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Research Paper

Ecological design of multifunctional open channels for flood control and conservation planning

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HIGHLIGHTS

- We propose 6 principles for a new design paradigm for flood control open channels.
- These principles are applied to simulate retrofits to an antiquated flood system.
- Co-equal goals of increased flood protection and wildlife habitat were demonstrated.
- Habitat of endangered species in river systems could be increased by this approach.
- Human communities would benefit from greater levels of flood protection.

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ABSTRACT

Historically, typical open channel flood control systems have been designed for a single function: to enhance human safety by preventing flood damage to human landscape infrastructure. This single-purpose objective is increasingly an untenable practice. Because river systems in human-dominated landscapes often play important conservation roles for biota (e.g. endangered species), it is important that flood control planning be integrated with conservation planning principles and goals. 'Regenerative design' seeks to intentionally enable an environment to continually replace ecosystem structures through natural processes, which is a design paradigm that can achieve multiple socio-ecological goals. In river systems, flood control channels need to be multifunctional where feasible, and be designed to accommodate vegetation as well as geomorphic processes, such as meander dynamics. A heuristic analysis of three areas from California's existing but antiquated Sacramento River flood control system (including two bypass channels) was used to illustrate these concepts with a series of expansion scenarios for each channel. Minimum dynamic area was gamed (by expanding the average channel width and adjusting Manning's *n* roughness coefficients) in the main channel (river miles 84–144) to more than double the existing conveyance, which resulted in nearly quadrupling the roughness coefficient allowing for increased riparian vegetation. The bypass channel widths and roughness coefficients were also gamed to achieve 100- and (alternatively) 200-yr flood protection while providing increased potential for riparian vegetation and flood refugia for terrestrial animal species. These scenarios conceptually illustrate that expanding the flood channel footprint while increasing design roughness coefficients can effectively meet multifunctional objectives.

1. Introduction

In developed countries, rivers proximate to urban development typically have open channel flood control systems designed with fixed parameters and narrow objectives that frequently overlook important ecological functions of river systems, making these channels of limited value to ecological conservation. The conventional single objective for open channel design is to convey water as efficiently as possible, and historically such designs have been implemented to protect urban and rural infrastructure. Using this utilitarian goal, flood water is efficiently routed to prevent property damage and loss of human lives, and the open channel design is mainly driven by minimizing construction costs. The most extreme form of this open channel design replaces the entire river channel

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and its floodplain by smooth trapezoidal-shaped concrete conveyance structures with walls high enough to contain design flows. This is a common practice in urban landscapes throughout the world. In this paper we propose that open channel flood control designs have co-equal goals of flood damage reduction and ecological conservation. This multifunctional approach necessitates adopting a 'regenerative design' paradigm (Cole, 2012; Zari, 2012) combined with 'reconciliation ecology' (Rosenzweig, 2003) to create and sustain viable and productive river systems. Our approach builds on previous work such as the "space for the river" concept proposed in the Netherlands and elsewhere (Nienhuis & Leuven, 1998).

In recent decades it has been increasingly recognized that riverine and riparian ecosystems have important ecological conservation values and provide human communities with numerous ecosystem services (Opperman et al., 2009; Thorp et al., 2010). Various aspects of the fundamental mechanics of these ecosystems have been described relatively recently in the literature and they illustrate why conventional open channel flood channel design has been detrimental to ecological conservation. Key essential natural community and ecosystem patterns, processes, and concepts, which are not considered in conventional flood control channel design, include: naturalized flow regimes (Poff et al., 1997), flood-pulse (Junk, Bayley & Sparks, 1989), geomorphically effective stream power (Larsen, Fremier, & Greco, 2006), channel meander (Hickin, 1974), floodplain age (Greco, Fremier, Larsen, & Plant, 2007; Hooke, Harvey, Miller, & Redmond, 1990), bedload transport (Kondolf, 1997), vegetation dynamics (Amoros and Wade, 1996), patch dynamics and minimum dynamic area (Greco, 2013; Pickett & Thompson, 1978; Wu & Loucks, 1995), minimum dynamic area for channel meander using setback levees (Larsen, Girvetz, & Fremier, 2006); river continuum (Vannote, Minshall, Cummins, Sedell, & Cushing, 1980), large woody debris recruitment (Latterell & Naiman, 2007), large river ecology (Johnson, Richardson, & Naimo, 1995), and riparian landscape ecology (Malanson, 1993). It is critically important that in future planning these riverine-riparian landscape patterns, processes, and concepts are considered and integrated into a multifunctional flood control open channel design process such that ecological values are maintained or enhanced for ecological conservation.

Systematic conservation planning is a land planning and design process for integrating and sustaining natural ecosystems within cultural landscapes (Margules & Pressey, 2000). An important design component and strategy of systematic conservation planning is the development of conservation-based ecological networks. An ecological network is a nature conservation system where large reserves are connected to each other via ecological corridors or 'stepping stones' across broad landscapes to facilitate recolonization and persistence of wildlife populations threatened with extinction or extirpation (Jongman, 2004; Noss, O'Connell & Murphey, 1997). Some European countries have used rivers as an organizing principle for national ecological networks (Jongman, 1998). Hydrologic networks are inherently a hierarchically connected system and logically meet the need for connectivity of many species in nature reserve systems. However, hydrological networks alone are insufficient to meet the functional connectivity needs of all organisms (Huber, Shilling, Thorne, & Greco, 2012; Jongman, 1998). Nonetheless, where river systems can contribute to ecological conservation and habitat connectivity, conventionally designed flood control channels often offer limited or no value because they commonly lack many of the important ecological attributes discussed above. It is vitally important to the health and viability of river systems that ecological conservation values be incorporated into the planning and design process of multifunctional open channel flood control structures.

1.1. Open channel flood control design

The utilitarian flood control channel design process begins with selecting an instantaneous peak flow that the channel must accommodate (Dunne & Leopold, 1978). In the USA this is typically the 100-year recurrence interval flow based on historical annual peak flow data. Open channel flow (Q) is calculated as:

$$Q = vA \tag{1}$$

where v is mean velocity and A is the cross-sectional area of the channel. Velocity is often computed with the Manning equation:

$$v = \frac{k}{n}(R^{2/3}s^{1/2}) \tag{2}$$

where v is velocity (in $\mathrm{ft}^3\,\mathrm{s}^{-1}$ or $\mathrm{m}^3\,\mathrm{s}^{-1}$), k is a constant (where $k = 1.49\,\mathrm{ft}^{1/3}\,\mathrm{s}^{-1}$ in US units and $k = 1.0\,\mathrm{m}^{1/3}\,\mathrm{s}^{-1}$ in metric units), s is the average channel slope, R is the hydraulic radius which is defined as the channel cross-sectional area, A, divided by the wetted perimeter, P, and n is the hydraulic roughness coefficient (Dunne & Leopold, 1978; Manning, 1890). The empirical Manning roughness coefficient characterizes channel surface roughness and thus characterizes the resistance or impedance to flow. Small values of n such as <0.012 describe a smooth surface with little resistance (such as concrete), whereas large values of n such as >0.15 describe a rough surface consisting of trees and boulders posing greater resistance (Mount, 1995). The Manning equation is a key tool used by civil engineers to design open channel flood control structures.

Because conventional flood control channel design seeks to minimize economic costs, the typical open channel footprint (land area) is minimized, the channel depth is maximized with the use of flood walls or levees (also known as "dikes" in some European countries), and the roughness coefficient is minimized. Herein lie the two main reasons why conventional flood channel design is of little conservation value. First, channel capacity or depth is created with artificial means to constrict the floodplain instead of using floodplain width to expand capacity and decrease depth. Second, the use of excessively smooth roughness coefficient values requires the routine, systematic removal of any trees, shrubs or woody debris that subsequently grow or get deposited within the channel that act to increase the roughness of the channel beyond its design roughness value. However, it is precisely this roughness component that has critically important habitat value for aquatic and terrestrial organisms.

Consider the ecological ramifications of these design objectives. Engineers will frequently design channels to create additional capacity (i.e., volume and conveyance) by creating higher walls along a narrow channel to contain floodwaters to a smaller footprint thus lowering land acquisition cost. At the design (peak) flow the water is typically deep and the velocity is high. Consequently any non-flying terrestrial animals living in the flood control channel must be able to reach refugia or drown. Refugia from floodwater can be provided by high ground, a nearby tree, or a debris pile that rises above the flood water surface. In large river systems flood control channels can be several miles wide with few or no trees in the floodplain, and for many terrestrial organisms traversing long distances to safety is dubious. In a study on the Sacramento River researchers found an 86% decline in the presence of small mammals in areas subject to flooding as compared to non-flooded areas (Golet, Hunt, & Koenig, 2013). The use of setback levees (i.e. widening the distance between levees to increase channel width) to reduce depth and create additional capacity and conveyance is a more ecologically beneficial design practice (Mount, 1995) and also provides opportunities for refugia habitat from floodwaters.

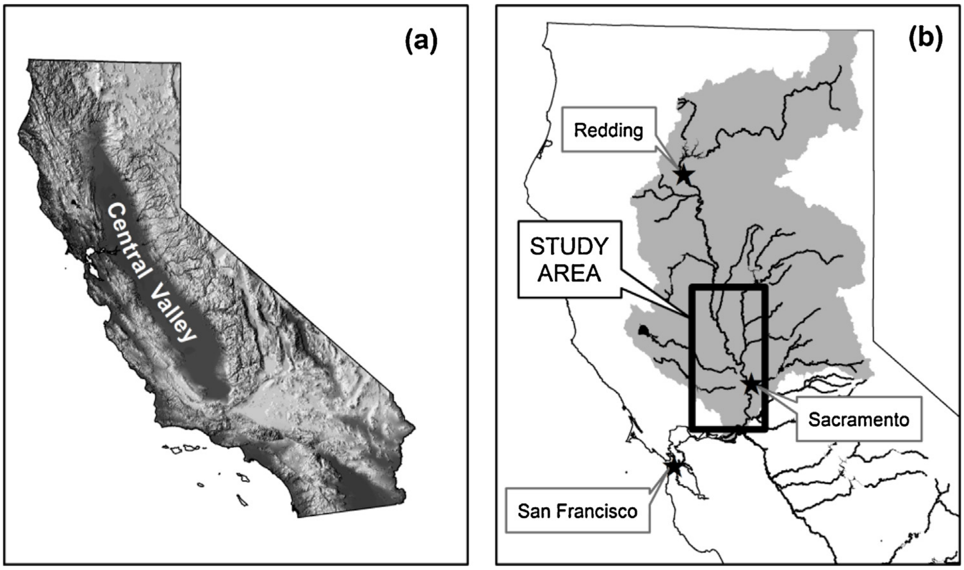

Fig. 1. Location maps of the study area, (a) the Central Valley in the state of California, and (b) Northern California and the watershed of the Sacramento River in gray, major rivers in the Central Valley, major cities, and the study area extent as depicted in more detail in Fig. 2.

The second problem with a conventional engineering approach is designing the channel with excessively smooth Manning roughness coefficients and requiring that the *n* value be maintained over time to pass the peak flow. Around the world millions, and perhaps billions, of dollars are spent to remove vegetation that grows near the channel or in the floodplain to maintain these excessively smooth roughness coefficients. In those same landscapes where flood control channels are cleared of their riparian vegetation there are numerous endangered terrestrial and aquatic species whose floodplain habitat is in short supply. An example in California is the federally listed endangered bird species Bell's vireo (*Vireo bellii* ssp. *pusillus*) whose preferred nesting and foraging habitat is dense willow (*Salix* spp.) thickets in large floodplains (Kus & Ferree, 2007). Unfortunately, the habitat for this endangered species is typically removed for flood control.

1.2. Study objectives

Using a case study approach (the study area is defined in the next section), our main research questions were: (1) What proportion of the historical floodplain is currently utilized for flood control, and where are the opportunities to expand flood capacity in the system? (2) How can flood control channel and flood bypass systems be designed or retrofitted to contribute conservation values to an ecological network while simultaneously providing *increased* flood control for surrounding areas? (3) How can increasing opportunities for woody tree and shrub cover through increasing design values of roughness coefficients be effectively incorporated into channel design? (4) How can ecosystem dynamics, such channel meander and the 'minimum dynamic area' concept, be effectively incorporated into channel design with levee setbacks? (5) How can downstream flood peaks be attenuated by expanding channel capacities upstream (i.e. using the "reservoir effect" or transitory storage), thus allowing for greater in-channel roughness downstream? Within the context of these questions we also discuss conservation planning and multifunctional channel design principles that can be integrated into the open channel flood control design process. Implementing such practices will produce higher value ecological networks with actively regenerating riparian zones and floodwater refugia for organisms of conservation concern.

2. Methods

2.1. Study area

The Sacramento River is located in the northern portion of the Central Valley, flowing south through the Sacramento Valley, California, USA (Fig. 1), and is an ideal river system to evaluate the novel concepts discussed above. The existing flood control system consists of: several river channel components flanked by levees, two major river bypass channels (the Yolo Bypass and Sutter Bypass) completed circa 1920, and a series of dams, including the largest one in California, Shasta Dam, completed circa 1943. The Sacramento River is the largest river in California and its watershed represents 17% of the state's land area (6.8 million ha). It provides about 70% of the freshwater produced in California for human consumptive uses (USACE, 1986). The Mediterranean-like climate is characterized by cool wet winters and hot dry summers. Precipitation in the watershed ranges from 300 to 2400 mm yr^{-1}. It is estimated that only 6% of historical wetlands and 11–13% of riparian vegetation remains in the Central Valley (GIC, 2003; Katibah, 1984). These riparian forests are considered "endangered ecosystems" in the USA (Noss, LaRoe, & Scott, 1995). The focus of this study is on the Sacramento River Flood Control Project in the southern portion of the Sacramento Valley, south of the town of Colusa (at river mile [RM] 144; Fig. 2b), where the main river channel is tightly constricted with levees and includes the two flood bypass channels that route high flows away from the main river channel protecting urban and agricultural lands from flood inundation.

We examined the southern part of the flood control system (Fig. 2b) by simulating expanded conveyance capacity in: (1) portions of the Yolo Bypass, (2) the Sacramento River channel from RM 84–144, and (3) the Sutter Bypass channel. Since this study was a heuristic analysis, each study component was treated as a "whole," meaning all the sub-reaches within any study component are averaged together; the only exception was our examination of the northern portion of the Yolo Bypass as a separate reach from the entire Yolo Bypass channel.

The Yolo Bypass channel (and the Sutter Bypass) was built with limited flow data in the early 1900s and today provides roughly 85-year (recurrence interval) flood protection (R. Johnson,

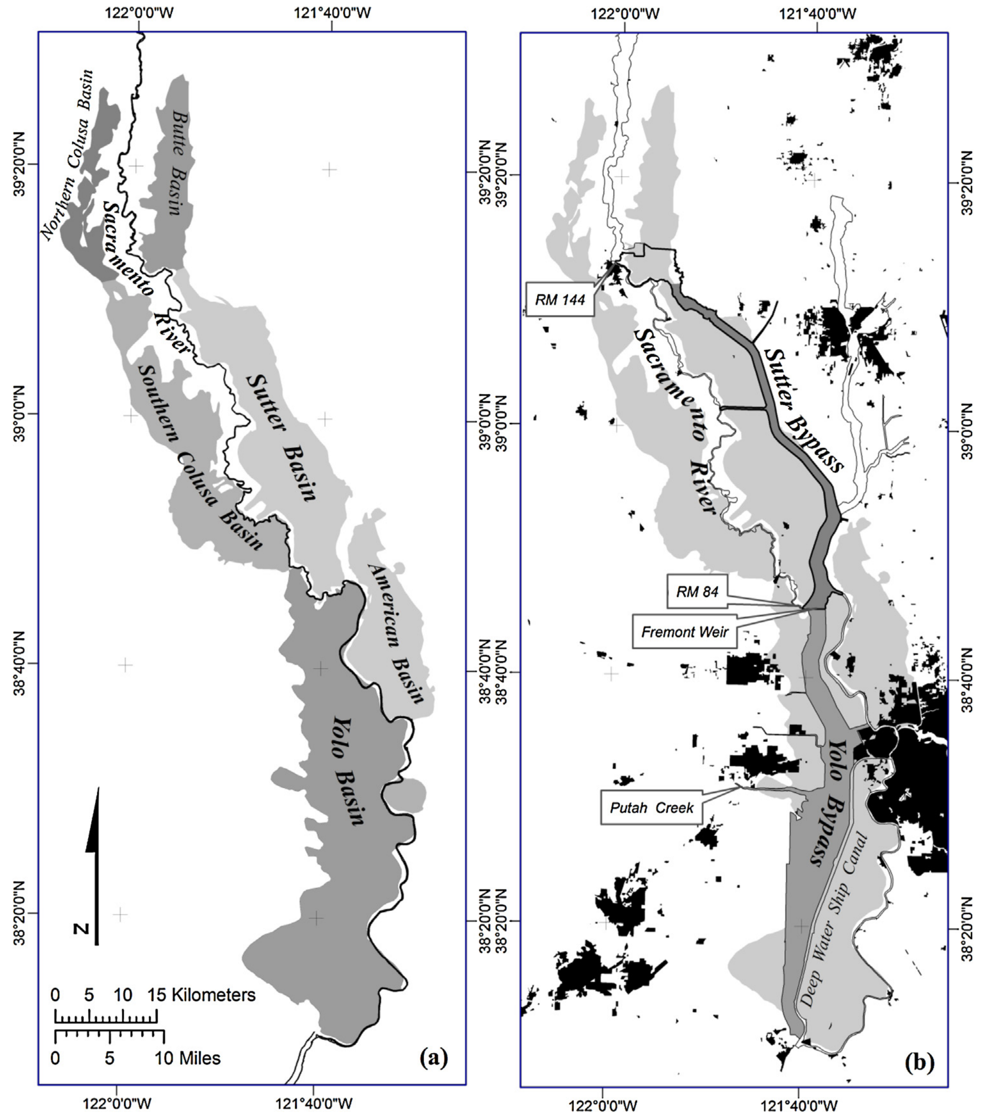

Fig. 2. (a) The historical flood basins and the Sacramento River ca. 1848, and (b) the present-day Sacramento River Flood Control Project channel levees, bypass channels in dark gray, urban areas in black, historical flood basins in light gray (for comparison), and key locations referenced in the text. The Sacramento River flows from north to south.

personal communication, September 12, 2013). The bypass system was primarily designed to protect farmland, but today it protects both agricultural and urban areas (Kelley, 1989). It is remarkable how well the bypass system has historically functioned, however, within the counties that the flood control system traverses in the southern portion of the Sacramento Valley, 22.5% of the land area is covered by the 200-year floodplain and over 500,000 people live in it (Hanak, 2008). The Yolo Bypass channel does not flow every year due to variable climatic conditions and it has a flood frequency of approximately 1.6 years (the Yolo Bypass flowed in 35 water years from 1955 to 2010), varying in duration from 3 to 83 days (from 1980 to 2010). The largest recorded peak flow in the lower Yolo Bypass was approximately 565,000 $\mathrm{ft}^3\ \mathrm{s}^{-1}$ (16,000 $\mathrm{m}^3\ \mathrm{s}^{-1}$) in the 1985–1986 water year when levees were stressed and emergency measures were enacted to protect levees from failure. The second largest recorded peak flow was approximately 529,700 $\mathrm{ft}^3\ \mathrm{s}^{-1}$ (15,000 $\mathrm{m}^3\ \mathrm{s}^{-1}$) in the 1996–1997 water year which caused several levee breaches upstream of the bypass and resulted in millions of dollars of property damage (i.e., the Olivehurst flood), the greatest flood losses in California state history (USGS, 1999).

Bottlenecks were identified in the flood control system in various reaches of the Sutter Bypass and the upper reaches of the Yolo Bypass (Greco & Larsen, 2007). According to a recent study (CDWR, 2011a), the entrance to the Yolo Bypass (at the Fremont Weir, see Fig. 2b) currently has a capacity of 290,000 $\mathrm{ft}^3\ \mathrm{s}^{-1}$ (8200 $\mathrm{m}^3\ \mathrm{s}^{-1}$); however, it requires at least a 500,000 $\mathrm{ft}^3\ \mathrm{s}^{-1}$ (14,200 $\mathrm{m}^3\ \mathrm{s}^{-1}$) capacity channel (also see CDWR, 2003 [map]) to accommodate the combined upstream peak flows. For the Yolo Bypass as a whole, the channel requires accommodation of a >500,000 $\mathrm{ft}^3\ \mathrm{s}^{-1}$ (14,200 $\mathrm{m}^3\ \mathrm{s}^{-1}$) flow for 100-year protection; however, it too is currently under-designed at a current conveyance of between 284,000 and 346,000 $\mathrm{ft}^3\ \mathrm{s}^{-1}$ (8042–9798 $\mathrm{m}^3\ \mathrm{s}^{-1}$; CDWR, 2011a). The estimated 200-year flow in the Yolo Bypass as a whole is 700,000 $\mathrm{ft}^3\ \mathrm{s}^{-1}$ (19,800 $\mathrm{m}^3\ \mathrm{s}^{-1}$) and in the northern bottleneck area it is 670,000 $\mathrm{ft}^3\ \mathrm{s}^{-1}$ (19,000 $\mathrm{m}^3\ \mathrm{s}^{-1}$) (R. McDowell, personal communication, September 10, 2013). Clearly the bypass channel needs to be expanded to increase capacity to alleviate the bottleneck in flow, and conveyance needs to be increased across the entire Yolo Bypass channel (CDWR, 2011b; Greco & Larsen, 2007). The state of California recently completed a new plan to upgrade the Central Valley's flood control system called the FloodSafe California

Program (CDWR, 2011b) and it calls for expanding flow capacity in these portions of the bypass channel to accommodate a 200-year flood event. The existing design of the flood control system presents an opportunity to redesign it as a multifunctional channel with co-equal goals of accommodating increased flood protection and enhancing the ecological conservation value of the channel.

2.2. Analysis of historical basin area versus flood control channel area

To put the *existing* flood control system into a historical perspective, geographic information system (GIS) data layers of the *historical* wetlands and flood basins prior to construction of the flood control system were obtained from the Bay Institute's ecological history study of the San Francisco Bay-Delta watershed (Bay Institute, 1998). Using ArcGIS (version 10, ESRI, Redlands, CA) we measured the footprint area of each respective historical flood basin and compared it to the footprint area of each respective existing component (i.e., bypass channel or river channel) of the flood control system and expressed it as a percentage. We examined four of the historical flood basins (Sutter, Yolo, American, and southern Colusa basins) and compared them to their respective existing flood control channel area footprints. In the next section of the analysis we focused on only the Yolo Basin, Sutter Basin, and the southern Colusa Basin (RM 84–144 of the Sacramento River) portions of the flood control system. The American Basin (presently known as the Natomas Basin), is not used for regional flood control, and currently contains extensive high density housing and commercial developments, the Sacramento International Airport, and farmland.

2.3. Co-equal goal assessment for flow and roughness

The main objective of this research was to broadly quantify the opportunities for increasing channel conveyance capacity to meet or exceed 200-year flood protection *and* to increase woody riparian vegetation cover within the flood control channels for ecological conservation value. It was a heuristic analysis and, as such, these simple calculations serve as "back-of-the-envelope" estimations to see if the co-equal goal opportunities are compatible with real-world needs in this system. A detailed hydraulic modeling approach was beyond the scope of this paper. The California Department of Water Resources is currently developing channel design scenarios and beginning to conduct detailed 2D hydraulic modeling which is expected to require several years to complete.

The approach was simple: we used a spreadsheet to calculate flow as $Q = vA$, and velocity was computed with the Manning equation (see Eqs. (1) and (2), above). Each parameter was measured using a GIS and geospatial data of the Sacramento River Flood Control Project. A GIS database of the flood control system's levees was acquired from the California Department of Water Resources (the California Levee Database) to measure the average channel width and length. Average channel width was calculated by placing equally spaced (500 m interval) transect lines (perpendicular to flow) across the channel and clipping them with the channel boundaries as defined by the levee centerline or the historical basin boundary. A digital elevation model (DEM) at 10 m resolution (pixel size) was constructed from CAD contour data derived from LiDAR for all the existing channels, and areas outside the existing channels were covered by 10 m resolution DEMs from the US Geological Survey. The CAD files (in DGN format) contained 1 foot contours and were acquired from the US Army Corps of Engineers (USACE, 2002). Using ArcGIS, floodplain and channel elevations were extracted to determine average channel slope and channel depth. Average channel depth did not assume any freeboard space below the top of the levee. Estimates for Manning's n (roughness coefficient) were derived from literature (Arcement & Schneider, 1984; Barnes, 1967; Dunne & Leopold, 1978; Mount, 1995). The existing system parameters were entered into the spreadsheet to calculate current channel conveyance capacity (Q) in $\mathrm{ft^3\,s^{-1}}$ and $\mathrm{m^3\,s^{-1}}$.

Channel expansion scenarios (Table 1) were subsequently developed by gaming the roughness coefficient and channel width while keeping the existing values of channel slope and depth constant. This allowed us to set a variety of new average channel widths based on available floodplain lands not currently developed for urban use (i.e., only existing agricultural land or conservation land was used to expand the channel width). Then for a target flow (Q) achieving a 100-year and 200-year recurrence interval protection the roughness coefficient was adjusted until the calculated flow met the target flow. This allowed us to assess how much floodplain area for woody riparian vegetation could potentially be accommodated for a given channel expansion scenario.

Each channel expansion scenario for the Yolo Bypass (as a whole and for the northern reach) has an upstream channel expansion scenario labeled as "up" in Table 1 (and in Tables 3 and 4 in the results section). These scenarios are designed to substantially decrease the target 200-year flow in the Yolo Bypass through attenuation of the flow peak through transitory storage or the "reservoir effect" from upstream. The two upstream channels are the Sutter Bypass and the Sacramento River channel from RM 84–144. The Sutter Bypass was expanded to a 200-year level of protection estimated to be 300,000 $\mathrm{ft^3\,s^{-1}}$ (11,327 $\mathrm{m^3\,s^{-1}}$), which is about 50,000 $\mathrm{ft^3\,s^{-1}}$ (4248 $\mathrm{m^3\,s^{-1}}$) greater than its current conveyance (CDWR, 2011b). The Sacramento River channel (RM 84–144) was expanded greater than two-fold, from about 43,000 $\mathrm{ft^3\,s^{-1}}$ (1219 $\mathrm{m^3\,s^{-1}}$) to 100,000 $\mathrm{ft^3\,s^{-1}}$ (2832 $\mathrm{m^3\,s^{-1}}$). The combined effect of both expanded upstream channels on the Yolo Bypass was assumed to reduce the 200-year peak flow in the Yolo Bypass (as a whole) by 100,000 $\mathrm{ft^3\,s^{-1}}$ (4248 $\mathrm{m^3\,s^{-1}}$), that is, from 700,000 $\mathrm{ft^3\,s^{-1}}$ (19,822 $\mathrm{m^3\,s^{-1}}$) to 600,000 $\mathrm{ft^3\,s^{-1}}$ (15,574 $\mathrm{m^3\,s^{-1}}$). The same assumption was made for the expansion scenarios for the northern reach of the Yolo Bypass (the bottleneck area).

2.4. Historical analysis of historic basin flow conveyance

The flood control system's existing channels and channel expansion scenarios were also compared to historical flood basin conveyance for the Yolo Basin, Sutter Basin, and southern portion of the Colusa Basin. To accomplish this objective the average depth of the basins were calculated by extracting floodplain elevations using the historical footprint of each basin. We assumed uniform flow across the historic flood basins (and used Eqs. (1) and (2) above) to give a us an *approximate* estimate of flow conveyance, but we also recognized that the actual hydraulics of the flood basins are more complex and would require more sophisticated modeling to obtain more realistic estimates of historic flow in the basins.

3. Results

3.1. Analysis of historical basin area versus flood control channel area

The results of the footprint area comparison between the historical flood basins in the lower Sacramento Valley and the current flood bypass channels of the flood control system are shown in Table 2. Just 21% of the collective historical flood basin area was represented by the channels of the current flood control system. High fortified levees lining the bypass channels, have made it possible to exclude floodwaters from former flood basins. Depth was maximized to minimize the footprints of the bypass channels. Note that just 6% of the historical southern Colusa Basin is utilized for flood control, and the smallest of the historical flood basins, the

Table 1
Flood control channel expansion scenario descriptions by reach.

Yolo Bypass (whole channel)
Expansion 1–100: Expand the average width of the channel from 4077 m to 6500 m and achieve a target flow of 436,000 ft^3 s^{-1} (12,346 m^3 s^{-1}) (the original design flow from Senate Document No. 23, estimated 100-year protection).
Expansion 1–200: Expand the average width of the channel from 4077 m to 6500 m and achieve a target flow of 700,000 ft^3 s^{-1} (19,822 m^3 s^{-1}) (estimated 200-year protection).
Expansion 1–200-up: Expand the average width of the channel from 4077 m to 6500 m and achieve a target flow of 550,000 ft^3 s^{-1} (15,574 m^3 s^{-1}) (estimated 200-year protection) with upstream levee setbacks from RM 84–144 and the Sutter Bypass expansion.
Expansion 2–100: Expand the average width of the channel from 4077 m to 7500 m and achieve a target flow of 436,000 ft^3 s^{-1} (12,346 m^3 s^{-1}) (the original design flow from Senate Document No. 23, estimated 100-year protection).
Expansion 2–200: Expand the average width of the channel from 4077 m to 7500 m and achieve a target flow of 700,000 ft^3 s^{-1} (19,822 m^3 s^{-1}) (estimated 200-year protection).
Expansion 2–200-up: Expand the average width of the channel from 4077 m to 7500 m and achieve a target flow of 550,000 ft^3 s^{-1} (15,574 m^3 s^{-1}) (estimated 200-year protection) with upstream levee setbacks from RM 84–144 and the Sutter Bypass expansion.
Expansion 3–100: Expand the average width of the channel from 4077 m to 14,193 m and achieve a target flow of 436,000 ft^3 s^{-1} (12,346 m^3 s^{-1}) (the original design flow from Senate Document No. 23, assumed to be 100-year protection). This scenario uses all the available floodplain space (undeveloped land; agricultural and conservation land only) based on the 100-year flood extent.
Expansion 3–200: Expand the average width of the channel from 4077 m to 14,193 m and achieve a target flow of 700,000 ft^3 s^{-1} (19,822 m^3 s^{-1}) (estimated 200-year protection). This scenario uses all the available floodplain space (undeveloped land; agricultural and conservation land only) based on the 100-year flood extent.
Expansion 3–200-up: Expand the average width of the channel from 4077 m to 14,193 m and achieve a target flow of 550,000 ft^3 s^{-1} (15,574 m^3 s^{-1}) (estimated 200-year protection) with upstream levee setbacks from RM 84–144 and the Sutter Bypass expansion.

Yolo Bypass (Bottleneck Area between the Fremont Weir and Putah Creek)
Expansion 1–100: Expand the average width of the channel from 3577 m to 5187 m and achieve a target flow of 390,500 ft^3 s^{-1} (11,058 m^3 s^{-1}) (the original design flow from Senate Document No. 23, assumed to be 100-year protection). This scenario is proposed in CDWR (2011b) which is to expand the Fremont Weir by 1 mile (1.6 km).
Expansion 1–200: Expand the average width of the channel from 3577 m to 5187 m and achieve a target flow of 670,000 ft^3 s^{-1} (18,972 m^3 s^{-1}) (estimated 200-year protection).
Expansion 1–200-up: Expand the average width of the channel from 3577 m to 5187 m and achieve a target flow of 520,000 ft^3 s^{-1} (14,725 m^3 s^{-1}) (estimated 200-year protection) with upstream levee setbacks from RM 84–144 and the Sutter Bypass expansion.
Expansion 2–100: Expand the average width of the channel from 3577 m to 9830 m and achieve a target flow of 390,500 ft^3 s^{-1} (11,058 m^3 s^{-1}) (the original design flow from Senate Document No. 23). This scenario uses all the available floodplain space (undeveloped land; agricultural and conservation land only).
Expansion 2–200: Expand the average width of the channel from 3577 m to 9830 m and achieve a target flow of 670,000 ft^3 s^{-1} (18,972 m^3 s^{-1}) (estimated 200-year protection) with upstream levee setbacks from RM 84–144. This scenario uses all the available floodplain space (undeveloped land; agricultural and conservation land only).
Expansion 2–200-up: Expand the average width of the channel from 3577 m to 9830 m and achieve a target flow of 520,000 ft^3 s^{-1} (14,725 m^3 s^{-1}) (estimated 200-year protection). This scenario uses all the available floodplain space (undeveloped land; agricultural and conservation land only) with upstream levee setbacks from RM 84–144 and the Sutter Bypass expansion.

Sacramento River RM 84–141 (Southern portion of the Colusa Basin)
Expansion 1: Expand the average width of the channel from 254 m to 500 m and achieve a target flow of 100,000 ft^3 s^{-1} (2832 m^3 s^{-1}) (double the original design flow from Senate Document No. 23). This average width accommodates minimal channel meander and no channel cut-off and sparse riparian vegetation.
Expansion 2: Expand the average width of the channel from 254 m to 1000 m and achieve a target flow of 100,000 ft^3 s^{-1} (2832 m^3 s^{-1}) (double the original design flow from Senate Document No. 23). This average width accommodates moderate channel meander and no channel cut-off and sparse riparian vegetation.
Expansion 3: Expand the average width of the channel from 254 m to 1600 m and achieve a target flow of 100,000 ft^3 s^{-1} (2832 m^3 s^{-1}) (double the original design flow from Senate Document No. 23). This average width accommodates optimal channel meander and optimal channel cut-off and moderate riparian vegetation.
Expansion 4: Expand the average width of the channel from 254 m to 2254 m and achieve a target flow of 100,000 ft^3 s^{-1} (2832 m^3 s^{-1}) (double the original design flow from Senate Document No. 23). This average width accommodates optimal channel meander and optimal channel cut-off and dense riparian vegetation.

Sutter Bypass (whole channel)
Expansion 1–100: Expand the average width of the channel from 1531 m to 1836 m and achieve a target flow of 247,250 ft^3 s^{-1} (7001 m^3 s^{-1}) (the original design flow from Senate Document No. 23, assumed to be 100-year protection).
Expansion 1–200: Expand the average width of the channel from 1531 m to 1836 m and achieve a target flow of 300,000 ft^3 s^{-1} (8495 m^3 s^{-1}) (estimated 200-year protection). This scenario is proposed in CDWR (2011b) which is to expand the Sutter Bypass by 1000 feet (305 m) and increase its flow capacity by 50,000 ft^3 s^{-1} (1416 m^3 s^{-1}) from its original design flow.
Expansion 2–200: Expand the average width of the channel from 1531 m to 3000 m and achieve a target flow of 300,000 ft^3 s^{-1} (11,327 m^3 s^{-1}) (estimated 200-year protection).
Expansion 3–200: Expand the average width of the channel from 1531 m to 6000 m and achieve a target flow of 300,000 ft^3 s^{-1} (11,327 m^3 s^{-1}) (estimated 200-year protection).

Notes: Design flows from Senate Document No. 23 are referenced in CDWR (2011a).

Table 2
Difference in footprint area between all historical flood basins and existing flood control bypass channels.

	Historical flood Basin area (ha)	Historical flood Basin area (ac)	Existing flood Bypass area (ha)	Existing flood Bypass area (ac)	% Area of historical basin
Sutter Basin	41,056	101,451	9342	23,084	23
Yolo Basin	85,096	210,272	27,567	68,118	32
Colusa Basin (south)	35,775	88,400	2073	5122	6
American Basin	22,094	54,595	0	0	0
Total	184,022	454,718	38,982	96,324	21

American Basin is not used for regional flood control, as previously noted.

3.2. Co-equal goal assessment for flow and roughness

Measured and gamed parameter values for the Manning equation and the calculated flow conveyance were calculated for: (1) the existing channels, (2) channel expansion scenarios, and (3) historical basins of each study site (Tables 3–6). Table 3 shows the results for the Yolo Bypass channel as a whole; Table 4 shows the results for just the northern portion of the Yolo Bypass, considered to be a bottleneck in the flood control system. Table 5 shows the results for various setback levee scenarios for the Sacramento River between RM 84 and 144, and Table 6 presents the results for expanding the Sutter Bypass channel.

The results for the Yolo Bypass (Table 3) indicate the existing channel's conveyance (308,000 $\mathrm{ft}^3\,\mathrm{s}^{-1}$ [8720 $\mathrm{m}^3\,\mathrm{s}^{-1}$]) is inadequate relative to its 100-year design flow (436,000 $\mathrm{ft}^3\,\mathrm{s}^{-1}$ [12,346 $\mathrm{m}^3\,\mathrm{s}^{-1}$]). This inadequacy is confirmed in the FloodSafe California Report (CDWR, 2011a). Below we will primarily discuss the results from the 200-year protection flow scenarios because this is the goal of the FloodSafe Program, however, the values for 100-year protection are also presented in Tables 3–6 for comparison. To meet the 200-year protection (700,000 $\mathrm{ft}^3\,\mathrm{s}^{-1}$ [19,822 $\mathrm{m}^3\,\mathrm{s}^{-1}$]), Expansion Scenario 1 widened the channel by over 2400 m, however, there was a significant loss of accommodation for woody riparian vegetation; the roughness coefficient (Manning's n) decreases from 0.030 to approximately 0.021 and only slightly increases with upstream channel expansion to 0.024 (a value that allows for something like bare soil). Expansion Scenario 2 widens the channel by over 3400 m and shows similar results for roughness (0.024), at the 200-year flow target and with upstream expansion it increases only moderately to 0.028 (a value roughly suitable for annual crops).

The most successful expansion scenario, in terms of accommodating riparian vegetation in the channel for the Yolo Bypass, was Expansion Scenario 3, which expanded the channel by over 10,000 m and achieved a roughness coefficient of 0.045. With upstream channel expansion the roughness coefficient increases to 0.053 (accommodating moderate riparian vegetation cover). The average width of the channel for this scenario (14,193 m) represents all the available land in the existing basin that does not contain urban development and is part of the known 100-year flood footprint. Note that the historical Yolo Basin has a smaller average channel width than Expansion Scenario 3 due to the fact that the historical basin was mapped using the boundary of the historical wetlands while a 100-year flood event is expected to exceed the extent of the wetlands and inundate uplands, therefore making the 100-year and 200-year floodplain significantly wider than the historical wetland boundary.

The northern portion of the Yolo Bypass is a bottleneck in the flood control system. Similar to the results shown above for the whole bypass channel, we calculated this northern reach to be nearly 200,000 $\mathrm{ft}^3\,\mathrm{s}^{-1}$ (5500 $\mathrm{m}^3\,\mathrm{s}^{-1}$) short of its 100-year design flow (Table 4). Again, we primarily discuss the results of the 200-year protection flow scenarios results. Expansion Scenario 1 reflects the recommendation in the FloodSafe Report (CDWR, 2011b) to widen the Fremont Weir (the entrance to the Yolo Bypass) by "about one mile" (1610 m) to an average width of 5187 m. However, doing so would result in a drastic reduction in the roughness coefficient to a value of 0.015, and with upstream channel expansion a value of just 0.017 (accommodating only bare soil). Thus, woody riparian vegetation would be absent in this zone and crops would likely be excluded as well. Alternatively, Expansion Scenario 2 utilizes all the remaining floodplain in this section and widens the floodplain by 3.9 miles (6.25 km) to an average channel width of 9830 m resulting in a near doubling of the roughness coefficients from the previous scenario to 0.028 and 0.033 (with upstream channel expansion), such that grasslands could be accommodated, but not woody riparian vegetation. Note that only under the 100-year protection flow can any riparian vegetation be accommodated in this reach of the Yolo Bypass (Manning's n is 0.048).

The Sacramento River channel that flows through the historic southern Colusa Basin (RM 84–144) is presently very narrow compared to its historical extent (Table 5). The existing average channel width of this river portion is 254 m whereas the historic basin had an average channel width of 6712 m, a 26-fold reduction in its floodplain. The existing average channel depth is 4.49 m whereas the historic basin was 1.23 m deep, increasing the depth by a factor of 3.5. The expansion scenarios in this section of the river were designed to examine the feasibility for the re-initiation of channel meander and channel cut-off activity and the natural recruitment of woody riparian vegetation through primary succession. By expanding the conveyance here, the Yolo Bypass channel to its south (downstream) would greatly benefit, reducing the needs for expansion in that channel or allowing for greater accommodation of woody riparian vegetation in the Yolo Bypass channel. The results of Expansion Scenario 1 for river miles 84–144, a doubling of the average channel width, show the target flow can be doubled, but that only very limited woody vegetation could be accommodated. Expansion Scenario 2, where the average channel width is 1000 m and the roughness coefficient almost doubles from current conditions, allows a moderate density of woody riparian vegetation to be accommodated. Expansion Scenario 3 (average channel width of 1600 m) attains the recommended minimum width in Larsen, Girvetz, et al. (2006b) for optimal meander and channel cut-off potential, and accommodates moderately dense stands of woody riparian vegetation with a roughness coefficient of 0.074. The best result to accommodate riparian vegetation is Expansion Scenario 4 where the average channel width is 2254 m and which achieves a roughness coefficient of 0.105, capable of allowing dense woody riparian vegetation.

The expansion scenarios for the Sutter Bypass to achieve 200-year protection were moderately successful at accommodating vegetation (Table 6). Expansion scenarios 2 and 3 attained roughness coefficients of 0.037 (grasslands) and 0.073 (moderate riparian vegetation), respectively, by more than doubling and quadrupling the average channel widths, respectively, from existing conditions. Another major benefit from widening the Sutter Bypass is to reduce peak flows downstream in the Yolo Bypass to allow for greater flood protection and accommodation of riparian vegetation.

3.3. Historical analysis of historic basin flow conveyance

As noted above, the results for estimating flow conveyance of the historical flood basins are shown in Tables 3 and 5, and 6 for the Yolo Basin, the southern Colusa Basin, and Sutter Basin, respectively. These results should be viewed in light of the significant assumptions discussed in Section 2. In the case of the Yolo Basin, the historical conveyance of 196,799 $\mathrm{ft}^3\,\mathrm{s}^{-1}$ (5573 $\mathrm{m}^3\,\mathrm{s}^{-1}$) is significantly less than the current Yolo Bypass channel at 307,947 $\mathrm{ft}^3\,\mathrm{s}^{-1}$ (8720 $\mathrm{m}^3\,\mathrm{s}^{-1}$), however, the average width of the bypass channel is just one-third that of the historical basin. The construction of high levees makes this possible; it is narrower, but much deeper, and therefore carries more flow. Again, we see the effect of maximizing average depth in open channel flood structure design.

In the case of the Sacramento River between river miles 84–144 we see a different pattern. Here high fortified levees were built nearly adjacent to the river channel, completely cutting off the historical flood basin floodplain from the channel. This accounts for the 47% reduction of flow conveyed by the current channel as compared to the historical flood basin. The depth of the existing

Table 3
Comparison of calculated target flow (Q) variables between the existing Yolo Bypass channel, bypass channel expansion scenarios, and the historical Yolo Basin, with target average design flows for 100-year and 200-year protection.

Flow (Q) calculation	Existing	Scenario Expan1-100	Scenario Expan1-200	Scenario Exp1-200-up	Scenario Expan2-100	Scenario Expan2-200	Scenario Exp2-200-up	Scenario Expan3-100	Scenario Expan3-200	Scenario Exp3-200-up	Yolo Basin historical
Yolo Bypass (whole channel)											
Slope S (m m^{-1})	0.000069	0.000069	0.000069	0.000069	0.000069	0.000069	0.000069	0.000069	0.000069	0.000069	0.000069
Average width W (m)	4077	6500	6500	6500	7500	7500	7500	14,193	14,193	14,193	12,561
Average depth H (m)	3.429	3.429	3.429	3.429	3.429	3.429	3.429	3.429	3.429	3.429	1.58
Hydraulic radius R (adjusted depth) (m)	3.423	3.425	3.425	3.425	3.426	3.426	3.426	3.427	3.427	3.427	1.580
Roughness coefficient n	0.03000	0.03375	0.02103	0.02453	0.03895	0.02426	0.02830	0.07375	0.04595	0.05360	0.04000
Velocity V (m s^{-1})	0.624	0.555	0.890	0.763	0.481	0.772	0.662	0.254	0.408	0.349	0.281
Estimated conveyance Q (m^3 s^{-1})	8720	12,350	19,823	16,993	12,351	19,830	16,999	12,353	19,826	16,997	5573
Estimated conveyance Q (ft^3 s^{-1})	307,947	436,131	700,025	600,058	436,147	700,244	600,280	436,215	700,127	600,202	196,799
[a]Existing target average design flow (ft^3 s^{-1})	436,000										
[a]Existing target average design flow (m^3 s^{-1})	12,346										
[b]Target average design flow (ft^3 s^{-1})	700,000										
[b]Target average design flow (m^3 s^{-1})	19,822										
[b]Target average design flow with upstream expansion (ft^3 s^{-1})	600,000										
[b]Target average design flow with upstream expansion (m^3 s^{-1})	16,990										

[a] Design flows from Senate Document No. 23; estimated 100-year flow.
[b] Estimated 200-year flow.

Table 4
Comparison of calculated target flow (Q) variables between the existing Yolo Bypass channel bottleneck area, and bypass channel expansion scenarios, with target average design flows for 100-year and 200-year protection.

Flow (Q) calculation	Yolo Bypass Bottleneck Area (Fremont Weir to Putah Creek)						
	Existing	Scenario	Scenario Expan1-200	Scenario Exp1-200-up	Scenario Expan2-100	Scenario Expan2-200	Scenario Exp2-200-up
Slope S (m m^{-1})	0.000067	0.000067	0.000067	0.000067	0.000067	0.000067	0.000067
Average width W (m)	3577	5187	5187	5187	9830	9830	9830
Average depth H (m)	3.129	3.129	3.129	3.129	3.129	3.129	3.129
Hydraulic radius R (adjusted depth) (m)	3.124	3.125	3.125	3.125	3.127	3.127	3.127
Roughness coefficient n	0.03500	0.02548	0.01485	0.01745	0.04831	0.02815	0.03310
Velocity V (m s^{-1})	0.496	0.681	1.169	0.995	0.360	0.617	0.525
Estimated conveyance Q (m^3 s^{-1})	5551	11,061	18,978	16,150	11,060	18,980	16,142
Estimated conveyance Q (ft^3 s^{-1})	196,018	390,586	670,178	570,323	390,553	670,252	570,018
[a]Target average design flow (ft^3 s^{-1})	390,500						
[a]Target average design flow (m^3 s^{-1})	11,058						
[b]Target average design flow (ft^3 s^{-1})	670,000						
[b]Target average design flow (m^3 s^{-1})	18,972						
[b]Target average design flow with upstream expansion (ft^3 s^{-1})	570,000						
[b]Target average design flow with upstream expansion (m^3 s^{-1})	16,141						

[a] Design flows from Senate Document No. 23; estimated 100-year flow.
[b] Estimated 200-year flow.

channel is 365% that of the historic flood basin. We see yet another example of maximizing average channel depth to minimize footprint area. Just 6% of the historic footprint of the southern Colusa Basin (Table 2) is utilized to convey flow in the existing channel.

The pattern in the historic Sutter Basin is more similar to the Yolo Basin. The Sutter Basin historical conveyance was 45,304 ft^3 s^{-1} (1283 m^3 s^{-1}) whereas the current bypass channel conveys more almost five times that flow at 222,433 ft^3 s^{-1} (6299 m^3 s^{-1}) using just 23% of historic basin's footprint (Table 2). The average depth of the historic Sutter Basin is just one-third of the existing bypass channel.

4. Discussions

Our analyses were done with the Manning n value to represent channel roughness. The authors readily admit that this is a crude and sometimes mis-used methodology. Our belief is that our conclusions are correct, while our numbers may only be broad

Table 5
Comparison of calculated flow (Q) between the existing Sacramento River channel between RM 84–144, channel expansion scenarios, and the historical southern Colusa Basin, with target average design flows for 100-year and 200-year protection.

Flow (Q) calculation	Existing	Scenario expansion 1	Scenario expansion 2	Scenario expansion 3	Scenario expansion 4	So. Colusa Basin Historical
Sacramento River RM 84–144 (Southern Colusa Basin)						
Slope S (m m^{-1})	0.00012	0.00012	0.00012	0.00012	0.00012	0.00012
Average width W (m)	254	500	1000	1600	2254	6712
Average depth H (m)	4.49	4.49	4.49	4.49	4.49	1.23
Hydraulic radius R (adjusted depth) (m)	4.337	4.411	4.450	4.465	4.472	1.230
Roughness coefficient n	0.0270	0.0231	0.0465	0.0745	0.1050	0.0400
Velocity V (m s^{-1})	1.068	1.263	0.631	0.395	0.280	0.314
Estimated conveyance Q (m^3 s^{-1})	1219	2835	2833	2836	2838	2591
Estimated conveyance Q (ft^3 s^{-1})	43,029	100,118	100,055	100,142	100,203	91,507
[a]Target average design flow (ft^3 s^{-1})	47,357					
[a]Target average design flow (m^3 s^{-1})	1341					
Target average design flow for expansion (ft^3 s^{-1})	100,000					
Target average design flow for expansion (m^3 s^{-1})	2832					

[a] Design flows from Senate Document No. 23; estimated 100-year flow.

Table 6
Comparison of calculated flow (Q) between the existing Sutter Bypass channel, and bypass channel expansion scenarios, with target average design flows for 100-year and 200-year protection.

Flow (Q) calculation	Existing	Scenario Expan1-100	Scenario Expan1-200	Scenario Expan2-200	Scenario Expan3-200	Sutter Basin historical
Sutter Bypass (whole channel)						
Slope S (m m^{-1})	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Average width W (m)	1531	1836	1836	3000	6000	7135
Average depth H (m)	4.1	4.1	4.1	4.1	4.1	0.82
Hydraulic radius R (adjusted depth) (m)	4.078	4.082	4.082	4.089	4.094	0.820
Roughness coefficient n	0.02520	0.02720	0.02241	0.03666	0.07340	0.04000
Velocity V (m s^{-1})	1.003	0.930	1.129	0.691	0.345	0.219
Estimated conveyance Q (m^3 s^{-1})	6299	7002	8499	8499	8497	1283
Estimated conveyance Q (ft^3 s^{-1})	222,433	247,276	300,130	300,125	300,068	45,304
[a]Target average design flow (ft^3 s^{-1})	247,250					
[a]Target average design flow (m^3 s^{-1})	7001					
[b]Target average design flow for expansion (ft^3 s^{-1})	300,000					
[b]Target average design flow for expansion (m^3 s^{-1})	8495					

[a] Design flows from Senate Document No. 23; estimated 100-year flow.
[b] Estimated 200-year flow.

approximations. We use this roughness approach because it is well known, it is simple to use, and we feel that it is adequate to the argument that we wish to make – that one can achieve adequate flood control *and allow for riparian forest growth, but to do so takes additional land area.*

The results of our heuristic analysis using the Sacramento River flood control system suggest that it is possible to achieve the co-equal goals of greater flood control protection and accommodation of moderate to dense woody riparian vegetation within redesigned flood control channels. Historically, open channel flood design sought to maximize average channel depth and minimize channel footprint area for a given target conveyance (e.g. the 100-year recurrence interval flow). California is presently faced with redesigning and retrofitting its antiquated flood control system in the southern Sacramento Valley to meet modern needs for flood protection. This offers an opportunity to do so with co-equal goals of increasing flood protection and enhancing riparian and riverine ecosystem attributes, which is a classic multifunctional landscape objective. Because the increased depth and velocity of flows within flood control channels is lethal to most organisms that cannot fly to escape floodwaters, the ecological conservation value to terrestrial animals of most flood control channels is minimal, offering at best only seasonal habitat. Thus, for terrestrial wildlife, conventionally designed flood control channels represent sink habitat. Sink habitat is defined as an area where an organism's population death rate exceeds the birth rate (Pulliam, 1988).

A prime example of this sink habitat problem is found in the Yolo Bypass with the federally threatened species, the giant garter snake (*Thamnophis gigas*), listed under the US Endangered Species Act. This reptile requires seasonal fresh water emergent marshes (wetlands) to forage in (it eats primarily fish) during the dry season (April–September) and it requires upland burrow habitat for overwintering during the cold, wet season (October–March). The giant garter snake will seek a wintering burrow up to 250 m from its foraging grounds (Miller & Hornaday, 1999). The Yolo Bypass contains ideal dry season habitat for the giant garter snake, however the average channel width of the Yolo Bypass is 4077 m, which far exceeds the ability of the snake to find suitable refugia from floodwaters. It is expected that the final recovery plan for this species will not permit the Yolo Bypass to be considered a recovery area because its expansive size lacks refugia from floodwaters, and it is extensively and frequently inundated. A potential solution to this problem includes lowering the average channel depth and constructing long linear islands parallel to flow that rise above the 200-year flow elevation to act as effective refugia for the snake's overwintering requirements. On these seasonally inundated "islands" woody riparian vegetation could act as additional refugia for other terrestrial animals.

It is important to note that inundated floodplains also function as source habitats for aquatic species. Increased floodplain inundation through flood pulses within the aquatic–terrestrial transition zone is correlated with increased fish productivity (Jeffres, Opperman, & Moyle, 2008; Junk et al., 1989; Roux & Copp, 1996). In an experiment conducted by Sommer, Nobriga, Harrell, Batham, and Kimmerer (2001) juvenile salmonids showed increased productivity (in size and weight) from floodplain feeding in the Yolo Bypass as compared to juvenile salmon that fed exclusively in an adjacent river channel. Experiments currently underway are assessing the potential for using flooded rice fields within the bypass channel to rear juvenile salmon. Incorporation of riparian vegetation into the rice field areas could contribute allochthonous inputs, increasing fish productivity and enhancing survival during outmigration to the Pacific Ocean. There are four races of chinook salmon (*Oncorhynchus tshawytscha*) on the Sacramento River and two, the spring and winter runs, are listed as threatened and endangered, respectively, under the US Endangered Species Act.

4.1. Regenerative systems and ecological design

A relatively recent theoretical design paradigm in the field of landscape architecture is 'regenerative design' (*sensu* Cole, 2012; Lyle, 1994; Melby & Cathcart, 2002; Zari, 2012) offering a set of potential long-term, sustainable solutions to problems associated with single purpose flood channel design. 'Regeneration' is defined as "the ability for something to happen again and again... to bring into existence again, to reproduce, to be able to continue to exist through continually applying certain processes" (Melby &

Cathcart, 2002, p. 15). John Lyle, an early proponent of this design approach, states “a regenerative system provides for the continuous replacement, through its own functional processes, of the energy and materials used in its operation” (Lyle, 1994, p. 10). Regenerative design, then, is intentionally creating patterns through the manipulation of processes to achieve desired states. In conservation and restoration ecology this approach is termed ‘process-based restoration’ (Beechie et al., 2010). In the case of a multifunctional river floodplain ecosystem, if habitat production is made a co-equal goal with flood protection, then encouraging floodplain forest regeneration through natural processes means designing flood control channels with high Manning's *n* roughness coefficients (e.g. 0.04–0.15) and using wide floodplain surfaces rather than high levees to create channel capacity. Facilitating natural riparian vegetation colonization is an important ecological design principle for open channel multi-functionality.

Another key regenerative ecological design principle for riverine-riparian ecosystem conservation is the concept of ‘minimum dynamic area’ which is defined as “the minimum area required for complete regeneration of the community, i.e. for the normal rejuvenation of all of its species” (Barkman, 1989, p. 97 citing Meijer Drees, 1951). From the perspective of patch dynamics, Pickett and Thompson (1978) define minimum dynamic area as: “the smallest area with a natural disturbance regime which maintains internal recolonization sources and hence minimizes extinctions” (p. 34). Thus, the design of a multifunctional flood control channel should provide for at least the smallest land area required for key ecosystem process dynamics such as flooding, channel dynamics (i.e. meander migration), and vegetation succession to continually regenerate a mosaic of habitat types and successional stages. Maintaining a stable but dynamic mosaic of all important habitat patch types using natural processes is one long-term sustainable goal of this open channel design paradigm.

In this study we used three channel components of the Sacramento River Flood Control Project to illustrate these concepts of regenerative ecological design. In particular, the Sacramento River channel from RM 84–144 was used to demonstrate the principles of regenerative design and minimum dynamic area. A study by Larsen, Girvetz, et al. (2006b) showed how various distances of levee setbacks could accommodate the hydrogeomorphic processes of channel meander and channel cut-off to produce: actively regenerating point bars, cut-banks that provide regenerative input of large woody debris, and the creation of oxbow lakes. In our current study we used a set of setback levee distances based on Larsen, Girvetz, et al. (2006) and we found that an average channel width of 1600 m representing both sides of the river channel produced results for channel dynamics and vegetation recruitment with a minimum channel footprint. At 1600 m the channel could meander, cut-off and accommodate moderately dense stands of riparian vegetation. However, an average width of 2254 m allowed for more extensive dense riparian forests. The riparian forest patches likely to regenerate as a result of this expansion scenario, and subsequent channel dynamics, would be capable of supporting another Sacramento River endangered species, the yellow-billed cuckoo (*Coccyzus americanus*), a state-listed Neotropical bird. Suitable habitats for this species' foraging and nesting are large patches (>40 ha in size and >200 m in width) of the cottonwood-willow plant association (Laymon & Halterman, 1989) that colonize on point bars and oxbow lakes of actively meandering channels. Maintaining these forest patches over time requires a patch dynamics approach to habitat management (*sensu* Greco, 2013; Pickett & Rogers, 1997). One of the largest population of yellow-billed cuckoos in California is located on the Sacramento River north of the town of Colusa (at RM 144). If riparian vegetation were accommodated in the flood control system channels south of the town of Colusa (including the Yolo and Sutter bypasses) the recovery area for the cuckoo could be significantly expanded.

The floodplains of the Yolo Bypass and Sutter Bypass are mosaic landscapes that include farmland, ranches, conservation areas, canals, roads, railroads, and bridges; however, they lack significant cover by woody riparian forests. Riparian vegetation in the bypass channels could be strategically located as discussed above with the giant garter snake. An average roughness coefficient for any particular floodplain can be calculated across a floodplain. In this way woody riparian vegetation can be incorporated into the design of flood control channels if it is strategically permitted to grow and regenerate along the edges of banks parallel to flow in the channel. The Yolo Bypass holds great promise as a multifunctional channel (Opperman et al., 2009; Sommer, Harrell, et al., 2001).

Another important design principle to accommodate more riparian vegetation in the Yolo Bypass is the use of upstream levee setbacks to expand conveyance in the Sutter Bypass and the Sacramento River from RM 84–144 through transitory storage, or the “reservoir effect.” Those expansions would act to attenuate the flood peak downstream in the Yolo Bypass. This, as well as how climate change is expected to alter the frequency and magnitude of those flows, is needed future research. Rising sea level will also influence upstream flows on the lower Sacramento River.

In many cases, however, rivers and their floodplains in human-dominated landscapes have limited or no space to restore a floodplain environment and its dynamics. In the case of the lower Sacramento River there are significant opportunities to so, but it cannot be returned to some ideal historical state. Thus, the role of reconciliation ecology (Rosenzweig, 2003) will play an important role in determining what is feasible. Reconciliation ecology seeks to re-engineer human landscapes to include more ecological functions and species diversity in novel and analogous ways (Lundholm & Richardson, 2010). While developed countries often lack the opportunities to retrofit existing flood control channels (unless these opportunities are planned over long time periods or people commit to adapting or removing urban infrastructure), developing countries can avoid the mistakes of past engineering practices in developed countries by incorporating the ecological design principles described in this paper.

5. Conclusions

This study demonstrates that open channel flood design can meet the co-equal goals of providing increased flood protection while meeting ecosystem conservation objectives. The key ecological design principles to enhance conservation values discussed in this paper are: (1) increasing the average channel width, (2) decreasing average channel depth and velocity, (3) allowing roughness coefficients to increase, accommodating increased stands of riparian vegetation and woody debris, (4) expanding upstream channel capacity to attenuate downstream instantaneous peaks, (5) providing floodplain refugia for terrestrial species from floodwaters, (6) promoting ecosystem processes such as natural flow regimes, channel meander migration, channel cut-off, and primary succession of riparian vegetation. Future research that could contribute to greater understanding of these principles would be to apply 2D hydraulic modeling to model systems, such as the one described in this paper, and also modeling the sedimentation rate from *increasing* roughness due to plant succession on the floodplains and their effects on flood control protection levels (see Makaske, Maas, van den Brink, & Wolfert, 2011). Multifunctional flood control channels can enhance environmental quality for both humans and wildlife populations, however, reconciliation ecology will play an important role in assessing the extent that floodplains can be restored and to what degree they can function in a socio-ecological context.

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