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

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ABSTRACT

Freshwater ecosystem health has been increasingly linked to floodplain connectivity, and some river restoration efforts now overtly target reconnecting floodplain habitats for species recovery. The dynamic nature of floodplain habitats is not typically accounted for in efforts to plan and evaluate potential floodplain reconnection projects. This study describes a novel approach for integrating streamflow dynamics with floodplain area to quantify species-specific habitat availability using hydraulic modelling, spatial analysis and statistical measures of flow regime. We used this hydro-ecological modelling approach to examine the potential habitat for splittail (*Pogonichthys macrolepidotus*), Chinook salmon (*Oncorhynchus tshawytscha*) and their food resources under two restoration treatments and two climate change flow scenarios for a study site on San Joaquin River in California. Even with the addition of new floodplain through restoration efforts, the modelling results reveal only 13 streamflow events in the past 80 years had the magnitude and duration required for splittail spawning and rearing, and 14 events had flows long enough for salmon rearing benefits. Under climate change, modelled results suggest only 4–17% of the years in the rest of this century are likely to produce required flow-related habitat conditions for splittail and salmon rearing along the study reach. Lastly, we demonstrate by simulating augmented reservoir releases that restoration of fish habitat will require a more natural flow regime to make use of restored floodplain and achieve the desired hydrologic habitat connectivity. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: ecosystem functions model; Chinook salmon; Sacramento splittail; hydrologic connectivity; GIS

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INTRODUCTION

Natural floodplains are rich biologically productive ecosystems, but their existence and associated biodiversity are increasingly threatened by overexploitation, water pollution, flow modification, habitat loss and invasive species encroachment (Tockner and Stanford, 2002; Dudgeon *et al*., 2006). Flood protection measures such as levees and dams cause many rivers and streams to lose adjacent periodically inundated floodplains. This loss compounds the effects of other stressors on freshwater ecosystems by diminishing natural processes and reducing the available habitat for fisheries and other species dependent on riverine systems (Opperman *et al*., 2010). The species that need floodplain habitat and periodic inundation to meet their life history requirements are profoundly impacted by flow regulation and floodplain reduction (The Bay Institute of San Francisco, 1998; Lytle and Poff, 2004). In highly managed rivers, meandering natural backwater-flooded sloughs have disappeared, causing declines in fisheries, riparian vegetation communities and food web complexity. Floodplain reconnection has multiple benefits, including providing necessary habitat for individual species, supporting an increase in floodplain services (e.g. nutrient cycling and aquifer recharge), reducing flood risk to life and property and fostering climate change resilience (Tockner and Stanford, 2002; Opperman *et al*., 2009).

For these reasons, restoration treatments now proposed in many river basins involve increasing the amount of floodplain area for native species and altering the flow regime, usually through dam operations to promote physical reshaping of the river–floodplain environment. Many management agencies are currently in the process of restoring floodplains through strategies such as the following: (i) facilitating flow into bypass channels; (ii) constructing overflow basins; and (iii) removing or setting back existing levees. All of these strategies can have advantages for flood relief, but more research is needed on the ecological benefits each may provide. The ecosystem returns associated with each option depend upon species requirements, expected flows and physiographic context. For inundation patterns to be ecologically functional, the magnitude, timing, duration and frequency of flood events must fall in the range required by species life history patterns (Poff *et al*., 1997). Additionally, exploring potential flow changes under climate change scenarios is essential to better understand the species' response in the future. Finally, spatially explicit modelling

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is required to estimate ecological benefits associated with floodplain restoration.

This study quantifies the benefits of increasing floodplain connectivity for a suite of species under past, current and potential future flow regimes and compares these benefits under several restoration options using integrated hydro-ecological modelling 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. Floodplain geomorphic and ecological processes depend upon a diverse range of flows, 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 (Kimmerer, 2004; Lytle and Poff, 2004; Sommer *et al*., 2004a). 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, allowing the biota to efficiently use the resources available in the aquatic–terrestrial ecozone. Flood pulses, occurring with greater frequency but lower magnitude than a 10-year recurrence interval flood, promote production of biologically available carbon and provide important spawning and rearing habitat for native fish (Sommer *et al*., 2001a; Sommer *et al*., 2005; Burgess *et al*., 2012). While researchers increasingly recognize that the reestablishment of frequent low-magnitude flood pulsing in riverine and tidal systems is an important step in floodplain wetland restoration (Middleton, 2002), larger floods (5- to 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 floodplain 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, 2002). 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 US Army Corps of Engineers (USACE) (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. Statistical models such as this allow users to define how river flow, floodway morphology and biological communities interact (Hickey and Dunn, 2004; USACE, 2009). These models provide a method to link biologic, hydrologic and hydraulic variables that can be applied to multiple study areas and alternative restoration treatments. We employ these species-specific models to assess the floodplain benefits under different flow regimes and channel morphologies.

We apply a new methodology for quantifying the benefits of floodplain restoration within part of the San Joaquin Delta using an integrated hydro-ecological model with fine-scale physiographic data and informed by functional ecosystem relationships (Matella and Jagt, 2013). We estimate 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. For the prerestoration and postrestoration scenarios, we examined the extent of floodplain habitat recovery that might result and note expected alterations under climate change flows. We considered changes in habitat for *Pogonichthys macrolepidotus* (Sacramento splittail) and *Oncorhynchus tshawytscha* (Chinook salmon). These species are valuable indicators of floodplain ecosystem health because they use Central Valley floodplains for spawning and/or rearing, and their populations have been in decline in recent decades (Moyle, 2002). Lastly, we quantify phytoplankton and zooplankton production benefits as they 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).

METHODS

Study area

With its headwaters in the Sierra Nevada, California's San Joaquin River watershed drains 83 000 km^2. It extends 560 km, flowing northward through the San Joaquin Valley to meet the Sacramento River in the Delta, a tidally influenced network of islands and channels that feed into San Francisco Bay. Annual precipitation in the San Joaquin River Basin ranges from 15 cm on the valley floor at Mendota to 178 cm in the Sierra Nevada. Snowmelt is the main source of freshwater in the San Joaquin River (DWR, 2010a), with peak snowmelt flows occurring historically from May through June, with the Stanislaus, Tuolumne and Merced tributary rivers contributing the majority of flow. The study area covers part of the Lower San Joaquin River in the South Delta, where several opportunities exist to adjust the river's flow path to provide the much needed flood relief for the downstream city of Stockton (Figure 1; DWR, 2010a).

Hydrologic data

The South Delta is a promising area for evaluating functional flows for ecosystem benefits under varying conditions because of a relatively long historical streamflow record

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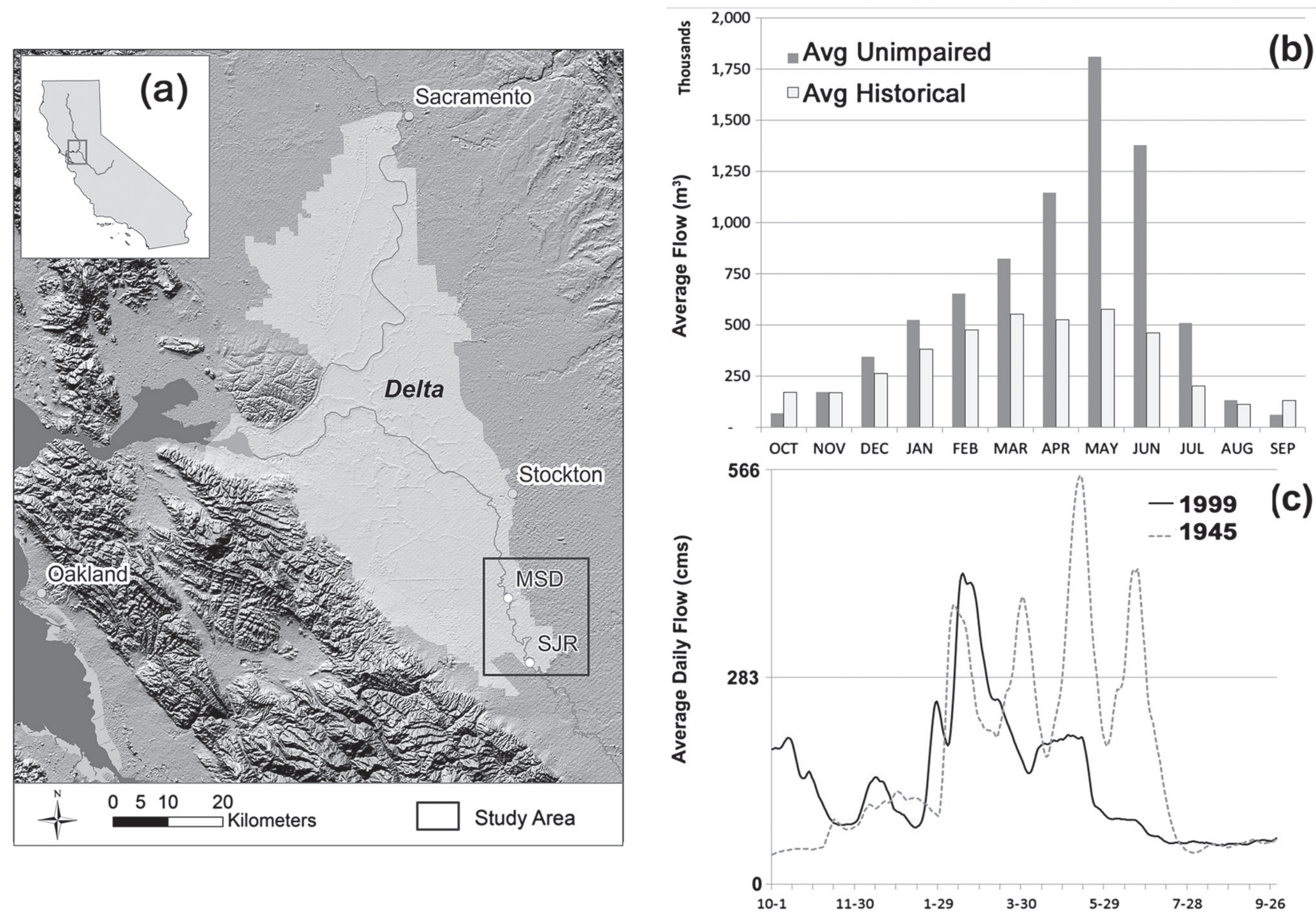

Figure 1. Map of San Joaquin River study area (a) highlighting Vernalis (SJR) to Mossdale (MSD) gauge locations and representative hydrographs, (b) monthly unimpaired (1920–2003) versus historical flow (1980–2003) averages, and (c) normal water year examples for regulated (1999) and less impacted flows (1945)

[since 1924 and continuously since 1929 at Vernalis, US Geological Survey (USGS) gauge no. 11303500] and available climate change streamflow projections (Figure 1). Because large dams and diversions have altered the San Joaquin river flow regime, we divided the historical record into two periods. The record of historical flows was considered prior to the establishment of the New Melones Dam (1929–1979), although other flow and floodplain alterations existed in this period. The recent period of record covers the period of large dams and diversion (1980–2010).

The Vernalis gauge was used as a basis for modelling future changes to flow based on expected changes to precipitation and temperature. Four future flow scenarios from 2001 to 2099 were developed by the USGS Computational Assessments of Scenarios of Change for the Delta Ecosystem (CASCaDE) project (USGS, 2009). USGS used the Bay Delta watershed model, a physically based hydrologic model, to generate streamflow at a daily time step with primary inputs of precipitation and air temperature. Analyses for this study used streamflow output from the best-case low emissions warm and wet future climate scenario (B1PCM) and the worst-case high emissions hot and dry scenario (A2GFDL) to represent the range of expected change. Other climate futures that include drier and wetter scenarios would influence results, but we chose models used by the CASCaDE project. The B1PCM model is now referred to as the B1 scenario and the A2GFDL model as the A2 scenario.

An additional consideration involved changing the historic record per a proposed flow criteria policy designed to provide sufficient flow for native fish in the Delta (SWRCB, 2010). This policy states that 60% of unimpaired flow from February through June is needed to achieve a Chinook salmon outmigration threshold flow of 142 cms (5000 cfs) in most years (over 85%) and 283 cm (10 000 cfs) in slightly less than half of the years (45%; SWRCB, 2010). Unimpaired flow is modelled run-off that would have occurred had river flow remained unaltered by major reservoirs or diversions. A revised historical hydrograph was created on the basis of this 60% retention rule (SWRCB, 2010).

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In sum, the models represent flows for four scenarios: (i) *historical* (1929–1979); (ii) *recent* (1980–2010); (iii) *future warm-wet* climate 2001–2099 (B1 scenario); and (iv) *future hot-dry* climate 2001–2099 (A2 scenario). In addition, a *minimum instreamflow* (60% of unimpaired flow for 1930–2003) criteria was considered because it could influence the number of years that estimated species-specific flow thresholds could be met.

Ecological data

Two species of fish were selected on the basis of the need for additional floodplain habitat for population recovery and life history requirements for a range of flood duration and timing. The native Sacramento splittail (*P. macrolepidotus*) and Chinook salmon (*O. tshawytscha*) use flooded areas for rearing in the Central Valley riverine system (Moyle, 2002). The Sacramento splittail is a native minnow found in fresh and brackish waters, endemic to the Sacramento–San Joaquin system and an obligate floodplain spawner (Sommer *et al.*, 1997; Moyle, 2002). The splittail does not reproduce well without access to significant floodplain habitat (Sommer *et al.*, 2002). Loss of floodplain habitat accompanied a major decline in splittail abundance over the last 30 years, leading to the splittail's temporary listing as threatened in 1999 (Sommer *et al.*, 2007). Splittail requirements help define functional floodplains because their recovery depends on improving and adding floodplain habitat. 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 abundant (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). For these reasons, splittail flooding preferences and Chinook salmon rearing requirements were used to define fish-related ecological floodplain inundation relationships (Table I).

It is well documented that floodplain-reared fish grows faster and bigger than their river cohorts (Sommer *et al.*, 2001a; Jeffres *et al.*, 2008). A richer food web is considered 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 floodplains provides high levels of nutrients for a productive food web and is a valuable source of biologically available carbon downstream (Ahearn *et al.*, 2006; Lehman *et al.*, 2008). The flooding conditions that are needed to produce phytoplankton and zooplankton are consequently included in the suite of ecological relationships (Table I).

Modelling

Statistical analysis. The USACE developed the Hydrologic Engineering Center Ecosystems Function Model (HEC-EFM)

Table I. Relationships of ecological relevance to hydrologic flow parameters

Ecological relevance	Season	Duration/rate	Frequency	Exceedance probability	Literature
Splittail spawning and rearing	February–May	At least 21 days	4-year return period	0.25	Sommer *et al.*, 1997; USACE, 2002; Williams *et al.*, 2009
Chinook salmon rearing	December–May	At least 14 days	2- to 4-year return period	0.25	Sommer *et al.*, 2001a; USACE, 2002
Phytoplankton production	December–May	At least 2 days	1.3-year return period	0.77	Jassby and Cloern, 2000; Sommer *et al.*, 2004a
Zooplankton production	December–May	At least 14 days	1.3-year return period	0.77	Baranyi *et al.*, 2002; Sommer *et al.*, 2004a; Grosholz and Gallo, 2006
Floodplain maintenance flow	December–September	NA	10-year return period	0.05–0.75	Opperman *et al.*, 2010

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to examine statistical relationships between hydrologic and ecological parameters (USACE and Rec Board, 2002; USACE, 2009). HEC-EFM uses a time series of daily mean flow and stage as well as 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 observed daily flows at Vernalis from 1929 to 1979, observed daily flows for 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 to 2003). EFM flow frequency curves were analysed for significant differences using the Wilcoxon signed-rank test (StataCorp, 2007).

Information on flow frequency, duration, seasonality, inundation and habitat characteristics is essential for describing floodplain suitability and establishing the conceptual framework for this analysis. Quantitative metrics were based on the habitat requirements for splittail, Chinook salmon and phytoplankton and zooplankton productivity. Table I details the specific flow requirements and characteristics of geomorphically relevant flows.

Integrated hydraulic and spatial modelling: scenarios of floodplain configuration. The proposed restoration treatments involving channel alterations include the following: (i) the current levee configuration; (ii) the addition of a backwater slough bypass; and (iii) setting back the eastern levee and removing cross levees (Figure 2). Given that velocity is not a critical parameter for the specified habitat area estimates, a one-dimensional hydraulic model [HEC–River Analysis System (RAS)] was used to define relationships between the flows and inundated floodplain area for the scenarios. HEC-RAS cross-sections created for a study by USACE 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, and a Manning's n value of 0.06 was applied for floodplain to account for light brush and trees (Chow, 1959). A rating curve was established at Mossdale for the downstream boundary condition. Flows were run from Vernalis assuming a steady state to create water surface profiles over a wide range of flows.

For spatial analysis, a physical template was constructed in a Geographic Information System using ESRI's ArcMap software. Land surface elevations were generated from light detection and ranging (LiDAR)-based surveys (DWR, 2010b), and USACE bathymetry was integrated into the final surface. After conducting hydraulic modelling using HEC-RAS, relationships were defined between the flows and inundated floodplain area for the three physical scenarios using the Geographic Information System.

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 $f = 1$, the expected annual habitat values can also be created to describe each ecologically functional relationship per physical scenario (see Matella and Jagt, 2013 for method details).

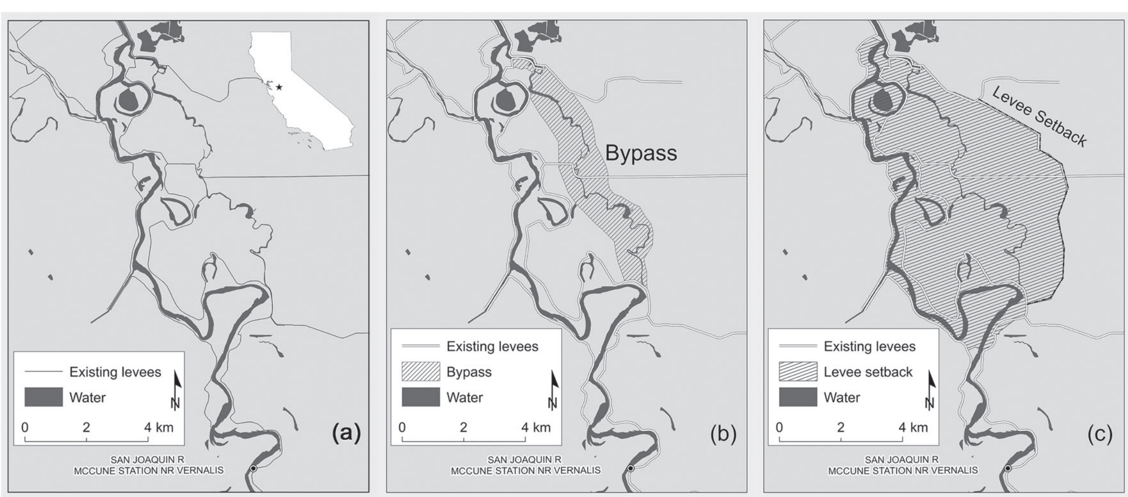

Figure 2. Map of treatment areas: (a) Existing conditions, (b) Slough bypass, and (c) Levee Setback area. Figure 1 shows a larger extent for project area

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RESULTS

The minimum flows that species require in order to take advantage of floodplain habitat are found by applying the criteria listed for each species in Table I and are presented for the four flow scenarios in Figure 3. Splittail and salmon flows that meet their habitat requirements have been higher in recent years than the average over the longer historical record. The reverse is true for phytoplankton, which depend upon more frequent, lower magnitude flows. The low flows are similar to the 1.3-year recurrence interval flows (for phytoplankton) and less than 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- or 10-year recurrence intervals) (Table I and Figure 3).

A nonparametric Wilcoxon signed-rank test to compare climate change season–duration–frequency curves (for relationships with the following durations in December to May period: 3-, 7-, 14-, and 21-day duration) indicated that hot-dry A2 and warm-wet B1 climate change flow regimes were significantly different from each other ($p < 0.001$). The combined historical and recent flow (1929–2010) 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 historical (1929–1979) and recent (1980–2010) records were not statistically significant for any EFM generated flow frequency curve.

In addition to the minimum flow threshold for functional floodplain habitat, flooding duration greatly influences productivity. Functional floodplain persistence for splittail spawning and rearing was explored as a function of duration. According to the models, 33 years out of the 81-year period of record (or 41% of years) met the flow threshold of 425 cms. Additionally, only 13 events in 42% of years meet the magnitude and duration requirements for splittail spawning and rearing (21-day duration), and only 14 events have flows long enough for salmon rearing benefits (14-day duration). Under hot-dry A2 climate change estimates, the 425 cms threshold was met in 16% of years for an average duration of 28 days, and warm-wet B1 scenario estimates included 30% of years with an average duration of 44 days duration.

Under the current system baseline, approximately 696 ha is the maximum recoverable floodplain habitat area within the 20 km reach considered (Figure 2). Levee setbacks add an estimated 1781 ha of habitat for potential inundation. The slough bypass option provides a 603 ha corridor only if a weir is included on the San Joaquin River, allowing flows of 396 cms to overtop it. Inundation area-flow curves indicate the current levee configuration has 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. However, the bypass scenario 2 inundates 460 ha more than the original levee configuration by 765 cms. At the same flow magnitude, levee setback scenario 3 more than doubles the inundated area of the original topography.

The flow–area relationships alone are not sufficient to inform management decisions; rather, they must be combined with the EFM modelling thresholds and hydrologic regime expectations to assess how species recovery could benefit

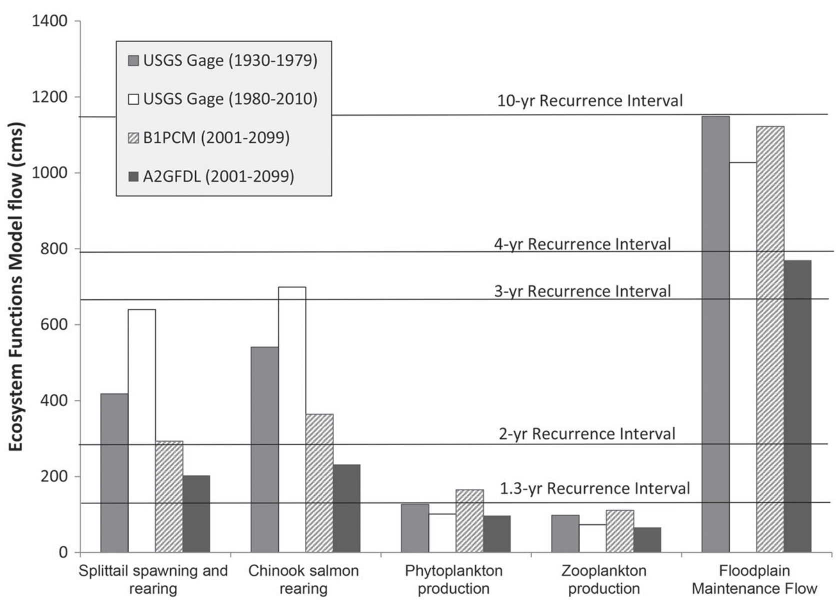

Figure 3. Ecosystem Functions Model (EFM) defined threshold flows at Vernalis for relationships specified in Table I

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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 be used in conjunction with physical habitat restoration to increase habitat area and frequency of inundation. The influence of a hypothetical State Water Resources Control Board adjustment to minimum flows on a hydrograph reflects this finding. Table II shows the percent of years that the species flow requirements were met during the historical record compared with the number of years that would have been achieved if the historical flows were adjusted to a minimum flow policy (SWRCB, 2010). In considering this policy with the 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. When the historical record flows are augmented to meet State Water Resources Control Board guidelines, every ecological relationship threshold is met more frequently.

The ADF curves plotted in Figures 4 and 5 illustrate how each ecological relationship fares according to physical (existing condition, bypass and levee setback) and hydrological scenarios [historical and recent flows (1929–2010), climate change flows (2011–2099) and a minimum instreamflow policy (1930–2003)]. The season and duration criteria shape the frequency curves that correspond to maximum possible inundated area. Floodplain maintenance benefits are greatest (about 1214 ha more than existing conditions) in levee removal scenarios, regardless of hydrology (Figures 4 and 5). Phytoplankton benefits increase by only 202 ha under any minimum instreamflow scenario compared with historical flows and climate change flows. Chinook salmon benefits between probabilities of 0.25 and 0.5 are greatest under minimum instreamflow policy flows with bypass or setback scenarios, but even these drop substantially (809 ha) moving from the less to more frequent flow criteria (Figure 4). Zooplankton benefits, on the basis of 14-day durations at the probability of 0.76, are similar to phytoplankton benefits at approximately 182 ha for the minimum instreamflow policy scenario compared with about 40 ha at all others. The splittail benefits achieved are again greatest in bypass or setback scenarios, both at 728 ha (Figure 5). For all ADF graphs, the hot-dry A2 climate change scenario indicates the least functional area. Notably, for all duration-based relationships, the physical alteration scenarios with historical flow regime achieve fewer functional benefit areas than if the hypothetical minimum instreamflow policy was enacted under existing levee conditions.

DISCUSSION

This research demonstrates the importance of coupling hydrologic and species habitat modelling to quantify habitat recovery potential from channel restoration efforts or changes to flow conditions. In this analysis, historical and future climate change scenario flows, as well as physical restoration alterations, influence floodplain habitat advantages for native fish. A suite of species life histories that span a range of necessary flow requirements allow us to examine an array of impacts associated with four flow scenarios for the San Joaquin river system. Notably, the modelled results project 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. Under historical flows, splittail and Chinook salmon thresholds for ecological benefits were lower than those estimated from the recent flow record. Our modelled results for the two periods did not reveal differences in estimated production of phytoplankton, which require frequent lower flood pulses. This is expected given that the river had regulated flows during both of these periods. Currently, the operation of over 80 dams within the San Joaquin River watershed reduces and eliminates most flow peaks (Cain *et al.*, 2003), limiting phytoplankton and zooplankton production. The duration of high 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.

Table II. EFM threshold flow results at Vernalis (USGS no. 11303500)

	Criteria	All historical (1930–2010)		B1PCM (warm/wet)	A2GFDL (hot/dry)	SWRCB Policy
Relationship	Season/duration/frequency	Threshold flow (cms)	% of years	% of years	% of years	% of years
Splittail spawning and rearing	February–May/21 days/4 years	435	25	17.3	6.3	42.9
Chinook salmon rearing	December–May/14 days/4 years	585	24.9	15.2	4	32.8
Phytoplankton production	December–May/2 days/1.3 years	118	77	83.1	65.2	98.3
Zooplankton production	December–May/14 days/1.3 years	90	76.3	80.9	60.3	98.5
Floodplain maintenance flow	December–September/NA/10 years	1057	10	10.7	1.7	10

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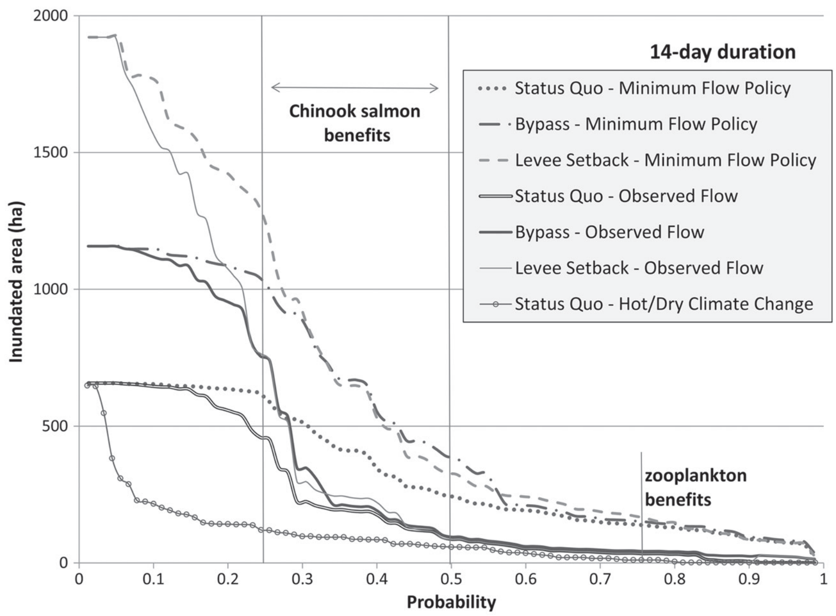

Figure 4. Area–duration–frequency curves for 14-day duration flows representing combinations of physical alterations and hydrology scenarios. At a probability range of 0.25–0.5, representing the flood that occurs 1 out of every 4 or 2 years, on average, we see Chinook salmon benefits. At a probability of 0.77, representing the flood that occurs 1 out of every 1.3 years, on average, zooplankton benefits emerge

Limited understanding of species' life histories adds uncertainty to estimates of environmental change impacts. In addition, the interannual variability of precipitation patterns in Mediterranean-climate regions mean that species often respond to environmental cues at different times each year. The modelling approach here does account for these adjustments in timing of seasonal flows. However, the EFM tool does not include additional factors such as temperature, suspended sediment, depth, velocity, vegetation, dissolved oxygen and organic matter (Opperman, 2012) in representing

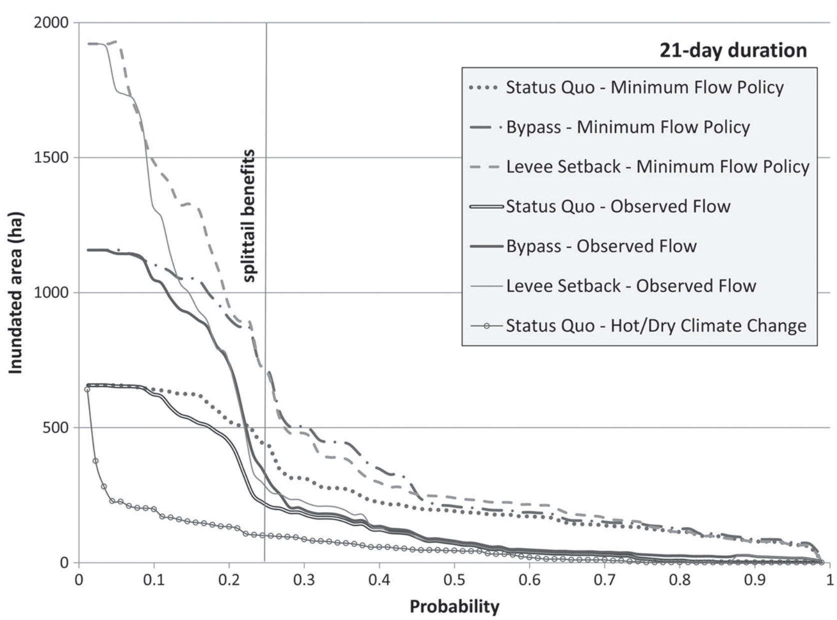

Figure 5. Area–duration–frequency curves for 21-day duration flows representing combinations of physical alterations and hydrology scenarios. Observed flow refers to the 1929–2010 flow record at Vernalis. At a probability of 0.25, representing the flood that occurs 1 out of every 4 years, on average, splittail benefits emerge

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floodplain habitat potential. The EFM tool produces threshold flows that might underestimate the amount of floodplain that has some ecological value.

The flood pulse concept of Junk (1989) correlates enhanced productivity with annual flood events demonstrating the importance of floodplain habitat to ecosystem function. Studies along the Yolo Bypass in California found greater diversity of native and non-native fishes on floodplain habitat than on proximate river habitat, with higher floodplain abundance of two federally listed native fishes, delta smelt and splittail and several alien sport fishes (Sommer *et al*., 2004a, 2004b). The higher habitat diversity and hydrologic variability of the floodplain can explain some of these results and inform our expectations for what additional restored floodplain can provide as ecosystem benefits. Seasonal floodplain in particular offers special advantages to native fishes that are not available in perennial habitat because floodplain is typically inundated in winter and early spring, when many native fishes spawn and rear (Sommer *et al*., 2001a, 2004a, 2004b).

Although the flow scenario results differ under mild or strong effects of greenhouse gas emissions, both climate change flow scenarios exhibit higher than historical winter/fall flows and reduced springtime peak flows (Cloern *et al*., 2011). 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 (phytoplankton and zooplankton production) can occur are shown to increase, but every beneficial flood pulse under the A2 climate scenario occurs less frequently (Table II). The greatest difference between the two climate scenarios is exhibited in floodplain maintenance flows, where the 10-year flood levels in the future are estimated to be as low as the flow levels observed at 4-year intervals historically. The B1 scenario indicates some flows may occur that are higher than what has been observed over the period of record. This characteristic of the B1scenario is likely to permit the floodplain maintenance flow to persist, but fish threshold flows decrease by half under this climate change scenario. Notably, the estimated production of phytoplankton and zooplankton may increase under the B1 climate scenario, given that long floodplain inundation periods are not required. With higher future flows falling outside of the functional season for fish, lower fish production would be expected given the parameters of this study. In sum, under the current physical configuration of the channel and floodplain in the study area, the climate change scenarios suggest a reduction in the area available, particularly for fish floodplain benefits.

Management actions similar to those examined in this study—such as levee setbacks, secondary channel restoration and levee breaches—have been used to restore floodplain connection and ecosystem function in US and European rivers (Buijse *et al*., 2002; Swenson *et al*., 2003; Opperman *et al*., 2010). Many European restoration projects have rehabilitated secondary channels to enhance habitats suitable for aquatic species across a flow gradient (Buijse *et al*., 2002). Swenson *et al*. (2003) demonstrated success at breaching levees to reestablish connectivity of the Cosumnes River and its floodplain, creating a habitat for salmon and splittail to the east of the Sacramento–San Joaquin Delta. Flow management is also part of the portfolio of strategies that managers are considering for floodplain restoration projects. For example, a Savannah River, Georgia, case study demonstrates how flows released from an upstream dam in experimental high-flow pulses were designed to enhance specific biological and physical processes (Opperman *et al*., 2010).

This integrated modelling approach allows for examination of individual and combined restoration treatments under different flow scenarios. The approach can provide data for managers to plan what environmental flows, defined as river discharge characteristics for the specific purpose of ecosystem benefits, are necessary for species recovery (King *et al*., 2003). Results of this study demonstrate that enacting a minimum flow policy would provide significant benefits at this site. Habitat availability declines under climate change flow regimes suggest additional flow will be required in the future, especially to sustain splittail and salmon. Although both 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 augmented flows. Plotting a range of inundation areas, as seen in the 14-day duration ADF curve for Chinook salmon benefits, can inform managers about model sensitivity with regard to selected criteria for floodplain species benefits.

In summary, we advance methods for planning floodplain restoration by utilizing and improving upon predictions of an integrated hydro-ecological model using functional ecosystem relationships. Maps and quantitative estimates of restoration outcomes can allow managers to assess where and what restoration projects might be more effective. This study also reveals that investing in floodplain habitat restoration alone is not sufficient to recover salmon and splittail but rather must be accompanied by environmental flows, especially if we move into a drier, hotter future.

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