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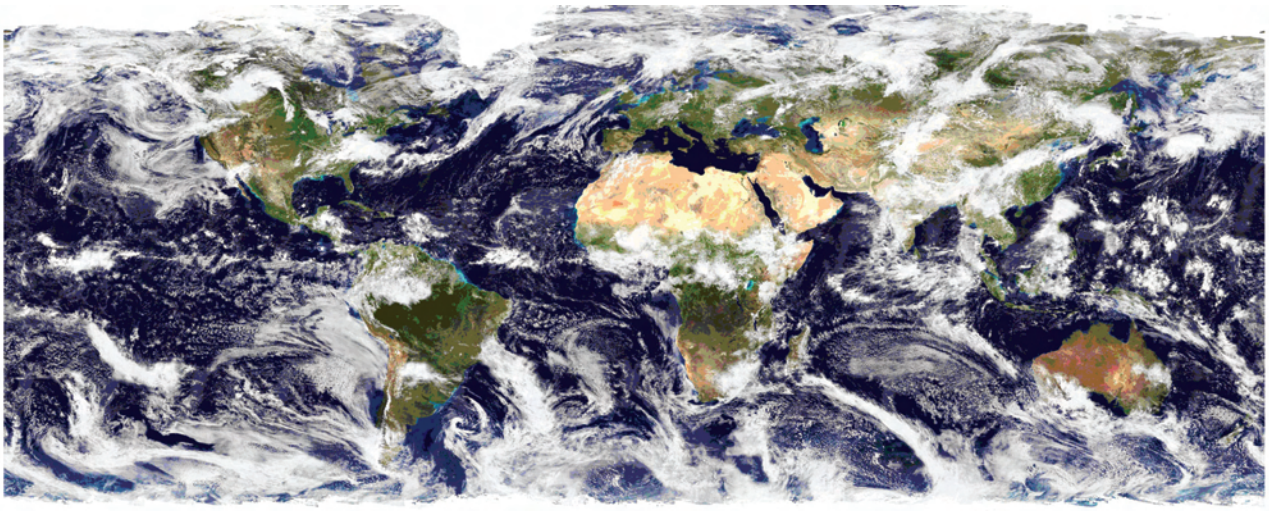

This spectacular "blue marble" image is the most detailed true-color image of the entire Earth to date. Using a collection of satellite-based observations, scientists and visualizers stitched together months of observations of the land surface, oceans, sea ice, and clouds into a seamless, true-color mosaic of every square kilometer (.386 square mile) of our planet. These images are freely available to educators, scientists, museums, and the public. This record includes preview images and links to full resolution versions up to 21,600 pixels across.

Credit*   NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).

INFLUENCE OF 19TH AND 20TH CENTURY LANDSCAPE MODIFICATIONS ON LIKELY GEOMORPHIC RESPONSES TO CLIMATE CHANGE IN SAN FRANCISCO BAY-DELTA AND WATERSHED

Joan Florsheim[1] and Michael Dettinger[2],
[1]University of California, Davis;
florsheim@geology.ucdavis.edu [2]U.S. Geological Survey Scripps Institute of Oceanography;
mddettin@usgs.gov

Introduction

Geomorphic processes in the Sacramento-San Joaquin River and San Francisco Bay-Delta watershed (Fig. 1) responded, on a variety of time scales, to the warm climates and coincident sea-level rise of the Holocene (the past ~10K years). Within this watershed, lowland river floodplains and Delta fresh-water wetlands adjusted to accommodate large, natural upstream watershed hydrologic changes and downstream sea level fluctuations. During the past two centuries, though, the natural geomorphic systems have been extensively modified by human activities. Now, human induced climate changes are projected that may increase magnitude, frequency, and variability of winter floods and, thus, releases from dams that regulate flow in the major tributaries draining the Sierra Nevada and the Northern California Coast Ranges. Moreover, sea level rise is expected to accelerate in response to future global warming (IPCC, 2001). Thus, geomorphic processes in the Bay-Delta watershed may soon face new challenges associated with anthropogenic climate changes affecting both the upstream watershed hydrology and the downstream sea level that provide the large-scale boundary conditions for geomorphic change.

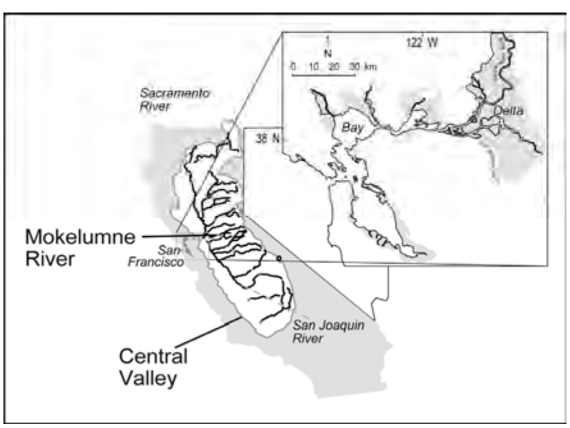

Fig 1. Sacramento-San Joaquin River and San Francisco Bay-Delta systems location map.

From our developing understanding of Holocene climate-induced physical changes in the Bay-Delta (Malamud-Roam et al., in review) and other lowland systems (e.g. Blum and Tornqvist, 2000; Brown, 2002; Aalto, et al, 2003), we can infer that currently projected climate changes (in response to anthropogenic changes in the global environment; Dettinger, 2005) probably would be sufficient to significantly affect geomorphic processes and in turn, floodplain and Delta wetland ecology. In this article, we outline some of the ways that geomorphic processes in lowland river systems may respond to future climate variations and change, with particular attention to the likely influence of 19th and 20th Century modifications of the Central Valley landscape on geomorphic responses.

River flow and the sediment budget

During the past two centuries, humans have built pervasive structural controls on floods and geomorphic responses to floods, and have dramatically changed sediment supplies throughout the Central Valley. Structure and function of floodplains and freshwater tidal marshes have been modified by dams and other structures that regulate flow and sediment transport from the highest elevation river reaches downstream to, and into, the tidal zone. Flows in most of the large tributaries draining the Sierra Nevada have been modified by dam construction. Hydrographs from streamflow gaging stations upstream and downstream of Camanche Dam on the Mokelumne River (Fig. 2) illustrate typical impacts of a dam on natural river flows. In 1997, the high magnitude flood peak was reduced by the presence of the dam while the duration of bankfull flow (about 140 m^3/s) was increased. In 2001, a drought resulted in relatively small reservoir releases throughout the year. The upstream gaging station (at Mokelumne Hill) is itself downstream of several large dams, reflected in the nearly constant dry season releases during both 1997 and 2001. Releasing bankfull flows for extended periods increases the period when the tractive forces of the river are sufficient to erode and transport sediment and thus these sustained bankfull releases could lead to increased duration of bed and bank erosion processes. Increased duration of bankfull flows also prolongs bank saturation, making banks more susceptible to erosion once the flow stage does drop. At the opposite end of the flow spectrum, prolonged dry-season flow reductions associated with dam (and diversion) operations are likely to impact riparian ecology and also may render banks more susceptible to erosion as the groundwater table drops. Moreover, longer drier seasons could lead to increased wildfire frequency that burns hillside vegetation and that potentially increases sediment supply to rivers.

Current projections of near-term climate change generally do not give much guidance as to whether droughts will become more or less common (Dettinger, 2005), but they do unanimously suggest that dry-season flows will decline due, in large part, to earlier snowmelt and runoff from the mountain watersheds. Furthermore, the trend towards earlier snowmelt and runoff is projected to take, in part, the form of increased flood magnitudes and frequencies (Dettinger et al., 2004). Thus, 21st Century warming of the region may aggravate several of the changes that dams and diversions already impose on the region's geomorphic systems.

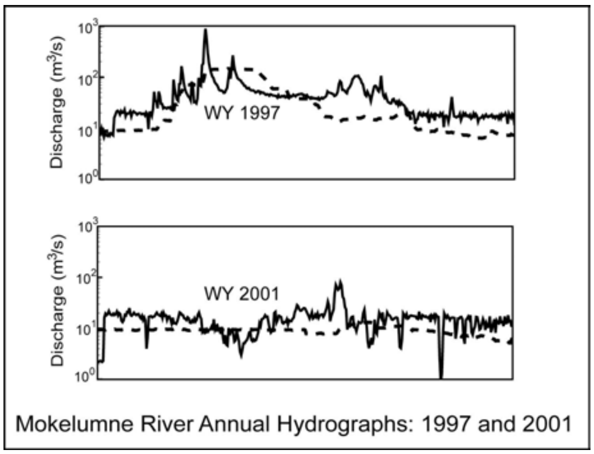

Fig 2. River flow regulation upstream (solid) and downstream (dashed) of Camanche Dam on the highly regulated Mokelumne River. Changes in magnitude, duration, and timing of reservoir releases during the high-magnitude 1997 flood and the 2001 drought.

In addition to modifying flow regimes throughout most of the watershed, humans have also changed land surfaces far and wide, and through these changes also have extensively (though inadvertently) modified the sediment budget of the Sacramento-San Joaquin River and San Francisco Bay-Delta watershed. Near the beginning of the last century, vast quantities of sediment were mobilized by hydraulic mining and other land uses and caused dramatic geomorphic changes in the Bay-Delta system (Gilbert, 1917), sending a pulse of sediment down the rivers and into the estuary. Then, during the 20th century, the upstream sources of sediment were markedly reduced by the end of hydraulic mining, the passage from the system of much of the large volume of sediment already in transit from the hydraulic-mining era, the progressive development of upstream reservoir storage, stream-channel aggregate extraction, and channel dredging for levee maintenance. Geomorphic responses to future climate changes will transpire in the context of these human activities and the controls that each still exerts on sediment sources, sinks, and transport in the system. Particularly, future geomorphic responses will depend on the presence (or absence) of remnants of the hydraulic-mining era sediments at critical points in the system, the relative dearth of sediment sources to supply future lowland geomorphic responses and recoveries, and the potential for accelerated channel incision and bank erosion into formerly stable alluvial deposits.

Climate-driven upstream and downstream geomorphic forcing factors

Climate drives watershed hydrology, which in turn plays a dominant role in downstream geomorphic processes. Current climate-change projections for California suggest that the total volume of snowmelt runoff that may be shifted from spring and added to winter flows may be as much as (or more than) 5maf/yr (Knowles and Cayan, 2004), a volume roughly equal to the reservoir storage that is set aside each year for the management of floods by the major foothill reservoirs of the Sierra Nevada. Changes in timing of reservoir releases to accommodate this shift could either add to the magnitude of winter flood peaks or add to their durations. These alternatives would have differing geomorphic consequences.

At the downstream end of the fluvial system, sea-level fluctuation is the major forcing factor affecting geomorphic processes. The combination of upstream and downstream forcing factors governs the avulsion[1] threshold, where avulsion is the natural dynamic processes by which multiple channel anastomosing fluvial systems break levees, create crevasse splay deposits, and switch channel location and where the threshold in question is the flow level at which avulsion begins. In lowland rivers, the avulsion threshold is exceeded when flow discharge increases to the level where natural or human constructed levees are breached. Sea level rise, either as a simple continuation of historical trends or in response to global warming, increases the probability of avulsion because it results in

[1] Avulsion is the natural dynamic processes by which multiple channel, or "anastomosing" fluvial systems break levees, create crevasse splay deposits, and switch channel location (a crevasse splay is a fan shaped sand or silt deposit formed on the floodplain where flow and sediment from the main channel is transported through the levee break).

overall decreases in along-channel slope and coincident increases in cross-valley slope associated with the aggradation., In lowland alluvial valleys, increases in cross valley slope occur on reaches that sit at higher elevations above the surrounding floodplain. This results from sediment deposition occurring in the channel and floodplain along an active channel belt, locally raising elevation higher than the elevation of adjacent relatively inactive portions of the valley bottom. Any increases in flood magnitudes associated with climate change could raise river stages enough to breach natural (or human constructed) levees, and allowing erosion and deposition of crevasse splay and channel complex sediment into lower elevation areas.

River and delta levee break thresholds

A review of historical geomorphic responses to floods illustrates the dominance of structural controls in the lowland parts of the present-day Sacramento-San Joaquin watershed. Levees concentrate flow into single channels and isolate floodplains from sediment and nutrient exchanges with adjacent river channels, banks, and floodplains. Flood basin wetlands, first described by Gilbert (1917), and multiple-channel floodplain systems were progressively developed into flood-bypass channels as levees confined channels and isolated floodplains (Florsheim and Mount, 2003). In the Delta, construction of levees that led to subsidence, along with alteration of sediment and flow regimes, invasions by alien species, contamination by pollutants, and other changes transformed the ecology.

Projected increases in wintertime flows accompanying already-large floods could increase overbank flood extents, erosion, and sedimentation, or alternatively could increase the depth and strength of confined flows and thereby increase the risk of levee failures. Earlier, winter runoff released from reservoirs as a relatively constant addition to winter base flows would increase the duration of bankfull or possibly "levee-full" flows, leading to bank and levee failures through increased saturation and seepage erosion.

The history of levee breaks since 1850 (Fig. 3) illustrates the important role of past floods in precipitating the breaches and shows that the numbers of breaks has not declined through time despite historical management practices. However, quite a few breaks in the Delta have occurred during dry seasons (e.g. 1980 and 2004) as a result of high tides, wind waves, or the inherent structural weakness in some of the levees (Florsheim and Dettinger, 2004; Fig. 3).

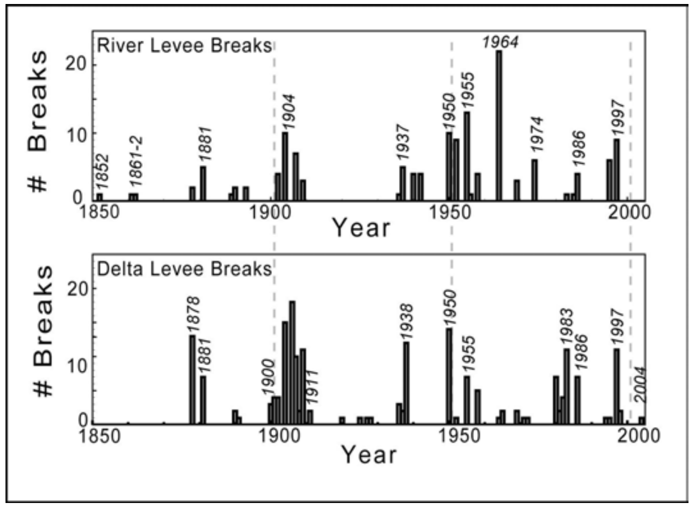

Fig 3. Sacramento and San Joaquin Rivers, tributary, and Delta levee breaks since 1850. Both river and Delta levee breaks are coincident with significant storms that occurred in the late 1800's, the early 1900's, 1937-8; the mid-1950's and about every decade since then. Some breaks occur during smaller floods, or for reasons not related to storm hydrology, e.g. the recent Jones Tract Delta levee break in June 2004.

The history of levee breaks shown in Fig. 3 shows that the existing infrastructure is primarily effective in controlling relatively low to moderate floods, so that levee breaks along the lowland Central Valley rivers and within the Delta are still quite common during decadal and more frequent floods, and are not even completely lacking during prolonged drier periods (Florsheim and Dettinger, 2004). Projections of an additional sea level rise of 20-80 cm during the 21st century would compound the vulnerability of subsided Delta Islands to levee failure (described in Mount and Twiss, 2005) and increase upstream backwater flooding.

If floods of magnitudes associated with increased channel erosion or levee breaks are exceeded with greater frequency as a result of future climate changes, future geomorphic responses will reflect the 19th and 20th Century structural changes, along with any reservoir-management changes undertaken to accommodate those flood changes. In this scenario, 19th and 20th Century structures pose major risks and threats to environment and structures. Whereas the natural geomorphic system was dynamic and adjusted to the climate variations of the Holocene creating ever changing patterns over the long-term throughout vast lowland areas, today, people struggle and engineer to moderate processes and confine the geomorphic system to control floods and accommodate development. In combination with the well documented, persistent and detrimental ecological effects of human activities isolating ecologically important floodplains from their intermittent sources of flood-borne nutrients and sediment, subsidence of Delta islands, and wide-scale land use conversions, the pervasive modification of the Bay-Delta watershed may actually have weakened the engineered capacity of the system to accommodate and prosper in the face of future climate variations and changes.

Conclusions

Geomorphic processes in 21st Century California operate in a landscape dominated by levees and dams. Thus, a critical question is: How have human activities influenced the way that climate variation and change will affect geomorphic processes in the lowland portion of the Bay Delta watershed? Based on review of currently available data, the survivability of existing infrastructure and decisions about timing, magnitude and duration of flow releases from upstream reservoirs appear likely to determine the nature of geomorphic responses to future climate variation and change. Based on this review, we suggest that 19th and 20th century modifications may have made the lowland portion of the Bay-Delta watershed more vulnerable to climate variations and changes than it was under natural conditions.

Acknowledgement

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Florsheim, J.L. and Dettinger, M.D., 2004. Influence of anthropogenic alterations on geomorphic response to climate variation and change in San Francisco Bay, Delta, and Watershed, Eos Trans. AGU, 85*(47), Fall Meet. Suppl., Abstract H51A-1108.*

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