

Climate and floods still govern California levee breaks

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[1] Even in heavily engineered river systems, climate still governs flood variability and thus still drives many levee breaks and geomorphic changes. We assemble a 155-year record of levee breaks for a major California river system to find that breaks occurred in 25% of years during the 20th Century. A relation between levee breaks and river discharge is present that sets a discharge threshold above which most levee breaks occurred. That threshold corresponds to small floods with recurrence intervals of ~2–3 years. Statistical analysis illustrates that levee breaks and peak discharges cycle (broadly) on a 12–15 year time scale, in time with warm-wet storm patterns in California, but more slowly or more quickly than ENSO and PDO climate phenomena, respectively. **Notably, these variations and thresholds persist through the 20th Century, suggesting that historical flood-control effects have not reduced the occurrence or frequency of levee breaks.** **Citation:** Florsheim, J. L., and M. D. Dettinger (2007), Climate and floods still govern California levee breaks, *Geophys. Res. Lett.*, *34*, L22403, doi:10.1029/2007GL031702.

1. Introduction

[2] The majority of the world's river systems are profoundly modified by direct human interventions including dams and flow regulation, levee construction, and channelization [Nilsson *et al.*, 2005]. Thus, modern rivers often accomplish geomorphic change in ways that reflect man-made structures and local engineering practices rather than natural processes. In rivers with pervasive levee systems, such as the ~153,000 km² Sacramento-San Joaquin fluvial system in California, one mechanism of modern geomorphic change is accidental levee breaks during floods. The destructive consequences of inundation, erosion, and sedimentation accompanying recent levee breaks such as occurred during Hurricane Katrina, LA, in 2005 [Nelson and Leclair, 2006] and that pose a risk in California's Sacramento-San Joaquin River Delta [Service, 2007] can be catastrophic. While it is generally accepted that levees break during floods, neither their relation to cyclic climate phenomena nor their frequency at the fluvial system scale has been addressed. Here we analyze the effect of climate-induced floods on consequent levee breaks in a long-term historical record to obtain insights about risks associated with future global warming in the lowland Sacramento-San

Joaquin River system. The significance of the results may presumably extend to many other rivers that have been equally engineered by humans.

[3] In this investigation, we use levee breaks as a metric of the potential for dangerous geomorphic change, representing one particularly catastrophic way that anthropogenically altered river systems respond geomorphically to floods. Here, we consider levee breaks in the Sacramento-San Joaquin River fluvial system upstream of the freshwater tidal San Francisco Bay Delta. We define levee breaks (also called breaches) as a physical failure of the engineered structure by fluvial erosion or mass failure due to overtopping, saturation, or seepage. Levee strength and integrity are dependent on original construction methods and foundation material, and change temporally as a result of cumulative erosion, rodent activity, etc. We exclude flooding that occurs from levee overtopping without causing a break, overbank flow in areas where no levees exist, and cases where incipient breaks are averted through labor intensive "flood fights." During levee breaks and associated floodplain inundation, water from rivers scours the floodplain near the breaks and deposits sediment down-floodplain in the direction of the flow. Despite, and in part because of a history of augmentation of natural alluvial levees, the modern Sacramento-San Joaquin River system continues to be susceptible to levee breaks as a significant geomorphic process.

[4] Current climate-change projections suggest that tributaries to the Sacramento-San Joaquin Rivers draining the Sierra Nevada, CA, will experience increased frequency, magnitude, and duration of winter flood peaks in response to global warming, involving increases in the frequency and spatial extent of rainfall during major storms, more opportunities for rain-fed floods, and for rain to fall on snow [Dettinger *et al.*, 2004]. Such storms enhance risks of flooding and, in turn, raise the risk of levee breaks and failure of their foundations in alluvial river banks and mining debris. A variety of fluvial responses to global warming are possible [Goudie, 2006], and many, including erosion and sedimentation responses, may be highly nonlinear [Vandenburghe, 1995; Bogaart *et al.*, 2003]. Together these changes and responses may be expected to aggravate future levee-break risks.

[5] The importance of climate on geomorphic processes is pronounced, with particular responses dependent on both the temporal and spatial scales addressed. Vandenburghe [1995] suggested that on the time scale of centuries, and relevant to the work described in this paper, thresholds are important. At the drainage basin scale, modeling results of Tucker and Slingerland [1997] suggest that cyclic climate events dominate hillslope erosion, with punctuated denudation rates during periods of increasing runoff intensity or

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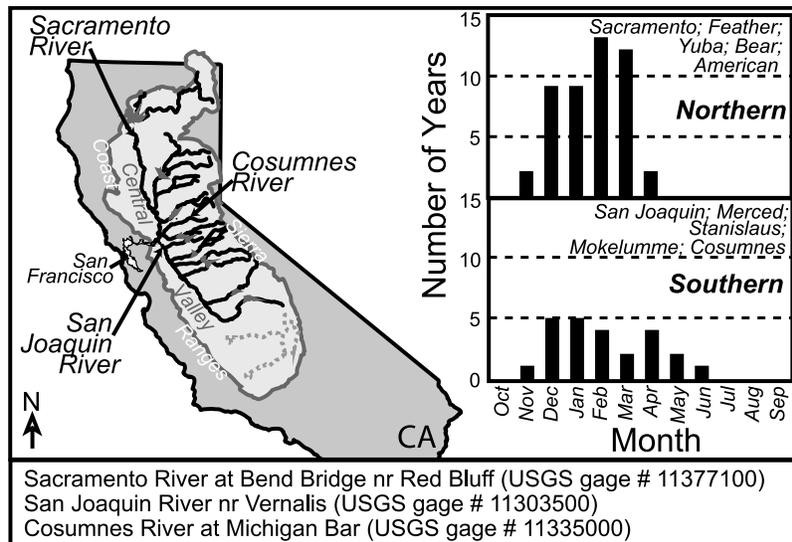


Figure 1. Sacramento-San Joaquin River system watershed; arrows point to location of three gaging stations. Bar charts show distribution of levee breaks indicating number of years with breaks occurring during particular months of the year for northern and southern portion of the system.

decreasing vegetation cover; both of which may be affected by future global change. Field data indicate the importance of cyclic climate phenomena such as El Niño Southern Oscillation (ENSO) on geomorphic processes, such as in generating landslides in southern California [Gabet and Dunne, 2002; Pinter and Vestal, 2005]. Recent work in the Amazon basin [Alto et al., 2003], where the river is unconstrained, shows the role of cyclic climate variability in geomorphic responses, namely floodplain sedimentation in unconstrained natural river systems that differ markedly from responses in constrained engineered river systems where floodplain development, constructed levees, and other anthropogenic changes prevent such responses. Late-Holocene paleo records for the Sacramento-San Joaquin system [Malamud-Roam et al., 2006, 2007] document past climate-driven geomorphic changes and suggest that, before the past few centuries, lowland geomorphic responses to climate variation and change in this system was accommodated through floodplain and channel erosion and sedimentation processes much like those in unconstrained natural systems today.

[6] It is well understood that climate characteristics such as precipitation and temperature influence river discharge, and that flood discharges in turn influence fluvial responses [Blum and Tornqvist, 2000]. However, previous studies that link climate phenomena and geomorphic processes have not addressed the influence of cyclic climatic phenomena on the highly altered fluvial systems of the Anthropocene—the past one or two centuries of global river modification. This paper addresses the relation between cyclic climate phenomena and levee breaks in a highly engineered river system. Our statistical approach has applicability for understanding the true risks of fluvial change in the majority of the world's fluvial systems that are heavily engineered, that will be

responding to climate change from starting points that lack natural resiliency to adjust to geomorphic change.

2. Study Area and Methods

[7] The Sacramento-San Joaquin River system is the largest watershed in California. Its tributaries drain the Sierra Nevada and the California Coast Ranges. Water from the rivers drain into the lowland Central Valley and then flow through the San Francisco Bay Delta Estuary en route to the Pacific Ocean (Figure 1). The large-scale integration of this watershed, which contains numerous different land uses, makes it an ideal locale to investigate the influence of climate change on modern geomorphic processes. Prior to environmental changes that accompanied the California Gold Rush in the mid-1800's, fluvial processes in this river system included channel migration and avulsion typical of lowland floodplain-channel systems globally [Gilbert, 1917; Florsheim and Mount, 2003]. In 1850, a strategy of raising and extending natural levees began in the Central Valley to confine flows to the main channels, increase flood conveyance, and route sediment through the system [Mount, 1995; Kelley, 1989]. This was accomplished by closing off inlets and outlets to floodplains and flood basins through crevasses and breaks in the natural levees that once existed along main Central Valley rivers. Subsequent flood control infrastructure programs such as levee construction, augmentation, and repair after erosion or breaks continue to the present day.

[8] Three streamflow gaging stations are selected for analysis because of their lengthy records or because of their locations at key points in the Sacramento-San Joaquin River watershed (see Figure 1). The Sacramento River at Bend Bridge (USGS gage 11377100) has a record spanning the period from 1879 to the present. In contrast, gaging stations

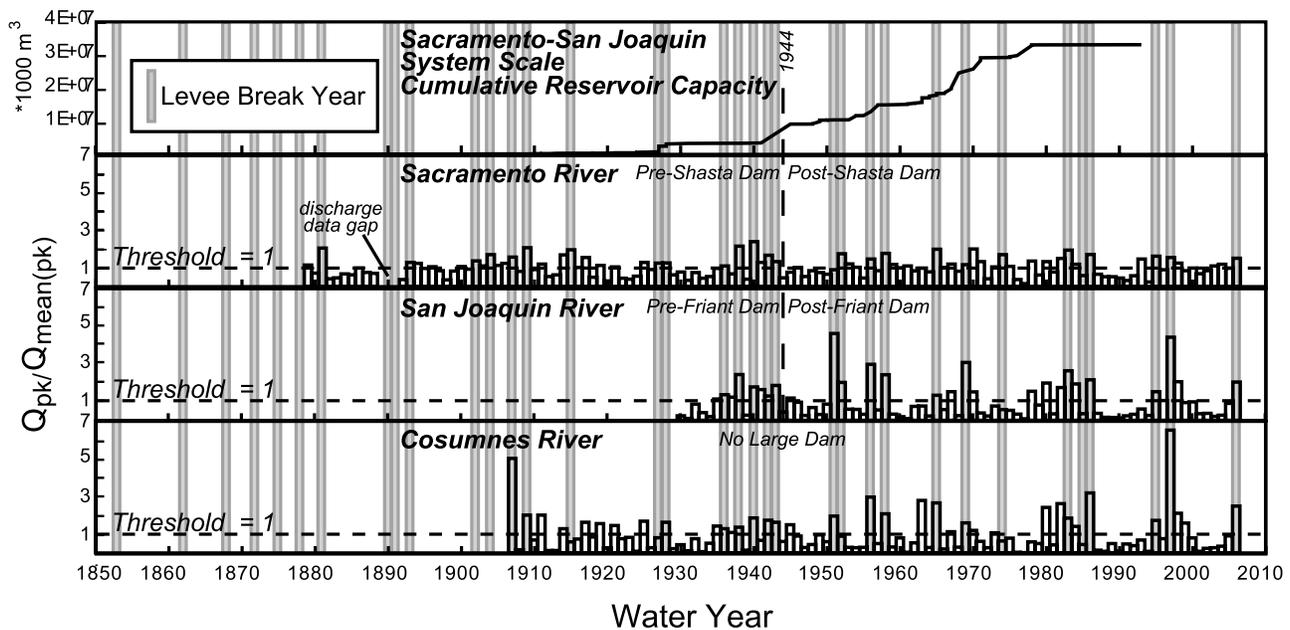


Figure 2. Cumulative reservoir capacity and time series of $Q_{\text{peak}}/Q_{\text{mean(pk)}}$ showing variation at three gages within the Sacramento-San Joaquin River system over same time period. Gray bars indicate year when a levee break occurred within the system (see auxiliary material for individual river within system where break occurred). Coincidence of break years and water years above the threshold $Q_{\text{peak}}/Q_{\text{mean(pk)}} = 1$ at at least one of the three gage locations suggest a strong system-scale relationship between levee break occurrence and climate variation.

farther downstream on the Sacramento River have relatively short records or do not incorporate the total volume of flows during floods when parts of the flows are routinely routed through a bypass system. The San Joaquin River at Vernalis (USGS gage 11303500) has a relatively short record spanning the period between 1924 to the present. Therefore, the discharge time series of the Cosumnes River at Michigan Bar (USGS gage 11335000), extending back to 1907, is also used as it exhibits variations similar to the San Joaquin River record during their period of overlap. In order to compare discharge time series from these three gaging stations, we use the dimensionless ratio of the peak annual river discharge to the long-term mean of the peak annual discharges ($Q_{\text{pk}}/Q_{\text{mean(pk)}}$) where the mean used to normalize the data is calculated separately for the periods prior to and after 1944. We conduct time series analyses to determine spectral density of this factor using methods including those described by *Ghil et al.* [2002] where spikes in the spectral density plot indicate recurring cycles. Annual peak discharge is used in this parameter in order to assess a threshold discharge value associated with levee breaks. Partial duration series were not used because reported discharge values represent the mean daily stream flow and thus underestimate peak discharges.

[9] For this study, we compile a 155-year levee break chronology based primarily on California Department of Water Resources (DWR) and United States Geological Survey (USGS) reports. This chronology includes ~ 200 – 300 separate levee breaks (see auxiliary material)¹ but represents a conservative estimate of the number of breaks

because some break data are presumed not to be available from these sources. Additional data may be dispersed among various agencies' unpublished historical records and photographs that show breaks. Because of this, we focus on relationships between climate and levee break years, or the water year during which the break occurred, rather than on the numbers of breaks per year. Focusing on levee-break years avoids placing too much emphasis on a few all-but-random high-damage or alternatively low damage levee breaks in the historical record and allows regularities in the levee-break record to emerge. We conduct statistical contingency analyses [*Press et al.*, 1986] to investigate relationships between river discharge, levee breaks, and climate phenomena.

3. Results and Discussion

[10] At the river-system scale, levee breaks occurred within the Sacramento-San Joaquin system during 25% (38 of 155) of the years since the first break in 1852. In the past 155 years, break events occurred between November and June (Figure 1), with all of the May and June breaks and the majority of April breaks occurring in the San Joaquin system, or the southern portion of the Central Valley, and the rest of the breaks dispersed throughout the system. The timing of breaks reflects the importance of winter storms throughout both northern and southern portions of the vast system as well as the significance of later spring snowmelt floods in the southern, San Joaquin drainage [*Dettinger and Cayan*, 2003].

¹Auxiliary materials are available in the HTML. doi:10.1029/2007GL031702.

[11] All levee break years except one coincided with river discharges above the threshold given by $Q_{pk}/Q_{mean(pk)}$ equals one (Figure 2). This system-scale levee break threshold corresponds to small floods with post-dam recurrence intervals of $\sim 2\text{--}3$ years, suggesting potentially frequent stochastic break events distributed within the anthropogenically modified system.

[12] A strong decadal signature exists in the time series for the parameter $Q_{pk}/Q_{mean(pk)}$ with a spectral time scale of 12–15 years; spectral density plots peak for the system as a whole near 13 years. This periodicity is unlike the shorter $\sim 3\text{--}6$ yr time scale of the interannual ENSO [Ghil *et al.*, 2002; ENSO-year list provided by K. Redmond, written communication, Desert Research Institute, Reno, Nev., 1999]. The ENSO phenomenon of the tropical Pacific includes the El Niño phase, associated with wet winters in southern California and dry winters in the Pacific Northwest states, and the La Niña phase, which reverses these precipitation conditions [Cayan and Webb, 1992]. The Sacramento-San Joaquin system is located near the null (no consistent precipitation response) of this ENSO connection and, thus, neither $Q_{pk}/Q_{mean(pk)}$ nor the occurrence of levee breaks is consistently related to ENSO. Contingency testing indicates that levee breaks occurred about as often during El Niño or La Niña phases (12% of the time) as when neither ENSO phase prevailed. Similarly, the multi-decadal Pacific Decadal Oscillation (PDO; Mantua *et al.* [1997]) is closely related to ENSO and yields much the same precipitation pattern, including the location of the null. The time scale of the PDO (~ 20 to 30 years; Dettinger *et al.* [2001]) is longer than the time scale of breaks; however, levee breaks occurred about twice as often (16% of the time) during warm PDO phases as during cold phases (8% of the time). Importantly, the precipitation, temperature, and atmospheric circulation patterns most closely associated with levee breaks were versions of the “warm-wet winter” atmospheric circulation patterns [Cayan and Peterson, 1993] that historically have brought heavy rainfall and enhanced flood peaks to California. These patterns are characterized mostly by a juxtaposition of anomalously high pressures over the southwestern US and low pressures offshore from northern California on a variety of time scales. These patterns result in warm storms fed by anomalously strong southwesterly winds, and heat and vapor transports, from over the subtropical eastern Pacific into California.

[13] A contingency analysis of the frequency of levee breaks, in the first and second halves of the 20th Century (i.e., before most of the major upstream reservoirs had been developed and under the modern, heavily engineered conditions, respectively) shows no significant tendency for fewer breaks recently. In order to test the possibility that a change in numbers and distribution of levee break years has been masked by some trend in $Q_{pk}/Q_{mean(pk)}$, we also conduct contingency analysis of the number of years with peak flows above the break threshold and the number of years with levee breaks before and after 1944, the onset of large dam construction during the 20th Century. Results show a difference of only 1%, so we conclude that similar values of the relationship between $Q_{pk}/Q_{mean(pk)}$ and break occurrence prevailed during the pre- and post-1944 periods. This analysis indicates that the extensive flood control

infrastructure developed during the 20th Century has not reduced the frequency of breaks.

4. Conclusions

[14] The historical record for the Sacramento-San Joaquin River system of California indicates that long-term climate and flood variability govern levee breaks at the system scale. In this paper, we add to this understanding by focusing on the influence of anthropogenic alterations, particularly levees, on fluvial processes affected by climate variability. Our results indicate that the frequency of breaks, at the system scale, has not changed from first to second half of the 20th Century, despite heroic engineering of rivers in both uplands and lowlands. Thus, the ability of these infrastructures to prevent impacts from even small floods has been limited and their capacity to forestall damages associated with flood changes in a warming climate is uncertain, at best. Because levees are common as a flood control measure on lowland rivers in the majority of the developed world, these results may have widespread relevance elsewhere where long-term relationships between levee stability and climate change has not yet been addressed. Future geomorphic responses to global warming in the 78% of the world’s major river systems that are significantly altered by humans, as is the Sacramento-San Joaquin fluvial system, will depend on a mix of factors. Critical factors include future climate changes, levee infrastructure and reservoir management, and restoration that recreates floodplain functions including accommodation of flood flows, that may be carried out to address the coming flood risks.

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