage at Oroville on the Feather River (Table 2-3). Table 2-4 provides a comparison of the Q2 and Q10 magnitude flows before and after major dam construction. The 2% flow (Q2), the daily *streamflow* rate that is exceeded on exactly 50% of the days, ranges from a reduction of 31% for the San Joaquin River (SJR) near Friant Dam to 90% for the Feather River (FR) at Oroville based on the pre- and post-dam flow regimes. The Sacramento River (SAC) near Bend Bridge location shows reductions in Q10, the 10% flow rate, is most reduced (-48%) compared to the other sites, but the Q2 reduction is of similar magnitude (-52%). The other locations show a smaller reduction in Q10 compared to the pre-dam record.

Table 2-3 Pre- and Post-dam impact duration-magnitude IHA parameters

Parameter	pre-dam (cms)	post-dam (cms)	Deviation	significance count	pre-dam (cms)	post-dam (cms)	Deviation	significance count
	<b>AMR</b>				<b>SJR</b>			
<b>3-day minimum</b>	4	27	548%	-	19	32	68%	0.004
<b>7-day minimum</b>	5	28	502%	-	20	33	62%	0.01
<b>30-day minimum</b>	6	32	421%	-	25	36	46%	0.03
<b>3-day maximum</b>	628	241	-62%	0.03	656	163	-75%	0.43
<b>7-day maximum</b>	441	238	-46%	0.05	603	155	-74%	0.44
<b>30-day maximum</b>	314	198	-37%	0.10	503	101	-75%	0.43
	<b>SAC</b>				<b>YOLO (Dayflow data)</b>			
<b>3-day minimum</b>	113	148	30%	-	-	-		
<b>7-day minimum</b>	115	148	29%	-	-	-		
<b>30-day minimum</b>	117	176	50%	-	-	-		
<b>3-day maximum</b>	2,342	1,422	-39%	0.02	980	1,031	5%	0.94
<b>7-day maximum</b>	1,723	1,222	-29%	0.12	831	810	-3%	0.96
<b>30-day maximum</b>	925	778	-16%	0.27	338	299	-11%	0.90
	<b>FR (Oroville)</b>				<b>YUBA (Smartville)</b>			
<b>3-day minimum</b>	36	12	-65%	0.00	5	17	212%	-
<b>7-day minimum</b>	38	14	-64%	0.00	6	18	191%	-
<b>30-day minimum</b>	43	15	-66%	0.00	7	19	169%	-
<b>3-day maximum</b>	1,071	38	-96%	0.01	539	193	-64%	0.22
<b>7-day maximum</b>	818	29	-96%	0.02	404	167	-59%	0.09
<b>30-day maximum</b>	432	24	-94%	0.00	240	131	-45%	0.04

### Climate change flow regime comparisons

The lack of downscaled climate model predictions of daily flows has prevented meaningful analysis of floodplain flows under climate change to date. Assessing flows at monthly time scales is not at a fine enough resolution to evaluate ecosystem functions relevant to high flow or flood events. The USGS CASCaDE data set provides a window into daily flow dynamics for some California watersheds.

Table 2-4 Reduction in Q2 and Q10 magnitude flows following major dam construction

Location	Q2	Q10
SAC	-52%	-48%
FR	-90%	-40%
AMR	-47%	-12%
YUBA	-54%	-15%
SJR	-31%	-21%

Comparing climate scenarios using magnitude values based on the Q2 and Q10 also shows the extent and direction of flow changes (Table 2-5). Under the warm-wet B1 scenario, Q2 flows increase by at least 19% except for SAC and YOLO. Under the hot-dry A2 scenario, Q2 flows for the tributaries FR, AMR, and YUBA also increase, though in significantly smaller percentages than under the B1 scenario. Magnitudes of Q10 flows under the A2 scenario decrease compared to the current flow regime for all sites. Under the B1 scenario, only SJR and YOLO show Q10 magnitudes decreasing from current flow regimes, while the other sites have increases in Q10 flow magnitudes under climate change.

Table 2-5. Flows that meet the frequency criteria used to define the small and large floods, based on calculations of 2-year and 10-year recurrence intervals, respectively, for the hot-dry A2 scenario and warm-wet B1 scenario compared to the current flow regime

Flows (cms) based on 2-year recurrence interval				Percent change	
Location	A2 scenario	B1 scenario	Current	A2 scenario	B1 scenario
SAC	1,111	1,484	1,502	↓ 26%	↓ 1%
FR	610	877	450	↑ 35%	↑ 95%
AMR	470	714	376	↑ 25%	↑ 90%
YUBA	433	616	326	↑ 33%	↑ 89%
SJR	204	329	277	↓ 26%	↑ 19%
YOLO	209	585	806	↓ 74%	↓ 27%
Flows (cms) based on 10-year recurrence interval				Percent change	
SAC	2,403	3,325	3,071	↓ 22%	↑ 8%
FR	1,666	2,581	1,992	↓ 16%	↑ 30%
AMR	1,361	2,265	1,664	↓ 18%	↑ 36%
YUBA	1,090	1,781	1,503	↓ 28%	↑ 18%
SJR	576	914	1,044	↓ 45%	↓ 12%
YOLO	3,716	6,697	8,260	↓ 55%	↓ 19%

*Environmental Flow Components: Magnitudes, durations, and timing*

The Q2 and Q10 thresholds inform the IHA generation of environmental flow components that I use to compare the current flow regime and climate change scenarios using median values and deviation factors (Table 2-6). These numeric results are summarized qualitatively by significance in the Table 2-7. Extreme low flows have smaller peaks for all sites and longer



durations under A2, but durations are not significantly different under B1. Both YUBA and AMR sites show the largest shifts in timing and demonstrate significantly earlier maximum annual flows in both B1 and A2 scenarios. Magnitudes of 30-day maximum and minimum annual peaks under the A2 scenario are lower for most sites. The B1 scenario 30-day maximum flows are significantly higher than under the current flow regime at AMR and FR.

The thresholds defining small floods (Q2) and large floods (Q10) used in the IHA generation of environmental flow components assign flow event types using the daily hydrographs (Figure 2-3). Small flood events are all shorter with the exception of those at SAC, where climate scenario events are longer than current regime events. The A2 scenario shows significant small flood duration deviations from 78% to 70% to 46% shorter for YUBA, AMR, and FR, respectively. B1 scenario small floods are also consistently shorter, with the exception of SAC and SJR. All sites' median small flood peaks are lower for both climate scenarios, except for at SAC and YOLO. Timing changes of small flood events presented a consistent pattern of shifts earlier in the year for both climate scenarios for all sites.

Large floods under the A2 scenario are of shorter duration than seen in the current flow regime, except for SJR. The B1 scenario large flood durations are shorter for all sites. Large flood peaks are greater than in the current regime for FR, SAC, SJR and YOLO under B1 scenario flows, though A2 scenario large flood peaks are all smaller than that of the current regime except for FR. Timing of large floods generally shows no significant trend in climate scenarios.

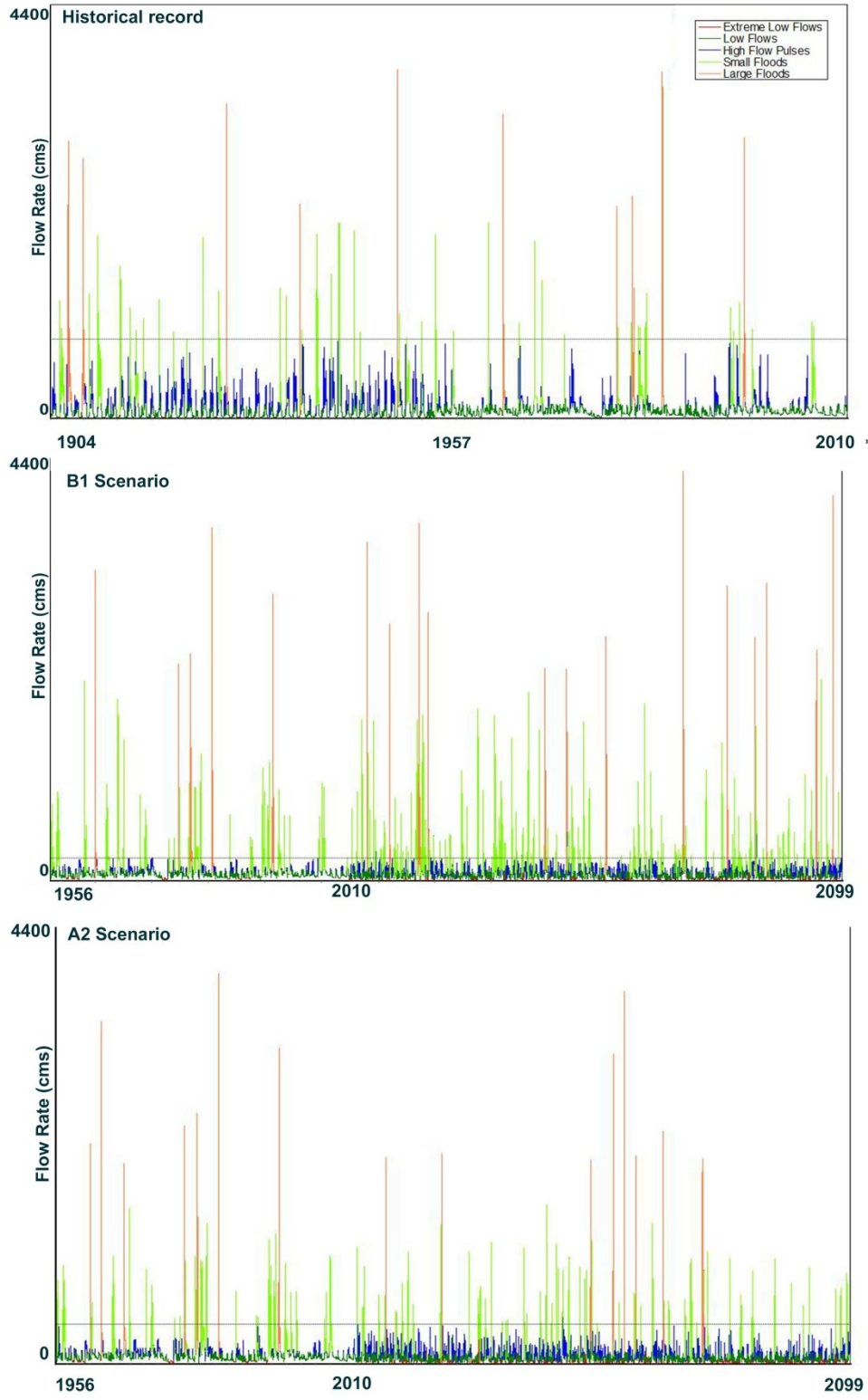


Figure 2-3. Example daily hydrographs for AMR site labeled as EFCs for extreme low flows (red), low flows (aqua), high flow pulses (dark blue), small floods (green), and large floods (orange) for pre-dam (1905-1957), post-dam (1957-2010), and climate change (2011-2099) records. Horizontal black line is the threshold for small floods.

Table 2-6. IHA results by flow type characteristic. \* indicates significant changes from current flow regime.

Location	EFC Parameters	Current	Future B1	Future A2	% B1 deviation	% A2 deviation
AMR	Extreme low duration (days)	8	9.5	13*	19%	63%
	High flow duration (days)	8.25	7.5	6.25	-9%	-24%
	Small flood duration (days)	60	19.25*	18.25*	-68%	-70%
	Large flood duration (days)	82	42	28.5	-49%	-65%
	3-day maximum (cms)	237.1	646.3*	395.2*	173%	67%
	7-day maximum (cms)	235.7	501.3*	336	113%	43%
	30-day maximum (cms)	194.6	250.1*	196.1	29%	1%
	Extreme low peak (cms)	21.42	17*	13.59*	-21%	-37%
	High flow peak (cms)	143	166.3*	158.8*	16%	11%
	Small flood peak (cms)	784.4	635.3	655.2	-19%	-16%
	Large flood peak (cms)	2384	2324	1987	-3%	-17%
	Extreme low timing (Julian day)	258	242	221*	-9%	-20%
	High flow timing (Julian day)	169	144.5*	133.8*	-13%	-19%
	Small flood timing (Julian day)	49	34.75	30*	-8%	-10%
Large flood timing (Julian day)	22	22.5	43	0%	11%	
FR	Extreme low duration (days)	6	11*	11*	83%	83%
	High flow duration(days)	16.75	10.5*	8.75*	-37%	-48%
	Small flood duration(days)	61.5	33*	33*	-46%	-46%
	Large flood duration(days)	60.5	54	53	-11%	-12%
	3-day maximum (cms)	363.4	824.1*	516.2*	127%	42%
	7-day maximum (cms)	324.2	711.4*	460.7*	119%	42%
	30-day maximum (cms)	242.3	405.2*	299.5	67%	24%
	Extreme low peak (cms)	29.59	15.7*	16.2*	-47%	-45%
	High flow peak (cms)	205.6	234.5*	230.1*	14%	12%
	Small flood peak (cms)	940.1	733.3	753.9	-22%	-20%
	Large flood peak (cms)	2461	2938	2507	19%	2%
	Extreme low timing (Julian day)	109	133	61*	13%	-26%
	High flow timing (Julian day)	189.5	175.5	179.5	-8%	-5%
	Small flood timing (Julian day)	60	58	57.5	-1%	-1%
Large flood timing (Julian day)	20.5	32	29.5	6%	5%	
SAC	Extreme low duration (days)	8	7	7	-13%	-13%
	High flow duration (days)	2.5	5*	4*	100%	60%
	Small flood duration (days)	38	42.5	44	12%	16%
	Large flood duration(days)	80	56	65	-30%	-19%

Location	EFC Parameters	Current	Future B1	Future A2	% B1 deviation	% A2 deviation
SAC	3-day maximum (cms)	1422	1471	876	3%	-38%
	7-day maximum (cms)	1222	1339	720	10%	-41%
	30-day maximum (cms)	778	793	471*	2%	-40%
	Extreme low peak (cms)	146	131*	131*	-10%	-10%
	High flow peak (cms)	517	464*	468*	-10%	-9%
	Small flood peak (cms)	2073	2015	2164	-3%	4%
	Large flood peak (cms)	3483	3516	3370	1%	-3%
	Extreme low timing (Julian day)	352	325*	344	-15%	-4%
	High flow timing (Julian day)	61	141*	138*	44%	42%
	Small flood timing (Julian day)	33	23	33	-5%	0%
	Large flood timing (Julian day)	61	28*	9	-18%	-28%
	YUBA	Extreme low duration (days)	5	6.5	6.5	30%
High flow duration (days)		4	5.25	5.5*	31%	38%
Small flood duration(days)		106.5	30	23.75*	-72%	-78%
Large flood duration(days)		147	42	31	-71%	-79%
3-day maximum (cms)		242.8	542.7	354.2*	124%	46%
7-day maximum (cms)		175.8	428.2	311.9*	144%	77%
30-day maximum (cms)		131	233.3	162.4	78%	24%
Extreme low peak (cms)		9.656	6.074	5.621*	-37%	-42%
High flow peak (cms)		99.11	111.5	111.5	12%	12%
Small flood peak (cms)		707.9	562.9	528.7*	-20%	-25%
Large flood peak (cms)		2622	2237	2178	-15%	-17%
Extreme low timing (Julian day)		217	207.3	199.8	-5%	-9%
High flow timing (Julian day)		50	112	72*	34%	12%
Small flood timing (Julian day)		60	39.5	30.75*	-11%	-16%
Large flood timing (Julian day)	1	23	15.5	12%	8%	
SJR	Extreme low duration (days)	4	4	5.5*	0%	38%
	High flow duration(days)	4.5	6*	4.5	33%	0%
	Small flood duration(days)	140	81*	89	-42%	-37%
	Large flood duration(days)	353	127	167	-64%	-53%
	3-day maximum (cms)	162.6	310.5*	187.5	91%	15%
	7-day maximum (cms)	154.9	297.3*	180.2	92%	16%
	30-day maximum (cms)	126.5	227.2*	140.1	80%	11%
	Extreme low peak (cms)	28.6	27.8	27.2*	-3%	-5%
	High flow peak (cms)	129.2	145.8*	143*	13%	11%
Small flood peak (cms)	684	367*	387*	-46%	-43%	

Location	EFC Parameters	Current	Future B1	Future A2	% B1 deviation	% A2 deviation
SJR	Large flood peak (cms)	1402	1383	1179	-1%	-16%
	Extreme low timing (Julian day)	230	228	224	-1%	-3%
	High flow timing (Julian day)	39	77*	74	21%	19%
	Small flood timing (Julian day)	68	58	57	-5%	-6%
	Large flood timing (Julian day)	35	36	55	1%	11%
YOLO	Extreme low duration (days)	4	5	4.5	33%	20%
	High flow duration(days)	8	9*	7	20%	-7%
	Small flood duration(days)	47	68	35.5	44%	-25%
	Large flood duration(days)	72	40	30.5	-44%	-58%
	3-day maximum (cms)	1031	506.9	176.9	-51%	-83%
	7-day maximum (cms)	810	371.2	112.8	-54%	-86%
	30-day maximum (cms)	299	176.2	39.3	-41%	-87%
	Extreme low peak (cms)	0	0*	0*	-100%	-100%
	High flow peak (cms)	48	61.74*	52.39	28%	8%
	Small flood peak (cms)	2818	3464	2870	23%	2%
	Large flood peak (cms)	10450	11380	9310	9%	-11%
	Extreme low timing (Julian day)	295	75	46	-80%	-64%
	High flow timing (Julian day)	48	82*	60.5	19%	7%
	Small flood timing (Julian day)	37	31	31	-3%	-3%
	Large flood timing (Julian day)	3	12	31	5%	16%

Table 2-7. Qualitative descriptions of significant flow changes by location and flow type

<b>Hot-dry A2 Scenario</b>					
<b>Site</b>	<b>Large floods</b>	<b>Small Floods</b>	<b>High Flows</b>	<b>Extreme Low Flows</b>	<b>Base flow index</b>
AMR	No sig change	Duration shorter; flows earlier	Peaks higher; flows earlier	Duration longer; Peaks reduced; flows earlier	Lower baseflows
FR	No sig change	Duration shorter	Duration shorter; Peaks higher	Duration longer; Peaks reduced; flows earlier	Lower baseflows
SAC	No sig change	No sig change	Duration longer; Peaks reduced; flows later	Durations longer; Peaks reduced	Lower baseflows
YUBA	No sig change	Duration shorter; Peak reduced; flows earlier	Duration longer; flows later	Peaks reduced	Lower baseflows
SJR	No sig change	Peaks reduced	Peaks higher	Duration longer; Peaks reduced	Lower baseflows
YOLO	No sig change	No sig change	No sig change	Peaks lower	No sig change
<b>Warm-wet B1 Scenario</b>					
AMR	No sig change	Durations shorter	Peaks higher; flows earlier	Peaks reduced	Lower baseflows
FR	No sig change	Durations shorter	Durations shorter; Peaks higher	Duration longer; Peaks reduced	Lower baseflows
SAC	Flows earlier	Durations longer	Durations longer; Peaks reduced; flows later	Durations longer; Peaks reduced; Flows earlier	Lower baseflows
YUBA	No sig change	Duration shorter; Peaks reduced; flows earlier	Durations longer; flows later	Durations longer; Peaks reduced	Lower baseflows
SJR	No sig change	Duration shorter; Peaks reduced	Durations longer; Peaks higher; flows later	Flows later	No sig change
YOLO	No sig change	Longer durations	Later events	Peaks lower	No sig change

*Seasonality changes*

The shifts of high flow and flood events by seasons were examined using seasonal magnitude-duration plots (Figures 2-4 to 2-9). Small and large flows defined by Q2 and Q10 threshold minimums were aggregated in a data set for the current flow regime and climate change regimes. The plots create distinct patterns of season, duration, and magnitude characteristics of flow events by site. The seasons are seen in the different marker shapes, plotted as flows versus durations. Overall, sites show larger winter peak flows in the B1 scenarios and the median spring duration of flow events is shortened and generally reflects smaller spring peaks. SAC B1 scenario flow magnitudes extend beyond the current flow regime range, while the A2 flows are mostly smaller and lack spring events. YOLO events under either climate scenario still

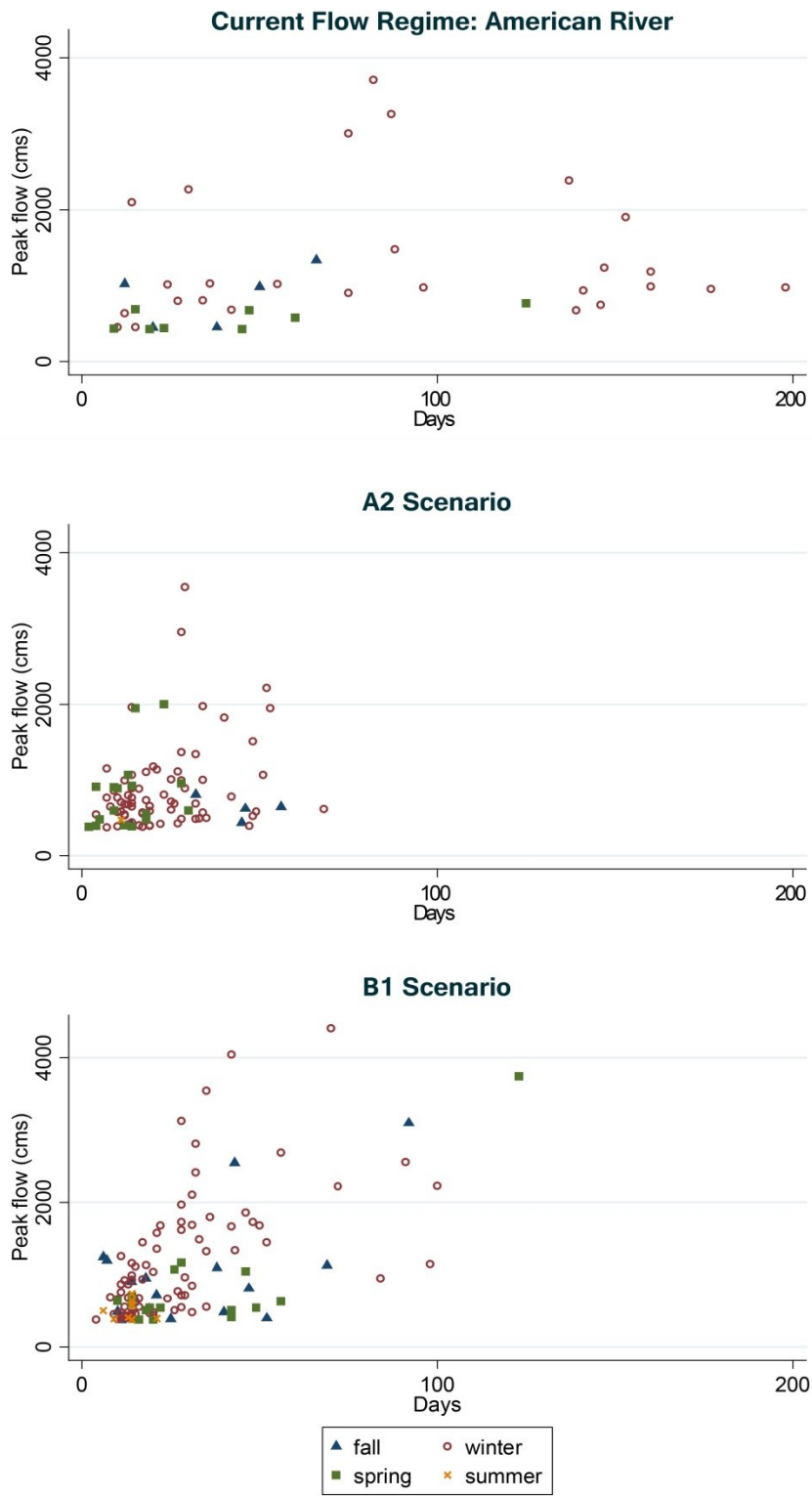


Figure 2-4. Season-Magnitude-Duration plot for American River at Fair Oaks (AMR) current flow regime (1956-2010) contrasted with climate scenarios (2011-2099).

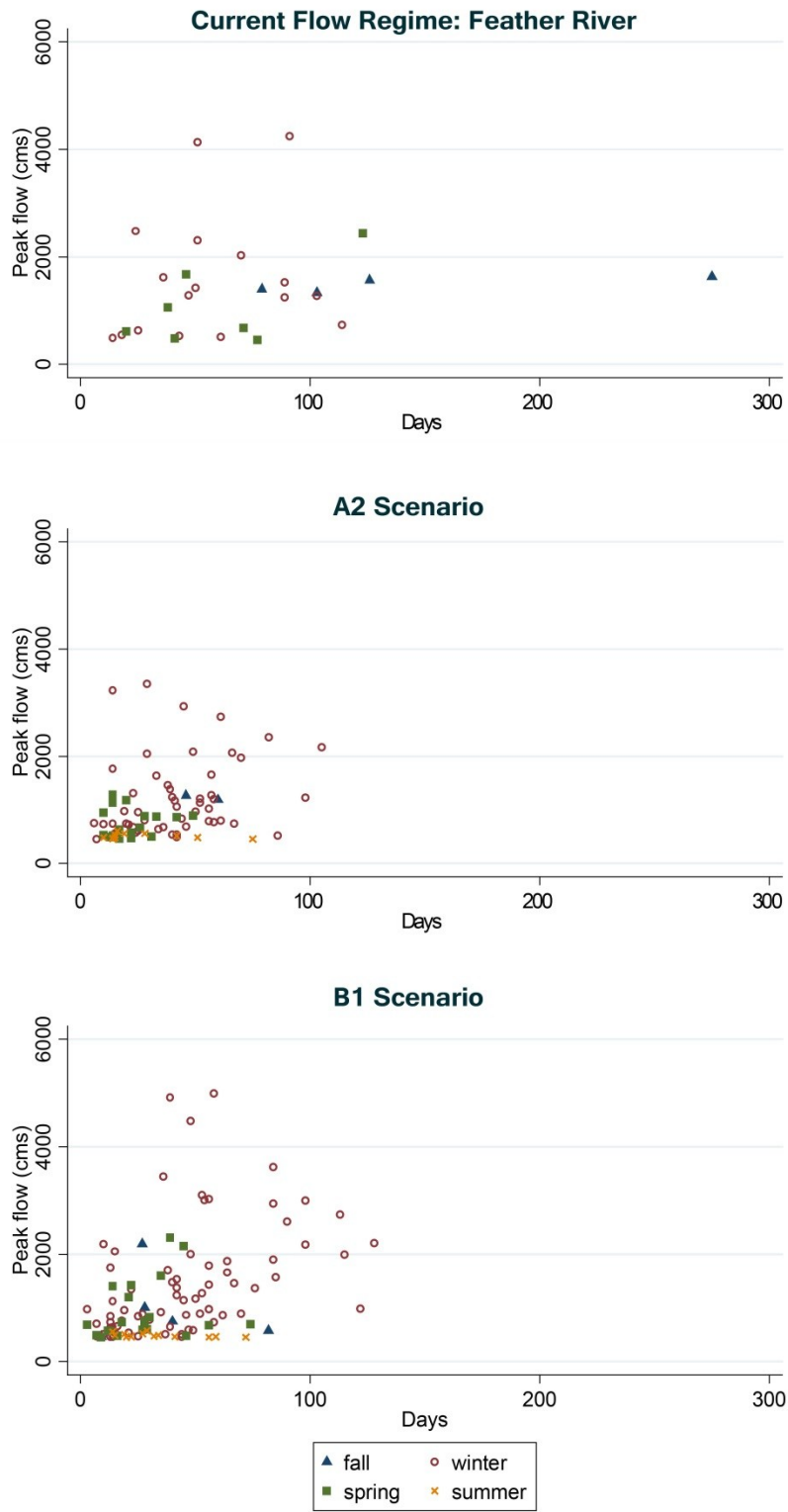


Figure 2-5. Season-Magnitude-Duration plot for Feather River near Gridley (FR) current flow regime (1968-2010) contrasted with climate scenarios (2011-2099).



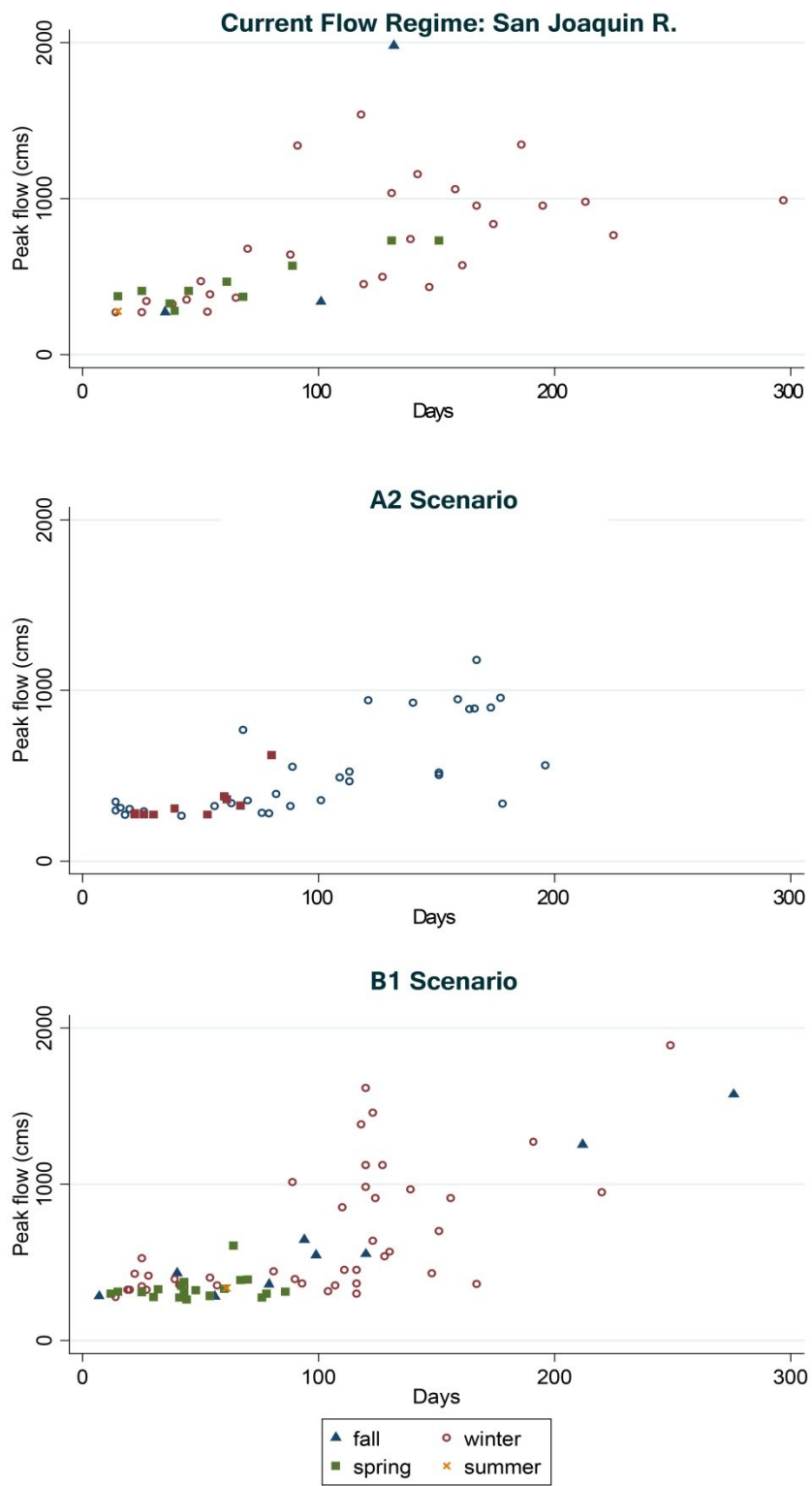


Figure 2-6. Season-Magnitude-Duration plot for San Joaquin River near Vernalis (SJR) flow regime (1943-2010) contrasted with climate scenarios (2011-2099). Note 9/2/1982 588 day flow event is not shown.

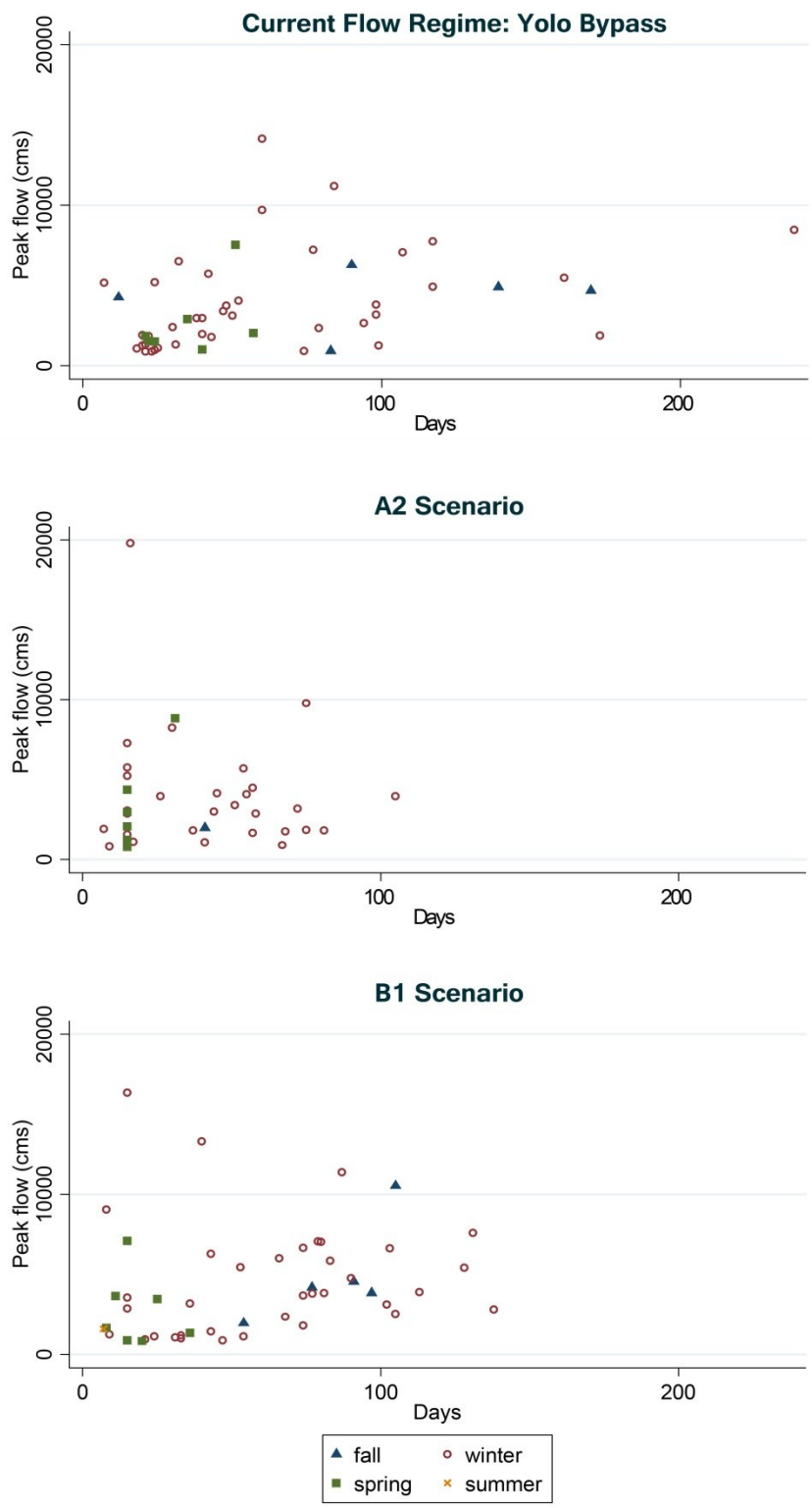


Figure 2-7. Season-Magnitude-Duration plot for Yolo Bypass (Based on DAYFLOW records) current flow regime (1945-2010) contrasted with climate scenarios (2011-2099).

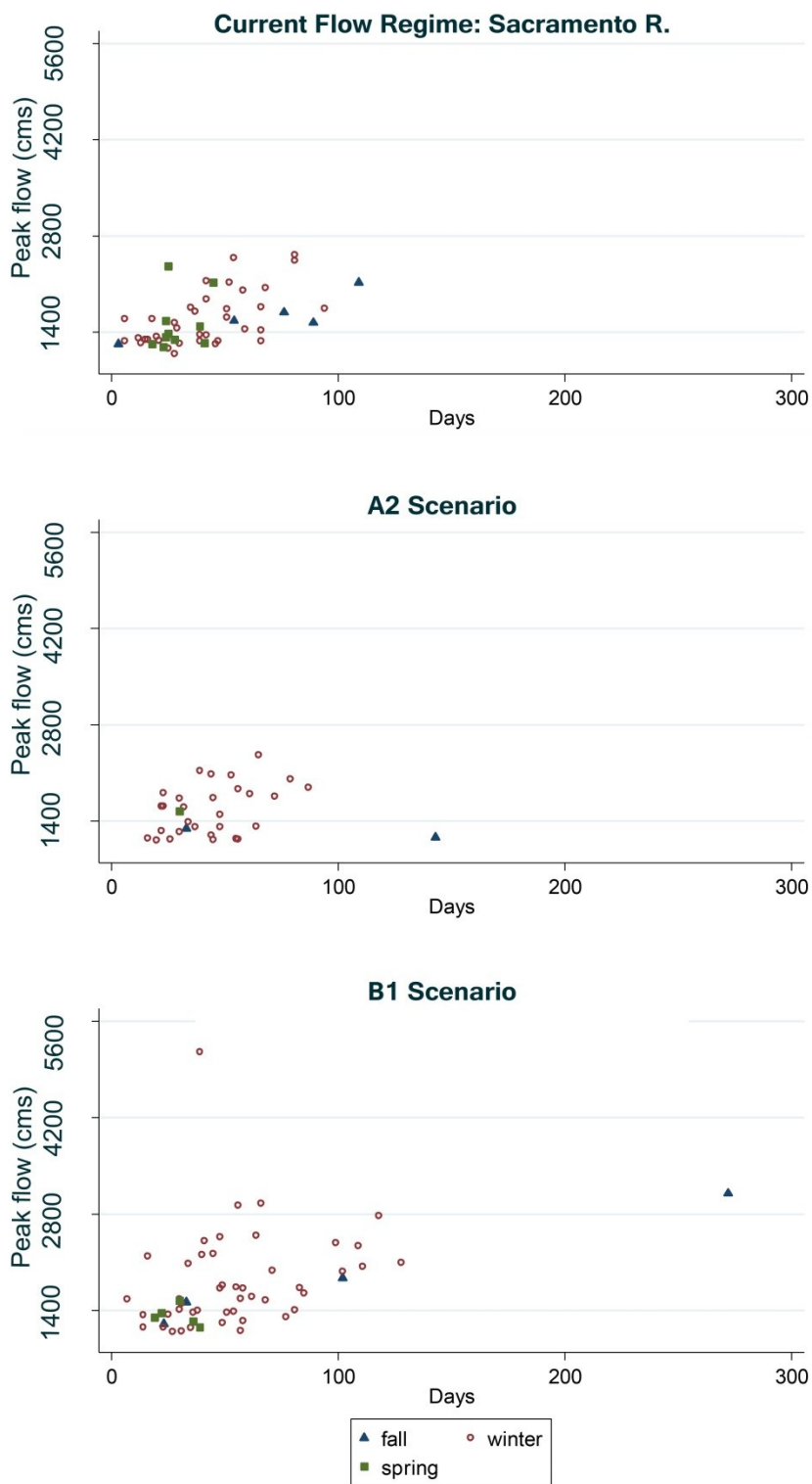


Figure 2-8. Season-Magnitude-Duration plot for Sacramento River above Bend Bridge (SAC) flow regime (1945-2010) contrasted with climate scenarios (2011-2099).

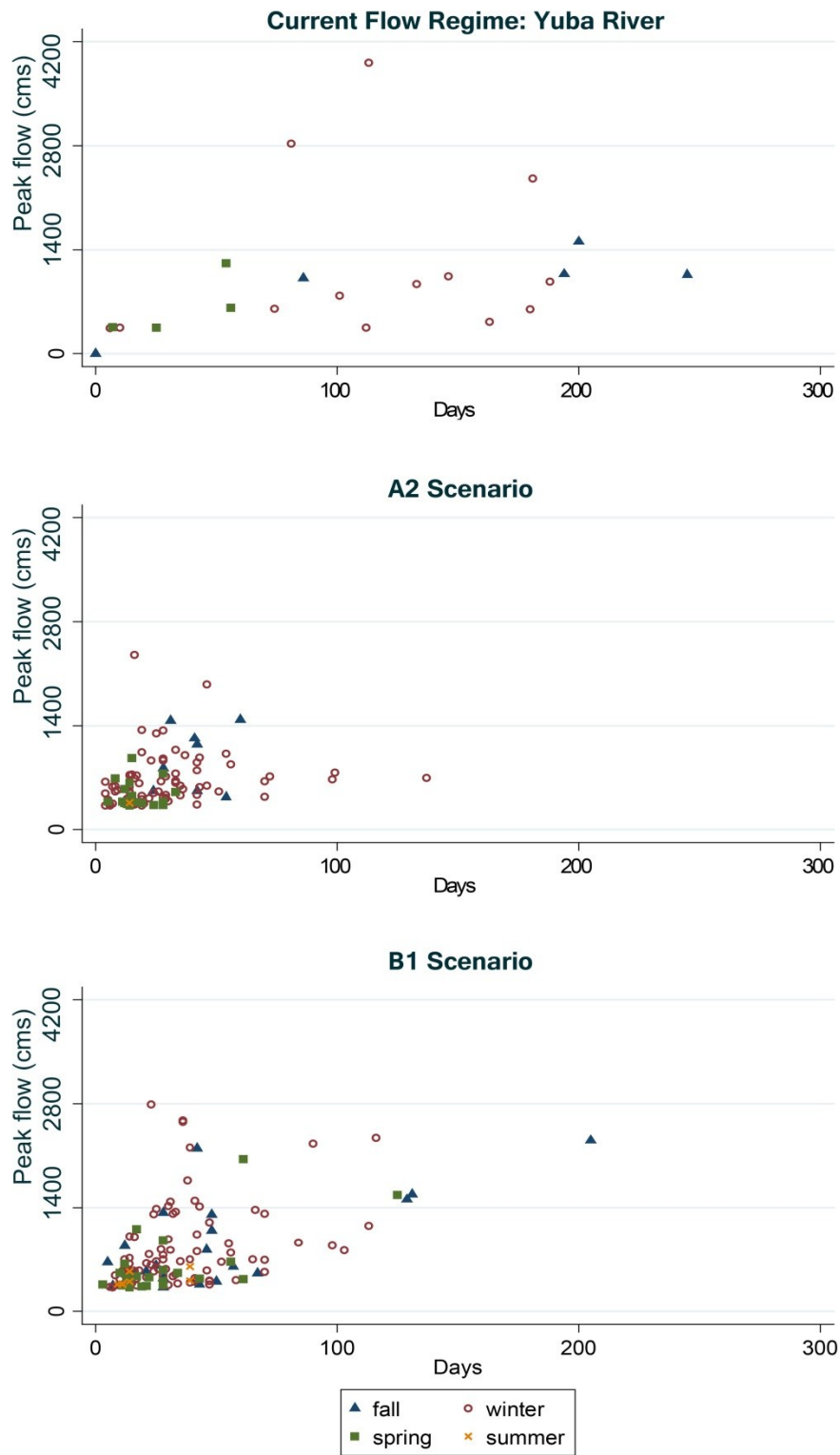


Figure 2-9. Season-Magnitude-Duration plot for Yuba River at Marysville (YUBA) current flow regime (1944-2010) contrasted with climate scenarios (2011-2099).

display extreme high flows, though long durations are rarer. The distribution of SJR B1 scenario events is similar to the current flow regime, though the A2 scenario events average a shorter duration.

The Sacramento River tributary watersheds AMR, FR, and YUBA all show more high flow/flood events occurring under both climate change scenarios than in the respective current flow regimes. In fact, the climate change events occur in over 90% of the years of record and the majority fall in winter. The tributary watersheds also have clusters of climate scenario events in the low duration-low magnitude range that include summer flows. While A2 regime events occur more frequently than current regime events in the tributary watersheds, SAC, SJR, and YOLO indicate fewer events under A2 regime. Of this subset, only SJR shows more frequent high flow events under the B1 regime compared to the current flow regime and 27% of the SJR B1 events occur in spring compared to 23% under the current flow regime.

Though there are more total events, spring events occur less frequently under both climate scenarios for the tributary watersheds AMR, FR, and YUBA. SAC shows decreases of at least 10% (B1 scenario) for the frequency of spring events under climate change. SJR shows higher frequency of spring events under the B1 scenario (+4%) and the A2 scenario (+1%). The YOLO events inundate a flood bypass and tend to start in winter and often last into the spring season, so the spring event changes under climate scenarios are less informative.

*Flow frequency comparisons*

Flow frequency relationships derived by fitting LPIII distributions to annual peak data for climate scenarios and the current flow regime were compared using Wilcoxon (Mann-Whitney) signed rank tests (Table 2-8). Figure 2-10 shows an example of overlapping flow frequency curves for SAC. The more frequent flows (higher than 50% probability of exceedance) are higher under the current flow regime than climate scenario curves, but begin to overlap for higher magnitude flows. Flow frequency curves at all sites show statistically significant differences between A2 and B1 regimes. Only AMR shows a lack of significance for A2 regime versus current flows at the  $p < 0.10$  level. At the  $p < 0.10$  value, SAC and YOLO do not show significant differences for B1 versus current flow regimes.

Table 2-8. Mann-Whitney p-values for signed rank test used to determine significant differences between flow frequency curves

Location	Flow regime comparison		
	A2 vs. B1	A2 vs. Current	B1 vs. Current
AMR	0.0016	0.1121	0.0001
FR	0.0024	0.0282	0.00001
YUBA	0.0043	0.0476	0.0001
SAC	0.0019	0.0024	0.8631
YOLO	0.0018	0.0001	0.2969
SJR	0.00001	0.0845	0.0576

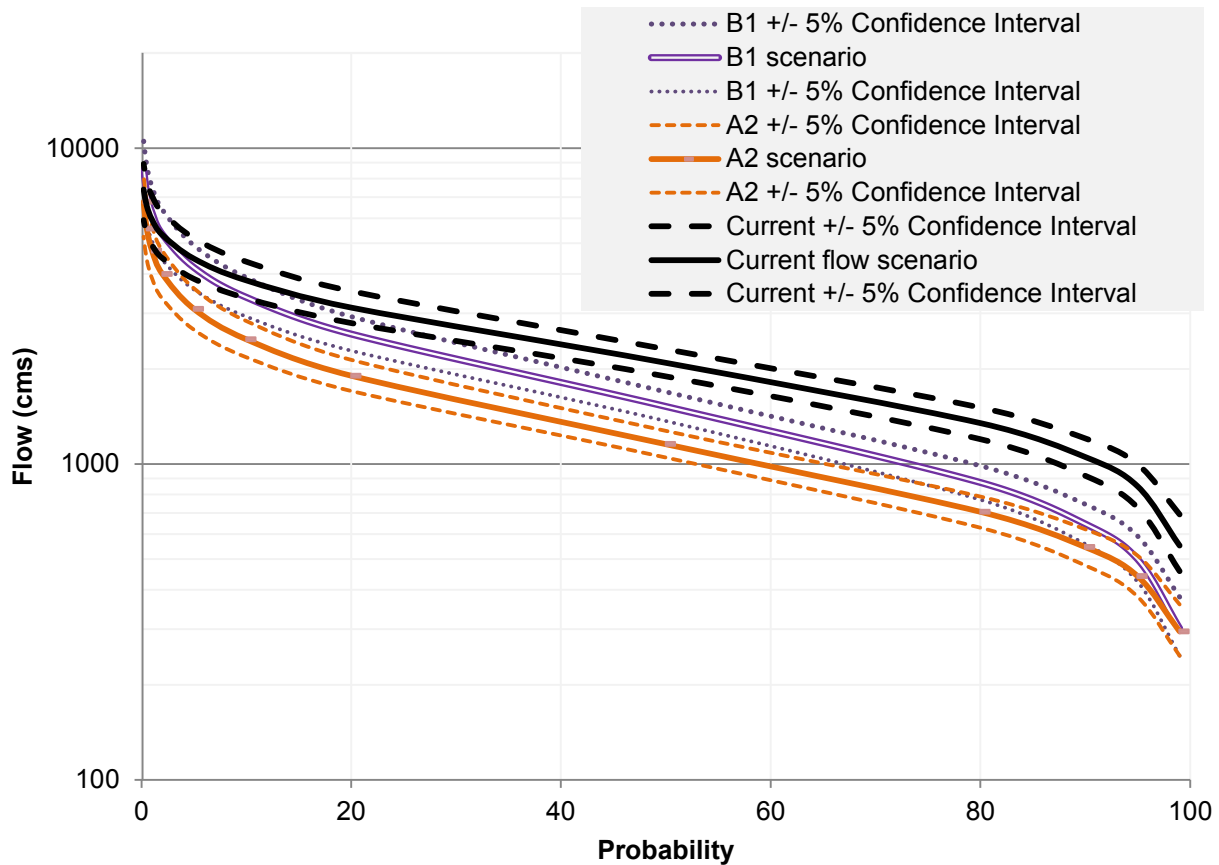


Figure 2-10. Example flow frequency curve comparison for SAC. The post-Shasta dam flow regime (1946-2010) is compared to frequency curves from hot-dry A2 and warm-wet B1 climate scenarios (2011-2099).

To compare not just annual, but seasonal flow frequency trends, I compared FDCs for the sites (Figure 2-11 and 2-12). The B1 scenarios all show some annual surplus except for at YOLO, with YUBA showing the highest percent change of 26%. Under the A2 scenario YOLO shows the largest annual deficit percentage (59%), followed by SJR and AMR. Seasonal trends point to the time of year the surplus and deficits are generally taking place. Fall shows largest deficits for YOLO under either climate scenario. Winter shows surplus flows for the B1 scenario for AMR, FR, and YUBA all over 35%. YOLO under the A2 scenario in winter is the largest deficit (-55%), followed by SJR (-35%). Spring comparisons reveal deficit values in all site scenarios except for YUBA and SJR, which each show 12% surplus ratios. The A2 scenario consistently results in larger deficits for all locations. Lastly, summer trends indicate surplus flows at FR of over 30% for either climate change scenario.

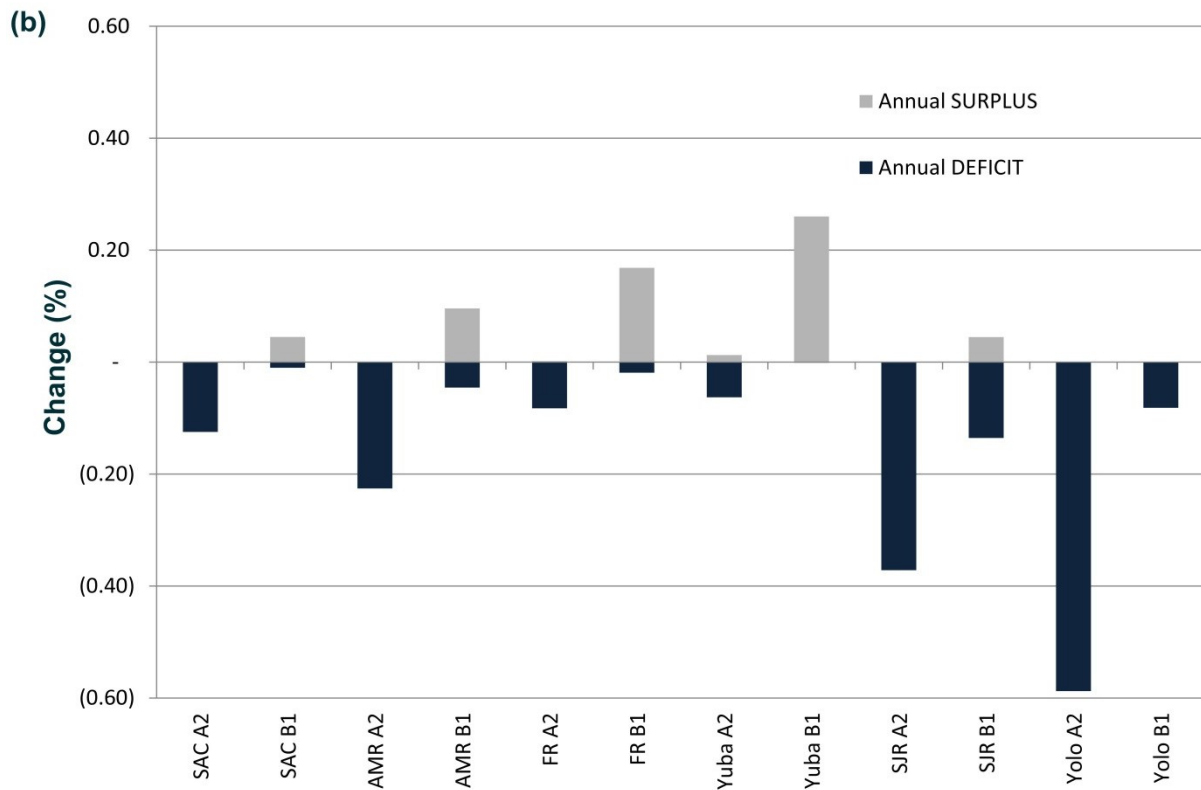
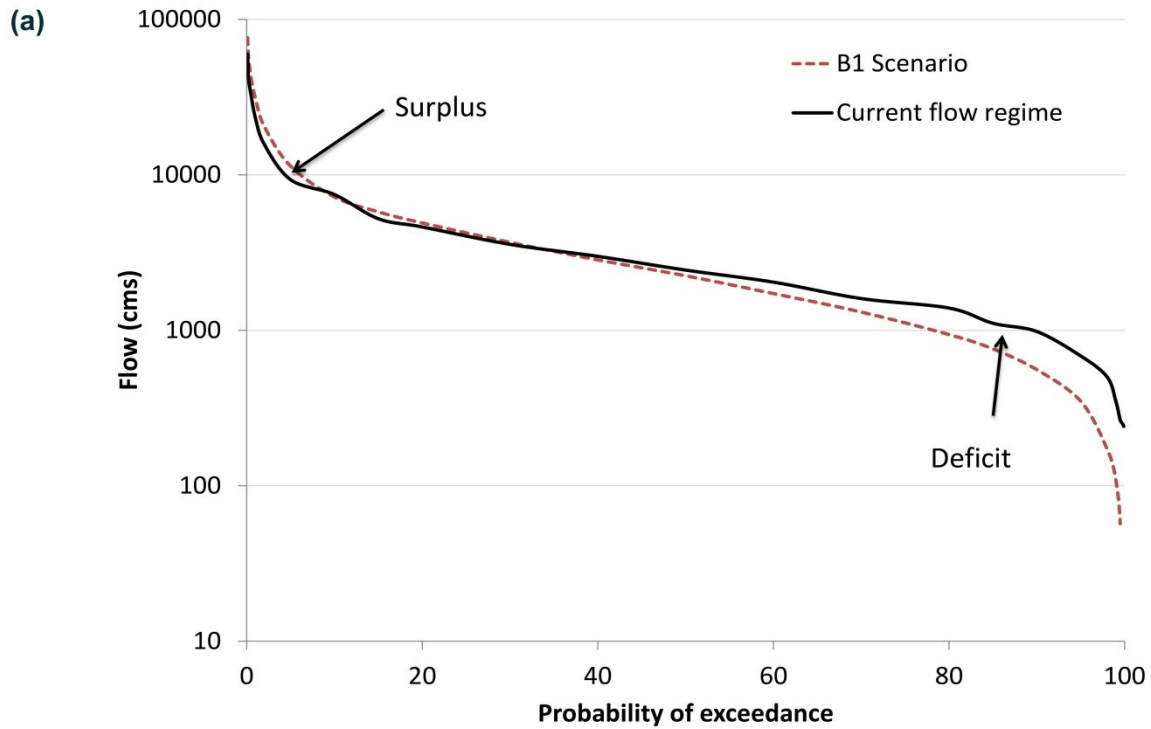


Figure 2-11. (a) Example of surplus and deficit flows for climate change and current flow regime FDCs at AMR and (b) Climate change scenario annual deficit and surplus values for all sites

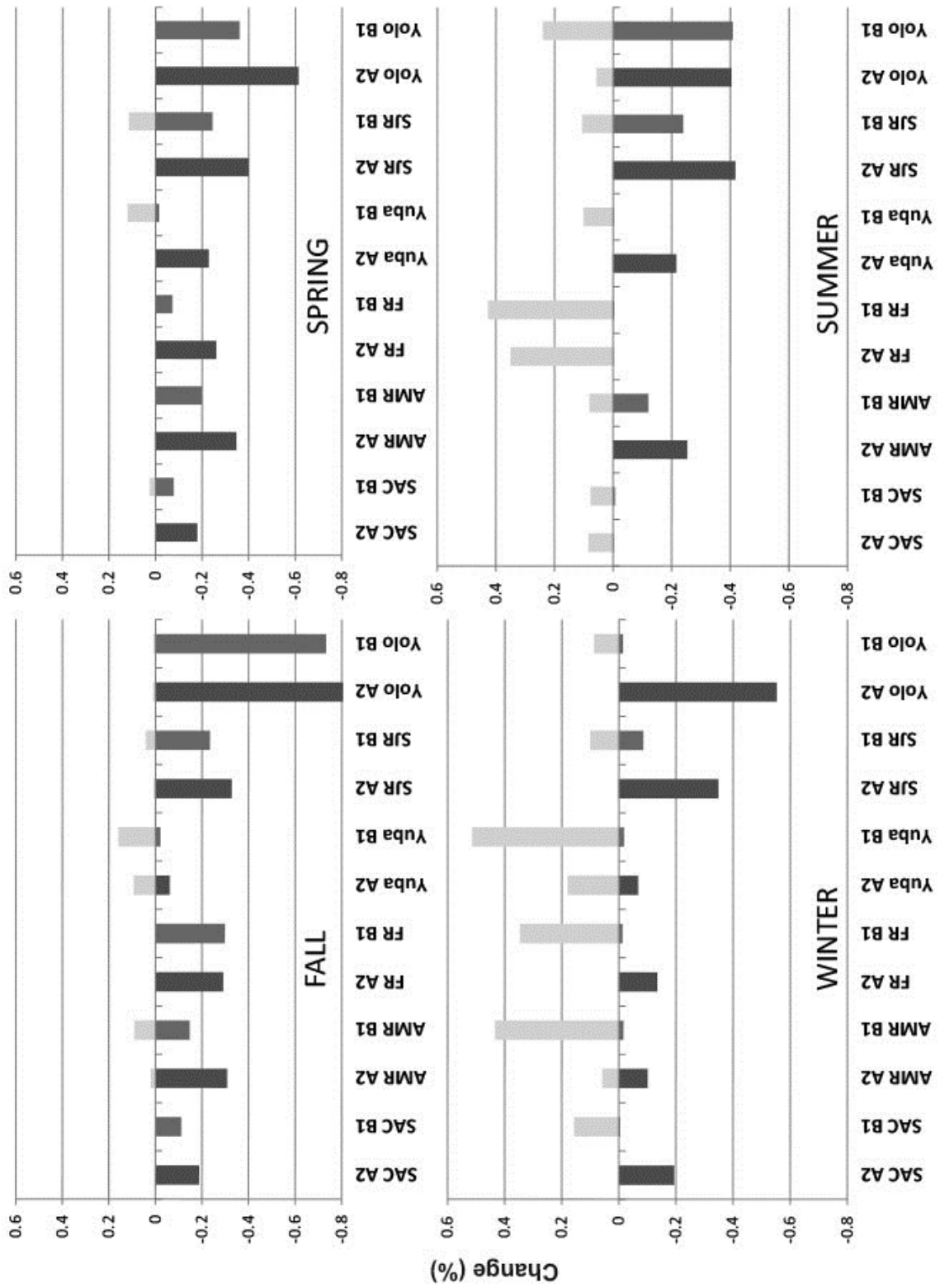


Figure 2-12. Seasonal deficit (negative values) and surplus (positive values) for SAC, AMR, FR, YUBA, SJR and YOLO



## DISCUSSION

Sacramento River tributary watersheds draining Sierra Nevada Mountain areas, the Feather, American, and Yuba Rivers, will likely be influenced by temperature changes that affect snow formation. As Null et al. (2010) point out, watersheds in the northern Sierra Nevada are most vulnerable to decreased mean annual flow. The analysis for FR, AMR, and YUBA demonstrate this effect with reduced mean annual flow observed for the hot-dry A2 scenarios. Watersheds with large areas that are at or near the historical snowline commonly experience winter rain or rain-on-snow occurrences, as seen in the Feather River watershed (NMFS 2009). Hence, the greatest change in the flow metrics is expected for these types of watersheds under the hot-dry A2 climate scenario. I did observe significant shorter small flood durations for FR, AMR, and YUBA, though no significant changes are seen in the characteristics large flood events.

Runoff timing changes were consistent with projections for southern-central watersheds (Null et al. 2010). A shift can be seen as small flood timing moves earlier in the season for both climate scenarios at SJR, the only site in the San Joaquin Basin. AMR and YUBA also display earlier small flood peaks under the climate change scenarios, which is consistent with these watershed's exposure to upstream snowmelt.

In the SAC location, results are counter to what was observed at the other sites. Under both climate scenarios small flood durations are longer than observed in the current flow regime. The Q2 flow is reduced in both climate scenarios, and high flow peaks are significantly smaller under climate change. The magnitude of the Q10 flow, however, is increased under the B1 scenario. Interpreting results for SAC are complicated by the operation of Trinity River water transfers into the basin and its large size (drainage upstream is over 23,000 km<sup>2</sup>).

Yolo bypass results are not completely comparable to sites directly on rivers. The bypass is typically inundated during the wet season when flows overtop Fremont Weir, but tributary input can be substantial and cause localized flooding at times when Sacramento River water is not spilling into the system. Only high flows under the B1 scenario at YOLO show significant differences between current flow regime with higher peaks, shorter durations and later events, but small and large floods also have higher peaks. Large flood durations are reduced at the bypass site for both climate scenarios, and A2 small floods will have shorter durations though similar peak flows to those seen in the current flow regime. While the B1 scenario could contribute to wet events that have higher peaks than are typical now, durations of flood events under climate change will likely be reduced. The frequency of the bypass experiencing flooding greater than or equal to the Q2 flow is also questionable, as flooding events under the B1 scenario only occur in 55% of years and 43% of years under A2, compared to the 78% frequency observed from 1946 to 2010. This change in flood frequency has potential to affect biota that depend on frequently inundated floodplain habitat (Benigno and Sommer 2008).

Overall, sites show larger winter peak flows in the warm-wet B1 scenarios and the median spring duration of flow events is shortened with lower peak flows. This is consistent with the expectations that warmer conditions can reduce the volume of the snowpack, contributing to higher flood peaks during the rainy season and reduced warm-season flows after April (Knowles and Cayan, 2002). Another way to approach seasonal analysis relies on using FDCs to compare flow regimes based on the percentage of time flow is equaled or exceeded. The most striking and consistent messages of the seasonal FDC comparisons are: 1) consistently higher surplus

percentage for B1 winter flows and 2) deficit flows in spring at all sites. This finding supports the evidence seen in the magnitude-season-duration plots that spring flows will consistently be reduced under climate change scenarios, even under the warm-wet B1 climate change scenario. Only the Yuba site shows more spring surplus under the B1 scenario. The dams upstream of the lower Yuba River (New Bullards Bar and Englebright Dam) do not currently suppress the effects of large floods; and the South and Middle Yuba Rivers have no large dams to abate winter floods associated with large rainstorms, rain-on-snow events, or spring snowmelt events (Yuba County Water Agency 2012).

FDC comparisons of surplus and deficit do not indicate the quantities of flow found in any given season, but only the proportion of change from the current flow regime. Thus, the 40% summer deficits in YOLO reflect small amounts of deficit flows from the current flow regime, as summer flows can be zero or quite small in the bypass. Another reason for a B1 scenario spring surplus at YUBA could be related to the overall increase in flow quantity that B1 climate change produces at the site compared to the current flow regime.

Evaluating the impact of climate change on flood frequency is complex, and there is no standard or agreed upon way to do it (Dettinger et al. 2009; Stedinger and Griffis 2011). The traditional concept of flood frequency requires the assumption that annual maximum floods are independent and identically distributed random variables. It is difficult to estimate flood frequencies from estimated future hydrographs under different climate scenarios because these models assume a directional trend that violates the assumption that each year is independent. The concept of climate change exemplifies non-stationarity as temperatures and precipitation reflects a trend over time (Olsen 2006; Stedinger and Griffis 2011). Future changes with respect to extreme flooding events are also difficult to predict. Using only annual maxima can lead to underestimating the flows for more frequent events. In cases where the hydrograph contains multiple flood peaks per year, a partial-duration flow analysis might be better suited for examining flows that occur more frequently than once every 10 years.

### **Implications for floodplain restoration**

The season-duration-magnitude plots show more extreme events, supporting recent studies of atmospheric storms by Dettinger (2011) that suggest increased opportunities for both more frequent and more severe floods in California under projected climate changes. The threat of more extreme wet weather in California is particularly important given the state's reliance on levees to protect lives and property. Florsheim and Dettinger (2007) found that climate governs flood variability and thus still drives many levee breaks, noting that levee breaks and peak discharges cycle on a 12-15 year time. Thus, they suggest that historical flood-control effects have not reduced the occurrence or frequency of levee breaks. If warm-wet storm patterns increase in California, flood risk might increase.

Risk-based planning offers a robust way to identify strategies to manage water resources under climate change (Brekke et al. 2009). Adjusting reservoir flood-control rules under climate change will give water managers an important tool for adapting to future changes. Vicuna et al. (2007) estimated climate change impacts in California will result in smaller stream flows, lower reservoir storage and decreased water supply deliveries and reliability. At the same time, extreme events pose risks to communities living near levees. California will be undertaking more water infrastructure projects (new and/or redesigned water conveyance and operation of the State

Water Project and the federal Central Valley Project) and plans to mitigate impacts with habitat restoration addressing ecological stressors are being developed (California Natural Resources Agency 2012). Results show warm-wet B1 scenario flows might be more similar to pre-dam flow regimes (peak magnitudes in particular) than the current regulated flow regime. Thus, planning for potential impacts of climate change will be essential if resource managers are to minimize negative consequences of climate change and maximize the potential benefits that it may offer (Burkett et al. 2005).

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**CHAPTER 3**

**AN INTEGRATIVE METHOD FOR QUANTIFYING ECOLOGICALLY SIGNIFICANT FLOODPLAIN**

Mary K. Matella



# An Integrative Method for Quantifying Ecologically Significant Floodplain

## INTRODUCTION

Floodplains, intermittently inundated lands next to river channels, are some of the most productive terrestrial habitats in terms of monetary value and net primary productivity (Costanza et al. 1998). To restore self-sustaining floodplain habitat, efforts to rehabilitate ecologically significant floodplain should strive to recreate the function of the habitat rather than focusing on desired physical features alone. Most previous efforts to restore floodplain have not captured essential dynamics of the flows that once created the transient inundation characterizing these productive ecosystems. In fact, many restoration projects have been undertaken without information about duration, frequency, and intensity of floods (Henry and Amoros 1995). Though many recent efforts to categorize and describe floodplain have made technological advances, they often rely on static definitions related to instantaneous wetted land cover area (such as the 100-year floodplain). Baseline assessment and planning using traditional floodplain definitions employ area estimates as metaphorical currency, though they might incorporate a measure of change over time by comparing pre- and post-project habitat unit areas [e.g., Habitat Evaluation Procedures (U.S. Department of the Interior, 1980)]. Other recent advancements couple remotely acquired images with field based habitat assessments to improve the resolution of floodplain habitat in a watershed context, but do not make explicit the temporal nature of the water-land interactions at the sites (Konrad et al. 2008; Anderson et al. 2010). Such efforts that put restoration project plans in context of reference sites and capture wet and dry season flood images provide valuable information for floodplain restoration prioritization (Anderson et al. 2010), but they do not incorporate flow dynamics that are relevant for many ecological functions. Ecologically significant floodplain depends on dynamic flow components, and researchers are beginning to couple physical models with ecosystem response models (Poff et al. 1997; Shenton et al. 2012). This approach is taken here in the development of new metrics that link the spatial and temporal characteristics of floods and the habitat they create.

Connecting the characteristics of flow and area of floodplain allowing ecological response involves hydraulic modeling, spatial analysis, and statistical measures of flow regime—all standard methods and practices already widely in use. While the tools and input data are not new, the advancement presented here is developing a standard method of correlating and combining disparate model results, habitat requirements, and hydrologic scenarios into singular, streamlined evaluation criteria. Information on flow frequency, duration, seasonality, inundation, and habitat characteristics describing floodplain suitability based on the literature are essential for setting up ecological points of reference. For example, the splittail, a species of concern in California, does not reproduce well unless it has access to significant floodplain habitat in the spring in 1 of every 4 years (Sommer et al. 2002); the “spring” defines the seasonal requirement and the 1 in every 4 years defines the habitat frequency requirement.

To illustrate how this method can be used to synthesize data to create new metrics for evaluating and comparing floodplain reconnection projects, a modeling case study was created for restoring floodplain habitat on the Lower San Joaquin River, California. Today, many levees are vulnerable to failure in the region, and seepage outside of levees is common at high flows (DWR

2011). Historically, large inundated flood basins, shallow seasonal lakes, and backwater sloughs were common during winter and spring when high river flows spilled onto the land (Katibah 1984) and the San Joaquin River once supported one of the most productive in-river fisheries for Chinook salmon (*Oncorhynchus tshawytscha*) in the state of California (Yoshiyama et al. 1998). The potential functional floodplain area that could be created using a levee setback for floodplain reconnection was quantified using metrics that capture temporal and spatial dynamics.

## **METHODS**

Assembling data sets for statistical measures of flow regime, hydraulic modeling, and spatial analysis is the first step of the method. Input data consist of a DEM or land survey, gage data from nearby stations, and habitat criteria for species of concern. The tools employed for modeling hydraulic, ecosystem, and spatial relationships are varied and interchangeable with others that might produce the same types of outputs.

The temporal variables describing ecologically significant flow were distilled using the US Army Corps of Engineers (USACE) Ecosystems Function Model (HEC-EFM) (USACE 2009). HEC-EFM scans a time series of flow data and filters for season, duration, and rate of change. HEC-EFM is populated with daily flows at gage stations located on the river reach of interest. The tool can provide the flow and/or stage that occurs in each year that meets the timing and duration requirements set forth by a targeted ecosystem function or species of concern.

Standard probability statistics were then applied to this data set to create flow-frequency relationships for each timing and duration in the study. The U.S. Army Corps of Engineers Statistical Software Package (HEC-SSP) was used to define these frequency relationships and associated confidence intervals. This method uses a Log Pearson Type-3 (LPIII) distribution. The end product of this hydrologic analysis is a flow-frequency relationship for each flood timing/duration combination that is ecologically relevant.

A standard hydraulic model (HEC-RAS) was used to define the spatial characteristics of the river and floodplain system. The hydraulic model should be run through the entire suite of flows the system could encounter at an interval that gives sufficient resolution in showing how increased flows results in increased wetted floodplain areas. The output of the hydraulic modeling is a curve that relates inundated area to flow which may either be a direct model output in the case of 2D and 3D models or it may require an additional processing step in GIS for 1D models.

Combining the hydrologic and hydraulic analysis described above, one can quantify the available habitat or production areas in the study reach. By correlating the hydraulic model results for potential habitat area (defined, for simplicity here, as total connected inundated area) via the modeled flows to the hydrologic frequency analysis resulting from the HEC-EFM and HEC-SSP relationships, probability distributions for the amount of habitat expected for each flood timing and duration combination can be created (Figure 3-1). The result is a set of Area-Duration-Frequency (ADF) curves that define the potential floodplain habitat as a function of frequency for each flood duration. Using these curves, one can visualize the potential habitat over several durations and across multiple frequencies of occurrence. ADF curves allow direct quantification

of the effects of projects and plans that change the river-floodplain landscape (levee setbacks, side channel creation) or river hydrology (reservoir operations, climate change scenarios).

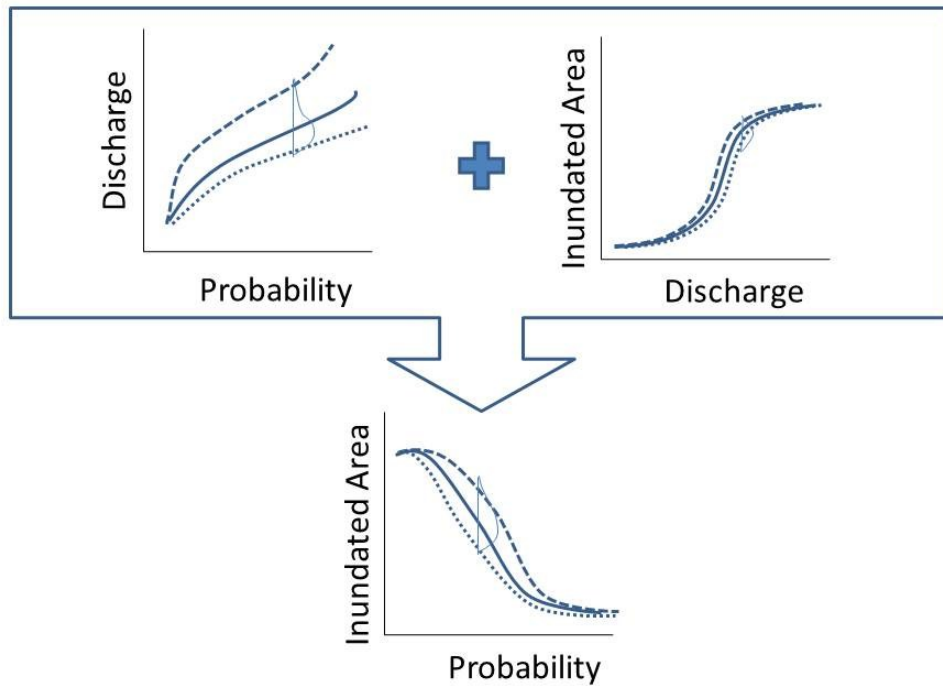


Figure 3-1. Components of Area-Duration-Frequency Curve Derivation

When considering the full probability distribution, one can create a value for expected annual habitat (EAH) analogous to the widely used expected annual damages (EAD) used in flood risk analysis (USACE 2008). By integrating each ADF curve over the interval  $f=0$  to  $f=1$ , annualized expected habitat values are generated which give the long-term statistical average quantity of habitat for each scenario. It is also possible to include bounds of uncertainty in the EAH method though the same process used in estimating uncertainty in flood damages (USACE 2008). For this study, Monte Carlo simulations were run to generate random numbers using a triangular distribution of possible values (low estimate 95% CI and high estimate 5% CI) at each 1% exceedance probability interval. The probability density function was used to calculate the probability weighted average habitat area by performing the following numerical integration and approximation:

$$EAH = \int_0^{\infty} Hf(H)dH \sim \sum_{i=1}^{i=N} H_i \Delta p \quad (1)$$

Where:

$H$  is habitat area

$N$  is number of observations

$p$  is exceedance probability

The discharge-exceedance probability and area-discharge functions were sampled with 1000 random iterations and EAH was computed each time by using the trapezoid rule to perform integration (Figure 3-2). The average of these simulations is the best estimate of the EAH.

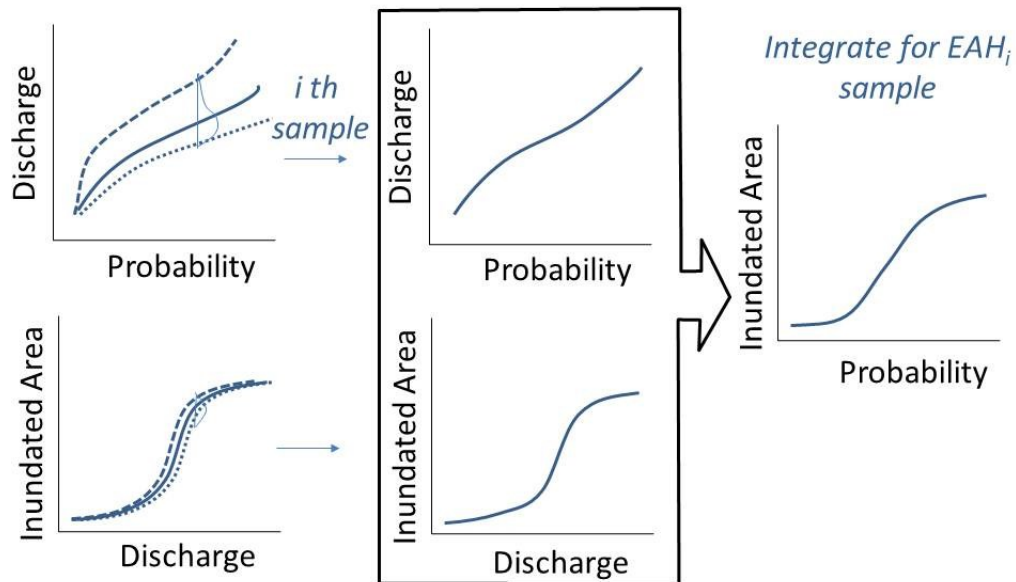


Figure 3-2. Diagram of Monte Carlo simulation algorithm to incorporate uncertainty in EAH estimates

## Case Study

In this case study, hydrologic connectivity for floodplain dependent taxa is examined for a small portion of the San Joaquin River, a waterway that once provided productive floodplain habitat for freshwater communities. The river reach from Vernalis to Mossdale on the San Joaquin River in the South Delta is vulnerable to levee failure and has been cited as a potential floodplain habitat restoration area (DWR 2011). Along this reach, a model of a hypothetical levee setback was constructed to explore restoration of ecologically significant floodplain (Figure 3-3).

The 1929-2010 record at the USGS Vernalis gage (station # 11303500) was used to specify the hydrologic regime, and served as the upstream end of the modeled reach. After establishing the daily flow regime in the EFM model, a seasonal filter was imposed for December-May. Then 1-day and 14-day durations were selected to span a range of flows beneficial to rearing salmonids (Moyle 2002). The resultant annual maximum flows that met these duration criteria were exported and fitted to a Log Pearson Type-3 (LPIII) distribution in HEC-SSP to generate 95% and 5% confidence intervals around the probability distribution.

The case study steady-state hydraulic model (HEC-RAS) represents two physical scenarios in the study area: 1) the existing condition where levees closely follow the channel alignment in the Vernalis to Mossdale Corridor, referred to as the “existing condition” and 2) a major setback of

the eastern levee along the Lower San Joaquin River including minor berm removals from nearby agricultural fields, referred to as the “levee setback” scenario. The physical scenario (i.e. the river and floodplain cross-sections) was created by combining a previously published model [USACE Comprehensive Study HEC-RAS model (USACE and Rec Board 2002)] with a topographic DEM derived from light detection and ranging (LiDAR) data (DWR 2010).

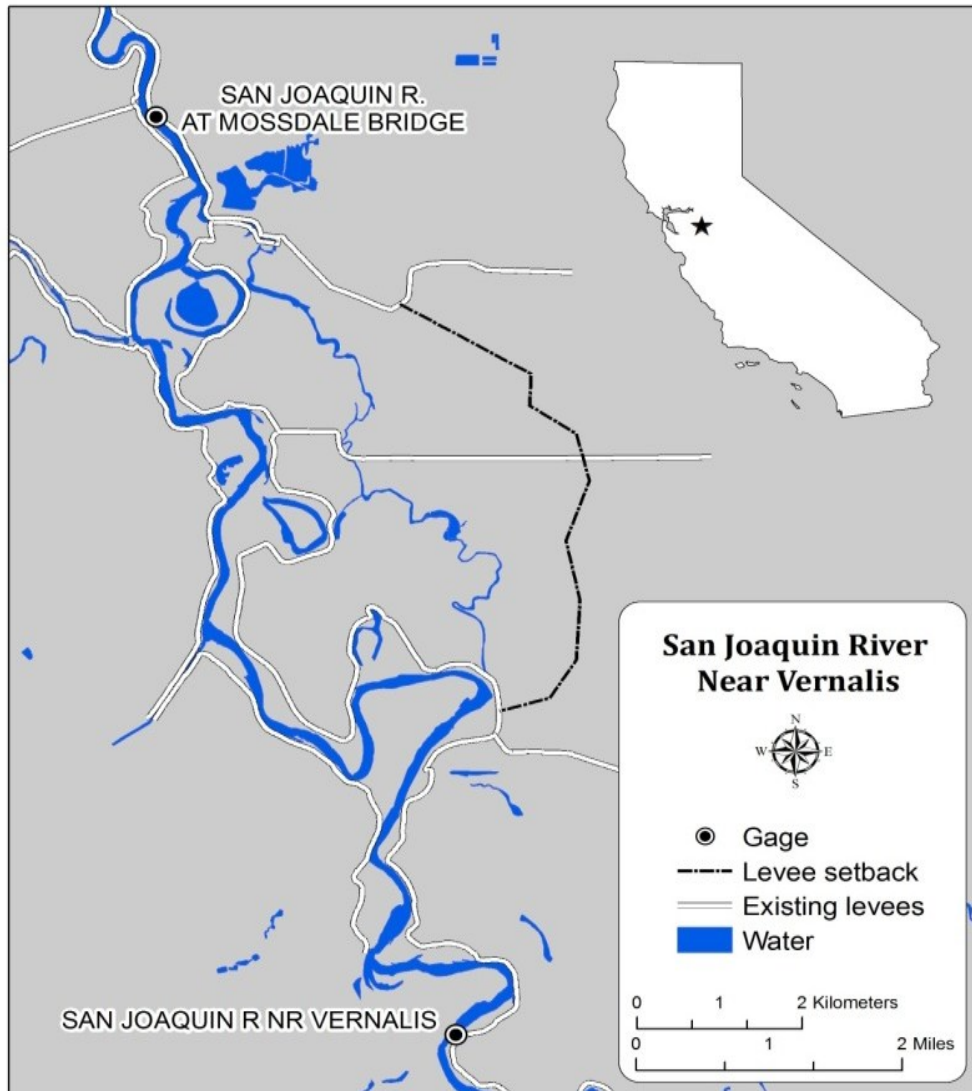


Figure 3-3. Map of San Joaquin River reach case study area detailing modeled levee setback location

## RESULTS

Spatial inundation results were straightforward to assemble. An example of how different flows translate into inundation area results can be seen in Figure 3-4 for existing conditions versus a

levee setback. Combining the hydraulic model results with the flows defined by the hydrologic frequency analysis, the area of potential floodplain habitat in each physical configuration was correlated with its frequency of occurrence for the two study durations to develop area-duration-frequency (ADF) curves for the reach (Figure 3-5). The existing configuration has a maximum value for inundated floodplain habitat of approximately 647 ha while the levee removal configuration expands the maximum potential to approximately 2469 ha. What is missing from these area values, however, is a consideration of the chance that this habitat is accessible or functional. The probability that the entirety of the additional 1822 ha of wetted floodplain habitat under the levee setback configuration is accessible is only 6% per year for a 1-day flow duration and 3% per year for a 14-day flow duration, meaning that the vast majority of the time, this additional space is not ecologically functional. ADF curves show significant inundation beginning at a recurrence interval of 3 years (~0.34 exceedance probability) for 1-day durations and 5-year recurrence interval (~0.20 exceedance probability) for the 14-day duration for both the existing and levee setback scenario.

In the case study area, floodplain habitat and processes are critical to several species including threatened and endangered Chinook salmon, which require inundation area for rearing at least every other year (Moyle, personal communication, October 5, 2011). Using this frequency requirement (exceedance probability of 50%), the levee setback achieves inundation levels indistinguishable from the range achieved under 14-day flows in the existing conditions configuration of the site. Splittail, however, which require inundation area for spawning and rearing in only one of every four years, would see approximately 121 ha additional habitat if the levee was set back.

The EAH metric captures a more comprehensive picture of the likelihood of flooded areas appearing in any given year. The 14-day duration EAH is 342 ha for the levee setback scenario, while the existing condition, on average, can only provide less than half of that habitat on average. For the 1-day duration, the setback scenario, on average, results in 297 ha more potential floodplain habitat than the existing condition; this is also a nearly two-fold increase.

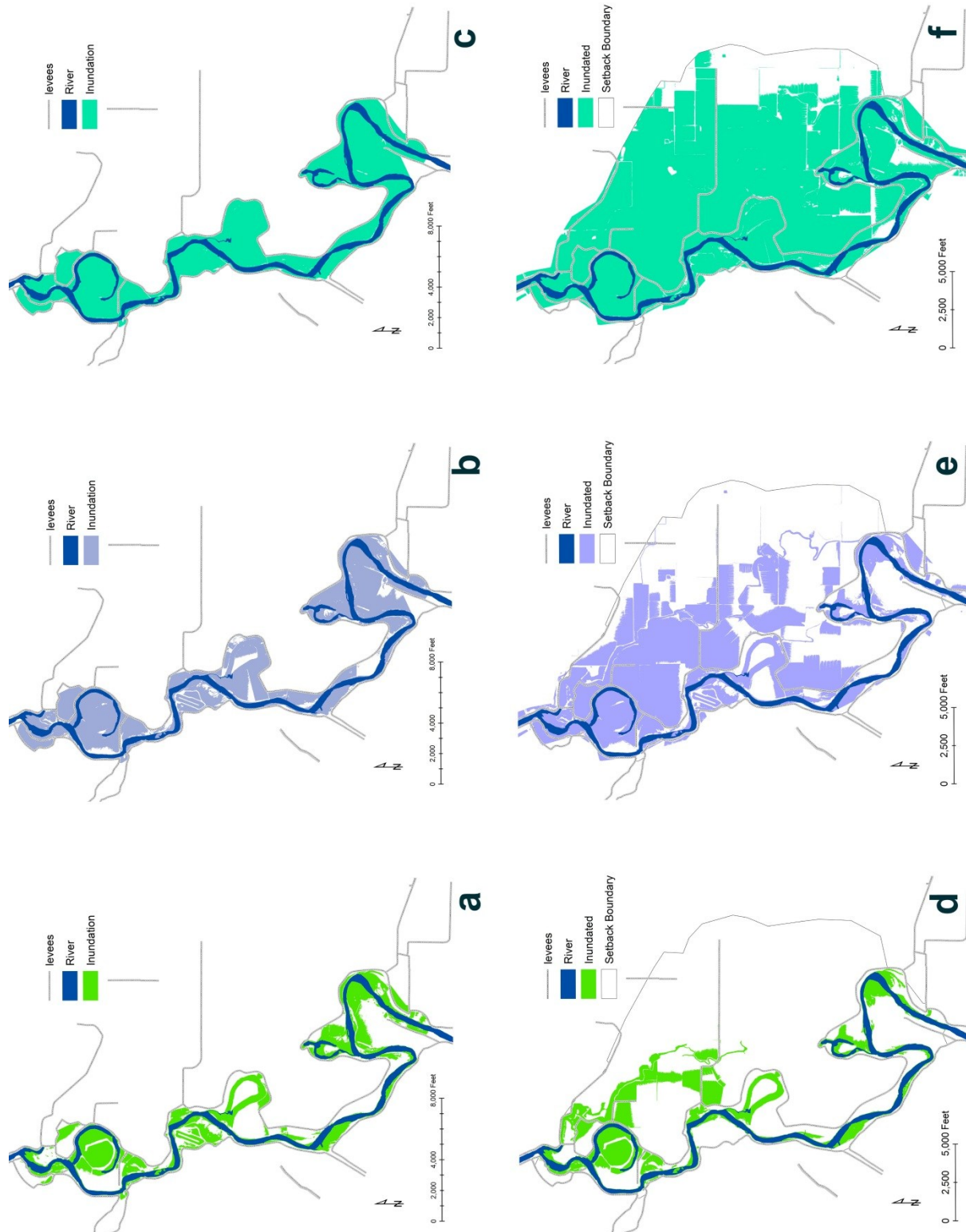


Figure 3-4. Inundation at 481 cms, 623 cms, and 850 cms for the existing condition (a, b, and c respectively) compared to inundation under the levee setback alteration for the same three flows (d, e, and f, respectively)

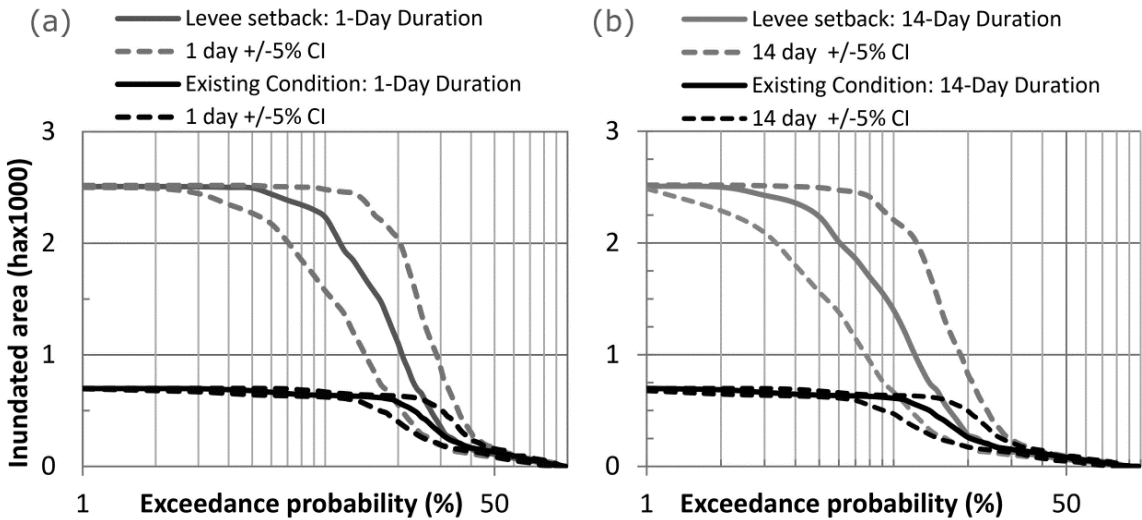


Figure 3-5. Area-Duration-Frequency (ADF) curve results for (a) 1-day and (b) 14-day duration floods for the levee setback versus existing condition scenario on the San Joaquin River

## DISCUSSION

The overarching message of the case study is that while the site could benefit splittail populations, the floodplain is not ecologically functional for rearing salmonids unless the configuration of the landscape is altered further or the reservoir operating regime is altered to produce higher pulse flows during the spring. The river stages produced under the current flow regime are influenced by dams and the smaller pulse flows (compared to pre-dam conditions) flowing downstream are not sufficient to inundate floodplain frequently and for longer durations given a simple levee removal and setback scenario. Thus, detailed consideration of flow regimes should be central to design of restoration projects. The ADF and EAH metrics allow exploration of the restoration elements that affect how successful a floodplain reconnection plan can be. The method has advantages in framing the potential restored area in terms of probabilities based on dynamics of flow timing, durations, and frequencies, though it does face limitations.

The case study employed a very broad definition for potential floodplain habitat. To apply this method and derive results for more specific habitat requirements (such as depth, velocity, or temperature) defined by a particular species screening can be done on the hydraulic model outputs and can be overlaid on maps of soil types, vegetation, and cover in a GIS which will redefine the flow versus area relationship curves. Changing species requirements for the seasonality of flow affects the hydrologic statistics that result from the HEC-EFM model. Even given these changes, the process of creating ADF curves and calculating EAH for any of these new scenarios and species requirements remains the same.

This study was performed using annual series hydrologic statistics, though in certain situations, partial duration frequency analysis may be more suitable when it is important to capture multiple flooding events that occur in any given year. The Lower San Joaquin system historical flows did not demonstrate intra-annual frequent flood pulses, likely because of the highly regulated nature



of the system, which lends itself to the use of an annual maxima series. This means evaluating one maximum flood event per year will not greatly underestimate the amount of flood flow volume for the site.

This new framework can be effectively used to create project screening metrics with minimal costs and basic knowledge of species needs, or it can be refined to measure very detailed habitat suitability curves using high resolution models. It can also be used to design projects to meet specific and measurable habitat objectives. This method and associated metrics comprise a transparent and replicable means to examine the effects and relative importance of policy decisions and river restoration projects. This chapter presents an example for evaluating proposed restoration actions based on a species' duration, seasonality, and frequency requirements. Without much alteration, this method can be adapted to consider other fish species, macroinvertebrates, nutrient cycling, channel morphology sculpting processes, and certain types of vegetation regeneration. It may even be possible to use this method to evaluate impacts to agriculture or recreation in floodplains. Future research could build upon the framework presented here by developing methods for model validation and translating habitat estimates more directly to species population responses (Poff and Zimmerman 2010; King and Brown 2006). While more factors influence ecological response than just timing, duration and frequency of floodplain inundation, incorporating these key characteristics into a restoration design can help create habitat more beneficial for ecosystem functions.

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## **CHAPTER 4**

### **SCENARIOS FOR RESTORING FLOODPLAIN ECOLOGY GIVEN CHANGES TO RIVER FLOWS UNDER CLIMATE CHANGE: CASE FROM THE SAN JOAQUIN RIVER, CALIFORNIA**

Mary K. Matella

## Scenarios for restoring floodplain ecology given changes to river flows under climate change: Case from the San Joaquin River, California

### INTRODUCTION

Freshwater biodiversity is more vulnerable than terrestrial biodiversity in the face of rapid change resulting from overexploitation, water pollution, flow modification, habitat loss, and invasive species encroachment (Dudgeon et al. 2005). Flood protection measures cause many freshwater bodies to lose adjacent periodically inundated floodplains. This loss acts in concert with these other threats to magnify stresses on freshwater, as the loss significantly impacts fisheries and other species dependent on riverine systems by diminishing natural processes and reducing available habitat (Opperman et al. 2010). The species populations that manifest effects of regulating and constraining flow are those that need floodplain habitat with periodic inundation periods to meet their life history requirements (Bay Institute 1998; Lytle and Poff 2004). In highly managed rivers, miles of meandering natural-backwater-flooded sloughs have disappeared and with them, fish, vegetation, and complex food webs are in decline. In many cases, species recovery will require floodplain reconnection and will support an increase in floodplain services, such as nutrient cycling and recharging aquifers, and might provide some climate change resilience (Opperman et al. 2009).

For these reasons, restoration treatments now proposed in many river basins might increase the amount of functional floodplain area for native species and might involve both physical reshaping of the river-floodplain interface and changes to river flows often controlled by upstream reservoirs. Expanding floodplain connectivity is a promising approach for reducing flood risks and restoring ecological functions (Opperman et al. 2010). Hence, many management agencies are currently in the process of restoring floodplains through strategies such as: 1) facilitating flow into bypass channels, 2) constructing overflow basins, and 3) removing or setting back existing levees. The ecosystem returns associated with each option depend upon species requirements, expected flows, and physiographic context. For inundation patterns to be ecologically functional, the timing, duration, and frequency of flood events must fall in the range required by species life history patterns. Exploring the influence of potential flow changes under climate change scenarios is essential to address how species might respond in the future. Meanwhile, estimating floodplain recovery that might be achieved through changes to physiographic context resulting from channel-restoration treatments requires spatially explicit modeling.

This study quantifies the benefits of increasing floodplain connectivity for a suite of species under past, current, and potential future flow regimes considering climate change, and it compares these benefits under various channel-restoration options using integrated hydro-ecological modeling in a spatially explicit framework (for more on the general framework see Merenlender and Matella 2013). Understanding ecological responses to floodplain restoration requires a synthesis of information about species life histories, expected flow, and geographic context. A diverse range of flows influences floodplain geomorphic and ecological processes, spanning frequent flows below bankfull to large, rare, and highly erosive floods (Poff et al. 1997). Researchers note how the evolution of some species' life histories has allowed them to take advantage of a range of periodic flooding events (Lytle and Poff 2004; Kimmerer 2004;

Sommer et al. 2004). The Flood Pulse Concept proposed by Junk et al. (1989) posits that annual inundation drives the existence, productivity and interactions of the major biota in river-floodplain systems and this predictable duration allows biota to efficiently use the resources available in the aquatic/terrestrial transition zone. These flood pulses, occurring with more frequency but lower magnitude than a 10-year recurrence interval flood, can promote production of biologically available carbon and provide important spawning and rearing habitat for native fish (Sommer et al. 2001a; Sommer et al. 2005). While researchers increasingly recognize that the reestablishment of flood pulsing in riverine and tidal systems is an important step in floodplain wetland restoration (Middleton 2002), larger floods (5-20 year recurrence interval events) are also important. Large floods sculpt floodplain morphology through erosion and deposition and maintain habitat heterogeneity on the floodplain.

Specifically linking physical flood frequency characteristics to an indicator of ecosystem function, such as fish population recovery, requires an understanding of the interactions between floodplain processes and species responses. In particular, inundation duration and seasonality are important because fish and other biota have adapted their life histories to these variations (Benke 2001; Moyle 2008). For this reason, Williams et al. (2009) proposed the floodplain activation flood concept that relies on a simplified conceptual model that links key floodplain functions to river stage, frequency, duration and seasonality. The U.S. Army Corps of Engineers and California Reclamation Board (2002) quantified additional relationships between hydrology and ecology in the lowland river-floodplain systems of California's Sacramento-San Joaquin Rivers Basin in developing a customizable tool. Such statistical models allow a user to define how river flow, floodway morphology, and biological communities interact (USACE 2004; USACE 2009). These models provide a process for linking biologic, hydrologic, and hydraulic variables that can be applied to multiple study areas and alternative restoration treatments. These species-specific models are employed here to assess the floodplain benefits under different flow regimes and channel morphologies.

This chapter uses a form of the Chapter 3 method for quantifying the benefits of floodplain restoration along a part of the San Joaquin River and takes advantage of an integrated hydro-ecological model using fine scale physiographic data and informed functional ecosystem relationships. I expand the application of the Chapter 3 method by assessing a broad suite of specific ecological functions, different flow regimes, and multiple restoration options. This approach culminates in estimates of the potential benefits of two floodplain restoration options (a levee setback and a bypass) for different taxa under historical flow patterns and future flow scenarios. The future flow scenarios reflect two climate change model runs for the San Joaquin River, California. Pre and post restoration scenario, the extent of floodplain habitat recovery that might result was examined, and expected alterations under climate change flows were also considered. Habitat for *Pogonichthys macrolepidotus* (Sacramento Splittail) and *Oncorhynchus tshawytscha* (Chinook Salmon) is considered as influenced by hydrology and inundation, noteworthy because these species use Central Valley floodplain for spawning and/or rearing and their populations have been in decline in recent decades (Moyle 2002). Phytoplankton and zooplankton are critical to the existing food web, which might be a limiting factor for fish species at risk (Jassby et al. 2006; Winder and Jassby 2011). Lastly, the relationship of germination and establishment of Fremont cottonwood (*Populus fremontii*) to hydrological

cycles in the spring and early summer is considered because of the cottonwood's vital role in providing shade and riverine habitat.

## **METHODS**

### **Study Area**

California's San Joaquin River Basin drains about 83,000 km<sup>2</sup> (32,000 mi<sup>2</sup>), with its headwaters beginning in the Sierra Nevada to the east and bounded by the Diablo Range to the west. The San Joaquin River runs about 560 km (350 mi), flowing northward to meet the Sacramento River in the Delta, a network of islands and channels that feed into San Francisco Bay. Annual precipitation in the San Joaquin River Basin ranges from about 15 cm (6 inches) on the valley floor at Mendota to about 178 cm (70 inches) in the Sierra Nevada, but snowmelt is the main source of fresh water in the San Joaquin River (DWR 2010a). Peak snowmelt flows historically occurred May through June, with primary tributaries of the Stanislaus, Tuolumne and Merced rivers contributing flows. The study area covers part of the Lower San Joaquin River, which offers several opportunities to adjust the river's flow path in order to provide much needed flood relief downstream where the city of Stockton, with a population of 280,110 in 2010, lies directly to the east of the river corridor (DWR 2010a) (Figure 4-1).

### **Hydrologic data**

Data on daily river flow exist since 1924, and continuously since 1929, from the USGS Gage (station #11303500) at the San Joaquin River near Vernalis (Figure 4-1). The long historical record and the availability of climate change projections at this location make the South Delta a promising area for evaluating functional flows for ecosystem benefits under varying conditions. Because the characteristic magnitude, duration, and seasonality of past San Joaquin Basin flows have been impacted by a number of dams and water extractions, the historical record was divided into two periods. The record of historical flows was considered prior to the establishment of the New Melones Dam (1929-1979) and for the recent period of record influenced by existing dams (1980-2010).

The Vernalis gage station was used as a basis for modeling future changes to flow based on expected changes to precipitation and temperature, allowing future flows (2001-2099) to be represented in the analysis. Four future flow scenarios from 2001-2099 were developed by the USGS CASCaDE: Computational Assessments of Scenarios of Change for the Delta Ecosystem project (USGS 2009). Climate change scenarios reflect CASCaDE estimates based on a University of Washington Land Surface Hydrology Research Group framework and Global Circulation Model (GCM) simulations of historical climate conditions, A2 future greenhouse-gas-and-sulfate-aerosols emissions scenarios, and B1 future emissions scenarios. The GCMs represented are the National Center for Atmospheric Research's Parallel Climate Model 1 (PCM) and the NOAA Geophysical Fluid Dynamics Lab's GFDL CM2.1 model. Modeled climate data reflect downscaling using the constructed analogs method of Hidalgo et al. (2008). USGS used the Bay-Delta Watershed Model (BDWM), a physically based model of hydrologic processes, to generate stream flow at a daily time step with primary inputs of precipitation and air temperature, simulating hydrologic variability throughout the watershed. Analyses for this chapter were based

on the best-case scenario for a warm and wet future climate represented by B1PCM and the worst-case scenario that is hot and dry represented by A2GFDL to examine the range of expected change. The B1PCM model is now referred to as the B1 scenario and the A2GFDL model as the A2 scenario.

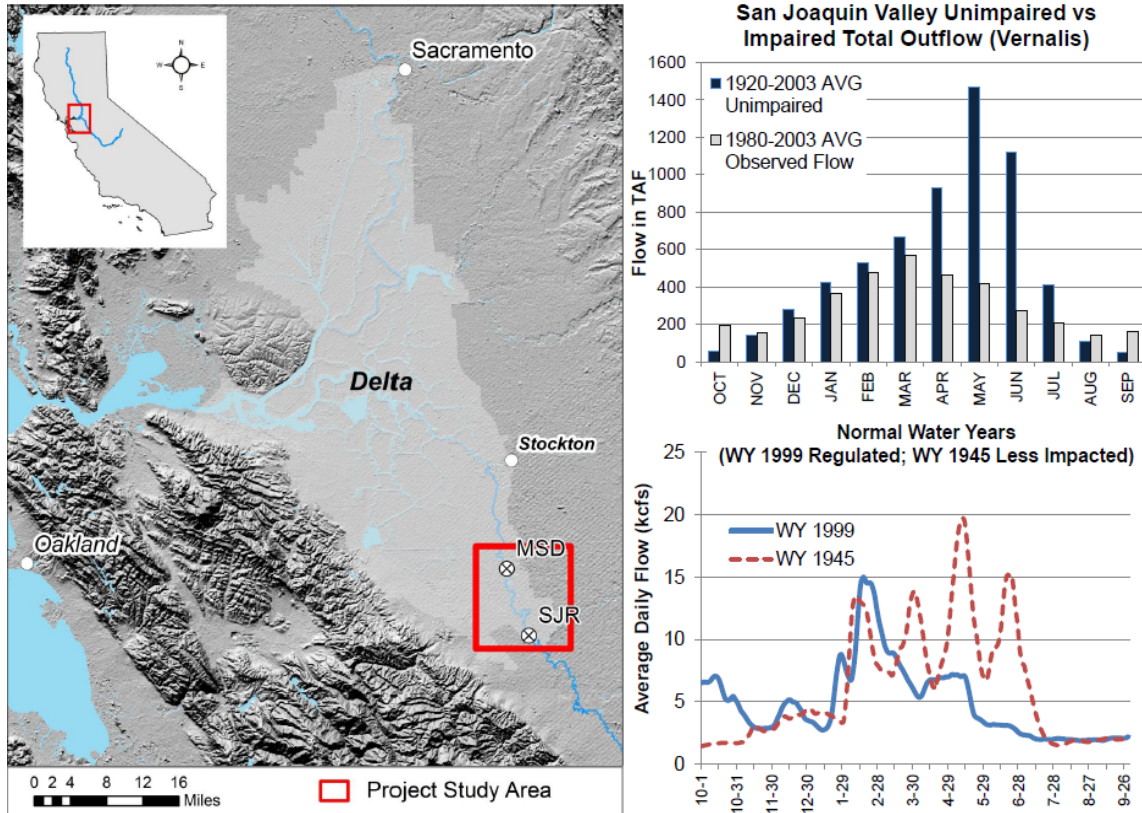


Figure 4-1. Map of San Joaquin River study area (A) highlighting Vernalis (SJR) to Mossdale (MSD) gage locations and representative hydrographs (B) Monthly unimpaired (1920-2003) versus observed flow (1980-2003) averages and (C) Normal water year examples for regulated and less impacted flows (1945).

Another hydrologic scenario was based on changing the historic record per a proposed flow criteria policy (SWRCB 2010) designed to provide sufficient flow for native fish in the Delta. The California State Water Resource Control Board (SWRCB) found that 60% of unimpaired flow from February through June is needed in order to achieve a Chinook salmon outmigration threshold flow of 142 cms (5,000 cfs) or more in most years (over 85% of years) and flows of 283 cms (10,000 cfs) in slightly less than half of the time (45% of years) (SWRCB 2010). Unimpaired flow is runoff that would have occurred had river flow remained unaltered by reservoirs or diversions. A revised historical hydrograph was created based on this 60% retention rule recommended by the SWRCB and Department of Water Resources (2007). To meet these targeted flows, substantial changes in reservoir management and water use would have to take place.



In sum, the models represent flows across four time periods; (1) *historical* (1929-1979), (2) *recent* (1980-2010), (3) *future warm-wet* climate 2001-2099 (B1 scenario), and (4) *future hot-dry* climate 2001-2099 (A2 scenario). In addition, a *minimum instream flow* (60% of unimpaired flow) criteria was considered because it could influence the number of years that estimated species-specific flow thresholds could be met.

## **Ecological data**

Species have a wide variety of flood condition requirements. A suite of species was selected that includes fish that need additional floodplain habitat for their populations to recover and species that need a range of flood duration and timing to demonstrate a full range of estimated ecological returns. The native Sacramento splittail (*Pogonichthys macrolepidotus*) and Chinook Salmon (*Oncorhynchus tshawytscha*) use flooded areas for spawning and rearing in the Central Valley riverine system (Moyle 2002). The Sacramento splittail is a native minnow that is found in fresh and brackish waters and is endemic to the Sacramento-San Joaquin system. The adult splittail migrates upstream annually from the estuary in late autumn and winter and spawns in flooded vegetation in winter and spring (Moyle 2002; Sommer et al. 1997). The splittail does not reproduce well unless it has access to significant floodplain habitat (e.g., the Yolo Bypass) (Sommer et al. 2002). Loss of floodplain habitat accompanied a major decline in splittail population abundance over the last 30 years, leading to the splittail's temporary listing as threatened in 1999 (Sommer et al. 2007). Splittail requirements are considered for functional floodplain because their recovery is dependent on improving and adding floodplain habitat in the Delta. Similar to the splittail, Chinook salmon were once abundant in the Sacramento-San Joaquin Basin, and of the four races of the species, only the fall-run remains comparatively prevalent (Yoshiyama 1999). Research supports the positive relationship of Chinook salmon growth, survival, feeding success, and prey availability to frequent floodplain inundation periods (Sommer et al. 2001a). Therefore, splittail flooding preferences and Chinook salmon rearing requirements are key elements of the ecological fish floodplain inundation relationships (Table 4-1).

It is well-documented that fish reared on floodplain grow faster and bigger than their cohorts rearing in river (Jeffres et al. 2008; Sommer et al. 2001a). A richer food web might be one reason for this advantage (Sommer et al. 2001b; Feyrer et al. 2007). Research supports the hypothesis that phytoplankton and zooplankton response to inundation of floodplain provides a valuable source of biologically available carbon downstream (Ahearn et al. 2006; Lehman et al. 2008). Thus, the flooding conditions needed to produce phytoplankton and zooplankton are included in the suite of ecological relationships (Table 4-1).

Flooding in the Sacramento-San Joaquin River system closely controls composition of vegetation in the woody riparian zone (Jones and Stokes 2000; Stella 2006). One of the better studied fixed-pulse-dependent riparian plant species is the Fremont cottonwood (*Populus fremontii*) which relies on periodic flooding during spring and early summer to regenerate (Mahoney and Rood 1998). To capture this type of ecological flow relationship, a model based on the timing and recession limb of the spring hydrograph required for cottonwood regeneration was included for consideration (Table 4-1).

Table 4-1. Relationships of ecological relevance to hydrologic flow parameters

<b>Ecological Relevance</b>	<b>Season</b>	<b>Duration/rate</b>	<b>Frequency</b>	<b>Exceedance probability</b>	<b>Literature</b>
<b>Splittail spawning and rearing</b>	Feb – May	At least 21 days	4 yr return period	0.25	Sommer et al. , 1997; USACE, 2002; Williams et al. 2009
<b>Chinook salmon rearing</b>	Dec – May	At least 14 days	2- 4 yr return period	0.25	Sommer et al. , 2001a; USACE, 2002
<b>Phytoplankton production</b>	Dec – May	At least 2 days	1.3 yr return period	0.769	Jassby and Cloern, 2000; Sommer et al. 2004a; Reynolds, 1994
<b>Zooplankton production</b>	Dec – May	At least 14 days	1.3 yr return period	0.769	Baranyi et al. 2002; Sommer et al. 2004a; Grosholz & Gallo, 2006
<b>Plant germination and establishment</b>	April 1-July 15	0.268 m (.88 ft)/wk stage decline rate	10 yr return period	<0.10	Mahoney and Rood, 1998; USACE, 2002
<b>Floodplain Maintenance Flow</b>	Dec – Sep	na	10 yr return period	0.05-0.75	Opperman et al, 2010

## Modeling

### *Statistical Analysis*

The U.S. Army Corps of Engineers developed the HEC-Ecosystems Function Model (EFM) to examine statistical relationships between hydrologic and ecological parameters (USACE 2002; USACE 2009). HEC-EFM uses a time series of daily mean flow and stage and parameters for variables such as season, duration, rate of change and frequency of occurrence to characterize an ecological response. Shafroth et al. (2010) used the EFM to model potential tree seedling response to flow scenarios, exemplifying how the EFM can produce spatial results linked to hydrologic alterations. EFM was populated with daily flows from historical records at Vernalis from 1930-1979, and the post-New Melones dam period of 1980-2010, the CASCaDE estimated future flows under B1 and A2 climate change scenarios (2001-2099), and protected flows (60% of unimpaired flow from 1930-2003). Using the Wilcoxon signed-rank test, EFM curves for the flow regimes were analyzed for significant differences.

Information on flow frequency, duration, seasonality, inundation, and habitat characteristics describing floodplain suitability based on the literature are essential for setting up the conceptual framework for this analysis (Figure 4-2). Values for these metrics were based on the habitat requirements for splittail, Chinook salmon, cottonwood seedling germination and establishment, and phytoplankton and zooplankton productivity. Table 4-1 details the specific dynamic flow requirements of these taxonomic groups as well as characteristics of geomorphically relevant flows.

*Integrated hydraulic and spatial modeling: Scenarios of floodplain configuration*

Hydraulic and spatial analyses were conducted for three scenarios in the study area: 1) the current physical flow path, 2) the flow path after removing levees, and 3) the flow path with the addition of a slough bypass. These scenarios were run with flow dynamics defined by the five stream flow options described above (historical, recent, future B1, future A2, and protected). The baseline scenario represents the current position of levees in the Vernalis to Mossdale Corridor upstream of Stockton, CA. The levee removal scenario reflects removal of eastern levees of the San Joaquin and some cross-levee removal from nearby agricultural fields. The slough bypass scenario engages the Walthall Slough as a flow path assuming a 6.1 m elevation-weir is in place to allow flow from the main stem San Joaquin River down the Walthall Slough, a remnant flow pathway.

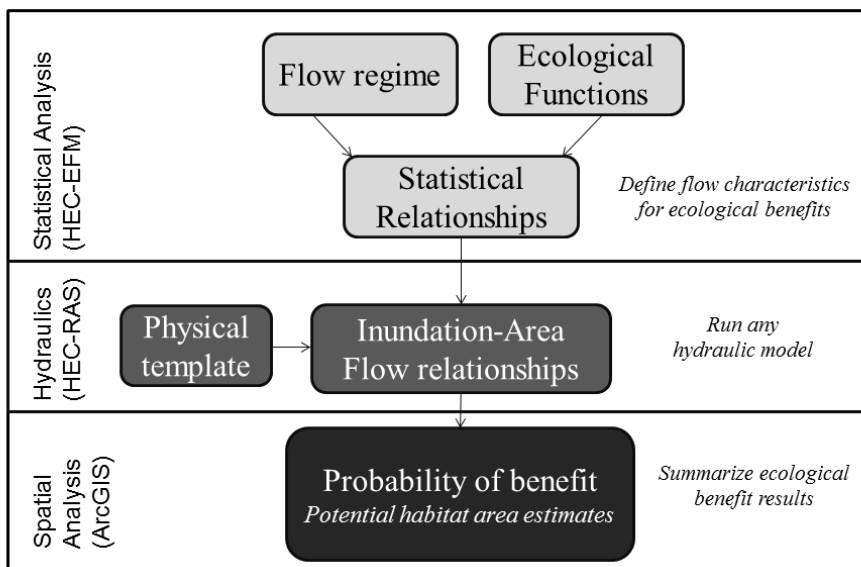


Figure 4-2. Framework for model integration

Hydraulic modeling (HEC-RAS) was used to define relationships between the flows and inundated floodplain area for the physical scenarios. HEC-RAS cross-sections created for the Army Corps of Engineers Comprehensive Study were the basis of the model, and were modified by extension across the floodplain for the scenarios (USACE and Rec Board 2002). A standard Manning’s roughness (n) value of 0.046 was employed for the channel (the same that was used in the Comprehensive Study) and a Manning’s n value of 0.06, which corresponds to a land cover of light brush and trees, was applied for floodplain (Chow 1959). Using DWR flow and stage data, a rating curve was established based on the average relationship between stage and discharge at Mossdale as the downstream boundary condition. Flows were run from Vernalis assuming a steady state to create water surface profiles at a range of flows from frequent pulses to large magnitude floods.

To conduct the spatial analysis for this study, a physical template was constructed in a Geographic Information System (GIS). Land surface elevations were generated from three-dimensional floodplain topography from light detection and ranging (LiDAR) based surveys

(DWR 2010b), and USACE Comp Study bathymetry was integrated into the final surface (USACE and Rec Board 2002). After conducting hydraulic modeling using HEC-RAS, relationships were defined between the flows and inundated floodplain area for the three physical scenarios by importing the results into GIS to determine the maximum possible inundated floodplain. HEC-RAS water surface triangulated irregular networks (TINs) were converted into GIS grid files and overlaid on the physical template to define inundation areas. GIS region group and proximity functions were used to remove inundation patches not connected to the flows of the main stem of the river.

Lastly, potential ecological function benefits of increased inundation were quantified by correlating the hydraulic model results for maximum potential habitat area with the flows defined by the hydrologic frequency analysis for ecologically significant floods. The maximum possible floodplain habitat was plotted against frequency for each duration period to develop area-duration-frequency (ADF) curves. By integrating each ADF curve over the interval  $f=0$  to  $f=1$ , expected annual habitat (EAH) values were created to describe each ecologically functional relationship per physical scenario (See Chapter 3 for method details).

## RESULTS

### Differences in flow related habitat requirements for species over time

The minimum flows that species require to be able to take advantage of floodplain habitat result from applying the criteria listed for each species in Table 4-1 and are presented in Figure 4-3 for four time periods. Splittail and salmon flows that meet their dynamic habitat requirements have been higher in recent years than the average detected during the historical record. The reverse is true for phytoplankton, which depend upon more frequent, lower magnitude flows. Flows meeting requirements for cottonwood seedling establishment are an order of magnitude lower (97 and 91 cms, respectively) in comparison to a 10% frequency of occurrence flow (1,062 cms). The low flows are similar to the 1.3-year recurrence interval flows (for phytoplankton) and below the annual flow frequency for a 1.3-year recurrence interval flow (128 cms). For every ecological flow relationship, the hot-dry A2 climate change regime results in lower flows meeting required flow criteria than the warm-wet B1 scenario, with larger differences observed for the relationships involving less frequent flows (i.e., 4-year or 10-year recurrence intervals).

A nonparametric Wilcoxon signed-rank test to compare climate change season-duration-frequency curves (for relationships characterized by Dec-May for the following durations: 3-day, 7-day, 14-day, and 28-day) indicated that hot-dry A2 and warm-wet B1 climate change flow regimes were significantly different from each other ( $p < 0.001$ ). The historical (1920-2010) regime was not significantly different from the B1 climate regime, but was significantly different from the A2 climate regime ( $p < 0.05$ ). Differences between the older (1930-1979) and modern (1980-2010) records were not statistically significant for any EFM generated flow-frequency curve.

In addition to the minimum flow threshold above which functional floodplain habitat can be created, the duration of time that flooding occurs greatly influences productivity. Functional floodplain persistence for splittail spawning and rearing was explored as a function of duration (Figure 4-4). The figure reflects conditions supporting splittail habitat in terms of duration and

frequency with which the threshold flow of 425 cms is met at Vernalis over the course of water years from 1930 to 2010. According to the models, 33 years out of the 81-year period of record plotted in Figure 4-4 met this flow threshold. Additionally, only 13 events in 42% of years have flows of the magnitude and duration required for splittail spawning and rearing (21-day duration) and 14 events have flows long enough for salmon rearing benefits (14-day duration). In wet years, the duration for 54 events averaged 43 days, compared to 12.5 days for 26 events occurring in above normal runoff years. Higher thresholds flows occurred even less frequently; for example, flows of 566 cms or higher were observed in only 27/81 years. Under hot-dry A2 climate change estimates, the 425 cms threshold was met in 16/100 years for an average duration of 28 days, and warm-wet B1 scenario estimates included 30/100 years with an average duration of 44 days duration. A higher threshold of 566 cms is exceeded in only 9 years in a hot-dry A2 future (mean duration 19 days/event), and in 20 years in a warm-wet future (mean duration 40 days/event). So, under the A2 climate scenario the mean duration of these events does not support the 21-day duration splittail requirement for inundation on the floodplain.

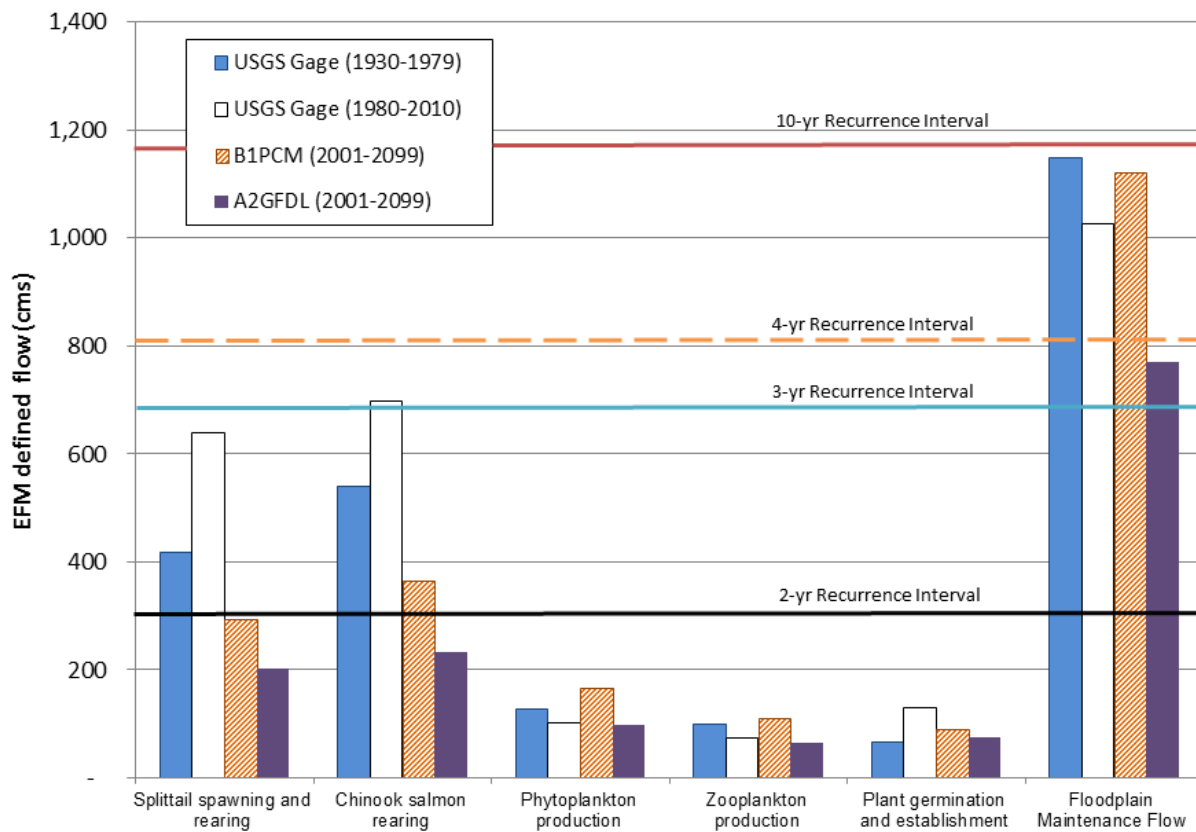


Figure 4-3. EFM defined threshold flows for relationships specified in Table 4-1

Examining ecological benefit thresholds defined for selected key species identifies a way to evaluate how the changing duration, season, frequency, and rate of change of flow criteria can affect results. By considering just the modern hydrograph scenario at the same frequency requirement (0.25), the splittail and Chinook salmon duration and season criteria produce a splittail threshold only 92% of the Chinook salmon threshold. However, by changing season for splittail from Feb-May to March-May, the threshold is reduced to 65% of the longer season

result. An even greater reduction in threshold results from changing the salmon frequency criteria to 0.5, as the threshold drops to 17% of the 0.25 frequency result. Varying the rate of change for declining stage from 26.8 cm per week (USACE and Rec Board 2002) to 17.5 cm per week (Mahoney and Rood 1998) reduced the threshold flow to 84% of the faster stage reduction.

### **Restoration alternatives and their added floodplain benefits**

The proposed restoration treatments involving channel alterations include: 1) the current levee configuration, 2) removal of the eastern levee/cross levees, and 3) the addition of a backwater slough bypass (Figure 4-5). Estimates of inundated floodplain were compared from river mile 69 to 57. Under the current system baseline, approximately 696 ha is the maximum recoverable floodplain habitat area. Removing the levees adds an estimated 1781 ha of habitat for potential inundation. The slough provides a 603 ha corridor available if a weir is installed off of the main stem of the San Joaquin River near river mile 67. Inundation area-flow curves for the newly flooded area as compared to the current configuration of floodplain constricted by today's levees provides a way to compare the potential of the three physical scenarios (Figure 4-6).

Figure 4-6 shows the current levee configuration as a steady but gradual increase in area inundated until flow reaches 708 cms. After flows exceed 708 cms, the additional inundated floodplain does not change much until it hits its maximum of 696 ha at 1982 cms. The inundation area of scenario 2 closely tracks that of scenario 1, until the curves diverge at 283 cms, when more inundation of floodplain in the levee removal scenario begins. By 765 cms, scenario 2 more than doubles the inundated area of the original topography. At the same flow magnitude the bypass scenario 3 inundates 460 more ha than the original configuration. While the bypass scenario 3 inundation area plateaus at close to 1214 ha, from 396 to 595 cms the bypass scenario inundates slightly more area than the levee removal scenario 2.

This flow information alone is not sufficient to inform management decisions; rather, it must be combined with the EFM modeling thresholds and hydrologic regime expectations to assess how species recovery could benefit from any treatment at the site. Restoration treatments for floodplain habitat include more than physical alterations for additional channel floodplain connectivity. Restoring a more natural flow regime can also increase habitat area and frequency of inundation. The influence of a hypothetical SWRCB adjustment to minimum flows on a hydrograph reflects this finding (Figure 4-7). Table 4-2 shows the percent of years that the species flow requirements were met during the historical record compared with the number of years that could have been achieved if the historical flows had been adjusted to the SWRCB-recommended 60% of 14-day average unimpaired flows February through June (SWRCB 2010). The values in columns 5-6 of Table 4-2 show how often threshold flow characteristics occur for the estimated hydrograph under climate change scenarios. The hot-dry A2 climate change flows meet the threshold flow far less frequently than the warm-wet B1 scenario flows. The warm-wet B1 scenario actually exceeds the minimum frequency of occurrence for phytoplankton and zooplankton production, though it falls short of meeting the frequencies for the fish benefits or cottonwood germination/establishment. When the historical record flows are augmented to meet current SWRCB guidelines, every ecological relationship threshold, except the cottonwood germination/establishment category, is met more frequently.

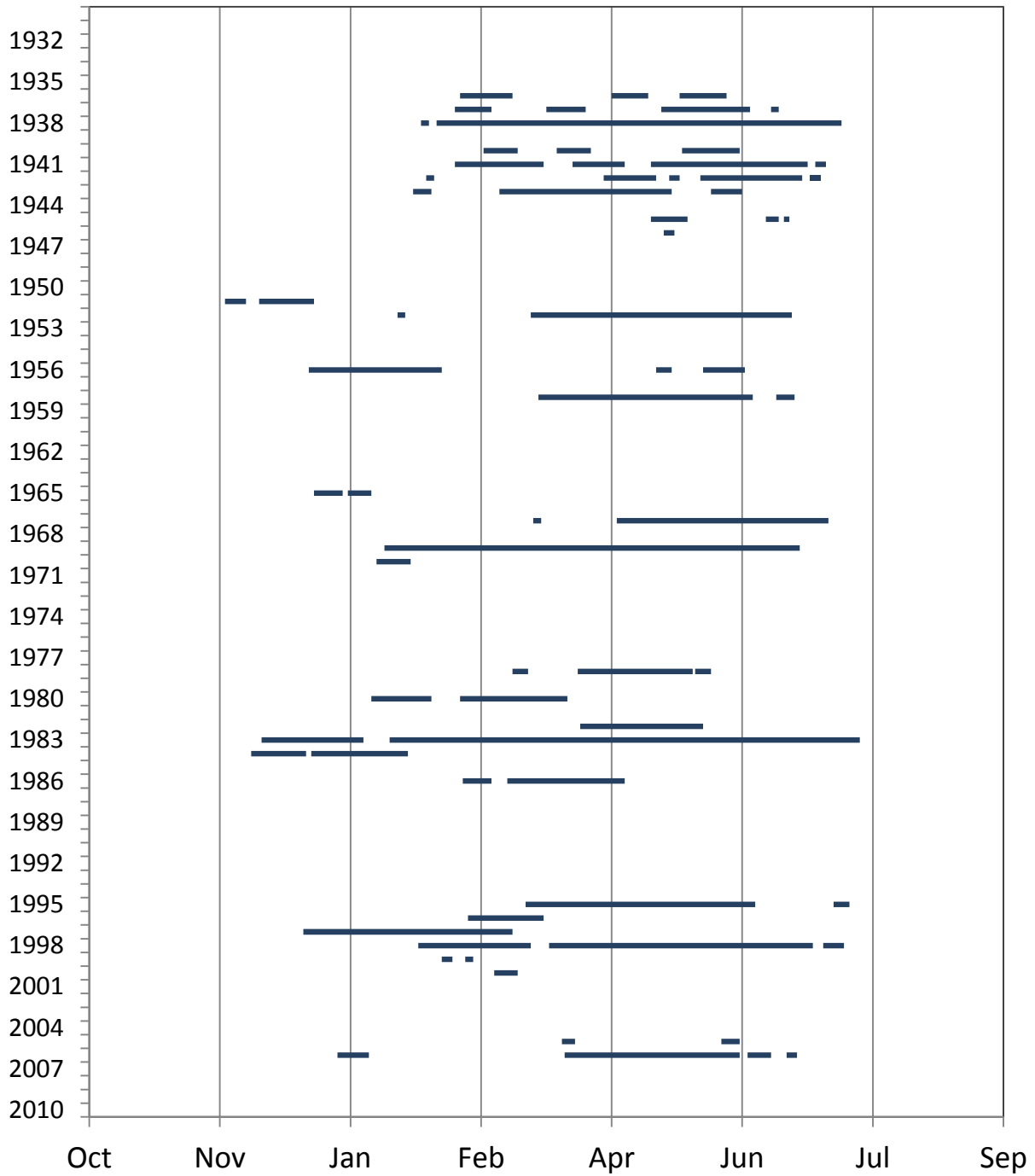


Figure 4-4. Days of flow met or exceeded 425 cms at Vernalis (USGS gage # 11303500) from water year 1930-2010.

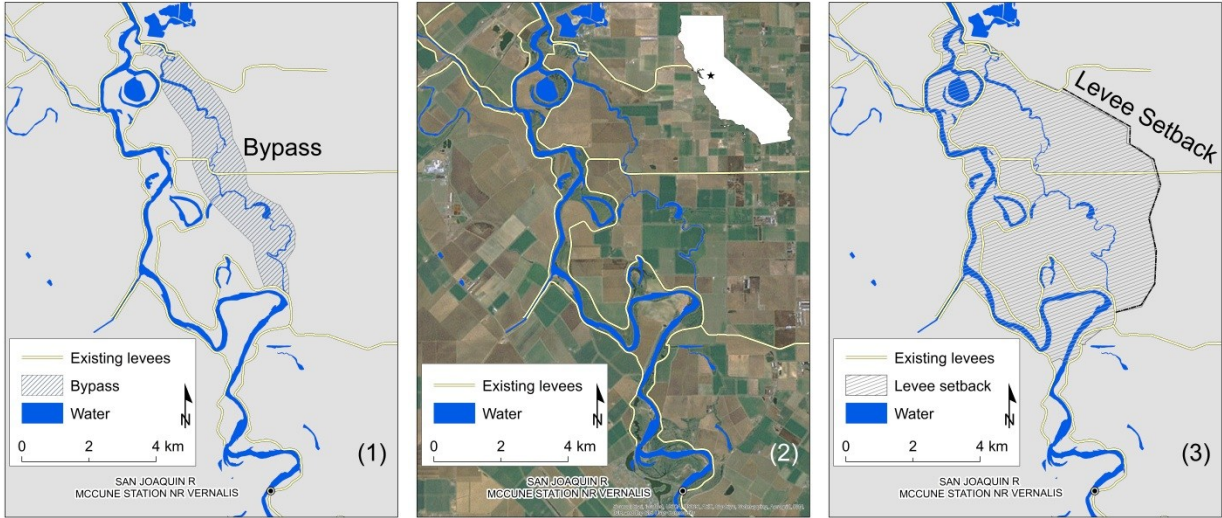


Figure 4-5. Map of treatment areas: 1) Slough Bypass, 2) Existing conditions, and 3) Levee Setback area. Figure 4-1 shows larger extent for project area.

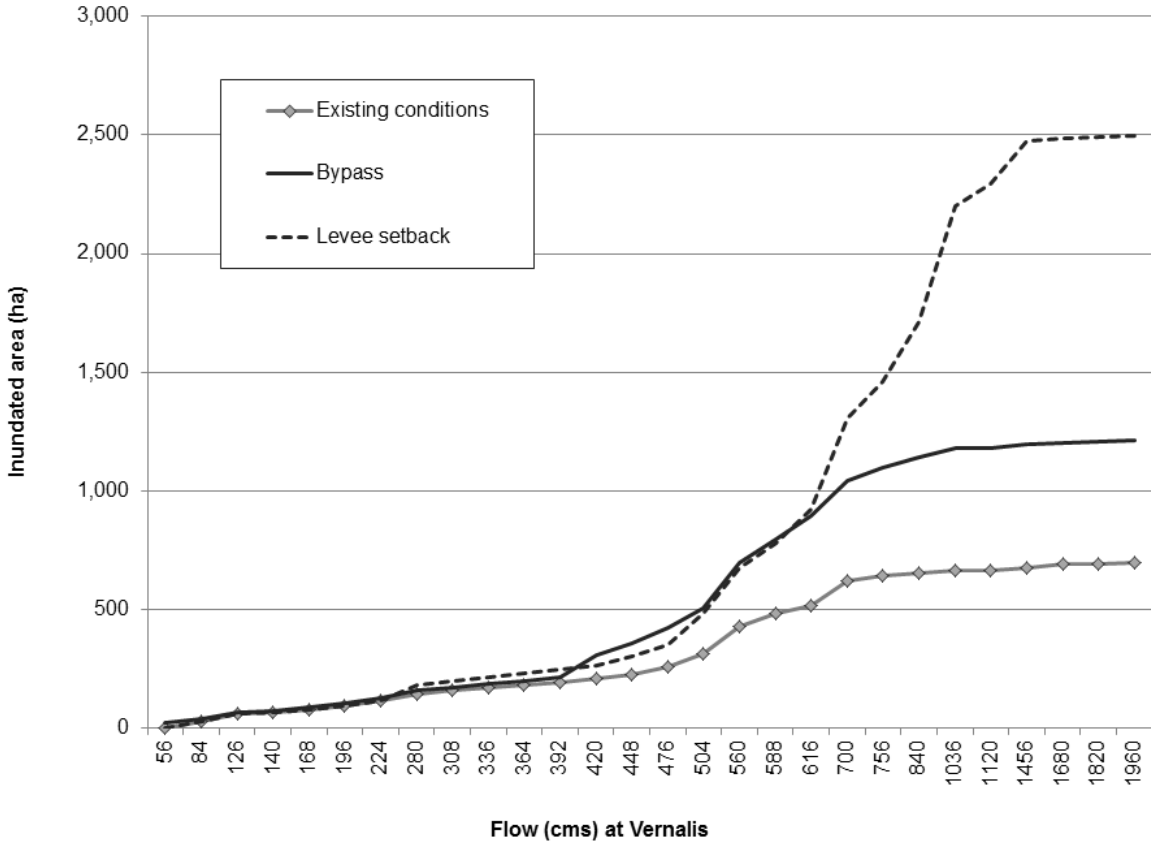


Figure 4-6. Inundation area curves for three treatments



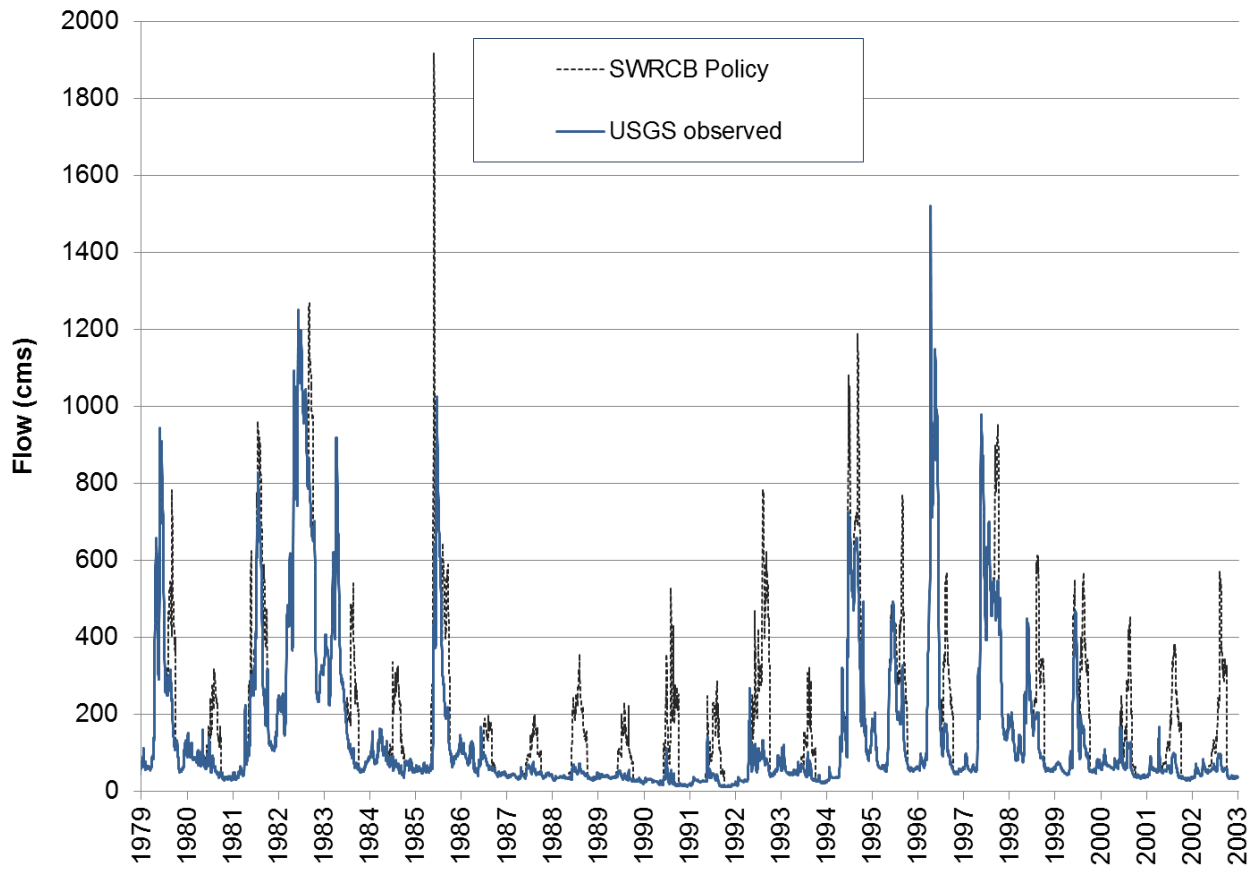


Figure 4-7. Dotted line reflects adjusted historical water year (1980-2003) record based on SWRCB policy recommendation of 60% of unimpaired flows. Solid line reflects the USGS gage observations at Vernalis.

The Area-Duration-Frequency (ADF) curves plotted in Figures 4-8 to 4-11 demonstrate how each ecological relationship fares according to physical (existing condition, levee setback, and bypass) and hydrological scenario [historical flows (1930-2010), climate change flows (2011-2099), and a minimum instream flow policy (1930-2003)]. The season and duration criteria underlie the frequency curves that correspond to maximum possible inundated area. The lines drawn at particular probabilities indicate the frequency criteria in the ecological relationships, showing how much functional area exists for each scenario combination. Thus, floodplain maintenance benefits are greatest (about 1214 ha more than existing conditions levels) in levee removal scenarios, regardless of hydrology (Figure 4-4 to 4-8). Phytoplankton benefits increase by only 202 ha under any minimum instream flow scenario compared to historical flows and climate change flows (Figure 4-9). Chinook salmon benefits that might be realized between probabilities of 0.25 and 0.5 show greatest achievement with minimum instream flow policy flows for bypass or setback scenarios, but even these drop approximately 809 ha moving from the less to more frequent flow criteria (Figure 4-10). Zooplankton benefits, while based on 14-day durations, are similar to phytoplankton benefit amounts reflected at the probability of 0.76, at approximately 182 ha for the minimum instream flow policy scenario compared to about 40 ha at all others. The splittail benefits achieved are again greatest in bypass or setback scenarios, which are very similar at the level of 728 ha (Figure 4-11). For all ADF graphs, the hot-dry A2 climate change scenario indicates the least functional area. The cottonwood germination and

establishment relationship was not plotted in an ADF curve because functional flows were not based on duration, but rather on the receding water stages in late spring and early summer. Notably, for all duration-based relationships, the physical alteration scenarios with historical flow regime achieve fewer functional benefit areas than if the hypothetical minimum instream flow policy was enacted under existing levee conditions.

Table 4-2. EFM Threshold flow results at Vernalis (USGS # 11303500 San Joaquin R Near Vernalis CA)

Relationship	Criteria	All Historical 1930-2010		B1PCM Warm-wet	A2GFDL Hot-dry	SWRCB Policy
		Season/Duration/Freq	Threshold Flow (cms)	% of years	% of years	% of years
<b>Splittail spawning and rearing</b>	Feb-May 21-day 4yr	435	25.0	17.3	6.3	42.9
<b>Chinook salmon rearing</b>	Dec-May 14-day 4yr	585	24.9	15.2	4.0	32.8
<b>Phytoplankton production</b>	Dec-May 2-day 1.3yr	118	77.0	83.1	65.2	98.3
<b>Zooplankton production</b>	Dec-May 14-day 1.3yr	90	76.3	80.9	60.3	98.5
<b>Plant germination and establishment</b>	Apr-July15 10yr	91	9.7	7.5	3.0	5.6
<b>Floodplain Maintenance Flow</b>	Dec-Sept 10yr	1,057	10	10.7	1.7	10

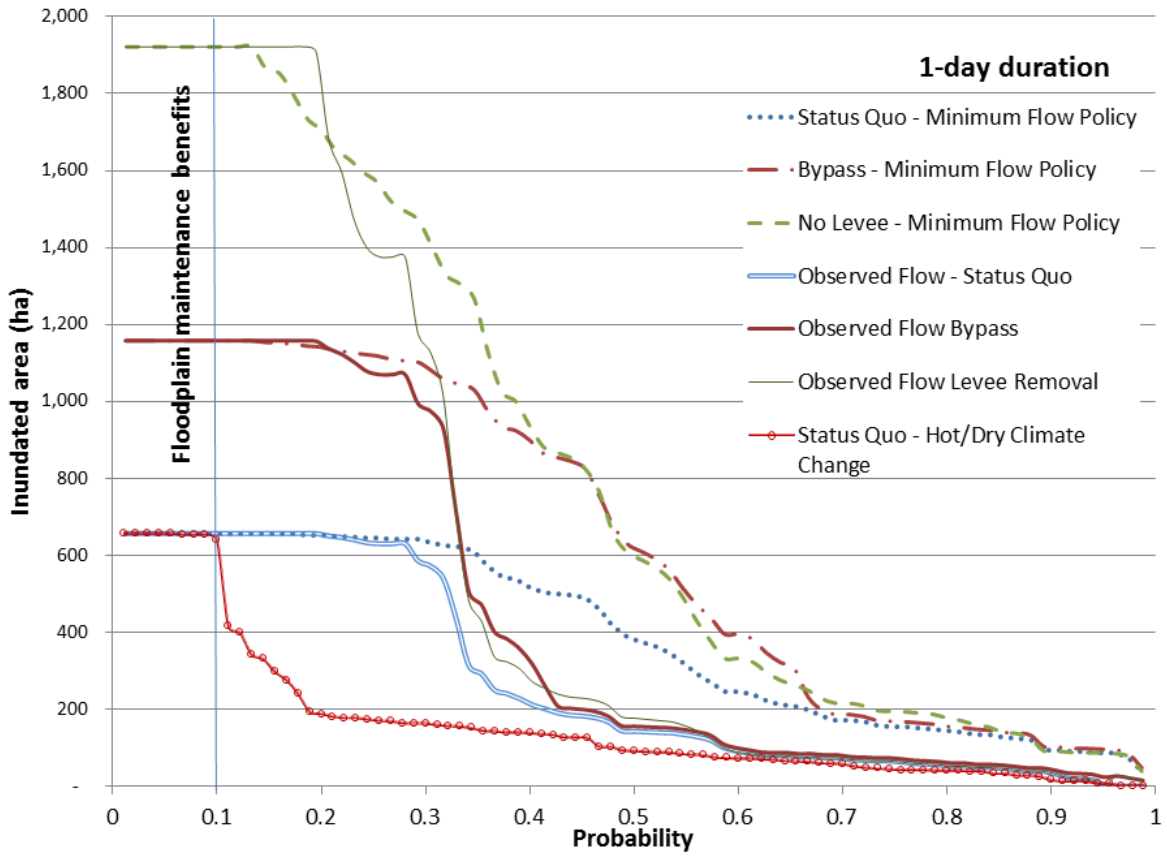


Figure 4-8. Area-Duration-Frequency (ADF) curves for 1-day duration flows representing combinations of physical alterations and hydrology scenarios. At a probability of 0.1, representing the flood that occurs 1 out of every 10 years, on average, floodplain maintenance benefits occur.

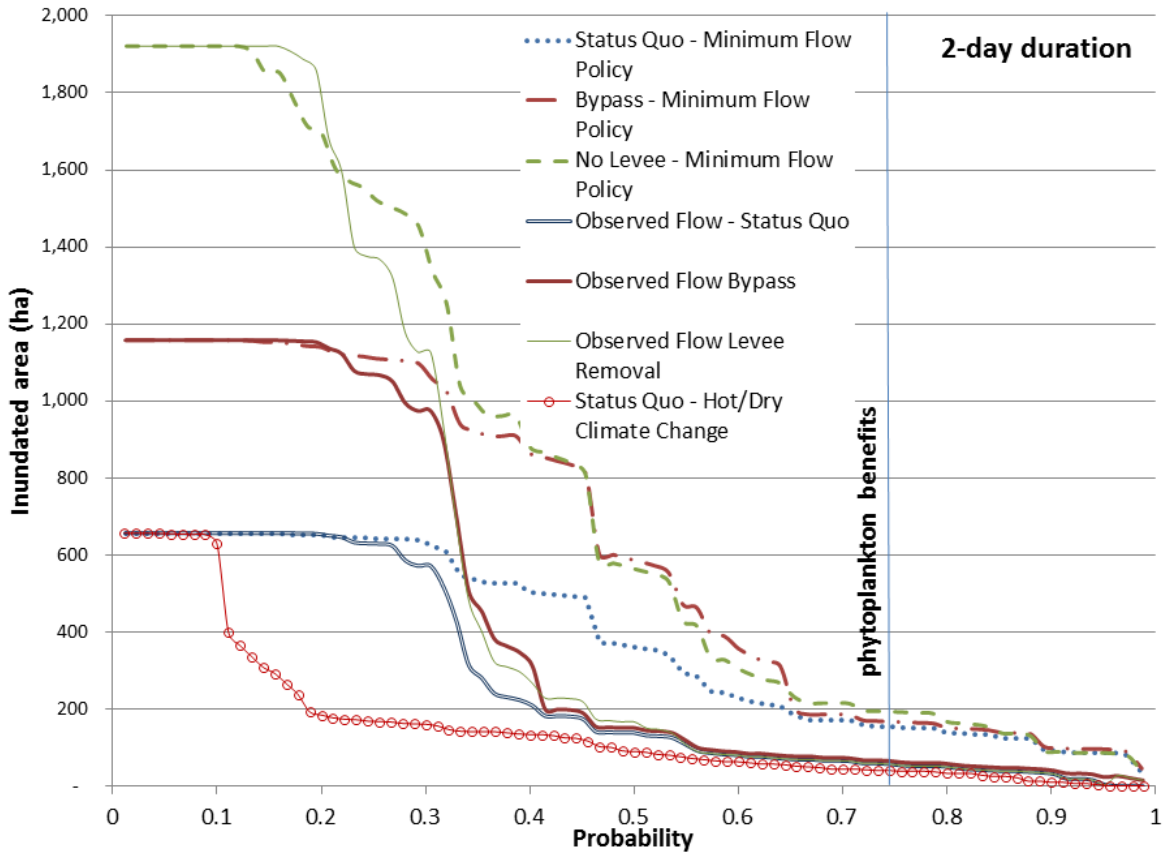


Figure 4-9. ADF curves for 2-day duration flows representing combinations of physical alterations and hydrology scenarios. At a probability of 0.76, representing the flood that occurs 1 out of every 1.3 years, on average, phytoplankton benefits occur.

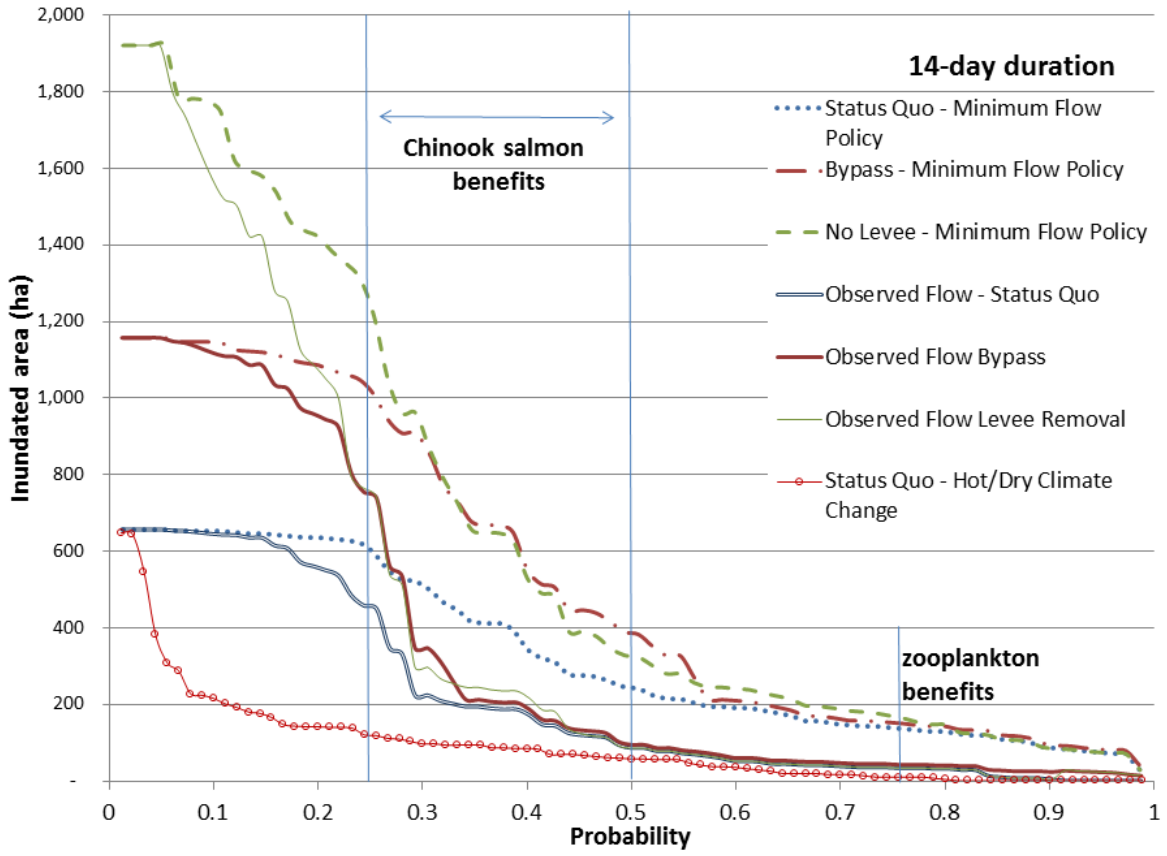


Figure 4-10. ADF curves for 14-day duration flows representing combinations of physical alterations and hydrology scenarios. A probability range of 0.25 to 0.5, representing the flood that occurs 1 out of every 4 years or 2 years, on average, Chinook salmon benefits occur. At a probability of 0.76, representing the flood that occurs 1 out of every 1.3 years, on average, zooplankton benefits occur.

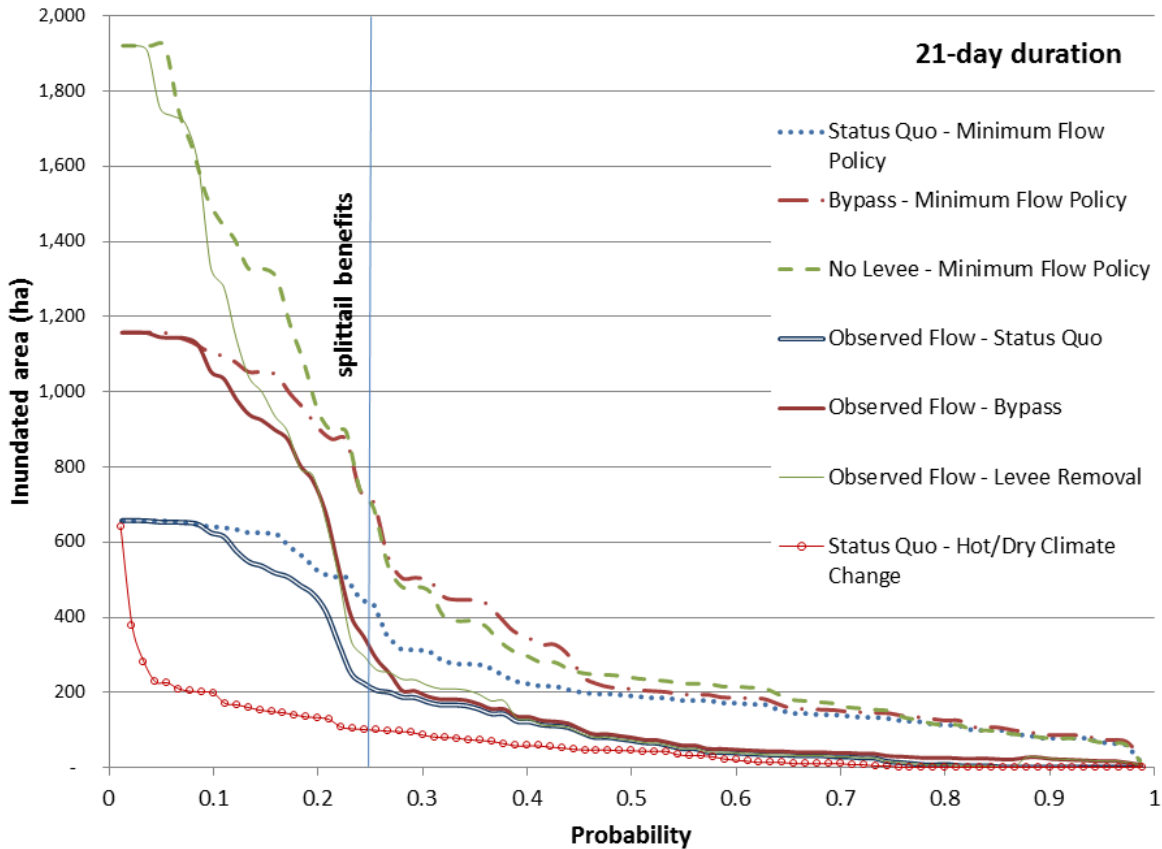


Figure 4-11. ADF curves for 21-day duration flows representing combinations of physical alterations and hydrology scenarios. At a probability of 0.25, representing the flood that happens in 1 out of every 4 years, on average, splittail benefits occur.

## DISCUSSION

This chapter demonstrates how historical and modern flow records and future climate change scenarios influence the likelihood of channel alterations providing floodplain that can be functional as habitat. The findings are for a suite of species that span a range of necessary dynamic flow requirements allowing examination of a wide array of impacts associated with four flow scenarios for the San Joaquin River system. Most importantly, the modeled results predict significant declines in the availability of flow-related habitat conditions for splittail spawning and rearing and Chinook salmon rearing in the future under two climate change scenarios. Results reveal that physical habitat restoration must be paired with additional instream flow rates to produce inundation that meets current and future flow frequency, duration, and seasonal requirements for these species.

### Historical and modern flows

The modern record contains more high annual flows in comparison to the 1930-1979 record. Under historical (1930-1979) Vernalis flows, splittail, Chinook salmon, and cottonwood

thresholds for ecological benefits were lower than those estimated from the modern flow record (1980-2010), although the lower results were not significantly different. Modeled results did not reveal differences in estimated production of phytoplankton, which require frequent lower flow pulses, under historic versus modern flow records. This results from the fact that the river had regulated flows during both of these time periods. Over 80 dams with a total storage capacity of over 9,498 million m<sup>3</sup> on the San Joaquin River and its primary tributaries capture or store more than 135% of the average annual yield of the basin (Cain et al. 2003). The management of these dams results in a more constant regulated flow pattern without periodic low pulses in flow rates and limits phytoplankton and zooplankton production which relies on frequent periods of low level flooding. Across the entire period of record, flows of 425 cms or higher are required to achieve floodplain inundation, and hence maintain floodplain habitat for fish and other services. The duration of higher magnitude maintenance flows varies greatly year to year, and in many cases does not last long enough to provide sufficient habitat for splittail and salmon (Figure 4-7).

A limited understanding of species life histories constrains forecasts of the effects of environmental change on species persistence. In addition, there is a great deal of inter-annual variability in rainfall patterns in mediterranean-climate regions, and species often respond to changes in flow regimes that do not occur during the same time each year. For example, splittail have a shorter season than salmon, waiting until Feb or March depending rainfall patterns, to spawn and rear in floodplain habitat. Including data from February to May (Table 4-2) for splittail naturally results in a different threshold flow than will result from examining flows between March and May. Considering just the modern hydrograph scenario, the flow thresholds are higher for splittail if from February-May rather than from March-May when a reduction of 35% is observed, which will result in barely enough flow to inundate any area. Another reason that the splittail are likely to have fewer hectares of functional floodplain at their disposal most years is the fact that they require longer continuous periods of inundation (21-days). In the case of salmon, some biologists assert that biennial flooding is necessary to support salmon populations in the long term (Moyle, personal communication, October 5, 2011). If this species in fact does require biennial flooding the study area scenarios cannot provide salmon rearing habitat. It is important to note, however, that estimating observed flood frequencies is dependent on the nature and length of the hydrologic record used and the observed variation in frequency can greatly influence the final habitat availability estimates.

Predicting habitat availability is further complicated when species have required rates of change in flow, in addition to seasonality, to meet their life history needs. This explains why the observed cottonwood seedling germination and establishment relationship is harder to achieve than one might expect given the low frequency flow requirements for this species (0.10). The dams upstream greatly accelerate the rate of flow recession during the spring season, limiting the period of time that cottonwood tap roots can remain in contact with the ground water table. In this system, because of both regulated flows and channel incision, varying the rate of change for declining stage did not significantly improve cottonwood habitat availability estimates. This finding suggests the required season and rates of change in flow will be harder to achieve for cottonwood than the flow frequency required year to year.

## **Changes under two climate change scenarios**

The USGS CASCaDE climate change flow scenarios are based on a physical model that takes into account a mild or strong effect of greenhouse gas emissions on stream flow. The future flow estimates under warm-wet B1 and hot-dry A2 climate scenarios are both significantly different from what has been observed in the past. Under the B1 climate change scenario the number of years certain ecological benefits can occur (phytoplankton and zooplankton production) may increase but every beneficial flood pulse under the A2 climate scenario occurs less frequently (Table 4-2). The greatest difference between the two climate scenarios can be seen for the flows required for floodplain maintenance, where the 10-year flood levels in the future are estimated to be as low as the flow levels observed at four-year intervals historically. The warm-wet scenario indicates some flows may occur that are higher than what has been observed over the period of record. This characteristic of the warm-wet climate change hydrograph is likely to permit the floodplain maintenance flow to persist, but fish threshold flows decrease by half under even under this climate change scenario. Notably, the estimated production of phytoplankton and zooplankton might increase under the B1 climate scenario, as this does not require long floodplain inundation periods. Additionally, the cottonwood germination flows, while representative of a 10-year recurrence interval event (e.g., larger magnitude flow event), still indicate thresholds below 142 cms, which is not high enough to allow for floodplain inundation, even for the low emissions B1 climate scenario. This is a result of the observed rapid recession rate of the estimated future spring hydrograph under a future warm-wet climate.

Another finding from the climate change modeled results is higher than historical winter/fall flows but reduced springtime peak flows in both scenarios. With higher future flows falling outside of the functional season for fish, lower fish production might be expected under both future climate change models. In sum, under the current physical configuration of the channel and floodplain in the study area, climate change scenarios suggest a reduction in the area available for floodplain benefits to fish.

## **Changes under two restoration treatments**

The three physical scenarios examined in the study area reflect how topographic alterations can increase the functional floodplain quantified inside the current levee configuration. Bypass flows could be diverted through the slough, which is a recently active flow path, by establishing a 6.1 m long weir where flows over 396 cms would spill over into and then flow down the slough. Removing levees is a popular treatment to restore floodplain area, and in this case a setback along the eastern banks can expose the most floodplain, as it is less confined in this direction as compared to the west side. The two alterations do show increased benefit of floodplain areas, and design and excavation could further enhance and expand these activated floodplain extents.

The power of the integrated modeling approach used (Figure 4-2) allows one to examine individual and combined restoration treatments under different flow scenarios. From these results (Figure 4-8 to 4-11) it is clear that enacting a minimum flow policy would provide significant benefits at this site. In addition, habitat availability for all species declines under climate change flow regimes, making it clear that even more additional flow will be required in



the future for this site to sustain splittail and salmon. While both of the physical alterations (setback or bypass) add additional floodplain area and allow for floodplain maintenance (1 in 10 year flow frequency), neither will facilitate the necessary flood frequencies for key species without augmenting flows. Another advantage of this approach is a visualization of ranges of potential inundation area as seen in the 14-day duration ADF for Chinook salmon benefits (Figure 4-10) that can inform managers about how sensitive results are to the selected criteria for floodplain species benefits and the hydrologic record used to calculate results.

## **Caveats**

EFM statistics rely upon the traditional concept of flood frequency, in which one assumes annual maximum floods are independent and identically distributed random variables. Other options exist for modifying statistical models to avoid violation of these assumptions, but are beyond the scope of this chapter. In light of planning to minimize flood risk, statistical models could be replaced by considering the probable maximum flood (Olsen 2006). The probable maximum flood corresponds to the event resulting from the most severe combination of reasonable critical meteorological and hydrologic conditions leading to flooding (USACE 1994). Regardless of the problems with the assumptions of annual maxima series, in cases where the hydrograph contains multiple flood peaks per year, a partial-duration flow analysis might be better suited for examining flows that occur more frequently than once every 10 years. The EFM tool does not have the capacity for this type of analysis and can subsequently underestimate the flows for these more frequent events.

The EFM tool relies on expert knowledge about species requirements. However, scientific understanding of how organisms respond to flooding and what timing, duration, and frequency will best support viable and growing populations remains uncertain. As knowledge about species biology increases, modeling assumptions such as those used in the EFM model should be updated (Fleenor et al. 2010). Another key element of EFM modeling that determines thresholds for estimating floodplain functionality is the hydrologic regime specification. Long term flow data sets are important for defining flows that occur more rarely, such as those derived here for fish relationships or for geomorphically relevant floods (e.g., occurring at or more rarely than once every 10 years, on average).

Setting fixed thresholds below which flood conditions are not deemed functional can underestimate the true beneficial floodplain functional area (e.g., water year 1965 in Figure 4-4). For example, in Figure 4-4 where the flow threshold was set for 425 cms, there may be some years where flows reached nearly that level and hence provided important habitat for longer than the results in Figure 4-4 reveal. Also, short interruptions in the required flows may not impact the total duration required for species habitat use, yet the models would not be able to account for this fact, again underestimating true functional floodplain area.

More factors than flow frequency, timing, duration, and seasonality influence truly functional floodplain habitat. Important interactions on a physical floodplain template also include temperature, suspended sediment, depth, velocity, vegetation, dissolved oxygen, and organic matter (Opperman 2012). A functional floodplain metric created by EFM that does not include these additional factors is a simplified representation of floodplain habitat potential. Despite

these limitations, EFM represents a maximum quantifiable area at a flow threshold, which is a useful place to start.

It is difficult to estimate flood frequencies from estimated future hydrographs under different climate scenarios because these models assume a directional trend that violates the assumption that each year is independent. The concept of climate change exemplifies non-stationarity as temperatures and precipitation reflect a trend over time (Olsen 2006; Stedinger and Griffis 2011). Using inundation threshold flows based on current flood frequency estimations may not be a reliable approach to forecasting habitat areas because of uncertainty surrounding what the flow dynamics will actually be in the future. Future changes with respect to extreme flooding events are also difficult to predict; however, the species modeling approach here does not rely on accurate predictions of extreme events. Evaluating the impact of climate change on flood frequency is complex, and while there is no standard or agreed upon way to do it (Dettinger et al. 2009; Stedinger and Griffis 2011), this empirical approach is reasonable for planning purposes.

A hypothetical policy scenario of flow alteration for increasing floodplain inundation potential at the site is a proof of concept. The suggested instream flow minimums in the policy scenario are likely higher than would be available from the reservoirs, and hence may not be achievable. However, these criteria were taken from previously discussed recommendations by the State Water Resources Control Board (SWRCB 2010).

The process of linking statistical, hydraulic, and spatial tools also yields potential for error due to inaccuracy and/or imprecision. The hydraulic modeling and spatial processes depend on a suite of factors such as physical data, spatial scale and resolution, and parameters for solving shallow water equations. Often these data sets are not available at the same spatial or temporal scale. In this case, downscaling monthly flow records to a daily time series required for EFM introduces additional error. Detailed downscaling of time series work is beyond the scope of this chapter, but the State is actively researching such advancements in Cal-Sim modeling of the water system (Ferreira et al. 2005). The inaccuracies of modeling in 1-D (HEC-RAS) are assumed to be less important than the efficiency with which the integrated modeling can be implemented compared to using 2-D or 3-D models (Werner 2001). Levee breach scenarios might require a 2-D model in order to capture lateral flow dynamics, but the restoration treatments were designed in this case study to capitalize on longitudinal flow as the bypass was set up as an additional flow path and the levee removal scenario simply extended the cross sections across the topographically smoothed boundary area. There exists a tradeoff in hydraulic modeling accuracy, but the intent of using the 1-D model was to simplify and assess how scenarios might be relatively different from each other. Scenarios using 2-D models and even groundwater modeling would make results from modeled restoration treatments potentially more accurate and should be considered if appropriate to the circumstances (e.g., groundwater influence on river reach flows, levee breaching scenarios, etc.).

## **Recommendations**

Restoring ecologically beneficial floodplain requires more accessible land surface proximate to the river channel and more flow, both of which interact to create time-dependent dynamic habitats. Monitoring river stage for flood frequency, duration, and timing, and coupling this

information in a tool like EFM, and updating topographic surveys can support an adaptive management approach to actual restoration of floodplain functions using various mechanisms like levee setbacks, bypasses, and altered reservoir operations (Williams et al. 2009).

Implementing a SWRCB recommendation of 60% of 14-day average unimpaired flows (February through June) onto the historic record could increase the frequency of most ecosystem benefit flows and provides the most benefit to zooplankton and phytoplankton production. However, to increase cottonwood benefits, the policy hydrograph would have to be more closely scripted with rules regarding the spring storm stage decline rates. Some form of managed reservoir releases will be vital to rehabilitating floodplain at the site and should be considered just as important as potential levee setback alterations when scoping restoration actions. This is particularly prudent in light of future flow regime scenarios for the next century, both of which will limit dynamic floodplain potential in the spring season unless managers release water from reservoirs at this time.

In summary, this chapter demonstrates advancements in methods for planning floodplain restoration by utilizing and improving upon predictions of an integrated hydro-ecological model using fine scale data and informed functional ecosystem relationships. Prioritization of floodplain restoration actions requires a method of comparing potential ecological benefits from topographic or flow changes in light of costs and constraints. Maps and quantitative estimates of habitat generated by the combination of EFM, hydraulic modeling, and spatial tools allow managers to assess where restoration projects might be more effective or suitable under scenarios of climate change or flows altered by reservoir management actions.

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## **CHAPTER 5**

### **FLOODPLAIN ANALYSIS FOR RESTORATION SITE PRIORITIZATION**

Mary K. Matella

## Floodplain analysis for restoration site prioritization

### INTRODUCTION

Ecological restoration has typically been considered a means to return a currently degraded ecosystem to its former condition (Hobbs and Cramer 2008). However, the question of what to restore is not always self-evident, and it must precede the question of what restoration projects to prioritize (Beechie et al. 2008). Projects to restore floodplain function not only require reconnection of river and proximate land, but also flow characteristics synchronized with species recovery needs. Climate change is likely to alter future patterns of stream flow and temperature, so restoration managers should accommodate potential climate change effects in species recovery plans as well (Palmer et al. 2005; Beechie et al. 2012).

Despite the risk that large floods pose to human life and property in developed areas, frequent floods provide benefits for natural floodplains. Natural floodplains provide many ecosystem services that benefit society and ecosystems, including habitat provision, floodwater storage, agricultural production, and recreation. One region that exemplifies these ecosystem services is the Sacramento River Valley, a region that historically experienced large magnitude, long duration seasonal floods and supported a vastly productive wetland ecosystem (Kelley 1989). Flowing south, the Sacramento River drains the Sierra Nevada Mountains, southern Cascades, and the eastern slope of the Northern Coast Range, meeting the northbound San Joaquin River in its inland delta, a 3,000 km<sup>2</sup> web of channels and reclaimed islands.

The Sacramento River basin has a mediterranean climate, with fall and winter tending to be cool and moist, while late spring and summer are warm and dry. Predictable annual floods historically shaped the dynamics of biotic and abiotic controls in Sacramento River riparian communities, though variable stream flow rates across space and time are characteristic of the mediterranean climate (Gasith and Resh 1999). In response to the intra-annual seasonality and inter-annual unpredictability of freshwater supply, Californians invested in intensive water management infrastructure to improve water supply reliability and provide flood control by constructing large dams and conveyance projects.

Over a hundred years ago communities fought against natural flooding of the Sacramento Valley by channeling floodwaters away from crops and cities with levees (Kelley 1989). Prior to 1917, when the Sacramento River Flood Control Project (SRFCP) was authorized, levees were typically constructed in response to a past flood, with little or no coordination between different localities. The SRFCP ushered in a comprehensive system of levees, overflow weirs, drainage pumping plants, and flood bypass channels, to safely convey Sacramento River and tributary flows. With approximately 2,100 km of levees, the project provides flood protection to about 850 thousand ha of highly productive agricultural land, as well as protection to the cities of Sacramento, West Sacramento, Yuba City, Marysville, Colusa, Gridley, and other communities.

In support of the Sacramento River Flood Control Project, in 1960 Congress authorized the Sacramento River Bank Protection Project (SRBPP), a continuing construction project, to provide protection for the existing levees and flood control facilities. The project was intended to maintain the integrity of the levee system of the SRFCP in its designed capacity (Figure 5-1). Under the SRBPP program, levees are inspected on an annual basis, and erosion is repaired on

about 10,000 linear feet of levee each year. Past fixes include rock revetment and combinations of rock protection, vegetation plantings, and placement of woody material as on-site biological mitigation, as well as setback levees which give the river more area to potentially inundate under high flows. The SRBPP project was intended to reduce costs of emergency repairs and downstream dredging, reduce land losses caused by erosion, and provide recreational areas along the river at selected sites.

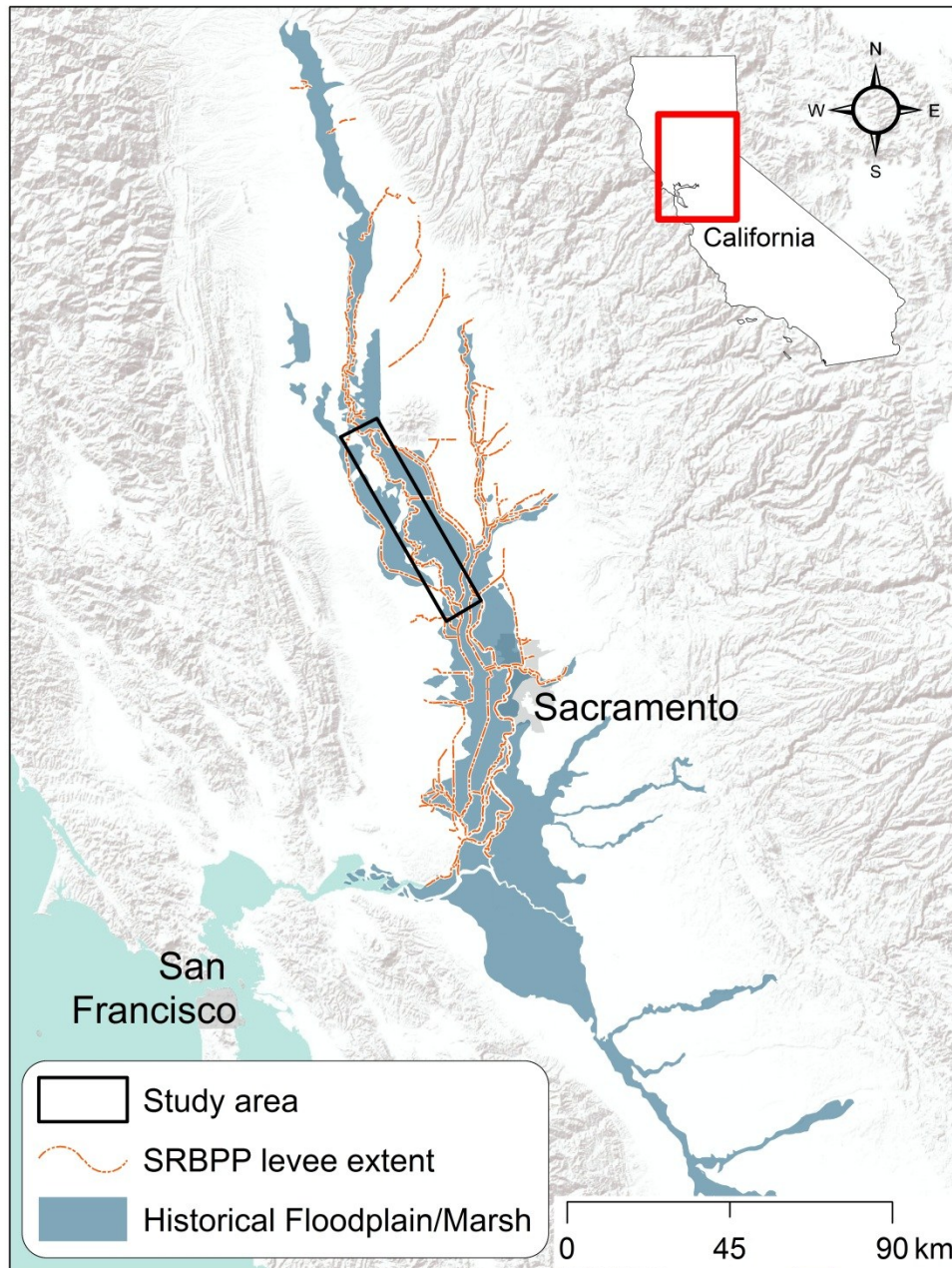


Figure 5-1. Location of lower Sacramento River study area and Sacramento River Bank Protection Project (SRBPP) extent of levees overlaid on historical floodplain (Bay Institute 1998)

The high potential in the region for flooding due to levee failure, overtopping, or extreme precipitation events makes flood management planning critical (Lund et al. 2007; DWR 2011a). Further complicating the problems facing the region, populations of endangered species in the Central Valley are declining while invasive species are encroaching. Structures and other existing development often limit the ability of managers to prepare for levee failure, saltwater intrusion, or earthquake disruption, as well as implement habitat restoration treatments for species recovery. Thus, planning for species recovery, climate change, and flood management is particularly important considering the challenges facing the region in the short and long-term (Eisenstein et al. 2007).

Water supply and flood protection projects have lowered the variability in stream flow, in some cases greatly reducing the quantity of flowing water, and disconnected rivers from floodplains in the Sacramento River system. Restoring historical patterns of flow for species recovery in the future will occur on a physical river landscape quite different from its pre-1800s state. Multiple stressors (e.g., invasive species, water diversions, pollution) will affect the success of restoration projects. Planning for species recovery in the watershed will require a landscape scale approach that can address the scale of the stressors and account for additive, antagonistic, or synergistic cumulative effects (Diefenderfer et al. 2011; Palmer et al. 2005). Research combining concepts of both hydrology and ecology must inform plans for satisfying both human and ecological needs for water (Palmer and Bernhardt 2006). Thus, an integrative hydro-ecological model offers support for decision makers considering where to rehabilitate floodplain processes upon which biological and social benefits depend.

Institutional barriers make it difficult to coordinate and maintain flood protection where federal or state authority over levee integrity exists, but there is potential for streamlining the planning process. For example, levee erosion repair projects that include levee setbacks could be used to reconnect floodplain habitat as they could be designed to both lower the stages of large potentially damaging floods, allow for groundwater infiltration, and increase areas that are inundated by ecologically beneficial non-damaging flow pulses (Williams et al. 2009). An understanding of the basic processes that affect habitat, and the scales at which they operate, can aid the adaptation of strategies to promote optimal benefits from reconnected floodplains (Opperman et al. 2010).

General strategies for prioritizing stream restoration projects can be based on logical and analytical approaches (Beechie et al. 2008). Logical approaches apply prioritization based on project types (e.g., prioritize project types that protect existing high quality habitat and connectivity first [Roni et al. 2002]) or based on a score sheet combining weighted measures (e.g., Sacramento River scorecard [Golet et al. 2011]). Analytical approaches target how a project affects species (single or multiple species) directly or via watershed functions relevant to species needs. Another analytical prioritization approach uses cost effectiveness (biological outcome measure divided by cost) to rank projects. This chapter incorporates elements of score sheet and analytical approaches to prioritization, culminating in a cost effectiveness ranking of floodplain reconnection projects.

Deciding where to rehabilitate hydrologic processes that shape characteristics of the physical floodplain habitat can be approached using an integrative hydro-ecological model. Such a model was used on the Lower Sacramento River to 1) extend the framework presented in Chapter 3 and 4 linking floodplain ecology and hydrology, 2) assess cumulative benefits of floodplain

rehabilitation scenarios, and 3) examine scenarios of changing topography and climate. Combining modeled outcomes of floodplain area benefits and some socio-economic factors, levee setback scenarios were ranked so that floodplain reconnection projects with high return potential can be prioritized.

## METHODS

The study area was delineated from the expanse of the SRBPP project area in the Sacramento River Basin. Levees along the Sacramento River from south of Hamilton City to Sherman Island and associated tributaries (e.g., Feather River, American River) are a part of the SRBPP system (Figure 5-1). Using the USACE and Reclamation Board (2002) Comprehensive Study (Comp Study) Appendix D sketches of potential levee setbacks and following discussions with SRBPP managers, I isolated a reach from Colusa to the Fremont Weir on the Sacramento River for more detailed floodplain reconnection analysis.

The floodplain analysis for restoration site prioritization along this Colusa-Fremont Weir reach integrated statistical measures of flow regime, hydraulic modeling, and spatial analysis. Information on flow frequency, duration, seasonality, inundation, and habitat characteristics describing floodplain suitability based on the literature is essential for setting up the conceptual framework for this analysis (Figure 5-2). This study utilized the Chapter 3 method with some species specific flow requirements described in Chapter 4. The following information specifies how the components were modified from the general method laid out in earlier chapters.

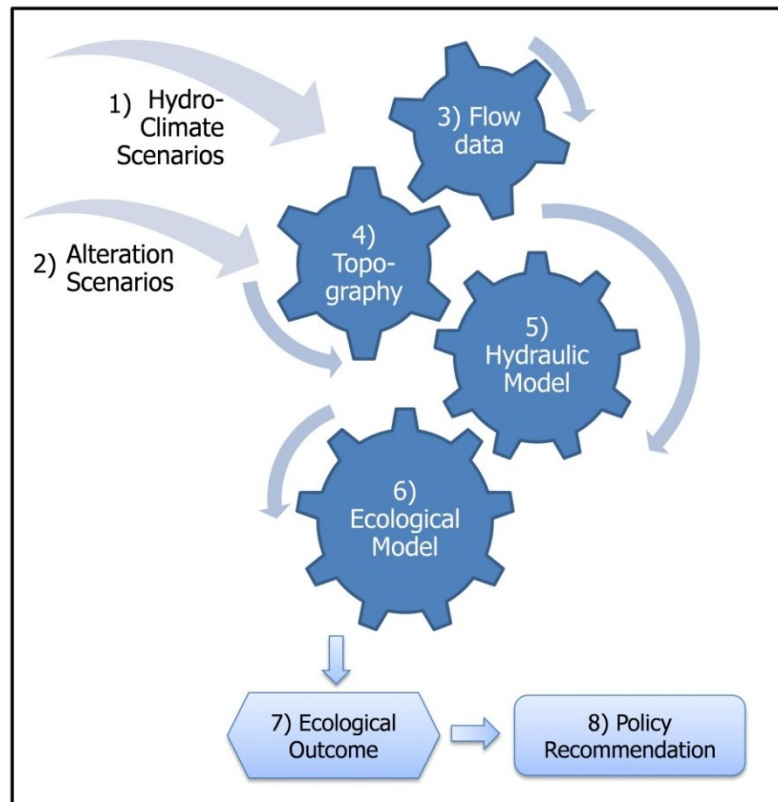


Figure 5-2. Steps of integrated analysis

## Flow characterization

Flow characteristics were identified based on the habitat requirements for splittail, Chinook salmon, and phytoplankton and zooplankton productivity. The USACE HEC-Ecosystems Function Model (EFM) was used to examine statistical relationships between hydrologic and ecological parameters (USACE 2009). HEC-EFM runs on a daily time series of mean flow and stage to derive flow thresholds using variables such as season, duration, rate of change and frequency to characterize ecological suitability. The EFM was populated with daily flows from historical records from Sacramento River at Colusa United States Geological Survey (USGS) Gage Station # 11389500 (1945-2010) and Sacramento River below Wilkins Slough near Grimes USGS Gage Station # 11390500 (1945-2010). The water years after 1945 were selected to capture fully regulated flows following the completion of Shasta Dam.

The USGS gage (#11377100) characterizing future flows at Sacramento River above Bend Bridge near Red Bluff was used to inform the climate scenario as a basis for modeling future changes to flow based on expected changes to precipitation and temperature, allowing an examination of future flows (2001-2099) in the analysis. Four future flow scenarios from 2001-2099 were developed by the USGS CASCaDE: Computational Assessments of Scenarios of Change for the Delta Ecosystem project (USGS 2009). The climate change scenarios reflect CASCaDE estimates based on a University of Washington Land Surface Hydrology Research Group framework and Global Circulation Model (GCM) simulations of historical climate conditions, A2 future greenhouse-gas-and-sulfate-aerosols emissions scenarios, and B1 future emissions scenarios. The GCMs represented are the National Center for Atmospheric Research's Parallel Climate Model 1 (PCM) and the NOAA Geophysical Fluid Dynamics Lab's GFDL CM2.1 model. Modeled climate data reflect downscaling using the constructed analogs method of Hidalgo et al. (2008). USGS used the Bay-Delta Watershed Model (BDWM), a physically based model of hydrologic processes, to generate stream flow at a daily time step with primary inputs of precipitation and air temperature, simulating hydrologic variability throughout the watershed. I chose to run analyses based on the best-case scenario for a warm and wet future climate represented by B1PCM and the worst-case scenario that is hot and dry represented by A2GFDL to examine the range of expected change.

While the USGS gage (#11377100) characterizing future flows at Sacramento River above Bend Bridge near Red Bluff was used to inform the climate scenario, I had to extrapolate those Sacramento River at Red Bluff climate change flows to Colusa using monthly linear regression relationships based on the historical record. Based on the Red Bluff and Colusa gage records from WY 1945-2010, water year types wet/dry/average were determined for average daily flows based on the upper, lower, and mid-range ~33 percentiles. Then, monthly regressions were done for flows at the two locations (X axis=flow at Red Bluff, Y axis=flow at Colusa). After the regression lines were fit, climate change flows for Red Bluff were translated into Colusa flows according to water year type and month.

After specifying the flow regimes for the EFM model, I created seasonal filters of December-May for the hydrologic records. Then 1-day, 14-day, and 21-day duration windows were selected to span the range of flows beneficial to phytoplankton productivity, rearing salmonids, and splittail spawning. The EFM tool creates annual maximum flows for the minimum flow that meets these duration criteria. The EFM model runs can determine the flow and stage corresponding to a frequency in addition to duration and season for the ecological functions.

Rather than output a single frequency value, however, the entire flow-frequency duration curves for the December-May season were exported in order to capture a range of frequency results.

The EFM results were imported into the U.S. Army Corps of Engineers Statistical Software Package (HEC-SSP) to create flow-frequency plots following the procedure of USGS Bulletin 17B "Guidelines For Determining Flood Flow Frequency" (1982). This method uses a Log Pearson Type-3 (LPIII) distribution for estimating quantiles and produces confidence intervals for estimates of flow.

Equation 1 describes the relationship between exceedance probability ( $p$ ) and return interval ( $T$ ). The return period of 2, or a 2-year recurrence interval event, corresponds to an exceedance probability of 50% and is a key criterion for meeting rearing salmonid needs.

$$p = \frac{1}{T} = \frac{m}{n} \quad (1)$$

Where:  $p$  is exceedance probability

$T$  is return interval

$n$  is number of years on record

$m$  is number of recorded occurrences of flood event

### Hydraulic modeling

To define relationships between the flows and inundated floodplain area for the physical scenarios, I conducted hydraulic modeling using the flood inundation model LISFLOOD-FP, University of Bristol Code release 2.6.2 (Bates et al. 2005). LISFLOOD-FP is a hybrid 1D-2D model based on a raster DEM, allowing researchers to take advantage of recent developments in the remote sensing of topography such as airborne laser altimetry for large areas (Bates and De Roo 2000). The model uses 1D kinematic or diffusion wave routing in the channel and routes water over complex topography. Once bankfull depth is exceeded, the model transfers water to neighboring cells using Manning's equation or a 2D diffusive wave applied over a raster grid using the storage cell concept. The model assumes that flood spreading over low-lying areas is driven by gravity and land surface elevations.

Channel flow reflects a 1D approach using continuity and momentum equations (Horritt and Bates 2002):

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \quad (2)$$

$$S_0 - \frac{n^2 P^{\frac{4}{3}} Q^2}{A^{10/3}} - \frac{\partial h}{\partial x} = 0 \quad (3)$$

where:



Q = volumetric flow rate in channel  
 A = cross sectional area in channel  
 q = flow into channel from other sources  
 n = Manning's coefficient of friction  
 t = time  
 S<sub>0</sub> = bed down-slope  
 P = wetted perimeter (approximated by channel width)  
 h = flow depth

Floodplain flows are also described by continuity and momentum equations, and discretized over a raster grid to represent 2D dynamic flows:

$$\frac{dV}{dt} = Q_{up} + Q_{down} + Q_{left} + Q_{right} \quad (4)$$

where:

V = cell volume

t = time

Q<sub>up</sub>, Q<sub>down</sub>, Q<sub>left</sub> and Q<sub>right</sub> = flow rates in each direction into (positive Q) and out of (negative Q) the cell

$$Q_x^{i,j} = \frac{h_{flow}^{5/3}}{n} \left( \frac{h^{i-1,j} - h^{i,j}}{\Delta x} \right) \Delta y \quad (5)$$

where:

$h^{i,j}$  = water free surface height at i,j

$h_{flow}$  = depth through which water can flow between two cells

$\Delta x$  and  $\Delta y$  = cell dimensions

Q<sub>x</sub>, Q<sub>y</sub> = volumetric flow rates between cells

n = Manning's coefficient of friction

Boundary conditions were set with flow at the upstream end of the reach and stage at the downstream end. The parameters required to run LISFLOOD-FP are channel width, bed slope, depth, and Manning's n roughness values. Width and depth are assumed to be uniform along the reach, using average values from channel surveys. HEC-RAS cross-sections created for the Comp Study informed the model parameters, and width of channel was derived from cross section banks and bed elevation was extracted using the center point of each cross section (USACE and Rec Board 2002). A standard Manning's roughness value of 0.035 was used for the channel and a Manning's n value of 0.06 was used for the floodplain, corresponding to a land cover of light brush and trees (Chow 1959).

Figure 5-3 shows water surface elevations observed from December 29, 1996-January 5, 1997, at cross-section 119.25 against the results of LISFLOOD and the Comp Study HEC-RAS model run. LISFLOOD results are similar to the HEC-RAS results for this baseline existing levee conditions model run.

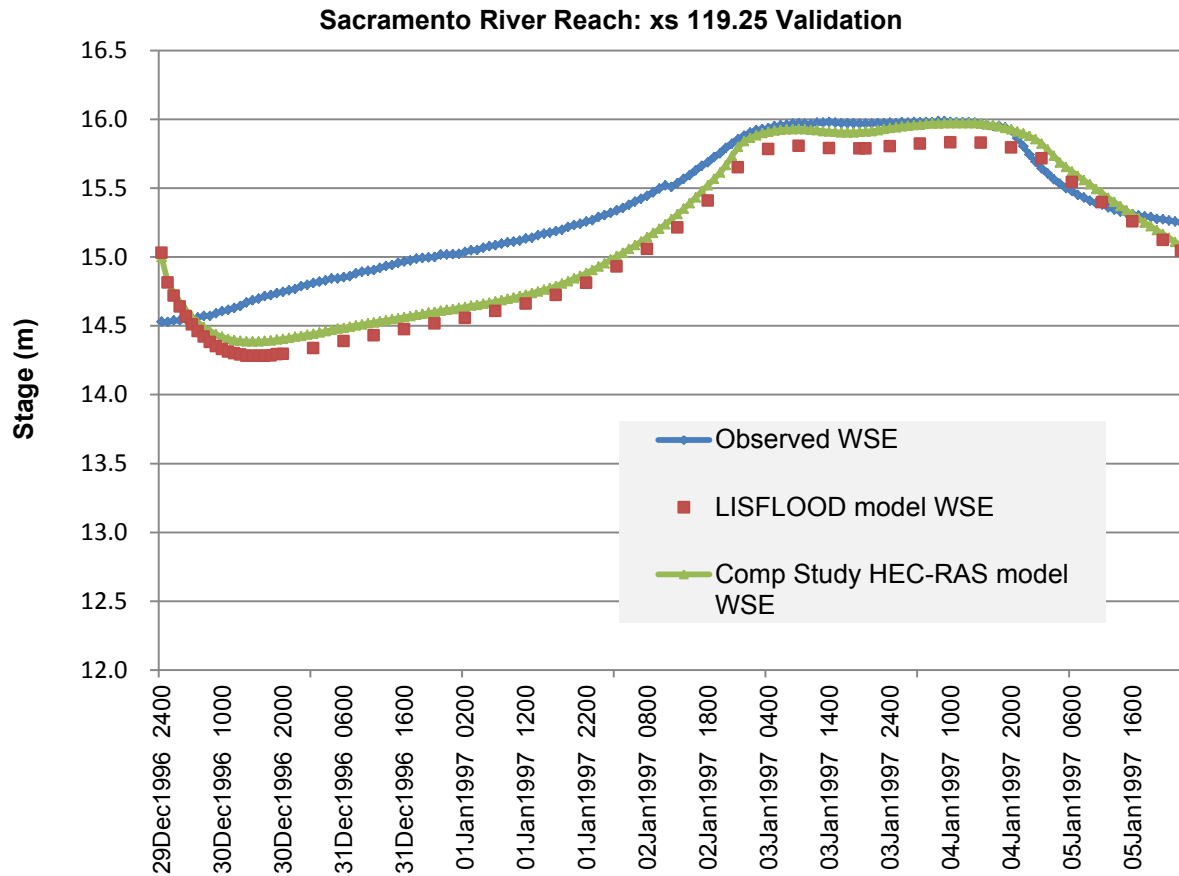


Figure 5-3. Validation model run water surface elevation (WSE) results comparing LISFLOOD, HEC-RAS, and Observed stages for December 29, 1996-January 5, 1997, at cross section 119.25

### Spatial analysis

To conduct the hydraulic and spatial analysis for this study, a physical template was constructed in a Geographic Information System (GIS). I generated land surface elevations from three-dimensional floodplain topography from light detection and ranging (LiDAR) based surveys (DWR 2010), and integrated bathymetry data for the study area using output from a previous Army Corps of Engineers Study (USACE and Rec Board 2002) for the Sacramento River reach from Colusa to Verona. I created 2 m (6.6 ft) resolution grids based on 1 m (3.28 ft) LiDAR tiles obtained from DWR, but aggregated the pixel size to 6 m resolution for flow modeling efficiency.

Digital elevation model (DEM) grid floodplain-channel surfaces were created for 26 setback scenarios. The Colusa to Fremont Weir area was divided into two sections to facilitate analysis and utilize hydrologic records at Colusa and Wilkins Slough gages. The lower section of the study area from Grimes to Fremont Weir includes Setbacks 1-6. The upper section of the study area from Colusa to Wilkins Slough includes Setbacks 7-16. To investigate cumulative impacts of setbacks, select combinations of setbacks were modeled (Table 5-1). Baseline model runs with the existing levee locations were designated as Run 27 for the upper section, and Run 28 for the lower section.

Table 5-1. Model runs and associated levee setbacks

<b>Model Run</b>	<b>Lower Region</b>	<b>Model Run</b>	<b>Upper Region</b>
<i>Single setbacks</i>			
1	setback 1	7	setback 7
2	setback 2	8	setback 8
3	setback 3	9	setback 9
4	setback 4	10	setback 10
5	setback 5	11	setback 11
6	setback 6	12	setback 12
		13	setback 13
		14	setback 14
		15	setback 15
		16	setback 16
<i>Setback combinations</i>			
17	setback 1-6	18	setback 7-16
19	setback 2&3	22	setback 9&10
20	setback 3&4	23	setback 10&11
21	setback 5&6	25	setback 7-9
24	setback 2-4	26	setback 12-15

I developed a GIS procedure in Python code (v.2.4) to remove current levee height and create new setback levees for scenarios using a surface elevation for removal of levees and using digitized lines for new setback levee locations. The elevation surface for cutting down levees uses the 2-year recurrence interval Sacramento River Centered Comp Study storm extracted from the Comp Study Hec-Ras model at a minimum level for the unsteady state run. A grid surface was created by converting bank points for each cross section into a tin data file. Using an allocation function, the processed grid extended the water surface laterally from the river cross sections. A grid was created for the scenario of all levee location setbacks in place. The Python

code iteratively generated new grids for every new setback levee in place with the old levee area set to the height of the removal surface.

After conducting hydraulic modeling using LISFLOOD-FP, relationships were defined between the flows and inundated floodplain area for the levee setback scenarios. The initial time of inundation was summarized by setback areas and habitat analysis areas (HAAs). The setback areas encompass the new additional area open when the current levee is removed and a new one is established away from the channel (Figure 5-4). The habitat analysis areas are smaller units (along 1-2 river miles) delineated as similar reach habitat (Table 5-2). These HAAs can be useful for developing stage/flow rating curves if stage is linked to an important ecological inundation relationship, such as cottonwood seedlings being dependent on a slowly declining stage (Mahoney and Rood 1998).

### **Socio-economic considerations for prioritizing floodplain restoration sites**

Three general steps were used to integrate socio-economic considerations into the prioritization process. Step 1 was the elimination of sites for which restoring floodplain land would be infeasible. For example, it is necessary to avoid “urban” or “residential” and other land use categories that are impractical. Step 2 was the identification of factors relevant to the specific setback area scenarios. This included assessing levee ownership/management, economic impact areas behind certain stretches of levee, and information from parcel databases. The final step was a comparison of specific setback options with no action using a numeric ranking system compatible with the ranking system used for ecological benefits. This comparison step could encompass the facets of flood damage reduction, economic impacts, and project cost.

#### *Flood Damage Reduction*

At this time a flood damage reduction assessment was not conducted. Consideration of flood damage reduction would include estimating flood damage under setback conditions minus current estimated flood damages. This would be based on the assumption that setback levees reduce probability of failure and therefore benefits are greater when setbacks are implemented in areas where potential economic damages are greater, and in areas where levees start off with a high probability of failure. Erosion sites served as proxy areas for places where levee failures are more likely, though the probability of failure and value of damages did not explicitly inform this site prioritization.

#### *Economic/Fiscal Impacts*

A full assessment of economic impacts was not conducted for this project. A more informed socio-economic characterization of setback sites would depend on whether one assumes that agricultural acreage is removed from production and converted to habitat, or if land remains in private hands and an easement is purchased.

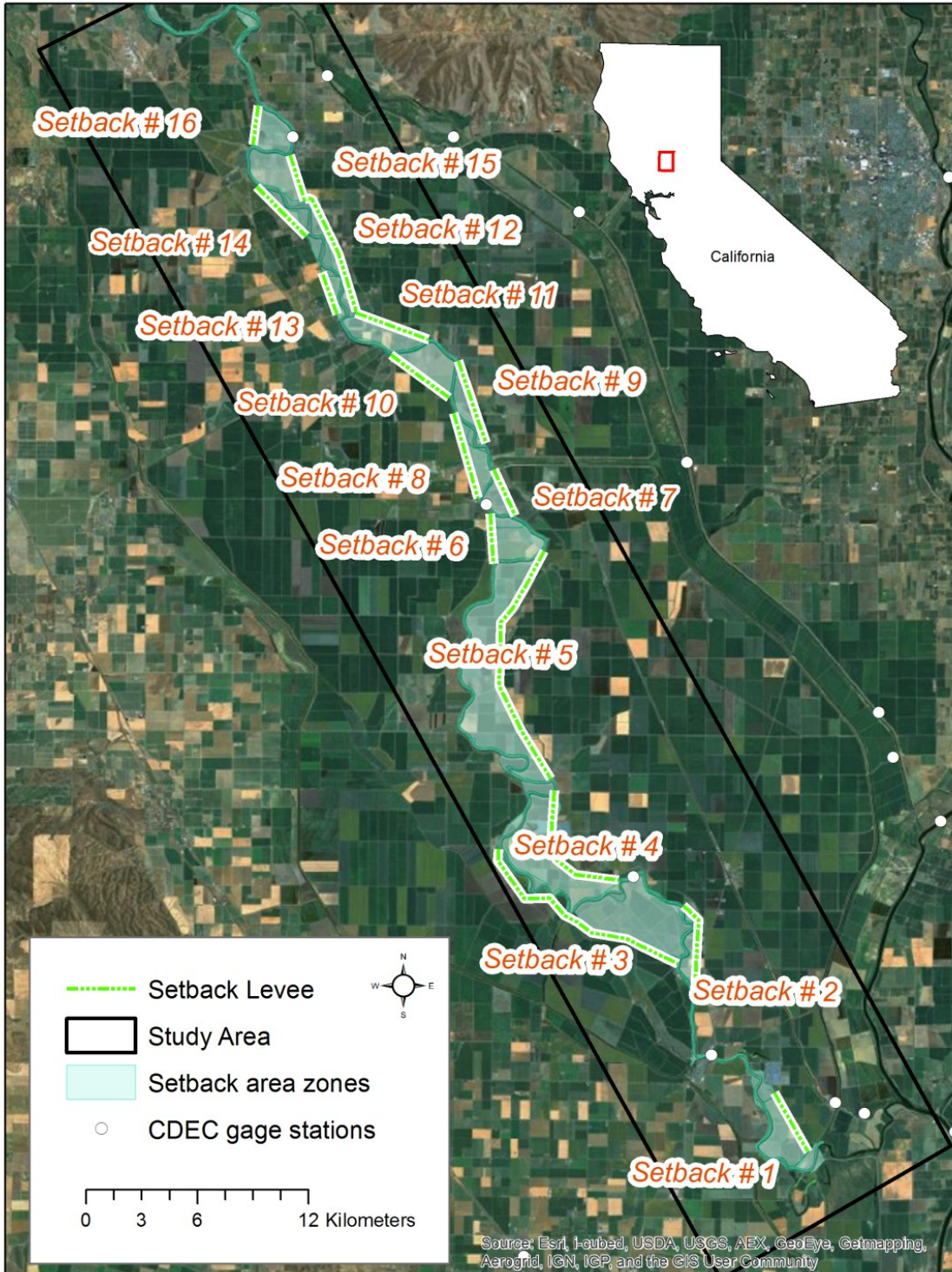


Figure 5-4. Map of setback area locations

Table 5-2. Habitat Analysis Unit Description and associated significant areas of native vegetation and potential “natural restoration” areas between levees from the Sacramento River Conservation Area Forum Handbook (California Resources Agency 2003)

HAA ID	Number of cross section	Upstream River Mile cross section	Downstream River Mile cross section	Significant Area of native vegetation
1	6	143.24	142.25	
2	15	142.25	138.75	Moon's Bend
3	8	138.75	136.75	
4	12	136.75	134.25	
5	16	134.50	132.50	
6	19	133.25	129.50	Ogden Bend-Girdner Bend
7	13	130.25	127.50	Ogden Bend-Girdner Bend
8	15	127.75	125.25	Ogden Bend-Girdner Bend
9	16	126.25	123.25	
10	15	124.25	121.25	
11	15	122.25	119.50	North of Tisdale Weir
12	16	121.00	118.25	North of Tisdale Weir
13	15	119.20	117.00	
14	11	117.75	116.00	
15	10	116.00	114.25	
16	11	115.75	113.50	
17	8	113.50	111.75	
18	9	111.75	110.25	Boyer's Bend
19	17	110.25	107.00	
20	13	107.50	105.75	Poker Bend
21	11	106.75	103.77	China Bend
22	8	104.38	102.50	Tyndel Landing
23	12	102.50	99.75	Upstream of Eldorado Bend
24	16	100.00	97.00	Missouri Bend
25	16	98.75	95.50	Victor Bend
26	12	95.50	93.00	Upstream and Downstream of Railroad Bend
27	23	93.25	90.00	
28	22	90.50	88.75	
29	11	89.25	87.00	Portuguese Bend/Mary Lake
30	13	87.00	84.25	

## *Project Cost*

If levee setback project areas are assumed to use purchased land, relative estimates of land value should be developed. According to USACE appraiser George Heubeck (personal communication, 2011), property values from county tax assessor are not necessarily closely related to actual market values, because of California's Prop 13 measure. Tax assessor values would only be reasonably accurate if properties recently changed hands, and the date of the most recent purchase does not always appear in the land parcel data. Appraising land for actual market value is a very detailed process, so I developed a simple method that George Heubeck indicated would be reasonable. Using county land value estimates at the high end of the range provided by the California Chapter of American Society of Farm Managers and Rural Appraisers (ASFMRA) 2009 Trends in Agricultural Land and Lease Report, values were attributed to land cover types in the 2010 USDA National Agricultural Statistical Service (NASS) data set. The high end of the value range given by ASFMRA was used. Parcel boundaries were overlaid on this raster data to generate an average value per parcel intersecting the setback areas in the scenarios. If structures were present in the assessor parcel database, the improvement value was added to the calculated parcel value, to incorporate a residential factor into the estimates. To include a measure of administrative costs of acquiring land for the setback areas, I note where administrative costs are likely higher as the number of parcels increases.

Other considerations for deriving estimates of project cost include the costs for levee construction and removal, levee repair costs, and restoration costs. According to the 2012 Central Valley Flood Protection Plan (DWR 2011b), the typical per mile costs for levee setbacks ranges from \$22 to 26 million per mile. Typical erosion repair costs are \$14-18 million per mile. A setback levee might result in lower on-going operation and maintenance cost, as would likely be the case for a site that is currently subject to frequent erosion (identified in the 2008 Ayres report). Restoration costs vary by original land use type and size, and restoration type (e.g., factors such as the cost of removal of orchard trees; active versus passive restoration).

## **Restoration Site Ranking**

I developed a ranking system to first prioritize levee setback areas using ecological benefit metrics (Expected annual habitat—EAH) developed according to Chapter 3 methods. Setback areas were initially ranked according to EAH at 1-day, 14-day, and 21-day durations. Rankings are also provided based on EAH per levee length removed from highest EAH-length ratio (rank-1) to lowest EAH-length ratio (rank-16). The benefit cost ratios of parcels overlapping the setback areas were also ranked from lowest cost per benefit hectare (rank-1) to highest cost per benefit hectare (rank-16).

## **RESULTS**

Flow frequency curves for 1-day, 14-day, and 21-day duration flows represent magnitude and exceedance probabilities for the Colusa (Figure 5-5) and Wilkins Slough gages. The 1-day duration results for both gages are mostly well within the confidence limits for flows with exceedance probabilities less than 90%, or events with greater than a 1.1 year return period. The 14-day and 21-day observations show a similar pattern at both gages, where 10-year return period observed event flows are consistently below the LPIII computed fit. This finding

indicates the LPIII 14-day and 21-day probabilities overestimate the flows for larger return periods. Another note about the 2-year return period, however, is that all duration results generally fall within the +/- 5% confidence intervals or observed events exceed the LPIII computed curves. I will therefore be conservative in any 2-year return period frequency floodplain characterization in the study area.

Flow-area curves reflect the hydraulic relationship of flow and inundation area according to the spatially defined reach extents. The Figure 5-6 curves for model runs reflect the effects of single setbacks on increasing inundated area. The lower reach is from the Sacramento River below Wilkins Slough gage to the Fremont Weir and the upper reach is from Colusa to the Sacramento River below Wilkins Slough gage. Baseline conditions reflect the water surfaces in channel and inside the current levee configuration. Figure 5-6 shows how much additional area is inundated given the topographic alteration commensurate with the setback compared to the baseline existing levee condition. I also created maps of probability of exceedance for the 16 setback areas by 1-day, 14-day, and 21-day durations (Figure 5-7). These maps associate pixels with a probability based on the respective duration flow at which a location is first inundated.

The flow-area relationships express how much flow is necessary to inundate each additional hectare of floodplain. To translate this type of data into an expression of how much floodplain gets inundated in an example year, daily average flow was plotted from water year 1965 with the corresponding area that would be wetted under a scenario of levee setbacks 7-16 concurrently opened (Figure 5-8). The figure represents the area inundated that falls within channel boundaries, within existing levee boundaries, and within the boundaries of new levee setbacks. By separating the area in channel from the channel edge (land between all wetted channel and the bounding levee), I attempted to classify floodplain habitat as distinct from permanent in-channel habitat. Existing floodplain is identified as that land periodically inundated between the channel (as defined by the channel delineated by DWR 2006) and the levee centerline. New floodplain can then be added when levee setbacks are enacted in modeled scenarios.

The potential ecosystem function benefit of increased inundation was quantified by correlating the hydraulic model results for maximum potential habitat area with the flows defined by the hydrologic frequency analysis for ecologically relevant floods. The Area-Duration-Frequency (ADF) curves reflect the maximum possible floodplain habitat against frequency for each duration period. Using these curves, one can visualize the potential available habitat over several durations and across multiple probabilities of occurrence (Figure 5-9). These ADF curves provide a variety of individual frequency metric possibilities. For example, the frequency of 50% (2-year recurrence interval) on a 14-day duration curve might be used to compare scenarios that would benefit rearing salmonids (Figure 5-10).



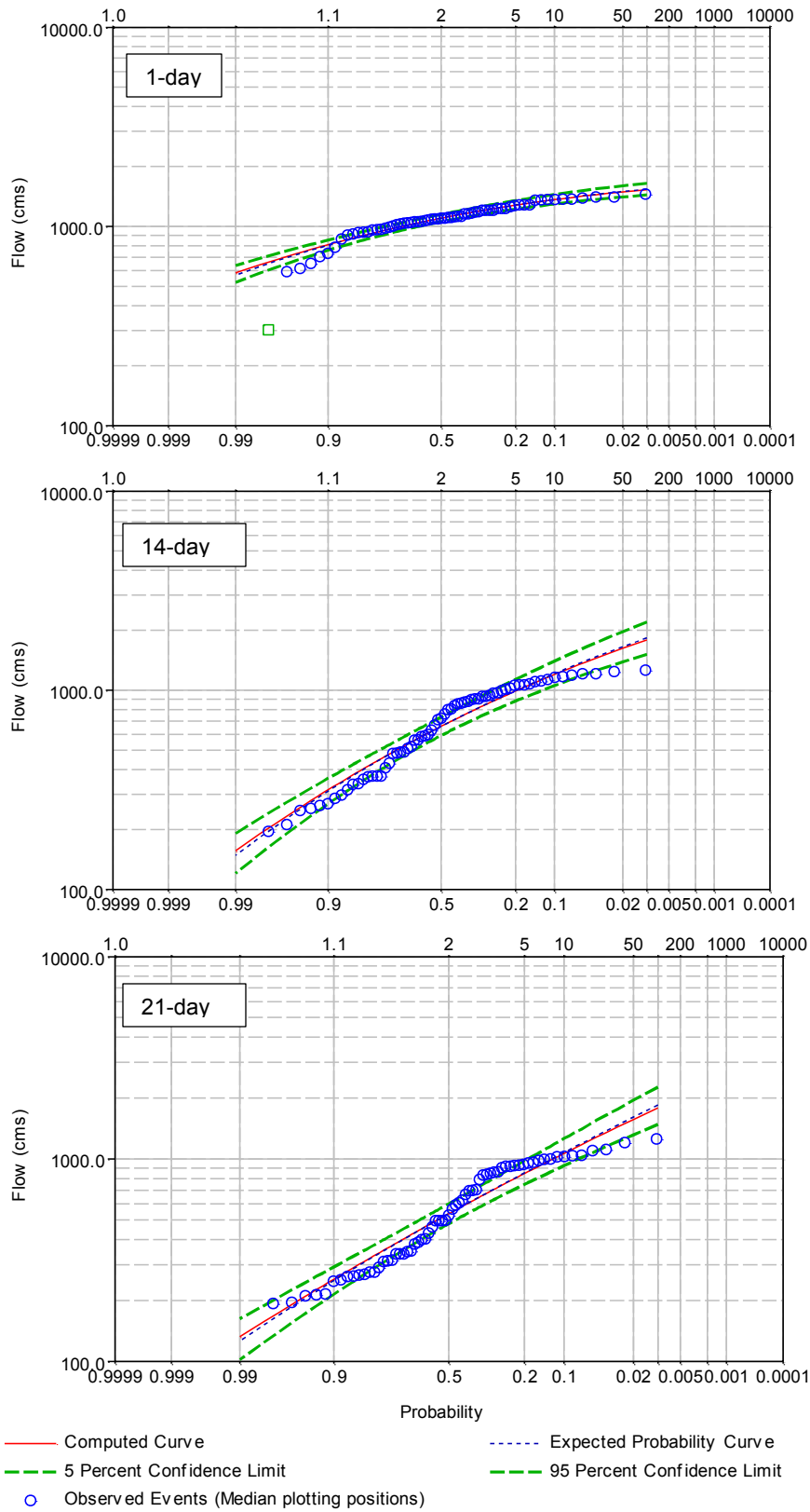


Figure 5-5. Flow Frequency Plot for Colusa gage 1-day, 14-day, and 21-day durations

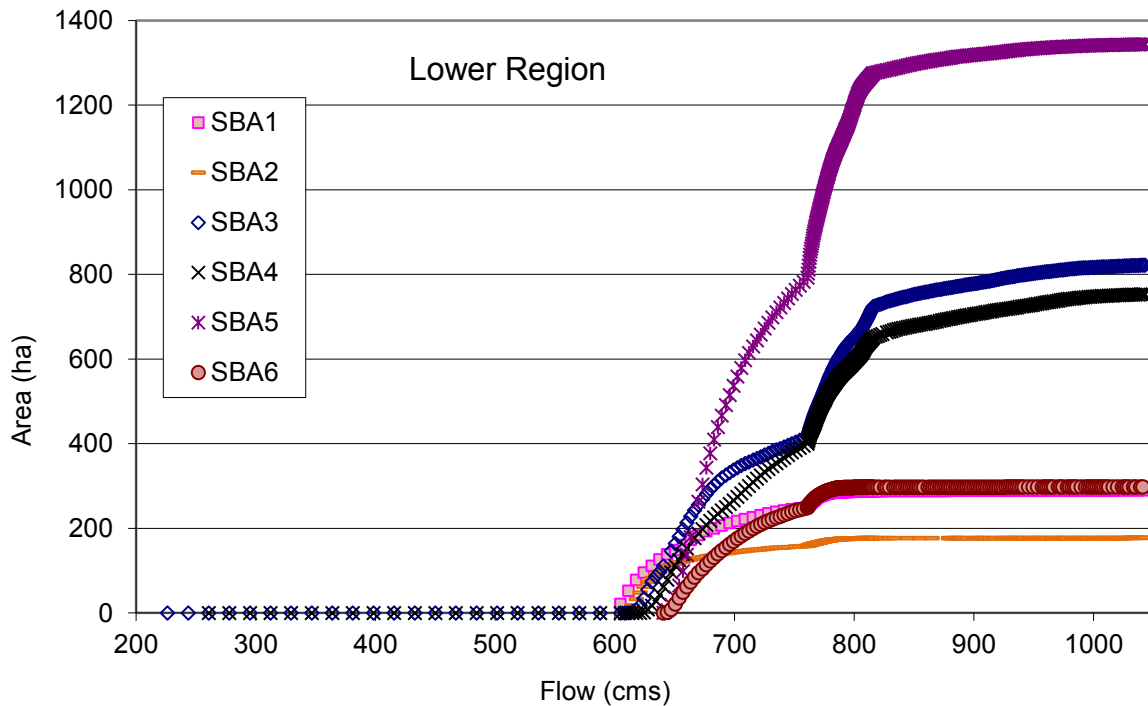
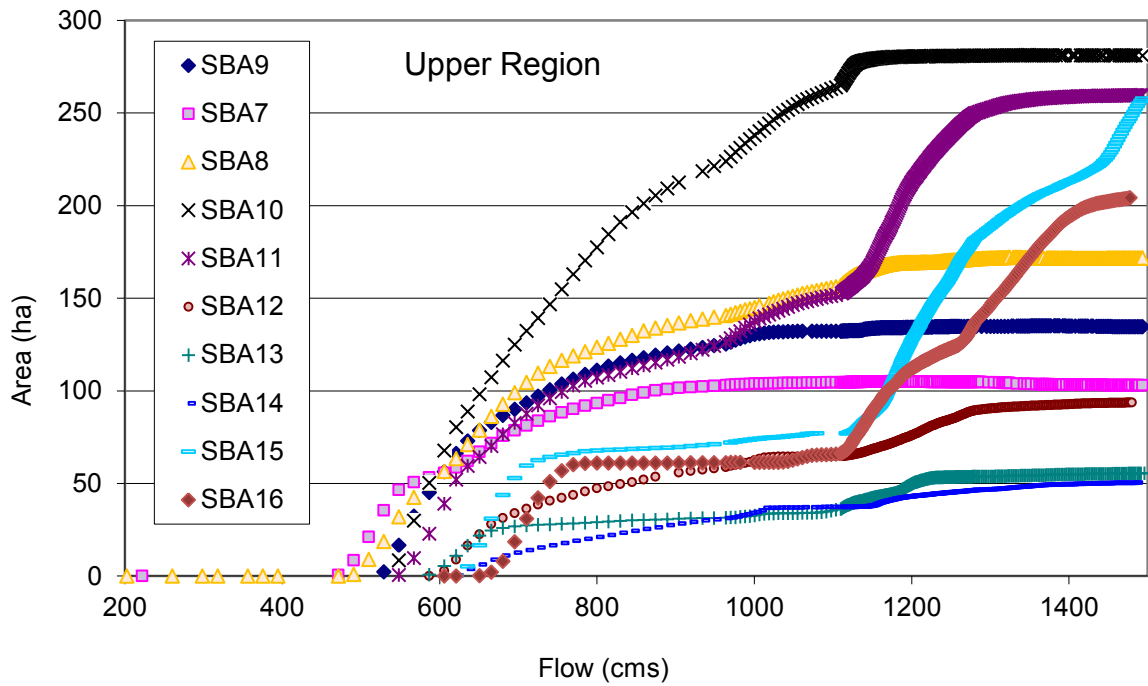


Figure 5-6. Area-flow plots for levee setback scenarios (Setback SBA#) by region. Lines reference increase in area compared to baseline conditions

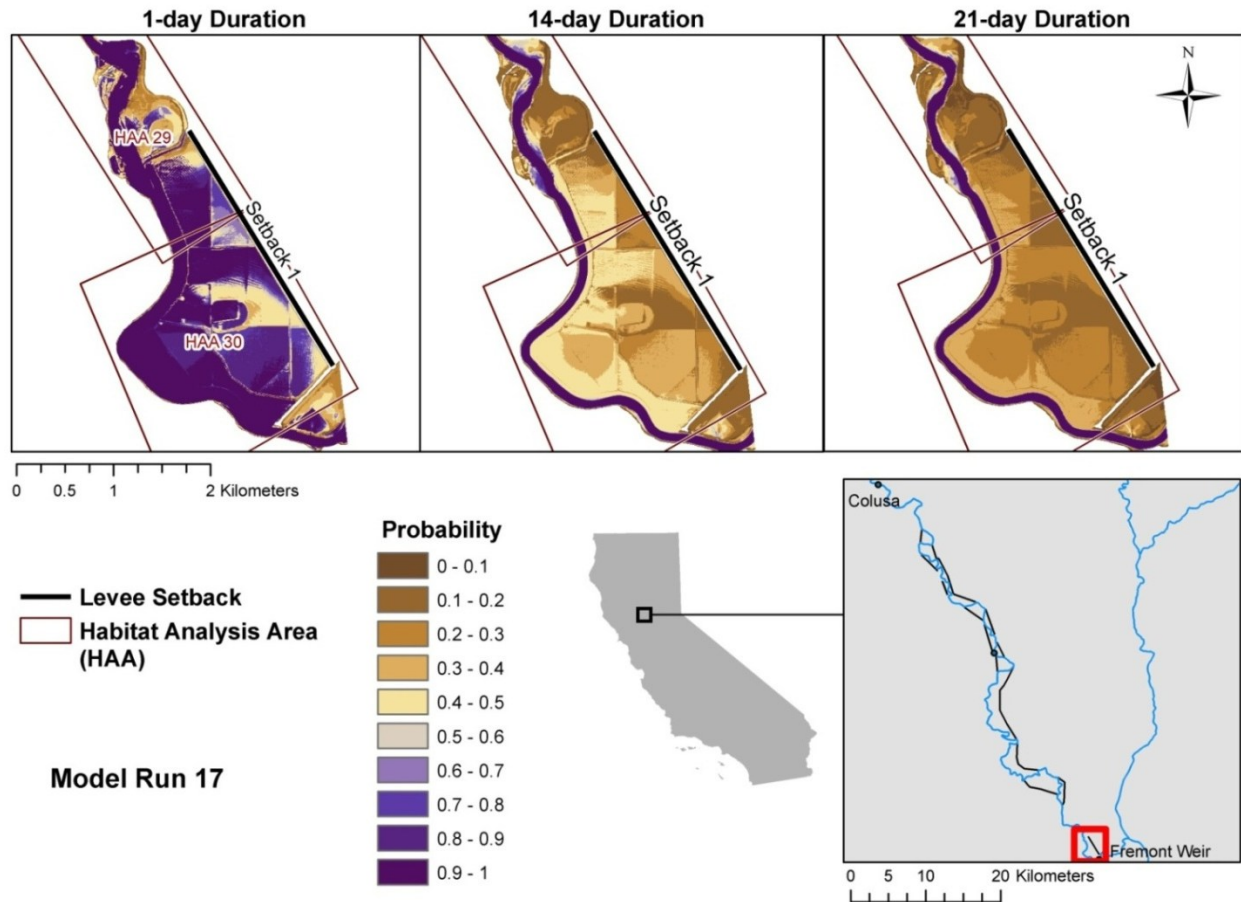


Figure 5-7. Example maps for probability of occurrence for inundation for 1-day, 14-day, and 21-day duration flows near Setback 1

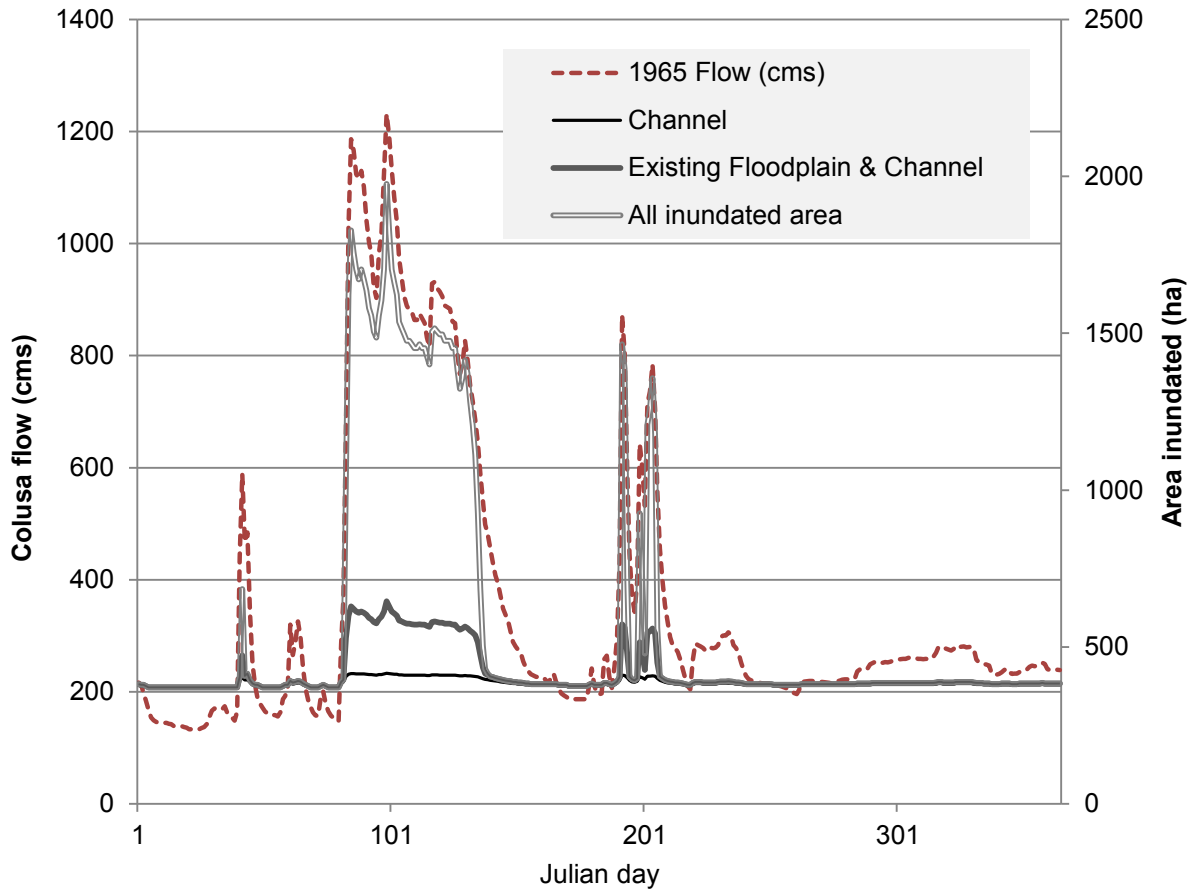


Figure 5-8. Example wet year hydrograph for water year 1965 (Flow on 1st y-axis) with associated inundated area (2nd y-axis) in channel, within existing levee extent (Existing Floodplain & Channel), and for whole upper reach if setbacks 7-16 are in place (All inundated area).

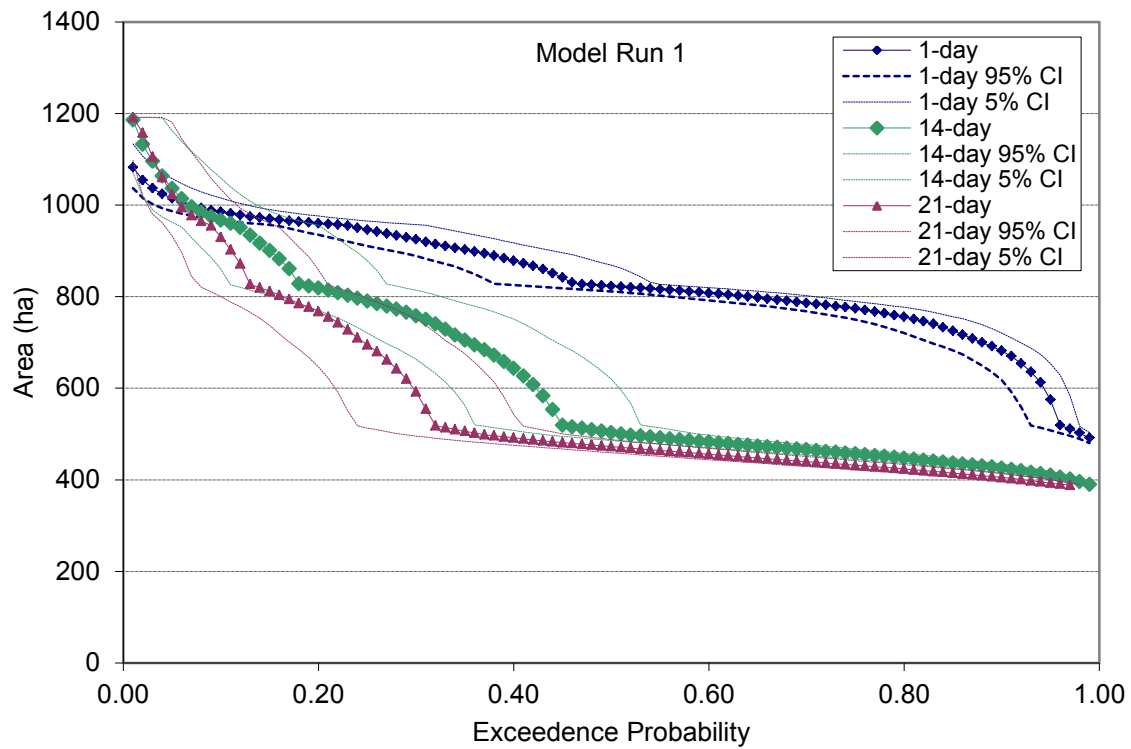


Figure 5-9. Example ADF curves for Model Run 1 (setback # 1) Area-Probability results for 1-day, 14-day, and 21-day duration flows

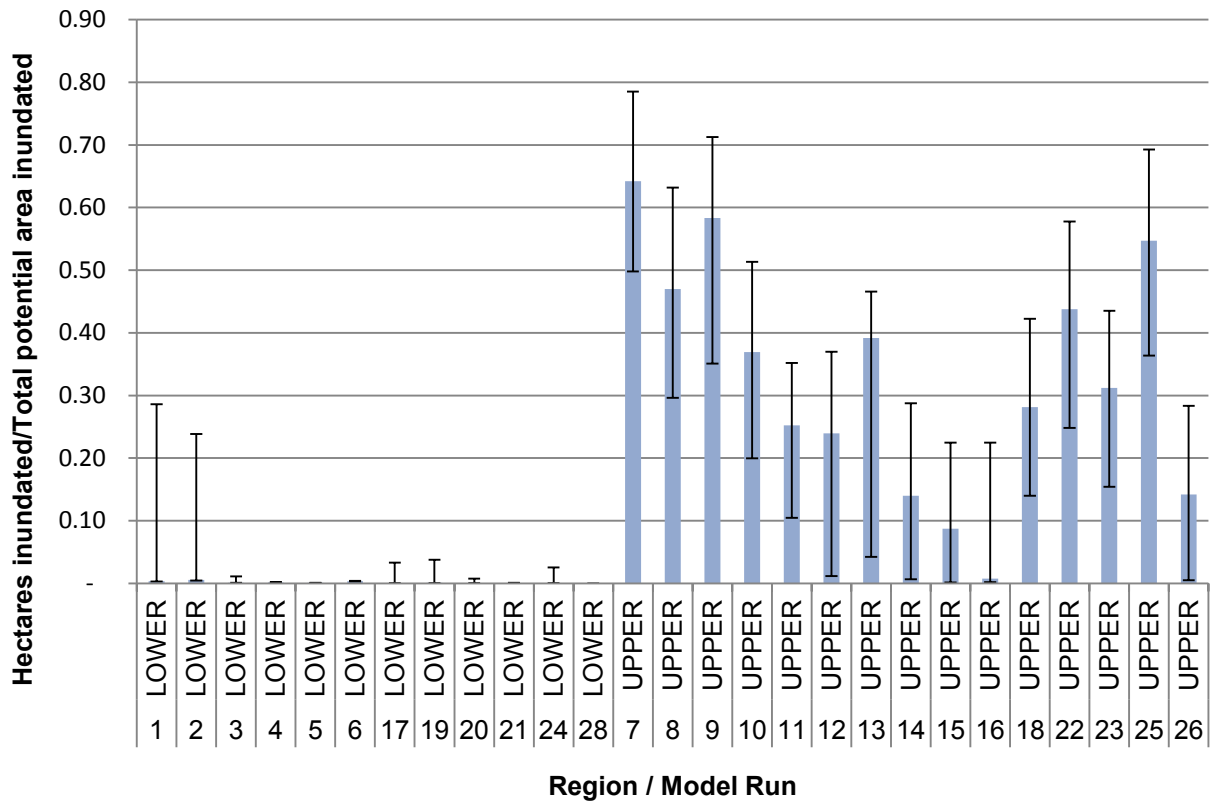


Figure 5-10. Model run results for new floodplain areas at 14-day duration flows occurring with 50% frequency

Because the main river channel habitat is very different from floodplain habitat (or side channel habitat), I removed that area from results in the following figures to isolate floodplain. The channel boundaries used in preparing Figure 5-10 include some floodplain edge, so the Central Valley Riparian Mapping Project (CSU 2012) riverine definition was used to equate in-channel area and further results do not include the in-channel area in results for floodplain habitat.

Using the full probability distribution of the ADF curves, floodplain EAH metrics were created for each setback scenario. The EAH additional area noted in Figure 5-11 reflects the land opened to inundation that might now flow over the lowered current levee extent. The existing floodplain EAH excludes channel surface area and counts land inside the bounds of current levees as existing floodplain. Some inundation area counted as existing floodplain is a product of the topographic alteration associated with the removal of existing levees for setback scenarios so it is included in these figures which give a more complete picture for model scenarios comparisons.

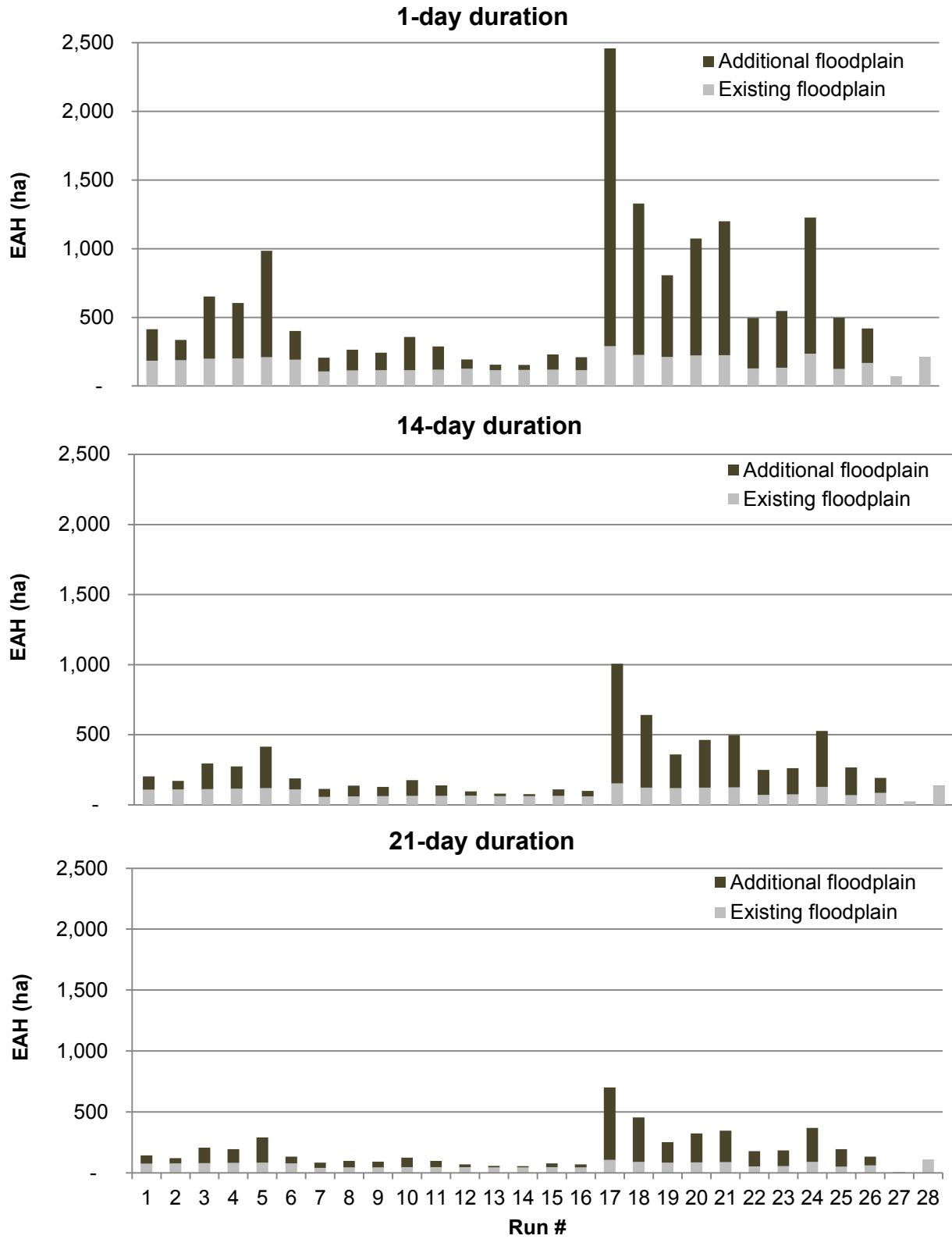


Figure 5-11. EAH for 1-day, 14-day, and 21-day duration model runs for existing floodplain inside levees versus additional floodplain opened by levee setbacks

## Inter-annual variation

The EAH presents an average metric for assessing inundated habitat, but another approach to measure potential floodplain habitat variation inter-annually can be taken by applying a water year type analysis. California’s mediterranean-climate consists of high levels of inter-annual variation in precipitation which translates into very different flow rates depending on the year. In the Sacramento River Basin, water year types are assessed for management purposes according to a runoff index (Sacramento valley 40-30-30 index). To illustrate the vast differences in floodplain habitat likely to result during different water year types, four example year hydrographs representing wet, above normal (an), below normal (bn), and dry water years were used to tally functional floodplain for the 1-day and 14-day duration December-May criteria (Figure 5-12). I summed inundated areas for each December-May day for channel edge, existing floodplain, and additional floodplain from levee setbacks 7-16 (model run 18). The dynamics of one of these water years (1965) was plotted in Figure 5-8 to demonstrate how inundation area changes over time in relation to daily flows. Flood peaks that do not last long enough for some duration criteria (e.g., 14-day duration) lead to removal of some floodplain habitat from the tally of habitat hectare days, or days of potential fish use. Wet and above normal years produce a four to six-fold increase in the habitat hectare days in new floodplain compared to the channel edge or existing floodplain. New floodplain in below normal and dry years only increases habitat hectare days from two to four times the channel edge or existing floodplain potential. The range of potential new 14-day floodplain benefit spans about an order of magnitude comparing a dry to a wet year.

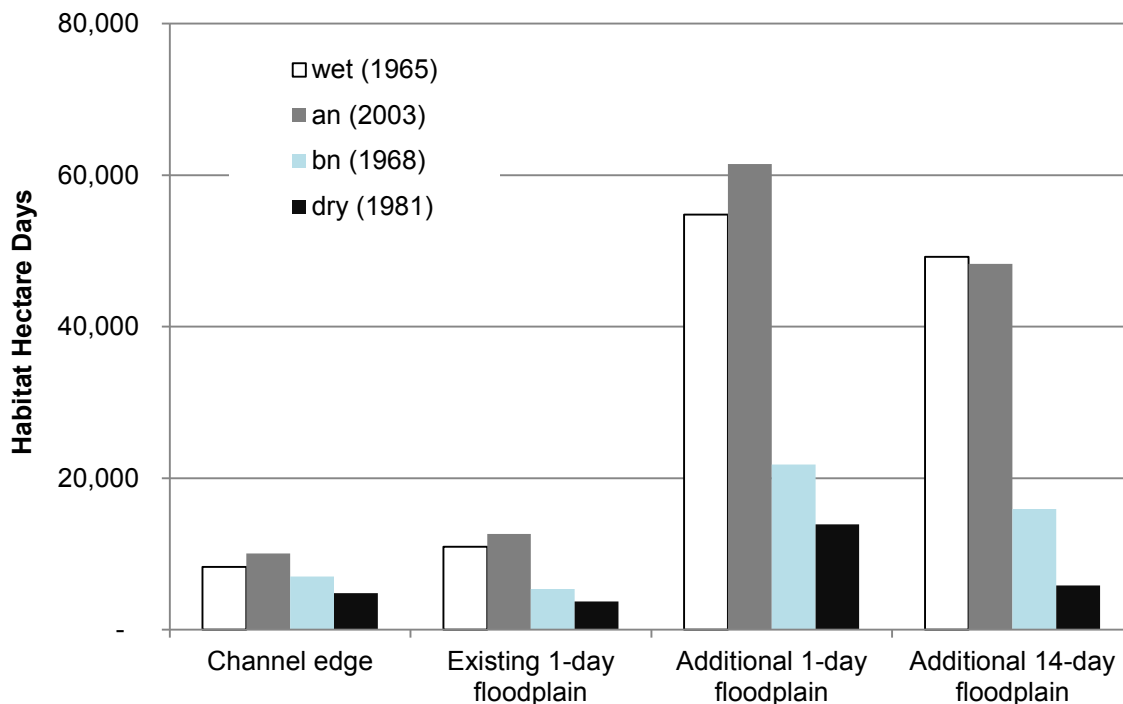


Figure 5-12 Inundated area for water year summed for each day (habitat hectare days) by channel edge, existing 1-day duration floodplain, and additional 1-day and 14-day duration floodplain features for model run 18 (setbacks 7-16)



## Site Ranking

A ranking system was developed to prioritize setback areas and initially characterize setback areas by potential floodplain area size and a ratio of area to levee removal length. Setbacks 5, 3, and 4 allow for the greatest potential expansion of floodplain area (Figure 5-13). When area is divided by levee removal length (Figure 5-14), the overall rankings remain similar, though a few setbacks change ranks (the new top ranking option is setback 3). By transforming area to the ratio of area to levee length, the setback options appear more similar in magnitude.

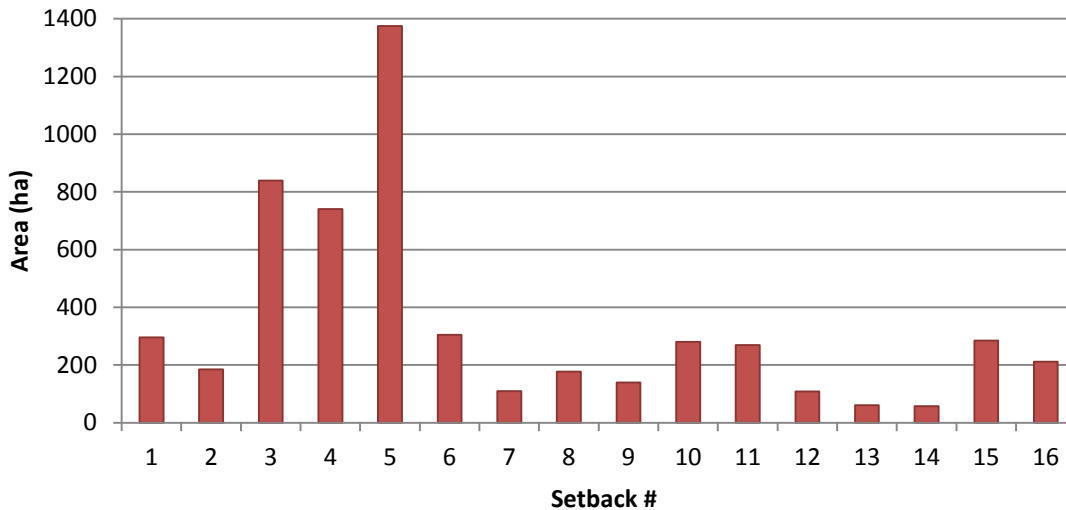


Figure 5-13. Area for each levee setback

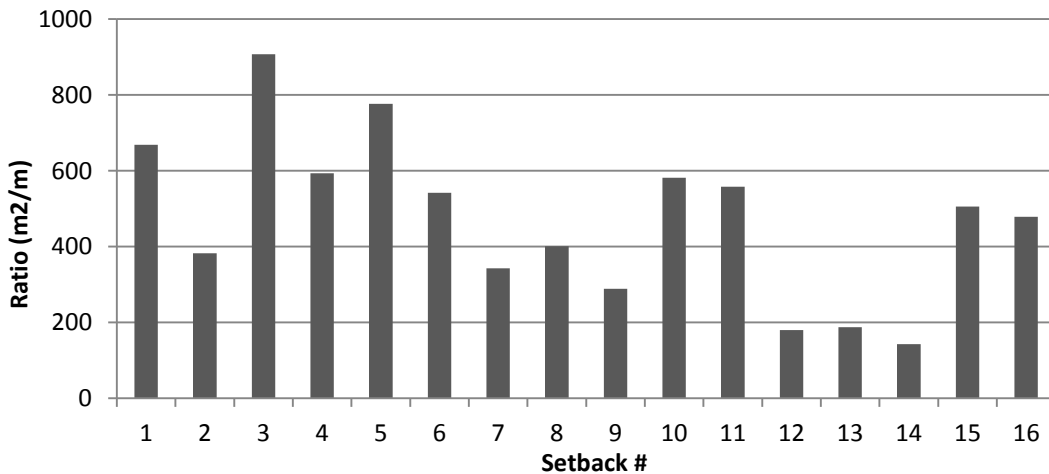


Figure 5-14. Levee setback ratio of area to levee length

Using this system, setback priority areas were first based on the EAH benefits per site as reflected in Figure 5-11. Land values associated with the flooded area (Figure 5-15) and the number of levee erosion sites identified within or near the setback area (Figure 5-16) also elucidate potential cost (e.g., land purchase price) and maintenance savings (e.g., levee setback

eliminating the need for future erosion repair). By building these criteria into the ranking assessment, a more informed comparative understanding of the setback scenarios is possible.

There are many ways to characterize ecological benefits: 1) annualized expected inundated habitat (EAH) alone, 2) inundated area (EAH) per levee unit length removed, and 3) area expected to be inundated at a 50% probability of occurrence. Priority was ranked for setback areas from high to low for the EAH metric alone (Table 5-3). EAH area ranking results indicate greatest benefit area in setback areas 3, 4, and 5. However, when the EAH results are divided by levee length required for each setback area, setbacks 13, 14, and 7 are the 3 top priority sites (Table 5-3). This means that these three sites provide the greatest amount of expected annual habitat (for all durations) per km of levee removed. If area inundated for 14 days every other year (exceedance frequency of 50%) reflects the key ecological criteria for restoration, then the top 3 ranked individual setback scenarios are setbacks 7, 8, and 9 according to percentage of inundation of available area (Figure 5-10). None of the scenarios downstream of the gage below Wilkins Slough at Grimes produced significant inundation at a frequency of 50%. This could be an artifact of how the 2-year flood stage was used to lower existing levee heights, but also reflects the flow record gage below Wilkins Slough at Grimes which is influenced by Sacramento River flow spilling over the Tisdale Weir. Thus, the potential for more average yearly inundation area exists for scenarios downstream of Tisdale Weir (lower region), but frequent flows (50%) inundate more acreage in the upper region of the study area (setbacks 7-16).

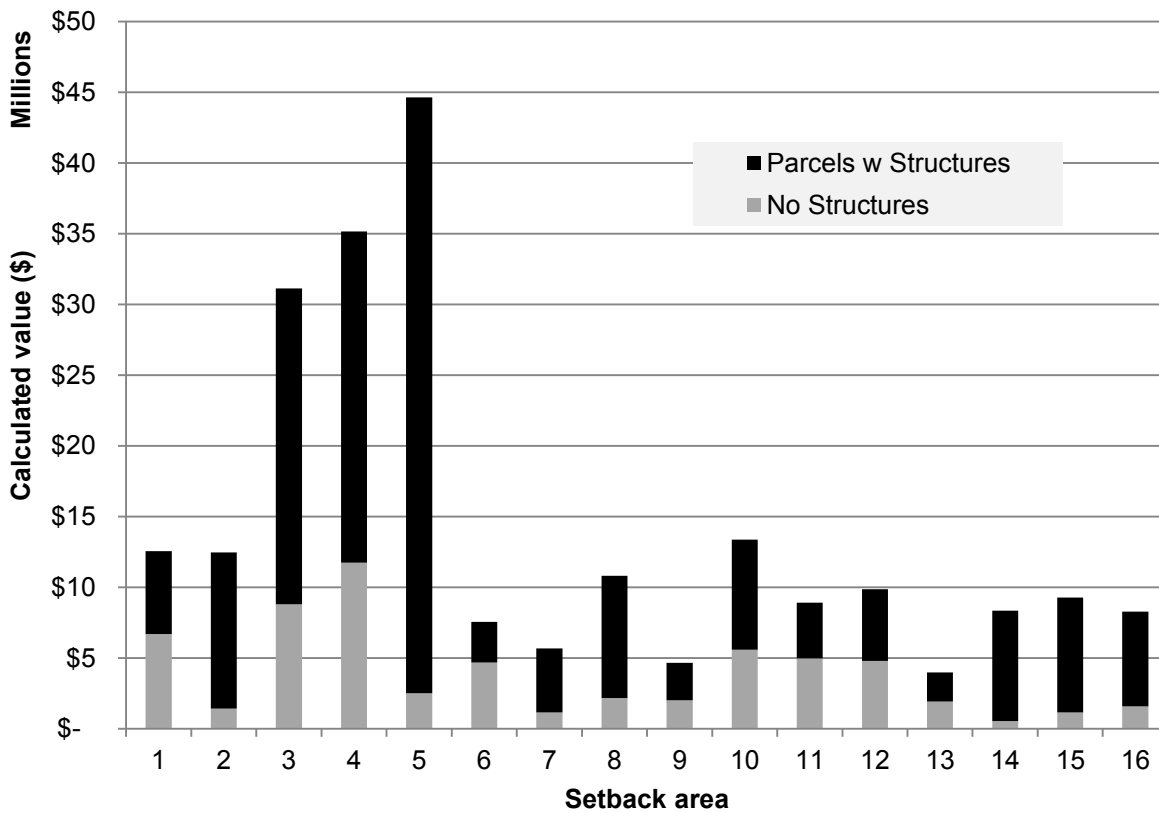


Figure 5-15. Value of parcels intersecting setback areas

Table 5-3. EAH ranking for setback areas

SET-BACK	1-DAY EAH	14-DAY EAH	21-DAY EAH	EAH PER KM 1-DAY	RANK	EAH PER KM 14-DAY	RANK	EAH PER KM 21-DAY	RANK
1	821	611	550	177.3	4	131.96	4	118.7	4
2	743	578	527	162.6	5	126.6	5	115.4	6
3	1,060	702	614	117.2	12	77.7	14	67.8	14
4	1,012	682	601	95.9	15	64.6	15	56.9	15
5	1,393	823	698	83.6	16	49.4	16	41.9	16
6	809	597	539	153.3	7	113.1	9	102.2	10
7	583	489	459	181.5	3	152.4	3	142.8	3
8	640	513	474	142.2	9	114.0	8	105.4	8
9	618	504	468	152.5	8	124.3	6	115.5	5
10	734	552	501	161.0	6	121.0	7	109.9	7
11	665	515	474	134.8	11	104.4	11	96.1	11
12	570	472	444	102.4	14	84.7	13	79.7	13
13	532	456	434	209.8	1	179.9	1	171.0	2
14	604	577	568	185.6	2	177.4	2	174.6	1
15	605	486	453	112.4	13	90.3	12	84.1	12
16	585	474	444	136.7	10	110.8	10	103.8	9

The benefit cost ratio (cost effectiveness) was examined using parcels overlapping the setback areas by ranking from lowest cost per benefit hectare (rank-1) to highest cost per benefit hectare (rank-16) (Table 5-4). Setback 13 is the most cost effective option, followed by setback 9 and 7. Setback 5, the largest alteration, remains as the lowest ranked alternative, as it is the least cost effective. Figure 5-17 shows locations of the calculated parcel values in quintiles, reflecting parcel size and number by setback area. Only three setback areas have parcel value totals over \$15 million (Figure 5-15). Setback areas 4, 5, 11, and 12 might have the largest administrative costs using number of parcels as a proxy for this consideration, as they all affect more than 30 parcels each. The rankings of adjusted EAH metrics--the area/levee length and benefit area/cost--were found to be different from total inundated area alone when comparing ranking results for all setbacks.

Levee erosion repair projects that include levee setbacks could be used to restore floodplain habitat, so a setback's proximity to erosion sites might influence its priority for consideration. The USACE 2010 erosion database was used to assess a levee erosion repair-based prioritization factor (Figure 5-16). More extensive erosion sites were identified for the lower section of the study area. With the exceptions of setback 5 (rank 11) and setback 15 (rank 5), the lower section has the higher ranked sites for potential operations and maintenance cost savings for setbacks addressing erosion (Table 5-4). Setback 6 would have the largest potential cost savings based on erosion issues, followed closely by setback 1. Notably, setback area 5 which has the longest river/levee length affected by the setback has lowest linear footage of erosion than all others in that region and most of the upper region setback areas as well.

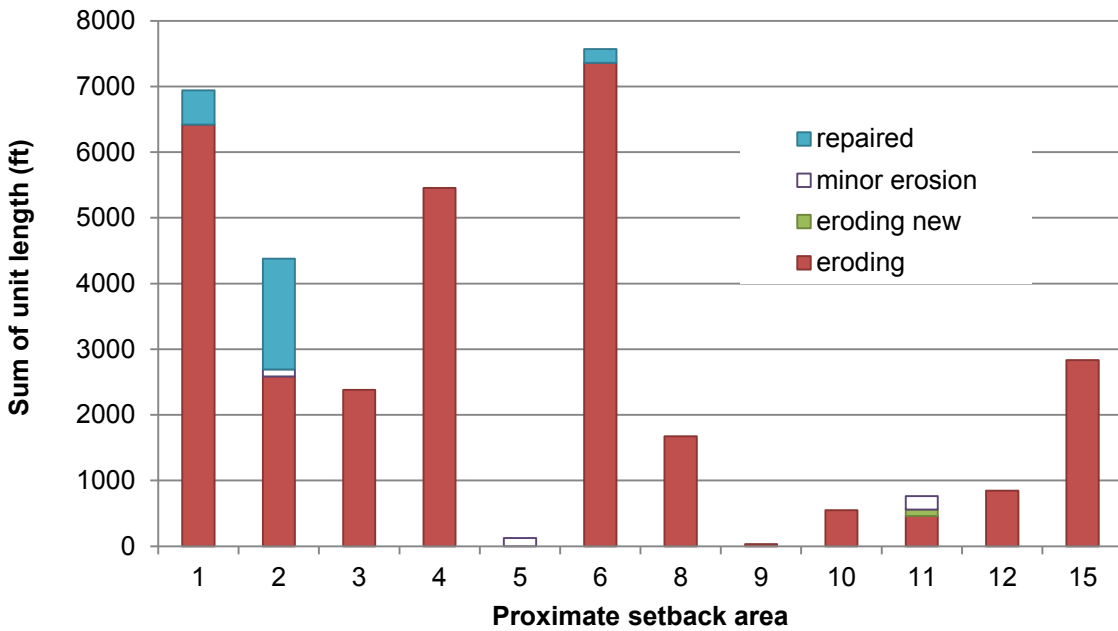


Figure 5-16. Length of erosion associated with proximity to setback area (USACE 2010)

Table 5-4. Land value and benefit cost rankings of setback areas

SETBACK ID	CALCULATED PARCELS VALUE (\$)	LAND VALUE RANK	# PARCELS	EROSION ISSUE RANK	14-DAY BENEFIT AREA-COST (SQ M)/\$	EAH BENEFIT -COST RANK
1	12,545,694	12	23	2	0.49	9
2	12,466,187	11	26	4	0.46	12
3	31,134,084	14	14	6	0.23	14
4	35,151,905	15	34	3	0.19	15
5	44,630,867	16	36	11	0.18	16
6	7,545,786	4	15	1	0.79	4
7	5,683,309	3	17	n/a	0.86	3
8	10,802,903	10	21	7	0.47	11
9	4,656,256	2	16	12	1.08	2
10	13,370,300	13	12	10	0.41	13
11	8,905,185	7	33	9	0.58	6
12	9,859,871	9	47	8	0.48	10
13	3,983,497	1	10	n/a	1.15	1
14	8,333,432	6	11	n/a	0.69	5
15	9,264,345	8	28	5	0.52	8
16	8,284,294	5	28	n/a	0.57	7

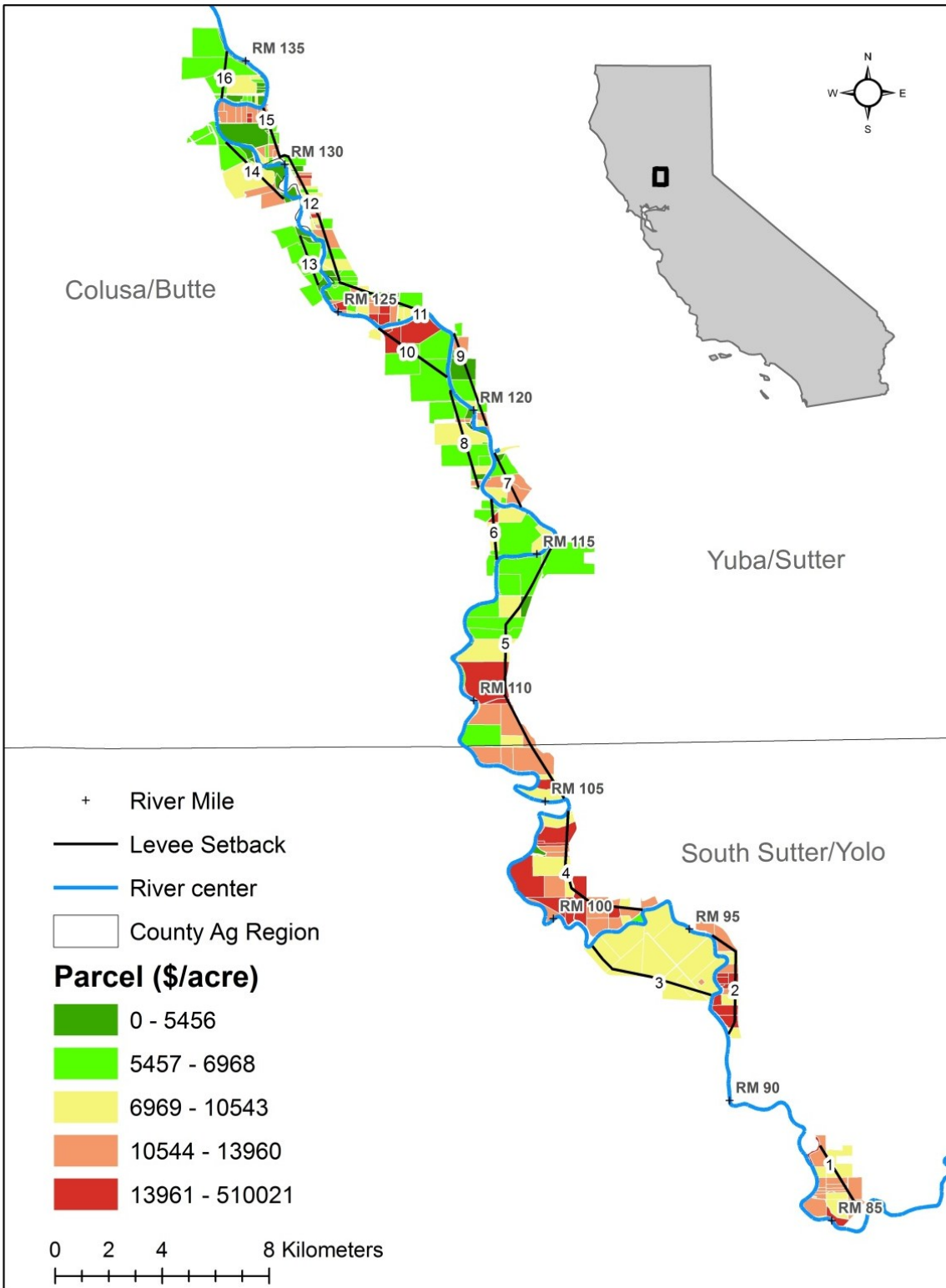


Figure 5-17. Location of parcels intersecting setback areas displaying calculated parcel value per acre

## Cumulative effects

An assessment of cumulative effects was based on comparing the results from individual setbacks for 14-day duration events with what occurs at each site when all the sites are set back within the same neighboring group of sites. This is one way of assessing how the setbacks interact. For each setback area, I plotted the difference between areas inundated due to the individual setback versus the inundated area resulting from the effects of a group setback scenario (Figure 5-18). Due to the shift in inundated area according to exceedance probability, a range from 1% to 50% exceedance probability was investigated more closely. The average percent difference for individual versus multiple setback effects ranged from 0.01% (setback 6) to 3.4% (setback 9). The most responsive areas to multiple interaction effects are setbacks 7, 8, 14, and 9 based on percent of available habitat area inundated for a 14-day duration event.

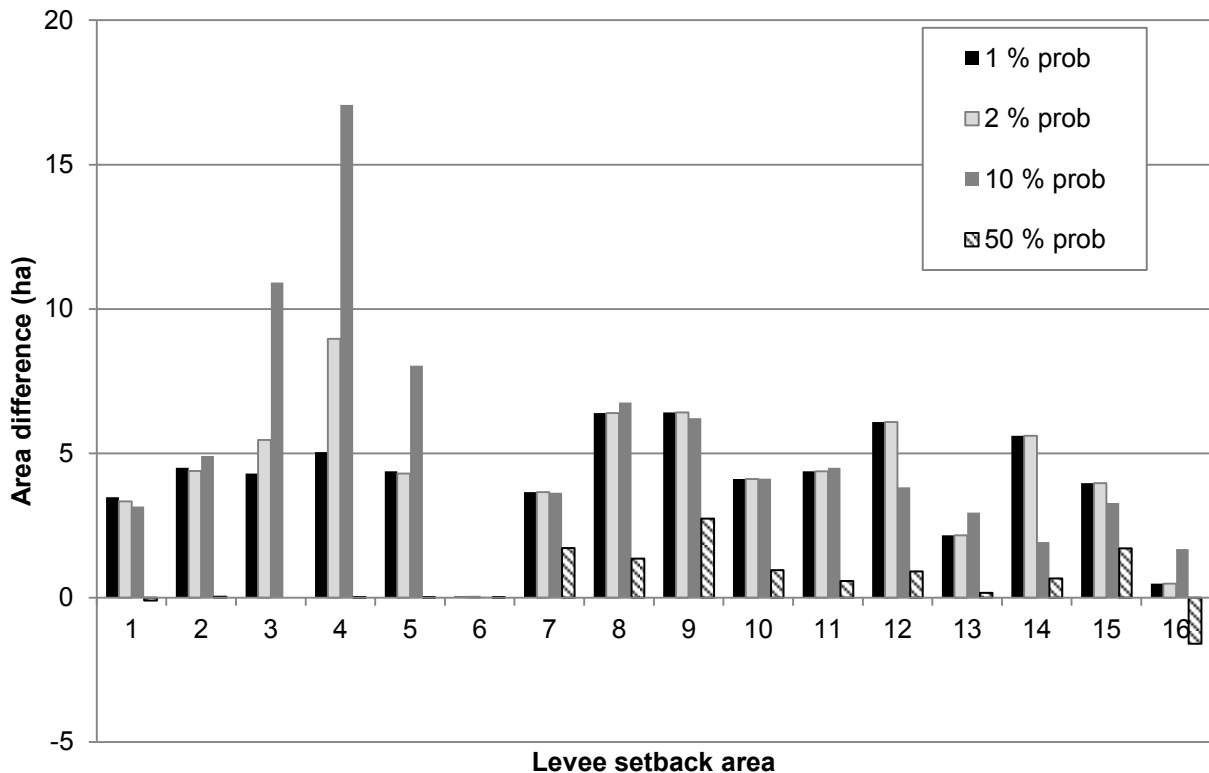


Figure 5-18. Cumulative effects of multiple setbacks displayed as the difference between area inundated due to individual setback and the inundated area from multiple setbacks for each setback area at four exceedance probability flows (1%, 2%, 10%, and 50%)

## Comparison of climate change scenarios

The hot and dry (A2) and warm and wet (B1) climate change scenarios were compared against the current flow regime results for the upper study area region. This set of comparisons allows a study of the relative impacts of the two extremes of the climate scenarios for a suite of model runs. The 14-day duration and 50% frequency flows show the greatest difference from historical reference, with Run 18 (all upper section setbacks opened) displaying a difference of 202 ha less under the hot-dry A2 scenario, though the warm-wet B1 scenario increases the inundated habitat by 22 ha. The A2 scenario consistently reduces the beneficial habitat at recurrence intervals of 2-years, but the B1 scenario expands the area, reflecting its warm and wet temperature and precipitation components.

How climate change might alter the potential annual probability of inundation (Figure 5-19) was also assessed. The EAH metric presents the inundation area expected in an average year, assuming the frequency distribution of the flow regime scenarios. The EAH 1-day, 14-day, and 21-day durations demonstrate that the historical flow regime and B1 scenario results overlap, with error bars making the findings indistinguishable for most model runs. The A2 scenario, in contrast, produces average annual habitat estimates that are significantly lower than the product of the historical and B1 scenario flow regimes. The baseline run (inundation of habitat within current levee configuration) shows the most contrast among the three scenarios: 1-day durations show higher B1 scenario area while historical and A2 scenario are similar; 14-day durations show a similar trend as the 1-day but with 48 additional hectares wetted under A2 scenario; and 21-day durations show lower inundation area for A2 scenario than the historical and B1 scenario, which are indistinguishable. The baseline run results show less than 100 ha of annual expected habitat in the upper region, which is about 2% of the potential area inside the levees. The maximum EAH areas coincide with model run 18, which opens setback areas 7-16, exposing a potential of 1698 ha to inundation, though only the 1-day duration flows can be expected to wet over 1000 ha in any given year.



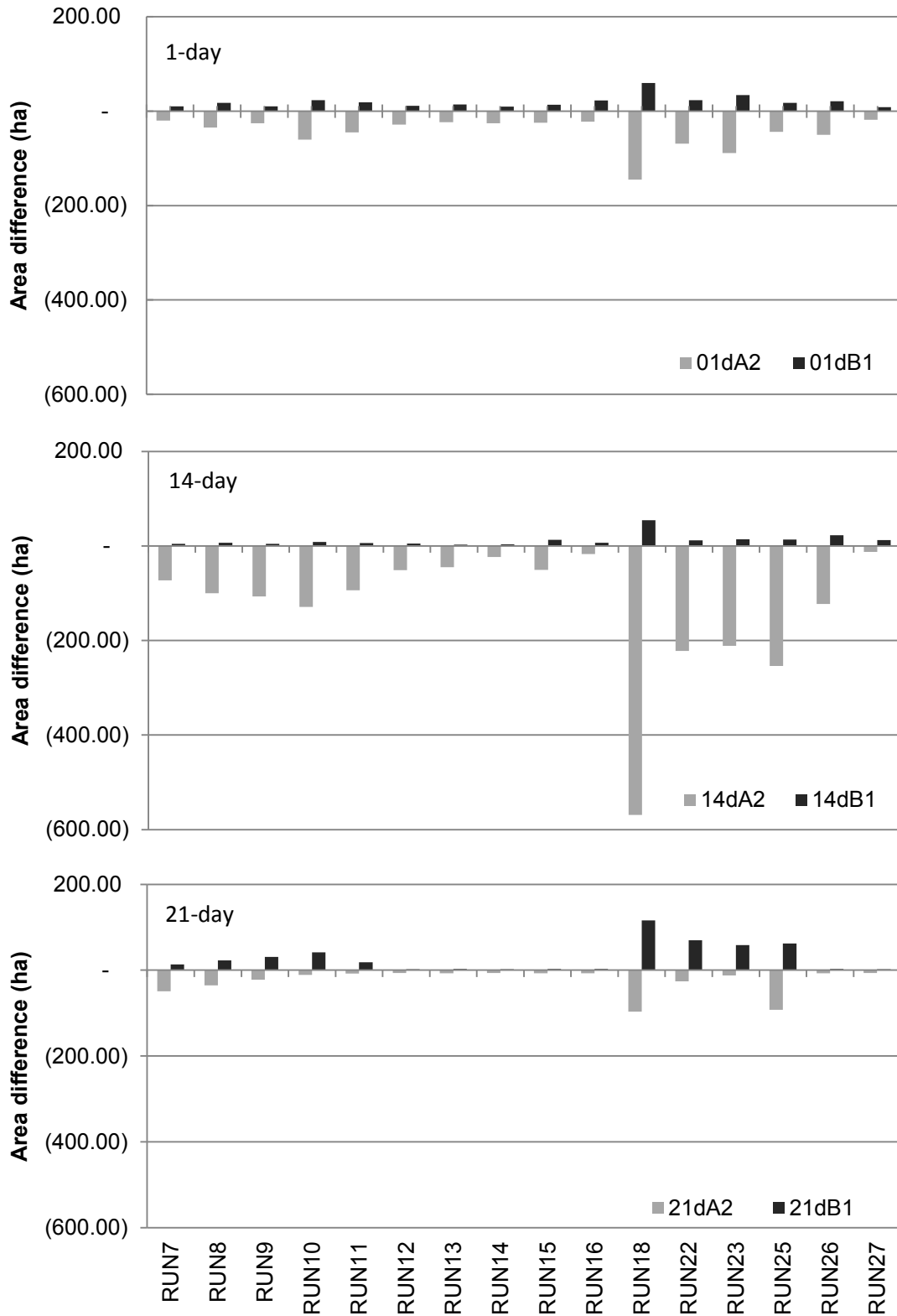


Figure 5-19. Climate change scenario area difference from historical flow regime at 50% frequency, for 1-day, 14-day, and 21-day durations for hot-dry A2 and warm-wet B1 scenarios

## DISCUSSION

Floodplain habitats are more ecologically beneficial for fish rearing, supporting higher rates of growth, than in-river habitats (Jeffres 2008). The dynamic nature of floodplain habitats is not typically accounted for in efforts to plan and evaluate potential floodplain reconnection projects. A standardized quantification method is needed to describe the inundation characteristics that suit ecological needs. The extent and quality of floodplain is not only a function of the aerial extent of inundation with suitable characteristics (temperature, velocity, depth) for a particular aquatic related species, but equally important are the frequency, timing, and duration of inundation.

The quantitative modeling approach presented in this chapter can be adopted by agencies that use GIS based hydraulic models and have access to long-term daily hydrologic data. Defining ecologically significant floodplain using tools such as the EFM to incorporate criteria of frequency, season, and duration is vital to planning for floodplain function restoration. Linking species flow dynamic requirements with hydraulic models and GIS, the expected annual floodplain habitat (EAH) method generates a metric that integrates both the spatial and temporal parameters that determine the value of inundated habitat for any given species. EAH curves are very similar to expected annual damage curves that are regularly developed in planning studies by the USACE and other flood management agencies (USACE 1996). Instead of providing a measure of average annual damages, however, they provide a measure of average annual benefits for floodplain habitat. The method also produces area-duration-frequency (ADF) curves that quantify not only the area inundated for various flow duration periods during a specified season, but also the frequency at which an extent of inundated area occurs. ADF curves can be used to create screening metrics or can be refined to measure very detailed habitat suitability curves using high resolution models.

I evaluated the relative floodplain habitat benefits of Sacramento River setback scenarios using 16 individual setback areas based on several criteria: 1) expected annual habitat (EAH) alone, 2) EAH area per levee unit length removed, and 3) a benefit cost ratio of EAH unit area/dollar. The appropriateness of using any of these perspectives depends on the primary objective for the project. If priority is given to addressing current levee erosion sites, for example, that might lead to stronger consideration of the lower region setback options. If long-duration and frequent inundation are the most important criteria, then upper region setbacks should receive attention. This analysis aids in comparing setback sites using consistent design criteria (2-year recurrence stage for levee removal), but would benefit from more focused contouring of the landscape and design of levee removal or breach options for ecologically significant inundation area. Analysis of the physical floodplain template is only a starting point for maximizing ecological returns while reducing flood risk and minimizing the required investment.

Cost does shift ranking priority for the setback alterations compared to priorities set by EAH area alone or EAH divided by levee removal length, so an evaluation of the benefit cost ratio should be considered. I caution that even using a benefit cost ratio requires critical attention to the numerator (benefit) and denominator (cost). If cost is too low, a ratio could be ranked highly despite a lack of significant benefit value. For example, setback 6 is ranked 9 for 14-day EAH per levee km, but a land value rank of 4 increased the setback to a rank 4 using benefit cost ratio.

Investments in moderate benefit and moderate cost options minimize the potential for application of skewed rankings.

I attempted to develop a proxy for operation and maintenance cost savings to consider along with the benefit cost ratio by using the spatial location of levee erosion sites (USACE 2010 erosion database). A better indicator of erosion potential facing Sacramento River levees might result from Eric Larsen's meander modeling work (Larsen et al. 2006). This would allow targeting and ranking of levees that a setback could potentially save from the river's predicted erosive movements over the next 50 years.

Ranking scenarios by single metrics like EAH or ADF specific frequency values compresses a range of data for the purpose of scenario comparison. This compression results in a loss of information, therefore the ADF curves themselves should always be a central consideration when setting target thresholds. Understanding the potential variation in the results and how a threshold value might miss an important response to inundation should be folded into any management decision about restoration priorities. In addition, maps of results should be carefully considered as they demonstrate the spatial variation of benefit area that might not be apparent from scenario rankings.

Another benefit type not captured by the EAH or ADF metrics relates to hypothetical levee setback projects (Setback area 7 or 9) that could include expanding Tisdale weir, exposing fish to more floodplain on the Sutter Bypass than would be within the local extent of a new levee setback. By contributing to more days of fish use of floodplain habitat on the bypass, levee setback 7 or 9 might provide benefits off-site. The bypass might not be wholly transformed to floodplain when Tisdale weir overflow events occur, however, so it is difficult to translate flow into floodplain area creation. Other entry points for the bypass also contribute to the existence of floodplain, so a full picture of area flooded associated with Tisdale weir flow needs to be supplemented with information on the previous events of the season and other sources of flow. Whether habitat in the bypass is better for fish, even just in permanent channels, and by how much, is a question for future studies.

The duration of inundation events greatly influences the probability of achieving functional floodplain habitat following setback alterations. The longer duration events of 14-days and 21-days are relevant for significant native fish rearing habitat, but often achieve far less inundation area in the modeled scenarios. When inundation due to the longer duration events eclipses that of the 1-day duration inundation, exceedance probabilities reflect large magnitude flows. Exceedance probabilities of 5% and lower (floods occurring with a recurrence interval of 20 to 100 years) should be viewed with some skepticism for 14-day and 21-day flows because of the weaker statistical relationships in fitting the flow-frequency curves. The duration results in the ADF curves can provide a useful way to compare setback configurations; however, as the curve inflection points can draw attention to when a setback can begin to achieve greater benefits than other setback scenario curves. These inflection points are important indicators of how each setback configuration can perform for all duration flows.

An evaluation of historical flows (1945-2010) and climate change scenario flows (hot-dry A2 scenario and warm-wet B1 scenario) was done for the upper region of the study area, using extrapolations from Red Bluff gage climate change flows to the Colusa gage. The magnitude of

differences between sites generally reflects the size of the setback area opened to inundation, so comparing positive and negative influence between sites and assessing magnitude of flow regime difference only within sites is most appropriate. The largest inundation area differences were found between the historical flow regime and the climate change flows for 14-day durations, but all durations showed similar trends. The A2 scenario flows reduced inundation area for the model runs, but B1 scenario flows increased inundation area for the same scenarios. The 21-day durations flows show a more marked increase in area due to the B1 scenario flow regime than the other duration flows. This indicates the B1 scenario flow regime allows for higher flows at longer durations than the historical post-dam record and the A2 scenario flow regime. The uncertainties surrounding climate change and the contrasting nature of the model results suggest it will continue to be difficult to predict how functional floodplain might change over the next 100 years, but the A2 scenario can serve as a measure for the lower bounds of functional area for measures of ecological significance.

Aggregating cumulative effects beyond the scale of the individual project is a significant challenge, yet an important consideration for strategic decision-making (Gunn and Noble 2011; Seitz et al. 2011). There are no agreed upon standard methods for doing cumulative effect analysis (Cooper and Sheate 2002; Seitz et al. 2011), so this assessment was based on a technique using best professional judgment. Comparing results for the same area per an individual setback versus inundation resulting from a group of setbacks, I derived measures of how the setbacks interact. It is intuitive that the most responsive setback areas are those that are close to one another or nearby setbacks. The average magnitudes of interaction effects are low (less than 4% of total area) for the 14-day duration flows. This result suggests that it is not critical to assess the cumulative effects of multiple levee setback projects that may be employed at once or sequentially in order to evaluate the 14-day duration benefits of each proposed levee setback for the study area examined.

### **Caveats**

The ADF curves and EAH metric developed here for ecologically significant floods rely upon the traditional concept of flood frequency, in which one assumes the annual maxima floods are independent and identically distributed random variables. Other options exist for modifying statistical models to avoid violation of these assumptions, but are beyond the scope of this chapter. Regardless of the problems with the assumptions of annual maxima series, in cases where the hydrograph contains multiple flood peaks per year, a partial-duration flow analysis might be better suited for examining flows that occur more frequently than once every 10 years. The EFM tool used to develop flow dynamic statistics does not have the capacity for this type of analysis and can subsequently underestimate the flows for these more frequent events. Thus, the ecologically significant inundation areas derived in this analysis are conservative.

Developing ecological benefit metrics relies on expert knowledge about species requirements. However, scientific understanding of how organisms respond to flooding and what timing, duration, and frequency will best support viable and growing populations remains uncertain. As knowledge about species specific habitat requirement increases, modeling assumptions should be updated (Fleenor et al. 2010). Another key element of developing ecological flow relationships that determines thresholds for estimating functional floodplain is the hydrologic regime specification. Long term flow data sets are important for defining flows that occur more rarely,

such as those for fish relationships or for geomorphically relevant floods (e.g., occurring at or more rarely than once every 10 years, on average).

More factors than flow frequency, timing, duration, and seasonality influence truly functional habitat (Opperman 2012). Important interactions on a physical floodplain template also include water temperature, suspended sediment, depth, velocity, submerged vegetation, dissolved oxygen, and organic matter. A functional floodplain metric that does not include these additional factors is a simplified representation of floodplain habitat potential. Despite these limitations, including measures of flow dynamics for identifying maximum functional floodplain area is useful place to start.

The process of linking statistical, hydraulic, and spatial tools also yields potential for error due to inaccuracy and/or imprecision. The hydraulic modeling and spatial processes depend on a suite of factors such as physical data, spatial scale and resolution, and parameters for solving shallow water equations. Often these data sets are not available at the same spatial or temporal scale. The inaccuracies of the LISFLOOD modeling were assumed to be less important than the efficiency with which the integrated modeling can be implemented compared to using more complex 2-D or 3-D models (Werner 2001). There exists a tradeoff in hydraulic modeling accuracy, but the intent of using the raster-based model was to simplify and assess how scenarios might be relatively different from each other. Scenarios using other 2-D models and even groundwater modeling would make results from modeled restoration treatments potentially more accurate, and should be considered if appropriate to the circumstances (i.e., groundwater influence on river reach flows, levee breaching scenarios, etc.).

A caveat should be made clear about the climate change scenarios used in this analysis. It is difficult to estimate flood frequencies from estimated future hydrographs under different climate scenarios because these models assume a directional trend that violates the assumption that each year is independent. The concept of climate change exemplifies non-stationarity as temperatures and precipitation reflect trends over time (Olsen, 2006; Stedinger and Griffis, 2011). Using inundation threshold flows based on current flood frequency estimations may not be a reliable approach to predicting future habitat area because of uncertainty surrounding what the flow dynamics will actually be in the future. Future changes with respect to extreme flooding events are also difficult to predict; however, the species modeling approach here does not rely on accurate predictions of extreme events. Evaluating the impact of climate change on flood frequency is complex, and while there is no standard or agreed upon way to do it (Dettinger et al. 2009; Stedinger and Griffis 2011), this study provides an empirical approach for planning purposes.

While this project integrates high resolution data, long-term flow records, and several well-established hydro-ecological relationships, uncertainty still exists and the results are hard to assess through validation. Despite this uncertainty, however, many researchers agree that evaluating modeled simulations is the best approach to evaluate how freshwater ecosystems respond to non-equilibrium conditions, to identify places that might be prone to failure, and to evaluate system performance under different scenarios such as increased development or climate change (McKinney et al. 1999). The scenarios used here are different in extent of floodplain area of being considered for reconnection, but the inherent error in the ecological functional relationships and climate change flow scenarios is the same between the various scenarios. Thus,

the relative change to floodplain habitat potential between the scenarios remains highly relevant to the restoration decision-making process.

This analysis used project cost estimates for setback levees and proximity to erosion sites to account for socio-economic considerations in prioritization. The final EAH benefit-cost rank was based on the ratio of 14-day inundation area divided by dollars. This acknowledges the importance of selecting the most cost effective options for mitigation with the top three setback levees being 13, 9, and 7. I assume that project cost would be the most useful social factor for distinguishing between setback areas in the study region, but other social considerations could also influence prioritization decisions. The socio-economic factors for inclusion in a ranking system could be added to with a flood damage reduction analysis and an economic analysis of regional economic impacts (e.g., an IMPLAN study).

The method of integrating environmental benefits, physical factors, and social cost for site priority ranking presented here and applied to various setback levee scenarios along the Sacramento River addresses the importance of selecting cost effective options for restoration. Most importantly, this research provides a method for studies to maximize ecological returns while reducing flood risk and minimizing the required investment. The tools developed through this research support systematic floodplain restoration planning for fish recovery in the Sacramento River.

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## **CHAPTER 6**

### **CONCLUSIONS AND FUTURE RESEARCH**

## Conclusions and Future Research

Despite a renewed worldwide effort to restore or rehabilitate floodplain habitats in order to promote species recovery, challenges remain for restoring ecosystem functions in a matrix of human dominated landscapes (Dudgeon et al. 2006; Rohde et al. 2006). Restoration planning for future conditions must take into account both climate change effects on river flows as well as human needs for water supply and flood control. Vicuna et al. (2007) estimate climate change impacts in California will result in smaller stream flows, lower reservoir storage and decreased water supply deliveries and reliability. At the same time, increases in extreme storm events pose risks to low-lying communities. California will be undertaking more water infrastructure projects (new or redesigned water conveyance and operation of the State Water Project and the federal Central Valley Project) and will need to mitigate the impacts of these projects with habitat restoration (California Natural Resources Agency 2012). Restoration planning is essential to maximize ecological benefits while minimizing the cost to the public. Restoration outcomes are generally fraught with uncertainty and the issue of uncertainty is confounded by climate change. Considering potential impacts of climate change will be essential if resource managers are to minimize negative consequences of climate change and maximize the potential benefits that it may offer (Viers and Rheinheimer 2011; Burkett et al. 2005).

The uncertainties surrounding climate change and the contrasting nature of model results suggest it will continue to be difficult to predict how functional floodplain might change over the next 100 years. California rivers will experience changes in flow dynamics based on location. Not all sites respond in the same way under identical climate change scenarios. In addition, while temperature and moisture regimes influence the distribution, productivity, and reproduction of biota, climate model predictions are not always consistent or easily translated into biotic response. Confounding effects of hydrologic alteration with other important environmental determinants of river ecosystem condition also contribute to uncertainty (Poff et al. 2010; Burkett et al. 2005).

Efforts to plan and evaluate potential floodplain reconnection projects for ecological benefits have been hindered by both the dynamic nature of floodplain habitats and the lack of a standardized quantification method. The extent and quality of floodplain is not only a function of the spatial extent of inundation with suitable characteristics (temperature, velocity, depth) for a particular species, but also needs to consider the frequency, timing, and duration of inundation. There remains an urgent need for more studies to link ecological data with hydrologic modeling and observations (King and Caylor 2011). This is especially true for mediterranean-climate rivers systems because of their reliance on a high level of variable flows which have often been eliminated in an effort to provide a more consistent year-round water supply to downstream agricultural and urban users.

Useful restoration planning tools for addressing future flow changes and multiple objectives require coupled hydro-ecological models, comparable ecosystem function metrics, and risk assessments or scenarios. Recent approaches to ecological habitat connectivity, as well as advances in integrated physical and ecological modeling, can now be used to estimate the consequences of different river management options on today's biota and inform climate change

adaptation strategies for river systems (Palmer et al. 2008). In order to integrate hydrological connectivity into an analysis of useful ecological outcomes that may arise from restoration of mediterranean-climate river systems, flow scenarios that reflect the spectrum of observed inter-annual variability must be compared. The scenarios considered in this dissertation differ in floodplain habitat extents, but the inherent error in the ecological functional relationships as well as climate change flow scenarios is the same between the various scenarios. Thus, the relative changes to habitat connectivity between the scenarios remain highly relevant to the restoration decision-making process. Another advantage of using these hydro-ecological models is the visualization of results, which improves public understanding of likely outcomes and engages stakeholders in the decision-making process.

The integration of hydrologic connectivity and functional metrics within the existing social context and evaluation of trade-offs is essential to reap the full benefits to management decision-making and improve the way funds are allocated to restoration options. Many restoration decisions are made without estimating the potential ecological outcomes of different options or the trade-offs between cost and ecological benefits (Viers and Rheinheimer 2011). Even more problematic, restoration seldom includes changes to stream flow dynamics because of dependence on water resources and the economic benefits associated with access to and control of freshwater (Kondolf 2006; Christian-Smith and Merenlender 2010). Risk-based planning also offers a robust way to identify strategies to manage water resources under climate change and rehabilitate floodplain (Brekke et al. 2009). For example, plans that allow for adjusting reservoir operation rules can give water managers an important tool for using floodplain habitat as flood control space so that higher volumes can be kept in reservoirs year-round.

The methods presented in this dissertation can be put to use now to support an adaptive management approach to restoration of floodplain functions using various mechanisms like levee setbacks, bypasses, and altered reservoir operations by monitoring river stage for flood frequency, duration, and timing, and filtering this information with species requirements in a tool like EFM (Williams et al. 2009). Consideration of potential future flows is key to developing a floodplain restoration design. Results in Chapter 2 indicate the warm-wet B1 climate change scenario flow regime allows for higher flows at longer durations than the historical post-dam record and the hot-dry A2 scenario flow regime. In fact, the B1 scenario flows might be more similar to pre-dam flow regimes (peak magnitudes in particular) than the current regulated flow regime. The A2 scenario can serve as a measure for the lower bounds of functional area for measures of ecological significance. These bounds on expectations for future flood levels can inform the design of restored floodplain surface elevations.

The original ADF and EAH metrics presented in Chapter 3 and developed in Chapters 4 and 5 allow exploration of the dynamic flow restoration elements that affect how successful a floodplain reconnection plan can be. The method has advantages in framing the potential restored area in terms of probabilities based on dynamics of flow timing, durations, and frequencies. I found that all species' functional habitat availability declined under climate change flow regimes in the San Joaquin River case study, making it clear that even more additional flow will be required in the future for this site to contribute meaningfully to splittail and salmon recovery. Thus, Chapter 4 demonstrates that the flow regime matters more than physical connectivity alterations for providing fish habitat in the San Joaquin River Vernalis to Mossdale

reach. In Chapter 5, however, estimates of floodplain habitat for salmon rearing helped identify the most potentially beneficial projects from 16 floodplain reconnection options along the Sacramento River.

Many restoration decisions are made without following strategies based on linking restoration goals to assessments of potential ecological benefits and costs. Project prioritization using cost effectiveness measures can provide direction to funding agencies and a more balanced view of tradeoffs between potential ecological benefits and costs (Beechie et al. 2008). By integrating environmental benefits, physical factors, and social cost for site priority ranking in Chapter 5 for various setback levee scenarios along the Sacramento River, I provide information on cost effective options for restoration. Combining physical modeling with flow scenarios allowed generation of probability maps for achieving floodplain habitat for salmon rearing and for comparing levee setback options individually and in combinations. Thus, the integrative hydro-ecological model and a cost effectiveness measure offer support for decision makers considering where to rehabilitate floodplain processes upon which biological and social benefits depend.

### **Future research directions**

The hydro-ecological model presented here is the foundation upon which refinements can be made. More factors influence ecological response than just timing, duration and frequency of floodplain inundation, so incorporating additional requirements into a restoration design could help enhance estimates of habitat for ecosystem functions. For example, determining probabilities for achieving necessary depths and velocities for fish movement would aid in comparing scenarios for fish species' benefit. Different species or suites of floodplain-dependent taxa could also be assembled for future analysis. The physical modeling done for this dissertation could be further improved by exploring techniques for using finer resolution topographical data and constructing more realistic floodplain designs for model scenarios. The prioritization using ecological benefits and costs could be weighted and run through optimization algorithms. Additionally, the socio-economic factors in the ranking system could be added to using a flood damage reduction analysis and an economic analysis of regional economic impacts (e.g., an IMPLAN study) to estimate regional costs of restoration projects.

Future research directions include quantifying current floodplain benefits (e.g., Yolo Bypass) with this method. Monitoring results from the field can be used to validate models and establish baseline measures from which to assess change. Field experiments can also be used to fill data gaps and test hypotheses about species-flow relationships. Moving beyond estimates of potential habitat, projecting species population response to restoration is a topic of future research that can be used to plan and to evaluate floodplain restoration success (Poff and Zimmerman 2010; King and Brown 2006). Thus, developing methods to model flow-ecology dynamics to allow the size, structure or condition of populations to be tracked through time and associated with flow variability could build on the method presented in this dissertation. Lastly, integrating measures of ecological benefits with water-supply and flood-control benefits in analysis of floodplain restoration options will provide decision makers with a more comprehensive understanding of tradeoffs and support long-term, systematic restoration planning.

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