Promoting Atmospheric-River and Snowmelt-Fueled Biogeomorphic Processes by Restoring River-Floodplain Connectivity in California's Central Valley

Joan L. Florsheim and Michael D. Dettinger

Abstract Potential biogeomorphic benefits from intentional levee breaks and weir overflow on the managed floodplain-river system of California's Sacramento and San Joaquin River watershed (Central Valley) are discussed here. Prior to the nineteenth century, the system was characterized by natural levees alongside complex multichanneled rivers and tributaries, and geomorphic processes such as channel migration and avulsion, typical in lowland floodplain-river systems globally, dominated. Today, the floodplain-river system has been heavily modified with infrastructure such as levee embankments that disconnect floodplains from channels and diminish key processes of floodplain-river ecology. Unintentional levee breaks in river systems where floodplains have been developed for agriculture or urban uses still occur regularly (in a quarter of twentieth century years) and are sometimes catastrophic. Floodplain inundation, erosion, and sedimentation, the dominant geomorphic processes that occur during unintentional levee breaks, are flood risks in such embanked river systems. Climate and flood variability still dictate the frequency of unintentional levee breaks despite many decades of engineering. Of particular consequence are the so-called atmospheric-river (AR) storms. Since 1951, 81 % of breaks have occurred as a result of AR storms and flooding, while most of the rest occurred during snowmelt floods. Intentional levee breaks or planned weir overflows that are designed for floodplain restoration can facilitate a return towards more natural and dynamic biogeomorphic processes. In areas where room for flood-driven geomorphic processes is available on floodplains, local sediment scour and deposition near a levee break promote topographic diversity that enhances vegetation establishment and floodplain habitat. This chapter summarizes our current understanding of climate processes and flood variability that govern unintentional levee breaks or weir overflow. We also review examples of alternative flood management approaches in the Central Valley that promote processes necessary to restore or sustain lowland floodplain biogeomorphology. Future climate-driven

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changes in flood regime, such as enhanced flooding during winter months or more frequent atmospheric rivers, could be accommodated by additional intentional levee breaks or planned weir overflow for restoration. Implementation of these alternatives could be used to improve restoration policy and management of floods in embanked river floodplains.

Keywords Floodplain · Sediment · Hydrology · Atmospheric river · Levee break · Weir overflow · Geomorphology · Biogeomorphology

1 Introduction

The Sacramento and San Joaquin Rivers and their tributaries are managed lowland-floodplain rivers bounded in many places by levee embankments. The Sacramento River drains the northern part and the San Joaquin River drains the southern part of California's Central Valley watershed (Fig. 1). The Central Valley is the California's largest watershed (153,000 km^2) and is bounded by the Sierra Nevada on the east and the Coast Ranges on the west. The two rivers meet in an inland freshwater-tidal Delta before discharging into the San Francisco Bay Estuary from the east. This chapter synthesizes recent findings regarding intentional levee breaks, planned weir overflow, and their promotion of lowland floodplain biogeomorphic processes in this setting, with special attention to the particularly important roles of atmospheric-river storms (Ralph and Dettinger 2011) in flooding and floodplain processes.

The Sacramento-San Joaquin River system is of critical importance in California because the rivers convey over 50 % of California's total streamflow. Historically, they supported a dynamic ecosystem with vigorous floodplain riparian forests, and thriving salmon, bird, and other wildlife populations (Sands 1977). Conservation and restoration of these natural resources has emerged as a management goal that is "co-equal" with traditional resource management and extraction objectives (Isenberg et al. 2008). In this context, the present synthesis provides an example of looking backward at historical changes as a basis for looking forward toward restoration of geomorphic processes on floodplains as a first step in conservation and management of critical natural resources in this heavily modified landscape.

This chapter begins with a brief review of historical biogeomorphic processes on lowland Central Valley floodplains and of climate-forcing factors that both supported ecology and governed changes prior to anthropogenic alteration. We then review anthropogenic alterations and their current influences on floodplain hydrology and biogeomorphic processes. In particular, we illustrate the system-scale effects of levees on changes in floodplain processes and hydrology within the embanked system. Finally, we provide two examples as case studies illustrating flood hydrology related to (1) intentional levee breaks and (2) planned weir overflow into flood basins or low lying floodplain areas. Both of these alternatives to more traditional approaches to flood management can be used to facilitate restoration of flows and biogeomorphic processes on floodplains within this system.

Fig. 1 Map of the Central Valley, California, indicating the Sacramento and San Joaquin Rivers

2 Central Valley Floodplain Processes Prior to nineteenth Century Modification

2.1 Biogeomorphic Processes

Prior to Euro-American activities and disturbances in the region, a main river channel augmented by interconnected networks of multiple smaller channels drained lowland portions of the Central Valley, as was common in many lowland systems globally prior to widespread channelization (Ward and Stanford 1995; Brown 1998; Ward and Trockner 2001). The main channel conveyed flow and sediment during a wide range of small frequent to large infrequent floods, with the larger floods also filling the secondary channels in low lying areas, or flood basins, adjacent to the main channel, but separated from it by natural alluvial levees (Fig. 2; Gilbert 1917; Bryan 1923). Main and secondary channels were connected through crevasses, or natural levee breaks, that formed during floods and remained open (Kelley 1989). In multiple-channel lowland fluvial systems, sediment transport in the main channel sometimes raises main-channel bed elevation above that of the adjacent floodplain, promoting avulsion, through levee breaks and crevasse splay and channel complex development, in the adjacent floodplain (Smith et al. 1989). Prior to the 1850s, floodplains in lowland Central Valley rivers and tributaries contained multiple channel networks, over-bank deposits, crevasse splays, abandoned channels and oxbows, and seasonal and perennial lakes, marshes, and inter-channel wetlands (Gilbert 1917; Bryan 1923; Olmsted and Davis 1961; Atwater and Marchand 1980; Florsheim and Mount 2002, 2003; Florsheim et al. 2006). Generally, the channels and floodplains were hydrologically connected in lowland areas of the Sacramento-San Joaquin River systems on a regular basis, during frequent floods. This connec-

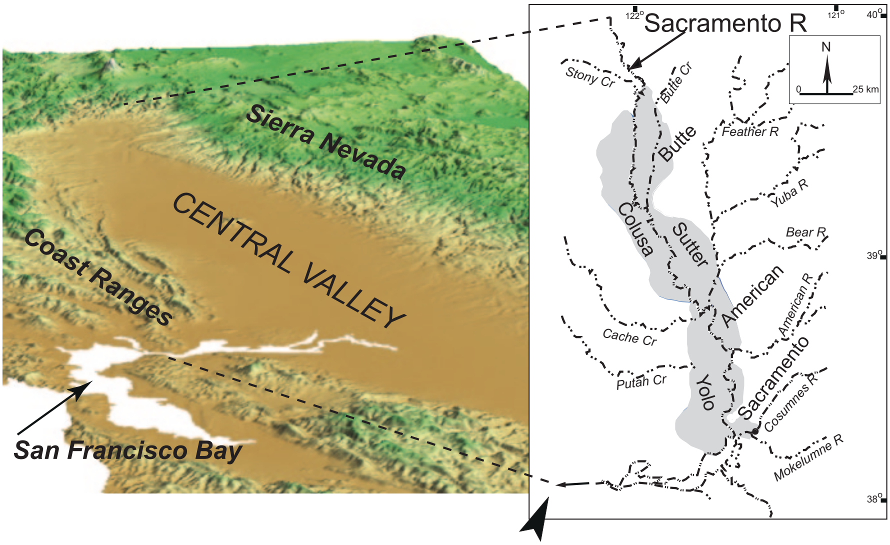

Fig. 2 **a** Oblique image of lowland Central Valley, **b** Flood basins (*gray areas*) along Sacramento River (Gilbert 1917; Bryan 1923), *arrowhead* indicates direction illustrated in oblique image

tivity facilitated transport of water, sediment, wood, and nutrients that supported heterogeneous habitats and riparian biodiversity.

Floods of a wide range of magnitudes created a dynamic system dominated by episodic avulsion, channel migration, erosion, and sedimentation. Biogeomorphic processes such as channel migration formed sediment deposits on the inside of river bends; new deposits supplied bare substrate that facilitated riparian establishment (such as currently occurs at along a meandering portion of the Sacramento River between Red Bluff and Colusa; Larsen et al. 2007; Michalkova et al. 2010; Micheli and Larsen 2011) and topographic diversity resulting in oxbow lakes (Costantine and Dunne 2008). Similarly, riparian establishment likely occurred in patches on new bare sandy crevasse splays similar to one formed following restoration on the Cosumnes River floodplain (Florsheim and Mount 2002, 2003). The resulting riparian settings and seasonal floodplain wetlands were important elements of the "Pacific Flyway" for migrating birds (Shuford et al 1998), and home to four salmon runs that once thrived in the complex multiple channel and floodplain system (Yoshiyama et al. 1998).

2.2 Climate and Floodplain Inundation

Prior to historical modifications, the dynamic fluvial system of the Central Valley was largely governed by floods associated with California's unusually variable climatic and hydrometeorological extremes (Dettinger et al 2011). In a review of paleoclimate evidence from the Central Valley, Malamud-Roam et al. (2006, 2007) indicated that large natural climate variations and changes capable of driving geomorphic change, such as erosion and sedimentation disturbances, were common during the past 5000 years, and indeed for most of that period the variations were large relative to the comparatively benign climate of the first part of the twentieth century.

Storms and floods differ from north to south and from west to east in the Central Valley. The Sierra Nevada mountains form the eastern ramparts and receive much of its precipitation as winter snows, rather than as rain. As a consequence, much of the precipitation from winter storms is stored in the mountains until springtime when snowfields melt. However, warm winter storms also arrive in California from time to time; so that large floods from the Sierra Nevada can be fed by immediate runoff from warm storms that rain heavily (even) in the Sierra. Even more regularly, moderate to high flood flows also arrive in springtime when abundant snowpacks melt rapidly. There are seasonal differences between north and south with the relatively high southern Sierra receiving more precipitation as snowfall than the lower elevation northern Sierra. Thus, the southern part of the valley experienced more spring snowmelt floods and associated geomorphic change than the northern portion of the valley (and, today, most levee breaks during spring floods occur in the southern portion of the Central Valley (Florsheim and Dettinger 2007)). The Coast Ranges form the western boundary of the Central Valley and are relatively low in elevation, receiving little precipitation as snowfall. Floods emanating from the Coast Ranges are primarily fed by rapid runoff from episodic winter rain storms. Floodplain inundation occurred in tributary channel-floodplain systems formed in the low gradient distal ends of alluvial fans emanating from the Sierra Nevada and Coast Ranges (Florsheim et al 2011) and within the flood basins, with inundation of flood basins lasting for months (Gilbert 1917; Bryan 1923).

In recent years, there has been a growing understanding that floods from both the Coast Ranges and Sierra Nevada arise mostly from a particular storm type called "atmospheric rivers" (Ralph and Dettinger 2011; Dettinger and Ingram 2013). Atmospheric rivers (ARs) are narrow, transient corridors of strong atmospheric water-vapor transport occurring upwind from mid-latitude winter cyclones. The corridors of intense winds and moist air are roughly 400–500 km across and thousands of km long. ARs routinely transport water vapor over the Pacific Ocean at rates equivalent to 7–15 times the average daily discharge of the Mississippi River, and when they reach the West Coast, they may deposit almost 20 % of that moisture load in the mountain ranges that they encounter there. The half dozen or so ARs per year that make landfall in California contribute an average of one third to one half of all the State's precipitation, thereby supplying much of the State's water resources. Meanwhile, AR storms also have been the causes of many (and in many rivers, most) historical floods in the State. For example, in the Coast Ranges north of San Francisco, all seven major (declared) floods of the Russian River since 1997 have been associated with landfalling ARs (Ralph et al. 2006), and of the 39 floods this large since 1948, 87 % have been directly tied to ARs. Further inland, streamflow increments on rivers entering the Central Valley from the Sierra Nevada are an order of magnitude larger when the storms are ARs than from other storm types (Dettinger 2004; Dettinger 2005; Dettinger et al. 2011). As far inland as the eastern slopes of the Sierra Nevada, eleven of the twelve largest peak flows on the East Fork Carson River since 1948 were caused by ARs.

The largest floods in the Central Valley, at least since the mid-1800s, have been winter floods—mostly associated with exceptionally intense AR storms. Because large amounts of winter and spring precipitation in the Sierra Nevada fall as snow and form deep snowpacks there, when in some years the snow melts and runs off quickly (Lundquist et al. 2004), springtime floods also are a part of Central Valley flow regimes. Because most springs have some snowmelt peak flows, high flows during the springtime snowmelt seasons are more reliably present, and probably a much more frequent driver of small to moderate flooding and biogeomorphic process in floodplains adjacent to the snowmelt-fed rivers.

3 Changes Leading to Modern Characteristics of the Central Valley River Systems

3.1 Levee and Dam Construction

During the past two centuries, major alterations to the rivers and floodplain systems in California's Central Valley have been made for flood management and to support agriculture, mining, logging, and urbanization, largely through the construction of levees and dams (Kelley 1989; Mount 1995). These changes altered sediment supplies to the downstream San Francisco Bay Delta (Wright and Schoelhammer 2004; McKee et al 2006), hydrologic and geomorphic responses to climate variability (Florsheim and Dettinger 2007; Florsheim et al. 2011), and the ecology (Sands 1977; Sommer et al. 2004) of floodplains and flood basins throughout the Central Valley.

Pervasive structural control of the rivers and floods was initiated as part of land reclamation efforts in the mid-nineteenth century when Euro-Americans began to exploit the region's many resources. Early efforts included attempts to keep even occasional small floods from inundating floodplains and flood basins. These attempts included filling crevasses in the natural alluvial levee system alongside main channels and tributaries, as well as progressive extensions of the length and height of these naturally formed low, alluvial levees (Kelley 1989). The land-reclamation efforts confined flood flows to the river channels to the extent possible, where previously they had spread over vast areas (Dettinger and Ingram 2013). As a result, and increasingly over time, flood basins and floodplains were separated from channels, impacting habitats that previously had sustained important floodplain-based ecosystems.

The attempt to concentrate flood flows into isolated main channels was made more difficult in the late 1800s by an overwhelming new sediment source, the addition of vast sediment loads to Sierra Nevada rivers by hydraulic mining for gold.

Hydraulic mining resulted in greatly increased sedimentation in the Sacramento River and tributaries draining the Sierra, raising the river-bed elevation at Sacramento by over 3 m between 1890 and 1900, reducing channel flood-conveyance capacities, and depositing sediment on farmed floodplain fields along tributaries such as the Yuba River (Gilbert 1917). The lowland floodplains also received large quantities of this sediment, e.g., as in the Sutter flood basin along the heavily mined Feather River (Jones 1967). An "anthropogenic" layer of sediment derived from the combination of hydraulic mining and coeval watershed scale agricultural disturbances averages 1.5 m thick on floodplains in the Sacramento flood basin near the confluence of the Mokelumne and Cosumnes Rivers (Atwater and Marchand 1980). This anthropogenic layer, consisting of a relatively coarse reddish-brown sandy clay layer, was rapidly deposited on the lowland Cosumnes River floodplain between 1849 and 1920 at a rate of about 25 mm/year, in contrast to the slower natural deposition rate of about 3 mm/year over the previous 1000 years (Florsheim and Mount 2003). Eventually the supplies of hydraulic-mining sediments were reduced so that after the initial significant rise, there has been a subsequent decline in sediment delivery rates over the past 150 years, leading to a change from excessive sedimentation to incision, a pattern documented on other heavily mined tributaries to the Sacramento River (James 1997).

Since in the mid 1850s, about 1600 km of levees along main channels and a series of overflow weirs leading to bypass channels have been completed in the Central Valley (DWR 2005; James and Singer 2008). For example, the Yolo flood basin was incorporated into the Sacramento River Flood Control Project as a bypass channel in the 1930s as an alternative to more widespread and damaging flooding by other adjacent and downstream parts of the Sacramento River (Sommer et al. 2001). Current river flows transport sediment downstream in leveed channels and inhibit sediment storage or erosion off-channel except in cases of occasional levee breaks, accidental or intentional (Florsheim and Mount 2002). Because of the efficient routing of sediment through the main river channels, the amount of sediment yield from the Sacramento and San Joaquin River systems has progressively declined since the cessation of hydraulic mining in the late 1800s and increased trapping of sediments upstream of dams built to store water in Central Valley tributaries since the mid-twentieth Century (Schoellhamer et al. 2007). Because these levee systems separate floodplains from channels, there have been significant losses of riparian wetlands that once functioned to delay and dissipate flood peaks.

Today, geomorphic processes in the Central Valley are driven by a population of floods reflecting this modified channel system, no longer reflecting the natural mix of floods and ecosystem processes. Nevertheless, some components of the hydrologic system are unchanged. For example, the largest ARs still cause large floods throughout the Central Valley, creating the highest magnitude and longest duration floods, albeit not always as large as they would have been in the natural system. Other more frequent and (generally) less intense floods have been largely restricted from reaching and modifying much of the landscape beyond the embanked river channels. Thus, the magnitude, frequency, durations, timing, and connectivity characteristics between channels and floodplains are now different from those characteristics prior to anthropogenic changes. For example, flood basins, such as the Yolo, that once were routinely hydrologically connected to the main Sacramento River now are primarily operated as flood bypass channels to shunt flood flows out of the main Sacramento River channel to reduce downstream flood stages and risks. Flood basins are regularly dredged to maintain flood conveyance (Singer and Aalto 2009). In Willow Slough, a creek draining eastward to the Yolo flood basin from the Coast Ranges, winter-spring floods once drove essentially all geomorphic changes, and low- to no flows and drought prevailed each warm season. Today, by contrast, irrigation flow diversions ensure that flow persists throughout the dry season. Along with channelization and levee construction, hydrologic alteration contributed to transformation of the transport-limited depositional system to an erosional and transport dominated system where small spring floods are contained in incised channels (Florsheim et al. 2011). Spring snowmelt floods from the Sierra, which once were a significant flood and geomorphic driver, now occur earlier (Stewart et al. 2005) and are most often contained within levees. Moreover, their influence on geomorphic processes is expected to diminish in the future as global warming further reduces the snowmelt and springtime flows further (Knowles and Cayan 2004).

3.2 Levee Breaks as the New Dominant Process of Geomorphic Change

Although snowmelt floods would often overtop or circumvent the low and discontinuous natural levees of the past, in the modern embanked system, levees are higher and more complete, and the mix of floods that impact both levees and floodplain geomorphic (and ecologic) processes has changed. One consequence of these changes is that, in the embanked Sacramento-San Joaquin River system, levee breaks and associated processes appear to have become the dominant process of geomorphic change.

Certainly, geomorphic processes in twenty-first century California operate on a landscape dominated by levees and dams, and while not all levee breaks have been catastrophic, they remain frequent in the Central Valley—occurring during a quarter of years in the twentieth century (Fig. 3; Florsheim and Dettinger 2007). Historical records indicate that climate and flood variability govern these unintentional levee breaks, even now. A review of the timing of 128 well-reported (unintended) levee breaks since 1951 (roughly when we can begin to differentiate between ARs and other flood mechanisms) indicates that, in today's embanked system, 81 % of levee breaks along Central Valley rivers occurred during floods generated by wintertime ARs, with only 15 % occurring during snowmelt floods (Fig. 4). In the pre-development era, the mix, seasonality, and especially frequency of biogeomorphically significant flood flows and levee breaks was presumably quite different. In the pre-development era, floodplains presumably were inundated during more years, because floodplain inundation would (without modern levee systems) have been caused by snowmelt during many, if not most, springs, resulting in a more regular

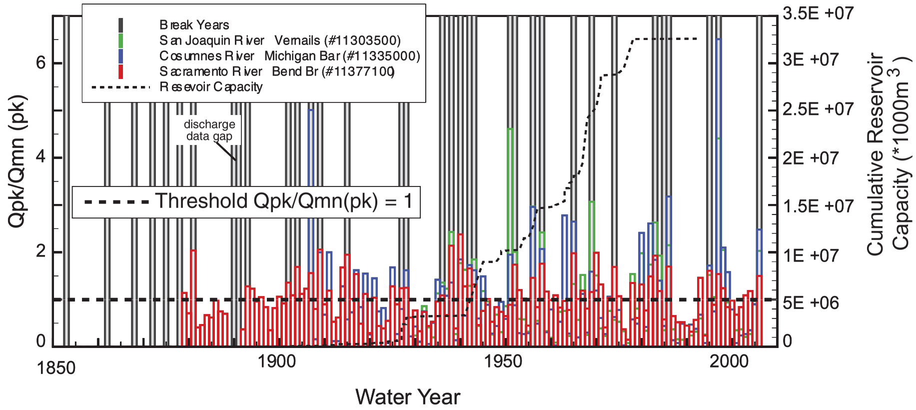

Fig. 3 Cumulative reservoir capacity and time series of $Q_{peak}/Q_{mean(pk)}$ showing variation at three gages within the Sacramento-San Joaquin River system. Gray bars indicate year when a levee break occurred within the system. Coincidence of break years and water years above the threshold $Q_{peak}/Q_{mean(pk)} = 1$ at at least one of the three gage locations suggest a strong system-scale relationship between levee break occurrence and climate variation. Adapted from Florsheim and Dettinger 2007

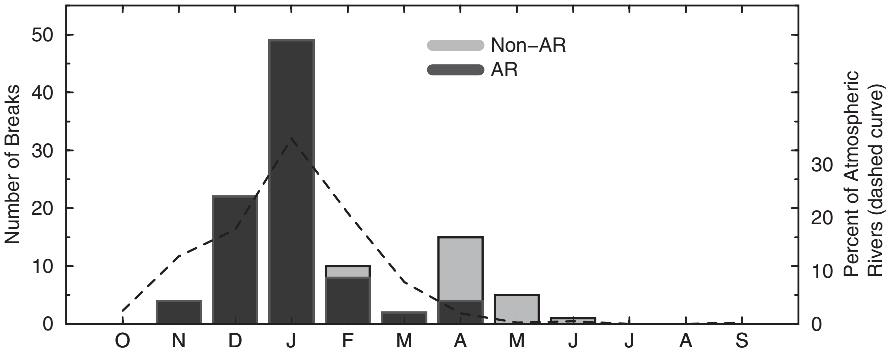

Fig. 4 Seasonality of 109 well-reported levee breaks on Central Valley rivers between 1951 and 2006, with indication of whether or not each levee break coincided with an atmospheric-river storm; *dashed curve* indicates average monthly frequencies (seasonality) of occurrence of all landfalling ARs in California (from Table 2, Dettinger et al. 2011)

"cycle" of inundations occasionally punctuated by very large wintertime floods, most often fed by ARs. Looking to the future, the mix of flood and geomorphic processes may change even more as global warming is currently projected to increase the frequency and magnitudes of ARs making landfall in central California (e.g., Dettinger 2011) while reducing the amount of snowmelt each spring (e.g., Knowles and Cayan 2004).

Unintended levee breaks are often damaging to economic assets, structures, and even human lives, and thus are generally viewed as extremely problematic. Furthermore, potential flood damage is not limited to humans. Loss of remaining vegetation and aquatic species during floods in constrained reaches where sediment deposits and large wood have already been removed can devastate struggling habitats. Thus alternative approaches to the use and design of levees, and to the management of storms and floods, may be in order. We provide two case studies as examples that illustrate the landscape-scale effects of intentional levee breaks and planned weir overflow on floodplain processes.

4 Examples of Intentional Levee Modifications and Management

Intentional levee breaks and planned weir overflows offer alternatives for river-floodplain flood management that may increase the capacity of the Central Valley lowlands to accommodate California's climate variability while providing direct biogeomorphic benefits. There are several examples of levee modifications for floodplain restoration along channels of embanked channels in the lowland Central Valley currently slated for intentional breaks or removal, e.g., in the Sacramento River National Wildlife Refuge: the Flynn and La Barranca Units in Tehama

County, and the Rio Vista Unit in Butte County (Kelly Moroney, Fish and Wildlife Service, personal communication 2012). Similarly, along the San Joaquin River, levee setbacks are under consideration as part of a program to restore floodplain flows to benefit fish habitats. Intentional levee modifications that allow flood flows onto floodplains provide an alternative management approach to achieve multiple goals including habitat restoration. The following describes two landscape-scale restoration projects that provide such benefits through intentional levee breaks and through planned weir overflow.

4.1 Cosumnes River Floodplain-Intentional Levee Breaks

A historical example of intentional levee breaks for floodplain habitat restoration comes from the Cosumnes River, a tributary draining the Sierra Nevada and entering the Central Valley near where the Sacramento and San Joaquin River join. Several agencies and nongovernmental organizations partnered to create intentional levee breaks, by excavating gaps in the levees, along the Cosumnes almost 20 years ago. In its natural state, the lowland reaches of the Cosumnes River were a distal part of the Sacramento flood basin (see Fig. 2; Gilbert 1917; Bryan 1923) with multiple-channel anastomosing river processes (including avulsion and deposition of crevasse splays and seasonal overbank floods) being the dominant geomorphic processes of floodplain deposition (Florsheim and Mount 2003). Flow in the Cosumnes River occurs mostly between October and May with the majority of the precipitation falling as rain. The lowland part of the Cosumnes River was a good location for a levee break restoration project because no large upstream dams are present on the Cosumnes to modify its hydrograph from natural regimes, thus allowing floodplain inundation during floods. Levee breaks constructed in 1995 and 1997 reestablished hydrologic connectivity between the Cosumnes River and its floodplain, allowing for ready inundation of previously farmed floodplain fields.

Of biogeomorphic interest, the levee breaks allowed sediment and large woody material to be transported onto the floodplain during floods. Floodplain inundation enhanced dynamic geomorphic processes such as erosion of the floodplain (near the constructed levee break) and down-floodplain deposition of sand splay and channel complexes that enhanced floodplain topography. That topography, in turn, enhanced habitat diversity (Florsheim and Mount 2002). Subsequent overbank flows that inundated the floodplain yielded a dynamic prograding system where sand was eroded from upstream parts of the splay and deposited at the distal end. Over the past decade, vegetation that preferentially established on the slightly higher elevations of the sand splay has thrived, and splay complex channels have become more defined as subsequent floodplain flows eroded, transported, and deposited sand (Fig. 5). These are precisely the kinds of changes needed to reinvigorate and support diversity in the Cosumnes floodplain ecosystem. The greater connection of the river to floodplain is also likely to provide a natural form of flood-risk amelioration downstream river reaches.

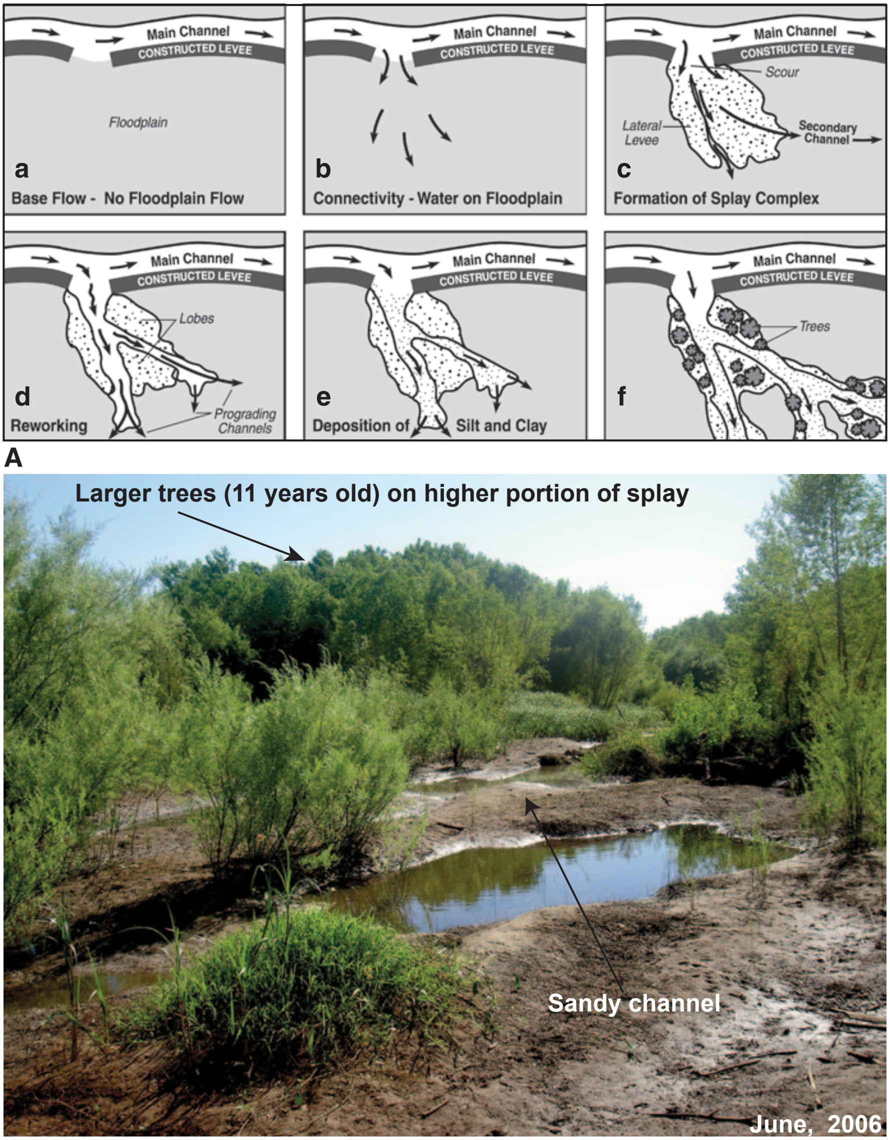

Fig. 5 A) Schematic of development of sand splay and channel complex on the Cosumnes River. **a** Low flow in main channel, **b** Connectivity of water from channel to floodplain, **c** Connectivity of bedload sediment from channel to floodplain and initial deposition of sand splay, **d** Continued or subsequent overbank flow that reworks sand splay and progrades channels, **e** Deposition of fine silt and clay as water recedes, **f** Establishment of riparian trees on higher portions of sand splay. Adapted from Florsheim and Mount 2002. B) 2006 Photograph looking down sandy splay channel at trees on splay

Analysis of the interaction between hydrology and geomorphic changes on the floodplain during the first eight years after the breaks were constructed (in 1995) suggested that the threshold for floodplain inundation (Q_c) was ~23–25.5 m^3/s (recurrence interval of ~1–3 years) and the threshold for bedload sediment transport from the main river through the break onto the floodplain was about 100 m^3/s (Fig. 6; Florsheim and Mount 2002; Florsheim et al. 2006). Finer silt and clay suspended in flows entering the floodplain through the break were deposited on the splay as flows receded. The number of days when flow (Q) exceeded the thresholds for hydrologic connectivity and for bedload sediment connectivity between 1995 and 2003 are illustrated in Fig. 7. During the first 6 years after the levee break, from 1995 to 2000, both flow and sediment connectivity occurred, whereas 2001 was a drought year, with limited connectivity. Conditions from 2002 to 2003 were also relatively dry—flows exceeded the threshold for flow connectivity, but were below the threshold for connectivity of sediment that moved on the floodplain as bedload. These observations show a high degree of climate-caused geomorphic variability, with water year 1997 being one of the wettest years and 2001 being one of the driest years of the century. However, the variability illustrated by this short-term record is representative of California's climate that Central Valley floodplain ecosystems had once been adapted to. This short-term variability did not hinder restoration of geomorphic processes needed to re-establish floodplain topography or provide substrate requisite for establishment of riparian vegetation. More work is warranted to answer questions about the likely trajectory that today's floodplain restoration projects will take over the long-term under current inundation duration and frequencies, or to answer questions about what inundation magnitude and frequency will be optimal for ecosystem sustainability.

To place the effects of the intentional levee break on the Cosumnes into a longer term perspective and to assess the role of atmospheric rivers there, we evaluated daily flow records from the Cosumnes River at Michigan Bar since 1930 (USGS gage #11335000) in terms of the historical occurrences of flows sufficient, given the recently intentional levees breaks, to result in river-floodplain flow connectivity (requiring flows $Q>Q_c$ or 25 m^3/s) and sediment connectivity (requiring flow $Q>4Q_c$ or 100 m^3/s). Figure 8a shows historical seasonality of flows above these thresholds. Flow connectivity would have occurred—and will now occur—often in winter and spring, on average 16 % of days during the year, whereas bedload sediment connectivity would have occurred more intermittently and mostly in winter, during 2 % of days. A survey of meteorology (not shown in Fig. 8a) on days with flows surpassing the sediment-connectivity threshold, since water year 1950, indicates that AR storms initiated the historical floods greater than the sediment-connectivity threshold on 61 % of the 88 historical occasions when connectivity lasting more than 2 days would have been established, and on 69 % of the 56 occasions when connectivity would have lasted more than 3 days. Thus, sediment connectivity would have been (and will presumably continue to be) dominated by floods initiated by the arrivals of landfalling AR storms. Smaller floods, below the threshold of bedload sediment connectivity, are much more diverse in their meteorological origins.

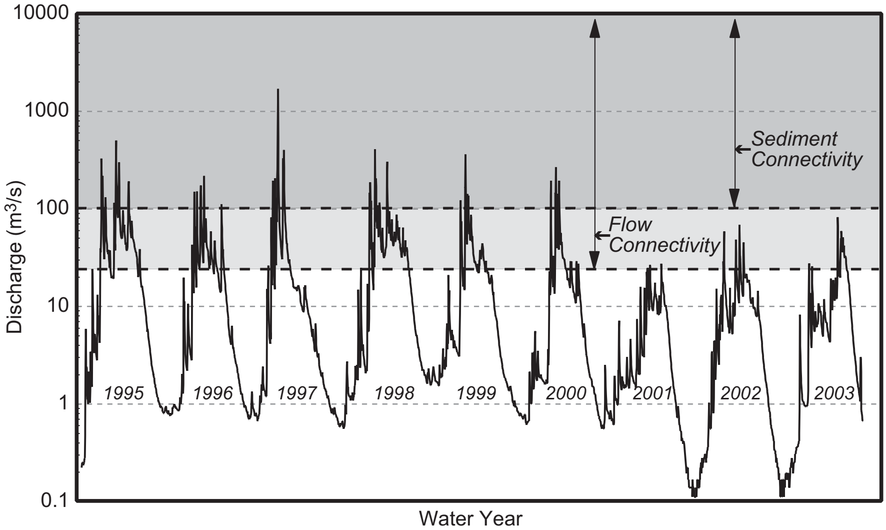

Fig. 6 Hydrograph from 1995 through 2003 showing thresholds for flow and sediment connectivity. Channel-floodplain flow connectivity occurred in all years, but sediment connectivity only occurred during 1995–2000. Adapted from Florsheim et al. 2006

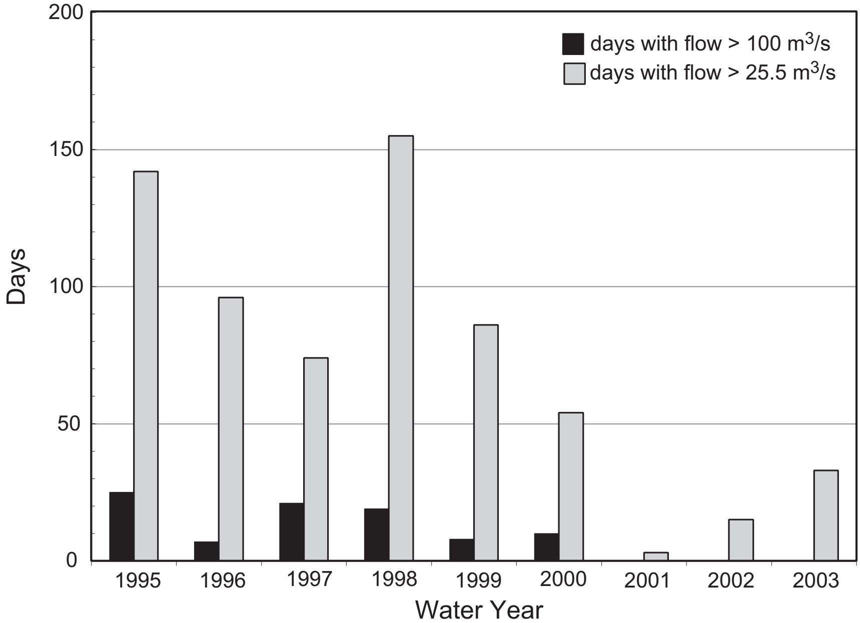

Fig. 7 The number of days when flow (Q) exceeded thresholds for hydrologic connectivity ($Q/Q_c > 1$ corresponding to 25.5 m^3/s) and sediment connectivity ($Q/Q_c > 4$ corresponding to 100 m^3/s) illustrated after intentional levee break for years between 1995 and 2003. Adapted from: Florsheim et al. 2006

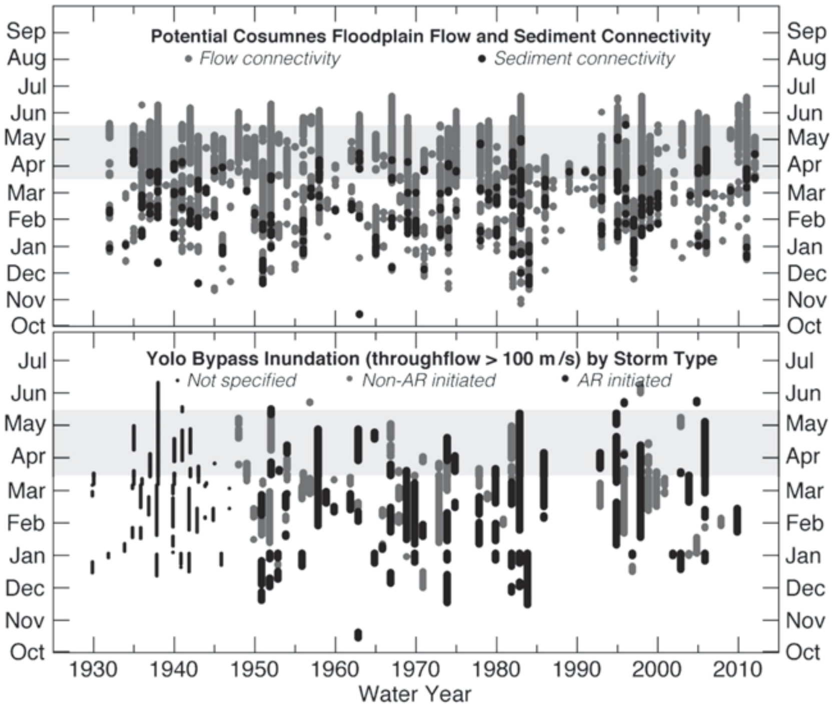

Fig. 8 **a** Timing and duration of Cosumnes River potential floodplain flow and sediment connectivity, under the scenario that existing levees that deter overbank flow had not been constructed, **b** Timing and duration of inundation of Yolo Bypass by day of year and water year, along with an indication of whether the inundation was initiated with an atmospheric-river storm (since 1948). *Pale gray band* indicates the March 15 and May 15 season of greatest floodplain-ecological benefit for fish (identified by Williams et al. 2009)

4.2 Yolo Bypass Floodplain-Weir Overflow

As a second example of intentional levee modifications, in the 1930s, the Yolo Bypass project was implemented on the western side of the Sacramento River, in a portion of the area formerly occupied by the Yolo flood basin on the opposite side of the Sacramento River from the Cosumnes system. Since 1997, about 25 % of the bypass has been converted to wildlife restoration areas compatible with flood control. The frequency and timing of Yolo Bypass inundations is critical to floodplain ecosystems there. Sommer et al. (2004) suggested that channel-floodplain connectivity supports rapid production in lower trophic levels in the restored Yolo system. Williams et al. (2009) suggest that a particular timing of spring floods, between March 15 and May 15, and inundation durations of at least seven days are required to activate and sustain key floodplain functions that support fish.

Sommer et al. (2001) summarize the complex hydrology of the system, noting that water inundating the low lying flood basin is derived from diverse sources, the most immediate being from the Sacramento River at the Freemont Weir, a passive weir that allows overflow from the Sacramento River over and onto the Yolo Bypass once the river exceeds a stage threshold, Qc (above 9.2 m NGVD). Water first enters the Yolo Bypass in the "toe drain," a small channel with capacity of ~100 m^3/s, and then, as stage rises, water spreads out to inundate the Yolo Bypass floodplain. Floodplain flows are augmented by water from local tributaries draining the Coast Ranges, including Cache Creek, Willow Slough, and Putah Creek. As an illustration to show how the Yolo Bypass functions as a flood-control mechanism, in 1999, flood flow in the main channel of the Sacramento River was kept below its 3100 m^3/s design flow by diversion of 1350 m^3/s onto the Yolo Bypass floodplain (Sommer et al. 2001). In addition to farmed areas within the bypass area, there are broad native habitats including wetlands, riparian, ponds, and uplands that are supported by flood flows greater than Qc.

A long-term perspective on the frequency, timing, and causes of these ecologically beneficial inundations of the Yolo Bypass can be obtained through analyses of histories of daily flows through the Bypass and of daily Central Valley outflows with and without management, based primarily on flow estimates from the California Department of Water Resources DAYFLOW Program (http://www.water.ca.gov/dayflow/; see Knowles 2002). The Program regularly estimates daily flow discharges in many parts of the Central Valley from observed flows and observed and modeled reservoir releases and water diversions. These estimates allow identification of occasions when the Yolo Bypass has been inundated since 1930. Combined with a 21-year set of records of upstream reservoir releases from the National Weather Service (NWS) California-Nevada River Forecast System, Knowles (2002) was able to further estimate the effects of modern water management on high flows that inundated the floodplain in the Yolo Bypass during the 1967–1987 sub-period.

Historically, the DAYFLOW estimates indicate partial inundations of the Yolo Bypass (>100 m^3/s into the toe drain) on 2030 days from 1948–2010. During that period, a survey of various meteorological sources (e.g., as in Dettinger et al. 2011) shows that 66% (1348 days) of those days occurred as part of floods that were initiated by AR storms. Figure 8b illustrates the timing and duration of such inundations since the early 1930s, along with indications of which inundations were initiated by ARs and which were not (since 1948). Of greater ecological concern, 68% of all inundations (in the 1948–2010 period) lasting longer than 7 days, and 76% of all inundations lasting longer than 28 days, were initiated by AR storms. Notice (in Fig. 4) that ARs most commonly arrive in California in winters, centered on Januaries, whereas Williams et al. (2009) argued that inundations between March 15 and May 15 were of greatest ecological benefit (pale gray band in Fig. 8). Nonetheless, because inundations associated with large ARs are so frequently long lasting, even in the March 15-May 15 season, 77% of inundation days are parts of episodes initiated by ARs. Thus, even though AR storms are predominantly initiated during the winter months, in California the duration of inundation caused by ARs is sufficiently long lasting that they remain the dominant climatic factor governing Yolo Bypass floodplain-ecological benefits. In several ways, then, inundations, and especially ecologically important inundations of the

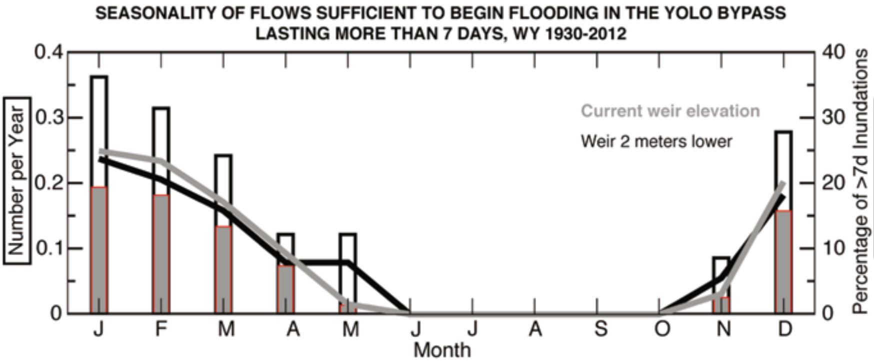

Fig. 9 Numbers (*bars*) and fractions (*curves*) of occasions when Sacramento River flows at Verona (USGS gage #11425500) were sufficient for overtopping the Fremont Weir that controls inundations of the Yolo Bypass floodplain, with the existing weir (*grays*) and for a hypothetical case of a weir height 2 m lower (*black*), from October 1929 through September 2012

Yolo Bypass floodplain, are overwhelmingly initiated, in the modern era, by AR storms and their attendant floods.

Human interventions and modifications of the rivers of the Central Valley have changed the role of these AR storms as initiators of sustained Yolo Bypass floodplain inundations from their likely role in the prehistoric past, in various ways. Locally, inundations of the Yolo Bypass are often determined by flows at Fremont Weir on the Sacramento River at the northern end of the Bypass. Flooding in the Yolo Bypass floodplain currently begins when the Sacramento River discharge at the Fremont Weir, which is upstream from the USGS Sacramento River at Verona streamflow-gaging station, exceeds 1585 m^3/s. Figure 9 compares the numbers and seasonalities of historical flows sufficient to initiate inundations (occurrences of flows greater than that threshold for overflow of the Fremont Weir) that lasted more than seven days, under current structural conditions at the Fremont Weir and under a hypothetical alternative configuration intended to (broadly) represent an intentional partial break or lowering of that weir. Gray bars and the gray curve in Fig. 9 correspond to the numbers and seasonalities, respectively, of occasions when that flow rate was exceeded for more than seven days in a row since October 1929. The black-edged bars and black curve in Fig. 9 correspond to numbers and seasonality of occasions when the flow rates exceeded ~1039 m^3/s for more than 7 days in a row; this lower flow rate corresponds to a river stage that would be needed to overtop the weir if it was 2 m lower. The bars indicate that, if the weir preventing the river from flowing into and through the Yolo Bypass historically had been 2 m lower, the Bypass would have received inflows twice as often (all other things being equal). Perhaps as importantly, the seasonalities of inundations indicated by the curves in Fig. 9 show that the weir reduces inundations disproportionately during springs, a time of year when Sommer et al. (2004) and Williams et al. (2009) have argued inundations are of particularly high ecological value. We have not specifically

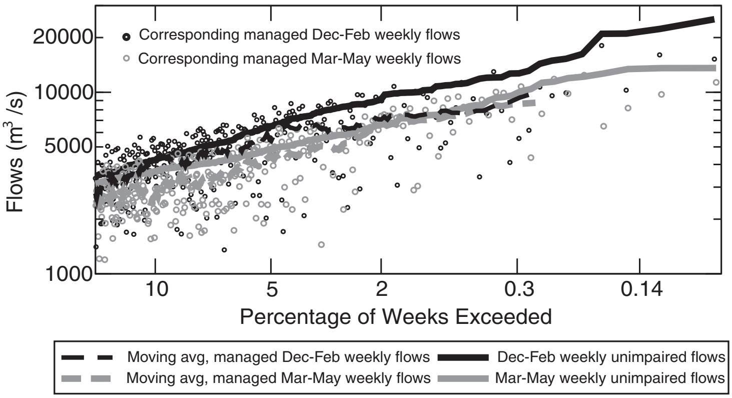

Fig. 10 Estimated exceedence probabilities (*solid curves*) of unmanaged 7-day average outflows from the Central Valley, above the Sacramento-San Joaquin Delta, in winters and springs, 1967–1987, with corresponding managed-flow estimates as *circles*, as based on time series from Knowles, 2002. *Dashed curves* are moving averages of circles, showing the 20-episode average managed flows around each level of unmanaged flow rate

separated snowmelt from atmospheric-river floodplain inundations in Fig. 9, but seasonality of effects of the weir (with largest reduction in the fraction of inundations happening in May when atmospheric-river storms are less common; dashed curve in Fig. 4) suggests that the local levee-weir structural control on Bypass inundations probably has preferentially reduced the opportunities for snowmelt-fed floodplain inundations compared to inundations caused by wintertime, often atmospheric-river storms.

On the larger scale of flow management in the Central Valley, river discharges and floods have been modified considerably with the introduction of hundreds of dams and diversions upstream from lowland floodplains like the Yolo Bypass. To understand some of the influences that these upstream controls have had on inundations at the Bypass, the daily estimates of Central Valley outflows, with and without reservoirs and diversions, at the high-flow end of a flow frequency diagram from Knowles (2002) are considered in Fig. 10. In Fig. 10, the solid curves are flow frequencies for the 7-day mean flows with upstream-reservoir effects removed (by Knowles 2002) during winter (black solid curve) and spring (gray solid curve). As discussed previously, the largest (natural) floods in the Central Valley are most often in winter with spring snowmelt peaks, on the whole, being smaller. For each 7-day flow comprising the solid curves in Fig. 10, there is a corresponding DAYFLOW estimate of the actual outflow from the Central Valley, inclusive of all the upstream-reservoir effects and diversions; these corresponding managed-flow values are plotted in Fig. 10 as the scatter of black and gray circles. Clearly, on many occasions historically, the managed outflows from the Central Valley have been larger than the unmanaged flows would have been, as water from various reservoirs and diversions has been added to the otherwise natural flow rates; on many occasions, water has been held back by reservoirs or diverted so that the managed outflows have been less than the unmanaged flows would have been. To determine the long-term net, the average effect of management on what would have been the highest outflows under natural conditions, a moving average was applied to the two (black and gray) clouds of dots. A comparison of the solid curves (unmanaged flood frequencies) with the resulting dashed curves (average of corresponding managed flood flows) shows that upstream management of 7-day flood flows during the 1967–1987 period reduced the largest winter flood flows just enough to make them just equal, on average, to the largest unmanaged springtime outflows. The management of springtime high flows, on average, did not reduce the outflows below the levels that would have been achieved under unmanaged conditions.

Although Fig. 9 showed that the local structural controls on inundation of the Yolo Bypass has disproportionately reduced the springtime snowmelt-fed inundations, at the larger scale of reservoir impacts on Central Valley flood flows more generally, reservoir impacts has left springtime flood flows more or less unchanged (on average) but has significantly reduced the largest wintertime flows. Thus at the whole-system scale of Central Valley outflows (of which the Sacramento River flows at Yolo Bypass are a large fraction), reservoir management has tended to de-emphasize wintertime floods, "starving" floodplains like the Yolo Bypass of those largest wintertime, and most often atmospheric-river derived, floods that the floodplains and floodplain ecosystems evolved under natural conditions to accommodate and indeed rely upon. A reduction of the Fremont Weir elevation, essentially an intentional partial levee break, would both increase the number of winter and springtime inundations towards somewhat more natural conditions, and could allow for more truly large inundations in winters (as in the natural state) along with an added emphasis on the ecologically crucial springtime floods.

5 Projected Geomorphic Response to Future Climate Variability and Change

As global warming progresses, winter floods increase, and spring snowmelt in Sierra Nevada progressively diminish, the historical tendency for winter inundations to be the most frequent and extreme inundations will likely be exacerbated (e.g., Knowles and Cayan 2004; Das et al. 2011). Under these circumstances, the nourishing floodplain inundations in the Central Valley may become more and more tightly interlinked with the most damaging floods. Alternative floodplain management strategies, including intentional levee breaks allowing easier and more frequent reintroduction of moderate flows onto the floodplains, especially from the remaining springtime snowmelt pulses, may be necessary to revitalize and even to sustain the Central Valley's floodplain ecosystems and to better accommodate future flood-regime changes.

Recent climate-change projections for California suggest that the total volume of snowmelt runoff that might be shifted from spring and added to winter flows under some of the more modest projections of change is roughly 195 m^3/s, an amount similar to the total unfilled (free-board) volume currently held in abeyance in the major low-altitude Sierra Nevada reservoirs each winter for flood–capture and management. That is, the volume of additional winter flows projected under projections of modest warming (about + 2.5 °C warmer by midcentury; Knowles and Cayan 2004) is roughly equal to the amount of flood-control space currently maintained in Sierra reservoirs. Those additional winter flows will come at the expense of a reduction of springtime flows of nearly equal volume. Any modification of the timing of reservoir releases to accommodate these changes (e.g., any attempt to directly capture the "extra" winter flows, by reducing the free-board flood-control space) would likely add to either the magnitude or duration of winter flood peaks downstream from the major reservoirs, each causing different geomorphic responses. These additions would lead to increased overbank flow and flood extent and floodplain sedimentation and erosion in unconfined reaches.

These same increases in wintertime flows would increase flood flow depths and erodibility of the downstream flows, which could increase the risk of unintentional levee failures. Runoff released from reservoirs as a relatively constant addition to winter baseflow would increase the duration of bankfull or possibly "levee-full" flows. This scenario could lead to bank and levee failures through increased saturation and seepage erosion. Thus, geomorphic responses to future climate variation and change on floodplains will be closely tied to infrastructure and reservoir management policies established in recent decades and in the future to accommodate increased winter flows (and reduced spring and summer flows), with the survivability of infrastructure. Decisions about the future timing, magnitude, and duration of flow releases from upstream reservoirs under climate change are likely to determine the form of those geomorphic responses.

6 Conclusions

Major changes in the biogeomorphology of California's Central Valley river-floodplain system have resulted from human activities. Prior to the nineteenth century, the lowland system was characterized by natural levees alongside complex multichanneled rivers and tributaries. Flood basins, a characteristic landform of the Central Valley, were connected to the main river through multiple openings in the natural alluvial levees. Since then, more than 1000 km of engineered levees have been constructed and embanked the system, limiting connectivity between channels and floodplains and greatly reducing ecological attributes of the Central Valley. Despite construction of levees and other flood-control structures, climate and floods continue to cause unintentional levee breaks. Of concern, structural and management actions in the Central Valley have apparently, inadvertently given greater importance to the largest wintertime (dominantly AR) storms and floods, while reducing the roles of the usually less extreme but (prehistorically) more regular springtime snowmelt floods, in terms both of unintentional levee breaks and beneficial floodplain inundations.

We reviewed two examples from California's lowland Central Valley illustrating that intentional levee breaks and planned weir overflow designed for floodplain restoration along embanked lowland rivers can promote dynamic biogeomorphic processes. These alternative flood management approaches facilitate lowland river-floodplain flow and sediment connectivity that allows morpho-dynamic processes needed for ecological functions to be restored and sustained. Setting aside space on lowland floodplains and intentionally engineering levee breaks or lowering weirs promotes floodplain biodiversity by accommodating both the smallest over bank floods that would occur frequently as a result of a range of climate conditions such as rainfall and snowmelt, as well as the largest AR floods that exceed thresholds for sediment and water connectivity that would occur primarily in the fall and winter. Moreover, AR storms during fall and winter are responsible for a large proportion of the longest duration floodplain inundations and, because of their long durations, they are the initiators of most of the long springtime inundations that provide the most ecological benefits of floodplain inundation in the Yolo Bypass restoration. Therefore, flood management approaches that anticipate and accommodate the special role of AR floods may help to achieve more natural hydrologic and biogeomorphologic regimes.

Future climate-driven changes in flood regime, such as enhanced flooding during winter months or more frequent atmospheric rivers, need to be considered in planning for floodplain restorations and management, and might be accommodated by additional intentional levee breaks or planned weir overflow for restoration. Expansion of such approaches could improve restoration policy and management of floods in embanked river floodplains.

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