Status of the Lower Sacramento Valley Flood-Control System within the Context of Its Natural Geomorphic Setting

Michael Bliss Singer[1]; Rolf Aalto[2]; and L. Allan James[3]

Abstract: The Sacramento River's flood-control system was conceived as a series of weirs and bypasses that routes floods out of the leveed main channel into natural floodways engineered to drain directly into the bay delta. The system, superimposed on a natural geomorphic setting consisting of geologic, sedimentary, and tectonic controls, still relies on weirs and bypasses to keep low-lying communities dry during floods. However, the Sacramento Valley bypass system exhibits widespread evidence of impairment by sedimentation, especially at prehistoric loci of alluvial splays. Episodic flooding in the basin delivers large volumes of sediment that accumulate throughout the flood bypasses, especially from legacy tailings fans that originated in the hydraulic mining era. In addition to decreasing flow capacity, these deposits promote colonization of vegetation, which, in turn, increases roughness and decreases flood conveyance. We document three bypass regions that are affected by natural geomorphic controls, where consistent sedimentation occurred prior to and since bypass construction. Deposits forming at the entrance to Colusa and Yolo Bypasses increase stage thresholds for flows entering the floodway, exacerbating flood risk in the main channel downstream of the entrance. Deposits forming in downstream reaches of bypasses such as Colusa Bypass affect flood conveyance, potentially causing backwater effects that could limit diversion of flood discharge into the bypass system. Systematic bypass deposition tends to occur in locations where local backwater effects are imposed by river confluences. One particularly acute choke point for sediment occurs at the confluence of Sutter Bypass, Feather River, and Sacramento Rivers, where the ancestral Cache Creek fan compresses valley drainage. These factors and concerns generated by the Katrina disaster have motivated sediment removal from the inlets to bypasses and levee repair along main channels, but it is unclear how effective these measures will be in the coming decades, especially within the context of flood conveyance throughout the entire system and regional climate change.

DOI: 10.1061/(ASCE)1527-6988(2008)9:3(104)

CE Database subject headings: Floods; Hydrology; Flood plains; Sedimentation; Weirs; Basins; Risk management; California.

Introduction

The flood-control system in the Lower Sacramento Valley, California, provides vital protection to many lowland floodplain communities including the metropolitan area of Sacramento (population >2 million). Its efficacy or lack thereof is widely discussed following major floods in the valley and elsewhere (e.g., after the recent destruction of Hurricane Katrina in New Orleans), because thousands of homes are situated well below historical inundation levels of the extensive flood basins. However, much of the public discussion centers on engineering levees along the main channels and on dams that reside on the basin periphery. Much less focus is put on the weir and bypass system that conveys the vast majority of discharge through these basins, the history of which is discussed in a companion paper (James and Singer 2008). While dry most of the time, this component of the flood-control system (Fig. 1) is the most important because it conveys high flows out of the main valley channels, Sacramento and Feather Rivers, through engineered conveyance floodplains to the Bay-Delta (a merging of the Sacramento and San Joaquin deltas and the San Francisco Bay). As such, the weir and bypass system is also the chief receptacle for sediment delivered from the uplands, but this aspect of its functioning is not acknowledged except for at the inlets to the system.

In the companion paper, we outline the political and engineering history that led to the creation of the existing flood-control system, which still functions ~90 years after its inception (James and Singer 2008). However, this weir and bypass system is evidently under threat from floods of increasing magnitude and frequency, which are associated with regional climate change (Knowles and Cayan 2002; Dettinger and Cayan 2003; Knowles and Cayan 2004; Singer 2007), and which can deliver large volumes of sediment capable of impairing the functioning of the bypass system. At the moment, there is poor understanding of how the system transports sediment during floods and its evolving sensitivity to sediment accumulation, especially within the context of the exogenous controls that predate human settlement of the valley.

---

[1] Lecturer, School of Geography and Geosciences, Univ. of St. Andrews, Irvine Building, North St., St. Andrews, Fife, Scotland KY16 9AL, U.K., and Assistant Researcher, Institute for Computational Earth System Science, Univ. of California Santa Barbara. E-mail: bliss@icess.ucsb.edu

[2] Associate Professor, Dept. of Geography, Univ. of Exeter, Exeter EX4 4RJ, U.K.

[3] Professor, Dept. of Geography, Univ. of South Carolina, Callcott Rm. 206, Columbia, SC 29208.

Note. Discussion open until January 1, 2009. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on August 3, 2007; approved on March 7, 2008. This paper is part of the ***Natural Hazards Review***, Vol. 9, No. 3, August 1, 2008. ©ASCE, ISSN 1527-6988/2008/3-104–115/$25.00.

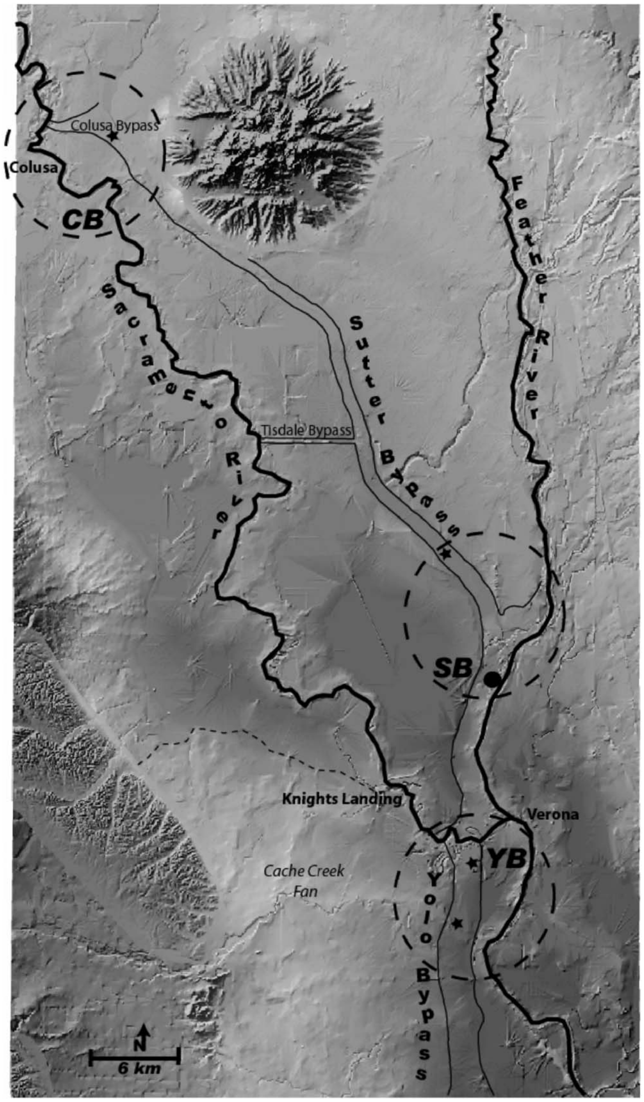

Fig. 1. Area of the Lower Sacramento Valley flood control system, including the Sacramento and Feather Rivers, the bypass system, and Cache Creek Fan (the northern extent of which is indicated by dashed line). Bold dashed circles highlight featured study areas. CB, SB, and YB, are Colusa, Sutter, and Yolo Bypasses, respectively. Stars indicate coring loci discussed in the paper and the filled circle in SB indicates surveyed deposit. Base map: USGS National Elevation Dataset, 1 arc second.

In this paper, we: (1) summarize the natural geomorphic setting of the weir and bypass system; (2) describe its evolving role in controlling floods in the Lower Sacramento Valley; (3) collate historic and recent observations of sedimentation in characteristic parts of this system; and (4) catalog challenges for system management. We intend this study to identify growing flood risks in the basin that are not well appreciated and to discuss them within the context of the valley's presettlement geomorphic history.

Study Area and Natural Geomorphic Setting

The 68,000 km^2 Sacramento Valley is drained by two main trunk streams, Sacramento and Feather Rivers, which derive flow and sediment from four primary geologic units in northern California: the Sierra Nevada to the east; Coast Ranges to the west; the Trinity Mountains to the northwest; and the Modoc Plateau to the northeast. Due to its relatively large drainage area in the Sierra Nevada range, the Feather River delivers the largest floods to the Lower Sacramento Valley, despite three major dams in the foothills (Singer 2007). It has historically also been the greatest source of sediment in the lower valley, due to the legacy of hydraulic gold mining in the Sierra (Gilbert 1917).

The trunk streams are naturally affected by valley tectonics and geology, as well as by the valley's sedimentary history. River position within the valley is generally controlled by valley tilting, faulting and folding, resistant outcrops and intrusive rocks, and large Pleistocene alluvial fans (Harwood and Helley 1987; Water Engineering and Technology 1990; Fischer 1994). For example, the alignment of the Sacramento River upstream of the city of Colusa closely follows the trace of the Willows Fault and is controlled by outcrops of the resistant Modesto Formation visible in bank exposures (Fischer 1994), until it encounters the buried Colusa Dome (beneath the city of Colusa), composed of relatively resistant uplifted Cretaceous rocks (Harwood and Helley 1987), which causes a major eastward deflection of river course (Fig. 2). This condition results in a decrease in downstream channel capacity, from ~7,000 m^3/s upstream of Colusa to ~2,000 m^3/s downstream [see Congressional testimony of Gen. U.S. Grant III and B.A. Etchevery from 1927 (Kelley 1972)], and sequestration of water and sediment in the reach of the Sacramento Valley upstream of the deflection (Singer and Dunne 2001, 2004b; Singer 2007).

The reduction in downstream channel capacity during floods causes a backwater to form in the Lower Feather River, which joins the Sacramento near Verona, ~100 km downstream of Colusa (Fig. 1). Similarly, the ancestral (Pleistocene) fan of Cache Creek, a west-side tributary of the Sacramento, apparently pushed the river northeastward downstream of Knights Landing in the vicinity of Fremont Weir so that its course to Verona trends west-east, instead of in the direction of the prevailing north-south valley slope (Fig. 1). The influence of Cache Creek fan on drainage in this region necessitated the construction of the Knights Landing Ridge Cut, a canal that cuts through the fan and routes flood waters accumulating in Colusa Basin to Yolo Bypass (Baugher 1984).

Within the confines of such geologic, tectonic, and sedimentary controls, the trunk streams meandered over aggraded beds, built natural levees along their courses, and overflowed frequently into relatively low natural flood basins that occupy the majority of the land area in the Sacramento Valley (Gilbert 1917; Bryan 1923; Kelley 1966), modulated by the influence of major runoff-producing cyclonic frontal storms and high postglaciation sediment supply. According to Kelley (1966):

> "The beds of the streams which cross the valley floor . . . could never carry the flood flows. Characteristically, the water rose to flow overbank in thin sheets over vast areas. Due to the decreased velocity of this outflow, it dropped its burden of silt near the banks of the streams and rivers, building up natural levees."

Under presettlement conditions, flow into the flood basins from the main channels tended to occur at locations where levee materials were weak enough to promote crevasses or at low points in the natural levee. Such exit locations, often at the entrance to sloughs (Kelley 1966), were often coincident with tectonic and geologic controls that forced repeated occupation of flow through these points of levee weakness (Fig. 2). Flooding

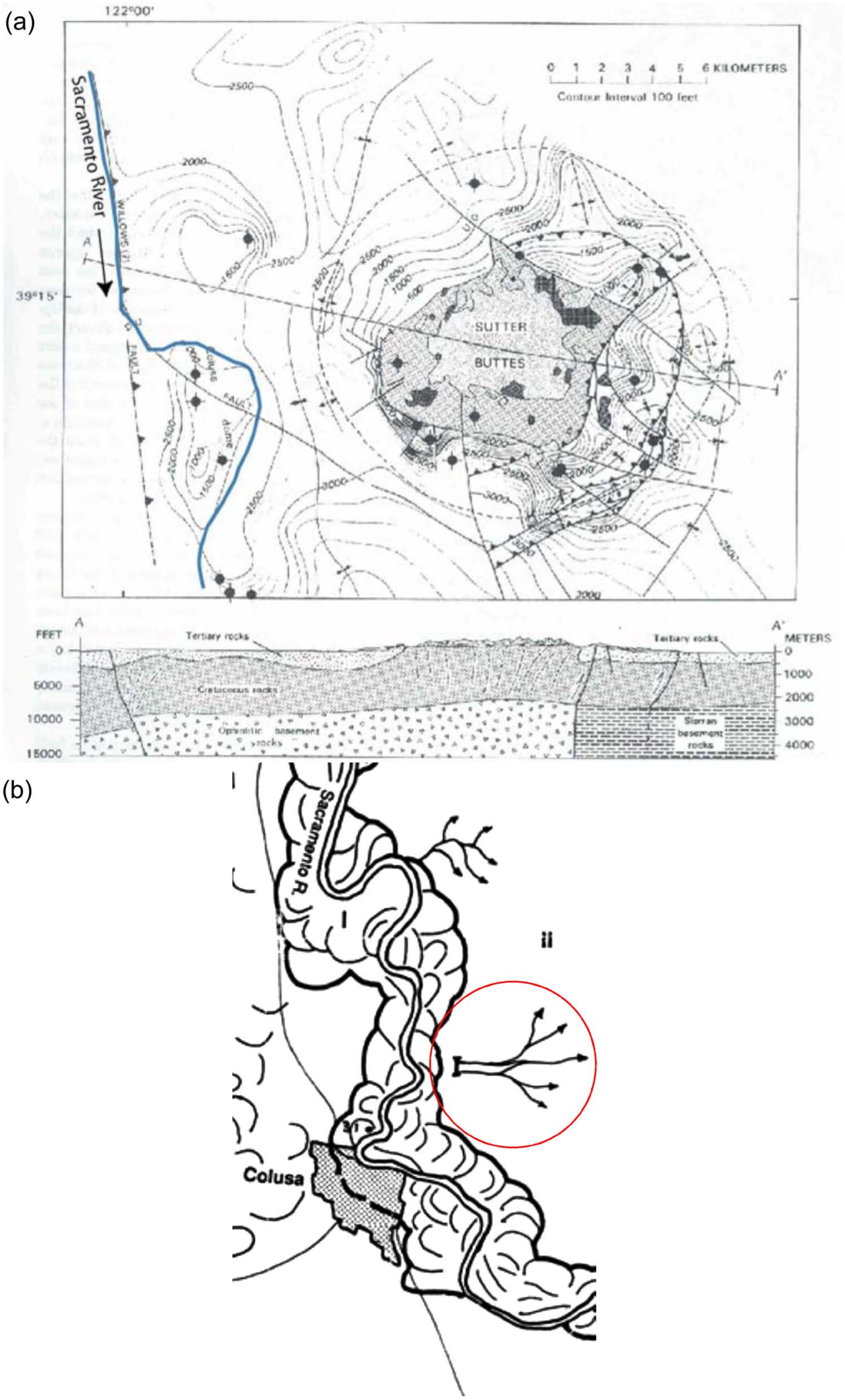

Fig. 2. (a) Tectonic and geologic controls on the Sacramento River [modified from Harwood and Helley (1987)]; (b) meander belt deposits and alluvial splay near Colusa [modified from Robertson (1987)]. Shading indicates city boundary.

would thus fill the contiguous flood basins (Fig. 3), resulting in the development of an "inland sea" that is well documented elsewhere (Kelley 1998) and discussed in the companion paper within the context of flood control development (James and Singer 2008). While valley flooding was essentially a seasonal phenomenon, its depth and areal extent were maximized during extreme floods. Based on flood history in the Sacramento River (USACE 1998), large, basin-filling floods have occurred in 17% of the years between 1878 and 2001 and likely occurred at a similar frequency prior to flood records.

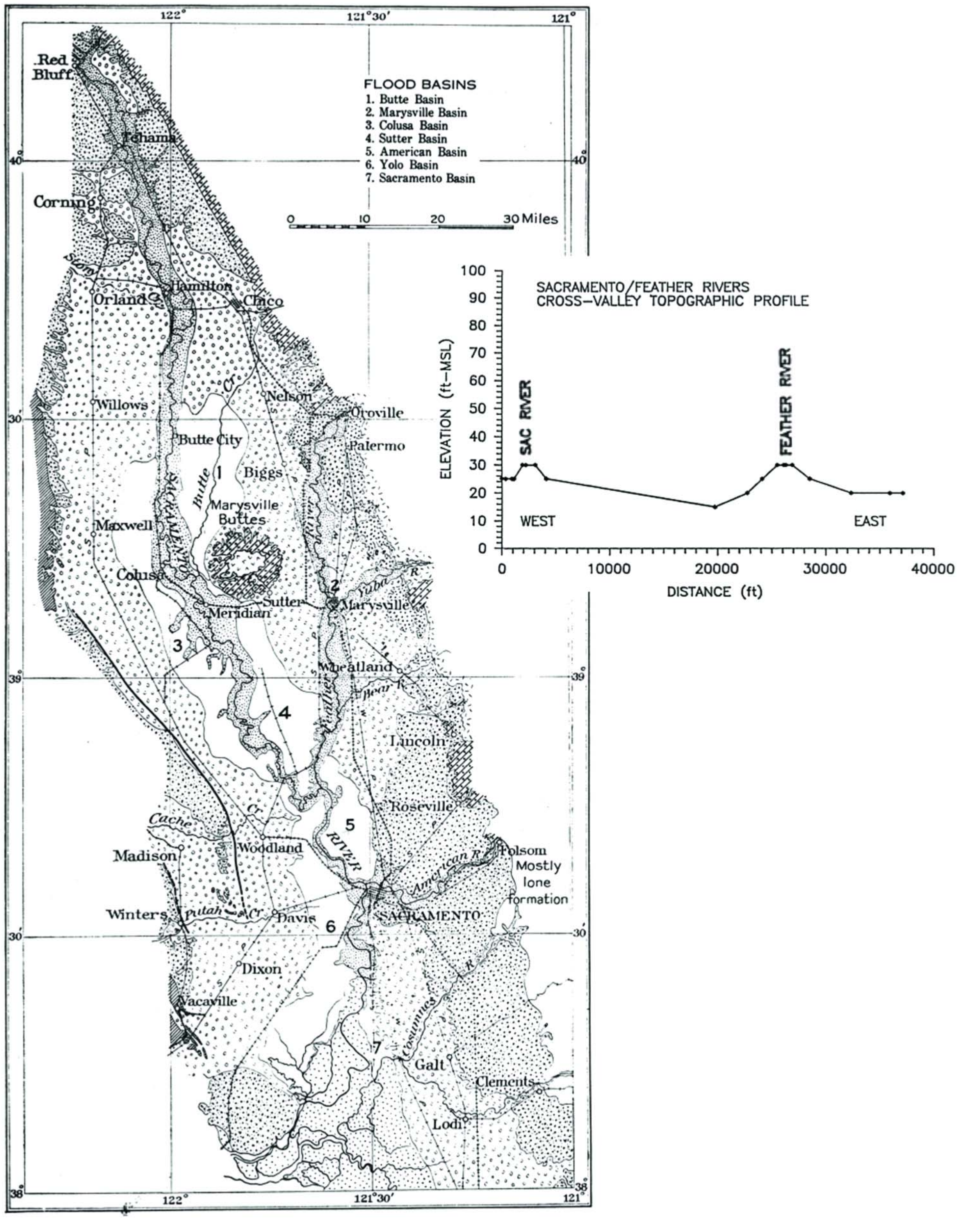

Fig. 3. Flood basins of the Sacramento Valley [from Bryan (1923)]. Inset: cross-valley topographic section [from Water Engineering and Technology (1990)].

Since the subsiding (Fischer 1994; Ikehara 1994) land surface outboard of the natural levee is lower in elevation than floodplains along the river corridor (Fig. 3), sediment carried primarily in suspension was transported by advection out of the channel through these exit loci into the bounding natural flood basins. The resulting pattern of sediment accumulation near the channel margins has been documented as alluvial splays along the Sacramento River (Robertson 1987) (e.g., Fig. 2). Other documentation of this natural process is provided in USGS 7.5 minute topographic maps of the Yolo Basin area (Fig. 4), which predate the flood control system and shows significant topography near the river channel in a pattern similar to natural levees observed on Strickland River in Papua New Guinea (Aalto et al. 2008) and the Brahmaputra River in Bangladesh (Bridge 2003).

These factors indicate valley-scale controls on the alignment of river channels, on the conveyance of flood waters, and on the disposition of sediments transported in suspension. It is within this context that permanent settlers arrived in the Sacramento Valley to practice agriculture and mine for gold. Farming required the construction of local flood control levees to "reclaim" fertile floodplain land located in natural flood basins for agriculture. Mining involved massive production of sediments in the Sierra foothills, much of which was delivered to the lower Sacramento Valley. Both activities exacerbated natural flooding in the valley and added to the need for the Sacramento flood control project (James and Singer 2008).

Superimposition of the Flood-Control System

At the time of the Gold Rush in the Sacramento Valley in the latter half of the 19th century, flooding was recognized as an impediment to human settlement and agriculture production

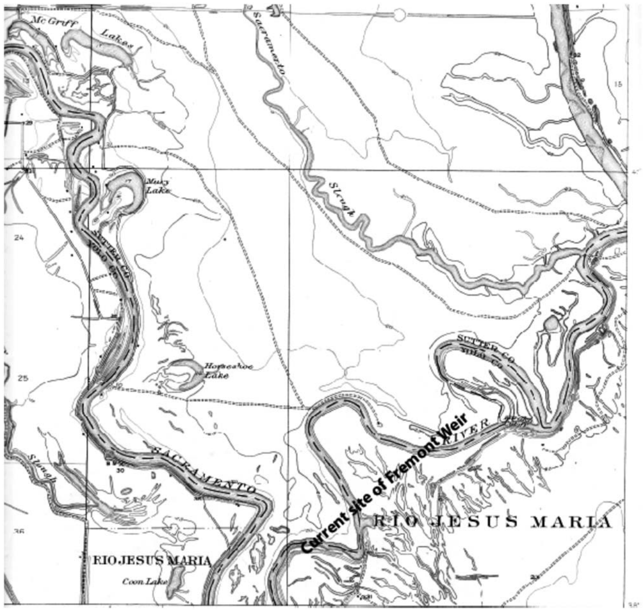

Fig. 4. Topographic expression of alluvial deposits along the southern margin of the Sacramento River at the current site of Fremont Weir [USGS (1910)]

(Kelley 1998). Although hydraulic mining was blamed at the time for causing extensive valley-floor flooding, extreme floods predated the period of hydraulic mining in the Sierra Nevada (Thompson 1960). The flood control system devised to mitigate these flood hazards utilized a subset of the aforementioned exit loci and lowland flood basins of the Sacramento Valley as weirs and bypasses, respectively. Between the 1930s and 1960s, major exit points along the mainstem Sacramento River were dug out and concrete grade control structures were installed to convey flows to the Bay-Delta through portions of the natural flood basins bounded by engineered levees (McClure 1927; Kelley 1966, 1998; James and Singer 2008). For example, one of these exit points was the ~75 m × 3 m "Jones Break," alternately called "Old Moulton Break," which occurred in 1896 and remained open until it became Colusa Weir several decades later (Kelley 1972). The flood control system, based on weirs and bypasses, was thus superimposed on the natural geomorphology of the Sacramento Valley floor and inherited natural topographic features and processes.

The flood control system was later enhanced with several dams located on the basin periphery, but they play a relatively minor role in controlling flooding in the Lower Sacramento Valley (Singer 2007). This was recognized by government authorities at the time of flood control construction (Jones 1926):

> " . . . owing to the small watersheds above…mountain reservoir sites, only a small part of the total runoff of the river can be caught in them and even complete storage of it can have but relatively slight effect on the flood height of the stream in the valley where flood protection is most needed."

During the design phase of the flood control system, there were discussions, debates, and legal challenges pursuant to the location and dimensions of conveyance channels, their geometry with respect to main channels, the elevations of weirs and levees, and the impacts of sedimentation. This concern was at least in part a response to the understanding among competent field scientists that natural geomorphic processes preserved within the engineered system could affect its operation for flood control.

Meanwhile, politics was also a factor in design of the flood control system, as exhibited by an influential reclamation district's successful lawsuit against the government for an eastward relocation of the proposed Sutter Bypass alignment, so as not to disturb their highly productive agricultural activities in the central part of Sutter Basin. This roiled the secretary of the Reclamation Board, whose primary concern was safety from floods. At a public hearing with a US Congressman in 1915, Ellis (1939) vocalized concerns:

> "The original plan of flood control formulated by Captain Jackson [of the US Army Corps] contemplated that this by-pass be located in the natural trough of that basin . . . Afterwards, this [Central] location of the by-pass was abandoned by the majority members of the State Reclamation Board . . . [for] what is generally known as the "Eastern location." This abandonment . . . was without my approval . . . [because] it was a radical departure from the basic principle laid down in the original plan . . . that all by-passes should follow the "natural troughs" of all the great basin areas . . . To oppose the natural laws and the habits of the flow of a large volume of water . . . is a most serious problem and experience should teach us that in deciding upon plans for the control of flood waters . . . the factor of safety must well be considered."

After losing the battle over placement of Sutter Bypass, Ellis (1939) anticipated problems of sediment accumulation and conveyance in the bypasses:

> ". . . the disposal of silt is going to be quite a problem in the flood control plan. In the Eastern location of the by-pass there is not a single inch of fall in ground level from the mouth of the Tisdale By-pass to Fremont Weir . . . [and therefore no] depression to [accommodate] such [a] silt deposit."

Gilbert (1917) had previously weighed in on sediment problems in his conceptual assessment of the system relevant to the legacy of hydraulic mining:

> "One of the consequences of the projected changes will be the exclusion of the river-borne debris from the lands now inundated. At the present time, as in past times, a considerable fraction of the fine debris carried by the flood waters is deposited on the inundated lands. The substitution of by-passes for flood basins is the substitution of channels for reservoirs. In these by-channels the velocities of flood waters will be sufficient to prevent permanent deposition . . . The canals [will] have sufficient fall to prevent clogging by sediments. So they will not be receptacles of debris; and when the system shall have been completed all the fine debris will be carried to the bays."

And in his outline of fundamental principles in the project design, the chief engineer for the State of California suggested (McClure 1927):

> " . . . the weirs should be so located as to permit the least possible amount of debris being carried into the by passes from the river channel."

It is clear from these discussions that there were concerns about the capabilities of the weir and bypass system to convey the floods and sediment delivered to them. The conceptual expectation expressed by Gilbert and McClure was that the combination of weirs and engineered floodways would limit the sediment input and maximize the sediment conveyed through the bypasses, respectively. However, given the uncertainties and limits to the state of contemporary knowledge of the natural geomorphic setting and processes (i.e., geology, tectonics, and sedimentary history), there was considerable potential for error in this conceptual design. The subsequent section summarizes, within the context of the natural system described above, the efficacy of the flood control system in disposing of sediment over the ~90 years since its inception, with implications for further topographic and stratigraphic evolution.

Historic and Recent Observations

Several sources of information on sedimentation in the bypass system document what has occurred since the system was created. In particular, these data highlight the features of the bypass system that were inherited from its natural geomorphic predecessor. There are estimates from a reassessment of Gilbert's classic work on sediment disposition from hydraulic mining in the Sierra foothills (USACE 1985), several engineering reports detailing sediment delivery, storage, and removal (State of California Resources Agency 1973, 1974; USACE 1985; California Department of Water Resources, unpublished), and recent field and laboratory findings of our own that include various measurements of sedimentation. The subsequent discussion outlines general patterns of sediment deposition in three key areas within the bypass system: Colusa Bypass, Sutter Bypass, and Yolo Bypass (Fig. 1). These locations illustrate the general patterns expected to occur at other key loci within the system.

The Colusa Weir, built on the site of an historic natural levee break upstream of the city (Kelley 1972), is a key evacuation point that diverts flood waters into Colusa Bypass and later drains into Sutter Bypass at its upstream boundary (Fig. 1). Largely due to the control of Colusa Dome on the Sacramento River near Colusa (Fig. 2), this principal entrance into the flood control system completely cut off overflow westward into Colusa Basin (Fig. 3). Therefore, Colusa Weir became fundamental to flood control in lower Sacramento Valley because it is the only major exit point for flood flows upstream of the aforementioned channel constriction.

Colusa Bypass was originally designed to include a sediment basin at its downstream end with a storage capacity of 765,000 m^3. In its early stages of implementation, the design was criticized for delivering huge quantities of unanticipated sediment to a flow easement zone, or privately owned area prone to flooding for which the owner is compensated (State of California Resources Agency 1973, 1974). Flood-control authorities were, thus, forced to purchase additional easements for sediment deposition, to bid out contracts for sediment removal, and to plant vegetative buffers in Colusa Bypass. Nevertheless, sediment continued to accumulate throughout the bypass such that 2.7×10^6 m^3 arrived between 1968 and 1982, or about one-third of the sediment that passed over Colusa Weir during this period (USACE 1985), with the remainder conveyed downstream into Sutter Bypass. For the water year with the largest sediment flux within this time span (i.e., 1969–1970), deposition was approximately equivalent to the design capacity of the sediment basin. Consequently, Colusa Bypass flow conveyance capacity progressively declined.

Sediment deposition in Colusa Bypass and sediment basin began at its downstream end (near Sutter Buttes, Figs. 1 and 2) and backfilled toward Colusa Weir (Fig. 5). Over time, this headward infilling caused a backwater in Colusa Bypass that limited flow escapement from the mainstem Sacramento River. This impairment is illustrated by increasing values of flow required to overtop Colusa Weir compared with flow on the mainstem Sacramento at Colusa (Fig. 5). These factors suggest a tendency for progressive and systematic infilling of Colusa Bypass and its sediment basin. Such bypass impairment was apparently of concern to flood control authorities, who have spent considerable funds to remove sediment from bypasses and installing riprap on channel banks to prevent further erosion upstream in the Sacramento Valley (USACE 1985). Internal documents from the California Department of Water Resources show that $\sim 4.8 \times 10^6$ m^3 was removed intermittently between 1983 and 1999. Although such sediment removal decreases the immediate impact of sedimentation, excavation appears to have been focused near the weir. Ongoing sedimentation may, therefore, continue to elevate the lower portions of the Colusa sedimentation basin.

According to our recent data for sediment accumulation in the bypasses, the deposition continues to this day during large floods. We extracted a 3 m sediment core from the Colusa sediment basin [Fig. 6(a)], analyzed it via ^{210}Pb (which has an excess activity lifetime measurable to approximately 2 half-lives, or ~45 years, in our basin) with techniques we have discussed elsewhere (Aalto et al. 2003, 2008). This core shows that ~2 m of sediment accumulated at this site during flooding in the past several decades, suggesting this area is a massive depocenter for sediment. Given that Colusa Bypass and its basin apparently only trap about one-third of the sediment transported over Colusa Weir (USACE 1985), such significant rates of deposition are likely to continue at locations downstream in Sutter Bypass.

Sutter Bypass extends downstream from its northern boundary near the Sutter Buttes through Sutter Basin (Fig. 3), receiving flow and sediment from Tisdale Weir and the Feather River confluence before reaching its terminus at the Sacramento River near Fremont Weir (Fig. 1). It is controlled at its downstream end by the deflection of the Sacramento River eastward by Cache Creek Fan (Fig. 1), which caused compression of drainages and a relatively northern convergence of the Sacramento and Feather Rivers. These factors, coupled with relatively small channel capacity in the Lower Sacramento River, force flow over Fremont Weir into Yolo Bypass (see below). However, the Fremont Weir (~10 m ASL) lies several m above the bed in the downstream portion of Sutter Bypass, limiting the rate of flow evacuation over Fremont. Ellis (1939) remarked on the elevation of Fremont Weir, the crux of the entire flood-control system in the Lower Sacramento Valley:

> "The Sutter By-pass, where now located, is of course a 'fixture' and cannot now be changed but as for the Fremont Weir, the greater portion of it, about its center, could be and, in my opinion, should be, 'chiseled down' to the same height as the floor of the Sutter By-pass . . . [Before the weir was built] flood waters had no difficulty in discharging into the Yolo Basin. Such is not now the case, since the construction of the Fremont Weir."

The height of the weir was set well above the elevation of the bed of the Sutter Bypass, in order to induce scour in the Sacramento River channel (Jones 1967; James and Singer 2008). As a consequence, southerly flow in Sutter Bypass tends to back up when there is significant flow in this convergence zone, leading to deposition in the bypass.

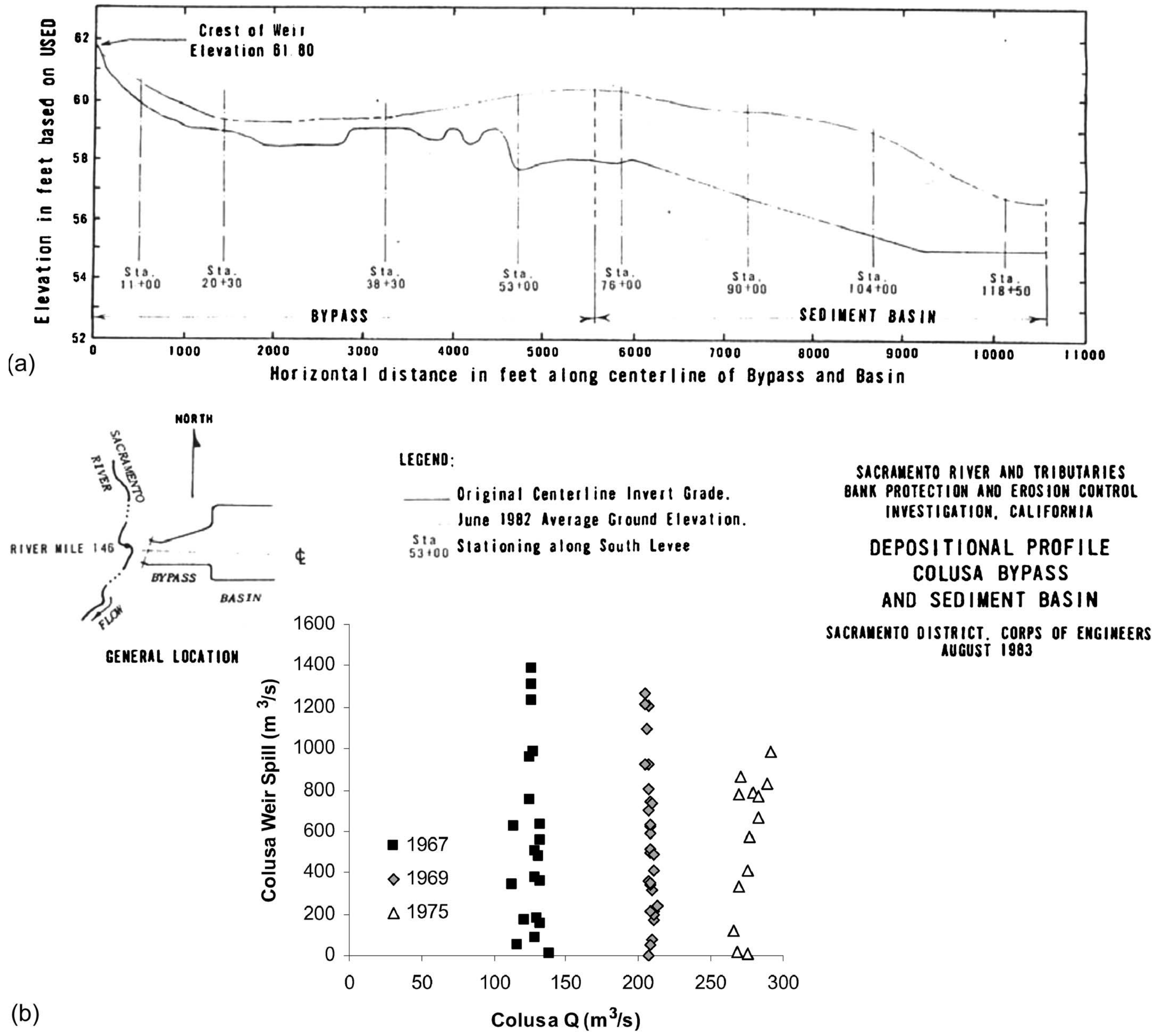

Fig. 5. Effects of sedimentation at Colusa Bypass: (a) profile downstream of entrance to Colusa Bypass indicating infilling of sediment between 1968 and 1982 [from USACE (1985)]; (b) the impact of sediment accumulation on flow entering Colusa Bypass over Colusa Weir (compared with flow measured along the mainstem Sacramento at Colusa)

Survey data on historical deposition between 1939 and 1979 indicate $\sim 23 \times 10^6$ m^3 of sedimentation in the whole bypass, but it is not uniformly distributed (USACE 1985). According to this survey, the majority of the sediment ($\sim 19 \times 10^6$ m^3) accumulated in the upper portions of Sutter Bypass between the Sutter Buttes and Tisdale Weir, while the remainder was deposited upstream and downstream of the Feather River confluence (Fig. 1). The Upper Sutter Bypass sediments largely originate from the Sacramento River escapement flow over Colusa Weir and pass through Colusa Bypass and sediment basin to the entrance of Sutter Bypass. Apparently very little sediment passes through Butte Sink, which receives flow from upstream diversions along the Sacramento and eastern tributaries. Sediment tended to pile up at the bypass entrance, which necessitated removal of 1.7×10^6 m^3 by flood control authorities in the early 1940s, soon after the bypass was constructed (USACE 1985).

The prior estimates for the lower portions of Sutter Bypass, in particular, likely significantly underestimate sedimentation because they were based on an extrapolated survey of 40% of the Sutter Bypass area that focused on its western side (USACE 1985). There are several reasons to believe that Lower Sutter Bypass sedimentation is substantially higher on its eastern side: relatively coarse grain sizes transported by the Feather River that deposit in close proximity to the channel, the apparent pattern of accumulation along the margin of Feather River (evident as a characteristic lobate form in elevation data on the eastern side of Sutter Bypass downstream of the Feather; Fig. 1), and the spatial extent of a survey we conducted of a recent deposit in this region of the bypass. This latter deposit of $\sim 2.5 \times 10^6$ m^3 arrived during a single flood in 1986 and buried a rice field in several m of sand, silt, and clay on the eastern side of the bypass (Figs. 1 and 7), which tapered down to less than 1 m on the western side. Many

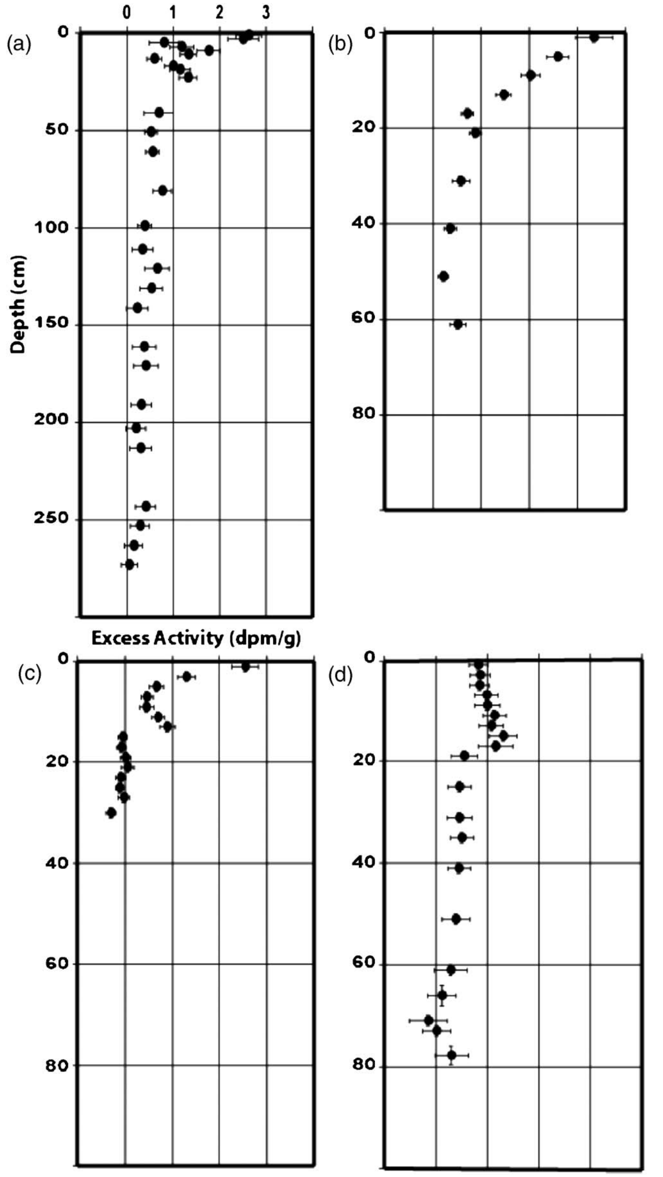

Fig. 6. Excess ^{210}Pb activity in sediment cores highlights deposition during individual sedimentation events in (a) Colusa Bypass; (b) Sutter Bypass; (c) Yolo Bypass below Fremont Weir; and (d) Yolo Bypass downstream of Cache Creek. Activity plateaus represent decadal-scale deposition, spikes above 2 dpm/g (horizontal scale in a) represent recent exposure.

such deposits have accumulated in the eastern part of Sutter Bypass, probably due to proximity to the channel and settling velocities of the sandy suspended sediment. Indeed, Jones (1967) recognized:

> "A large volume of the sediments from the Feather River have been permanently deposited in the lower [13 km] of Sutter Bypass with which that river is coincident and a large secondary delta has been built up at the northerly end . . ."

We have analyzed a core from Sutter Bypass upstream of the Feather confluence (Fig. 1) that shows ~40 cm of accumulation during large floods of the past several decades [Fig. 6(b)], which suggests this confluence also backs up Sutter Bypass flood conveyance and forces deposition of sediment carried from upstream portions of the bypass. In other words, evidence we have collected indicates that sediment builds up in the upper, middle, and lower sections of Sutter Bypass, though it is unclear how much of this sediment travels over Fremont Weir into Yolo Bypass.

Fig. 7. Image (U.S. Department of Agriculture DOQQ (2006) from http://datagateway.nrcs.usda.gov/) of backwater region of lower Feather River and Sutter showing deposition in the bypass along the Feather's western bank in the eastern portion of Sutter Bypass. Site is ~3 km upstream of Sacramento River confluence and flow is top to bottom on the photo. Deposition during the flood of 1986 built up the eastern portion of the bypass by more than 3 m. Woody vegetation, evident as darker patches, has colonized much of the deposit. Inset: photo from the western part of this deposit indicating more than 1 m of accumulation.

Yolo Bypass originates on the right bank or southern margin of the Sacramento River directly south of the Sutter Bypass terminus. It receives flow and sediment from the Sacramento River, the Sutter Bypass, and the Feather River, all of which mix in the convergence zone created by Cache Creek Fan (Fig. 1) and travel over Fremont Weir during floods. As mentioned prior, Fremont Weir is the rate limiting control on flow into Yolo Bypass. This flood flow into the bypass is joined by input of water and sediment from Cache Creek several km downstream (Fig. 1) and occasionally from the Sacramento Bypass routing floods out of the Sacramento River near its confluence with the American River. Yolo Bypass travels through Yolo Basin (Fig. 3) before reaching its end in the Sacramento River delta near Rio Vista.

Although historical records of sediment accumulation in Yolo Bypass do not exist (to our knowledge), sediment apparently tended to build up south of the current Fremont Weir site well before the flood-control system was constructed (Fig. 4). In addition, several sources of new information document recent sedimentation in the bypass. In addition to dozens of long sediment cores extracted from the upstream portion of the bypass and near the confluence with Cache Creek, we conducted a sediment pad study with the California Department of Water Resources that measured sedimentation across the upper part of Yolo Bypass after a moderately large flood in 2006. This involved the emplacement of clay feldspar pads on the floodplain surface that record subsequent sediment deposition.

These data provide ample evidence of sediment deposition in the upper portion of Yolo Bypass downstream of Fremont Weir. First, sediment pads recorded several cm of accumulation downstream of the weir during a moderate seasonal flood. Second, the topographic signature of deposition is evident in a map that pre-

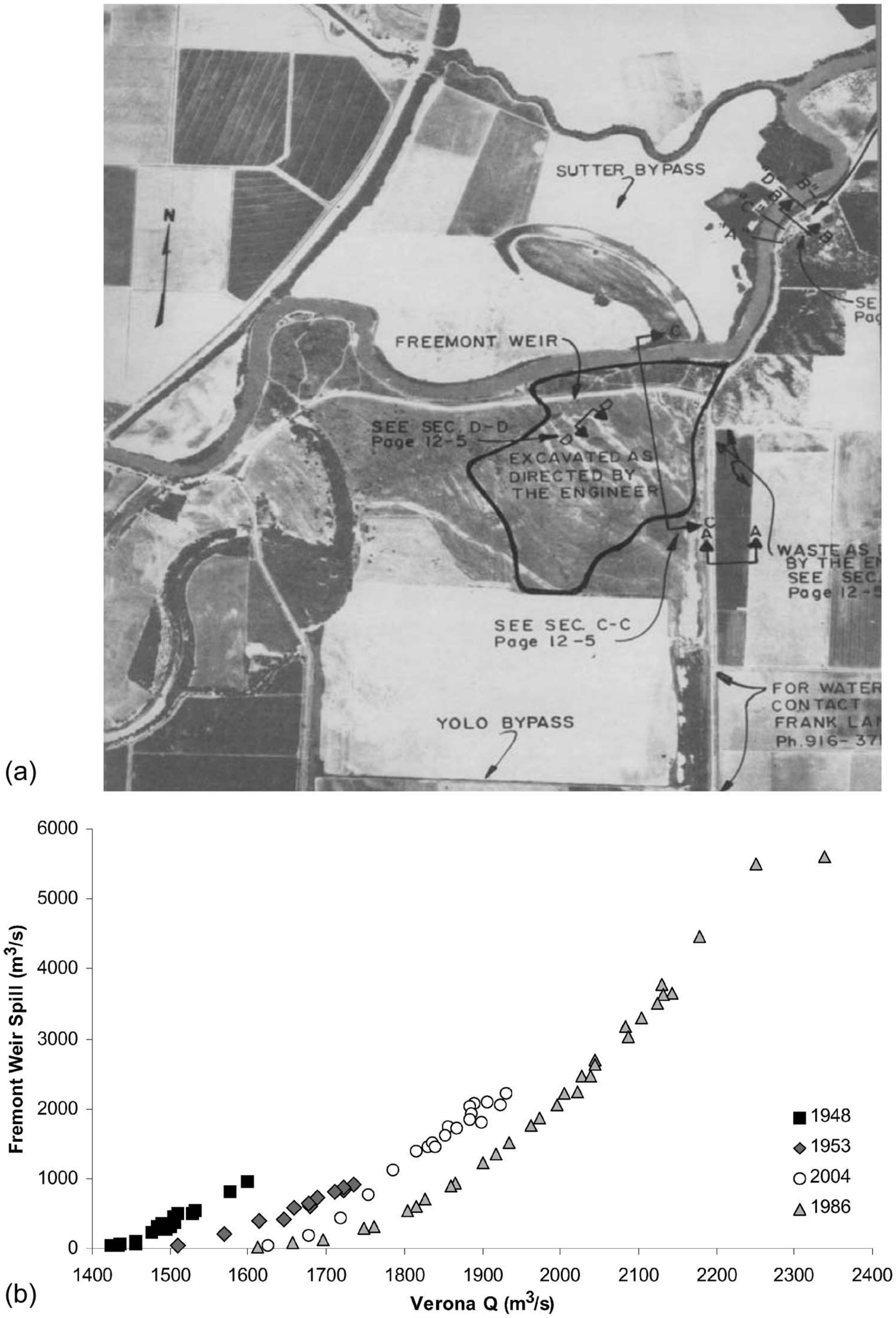

Fig. 8. Effects of sedimentation near Fremont Weir: (a) excavation diagram [data from California Dept. of Water Resources (1991)]; (b) comparison of Fremont Weir spill to flow nearby on the mainstem Sacramento River downstream at Verona gauge. Data from 2004 indicate reduced impairment associated with sediment removal.

dates the bypass (Fig. 4), in the aforementioned lobate signature in recent elevation data (Fig. 1), and in documentation of natural levee formation in the recent past (Singer and Aalto 2008). Third, sediment removal campaigns have been frequently practiced in the last few decades. For example, the California Department of Water Resources removed 2.7×10^6 m^3 of sediment from the area around Fremont Weir between 1986 and 1991 (Fig. 8), and a recent campaign in 2007 removed an additional $\sim0.7\times10^5$ m^3 (M. Ng, California Department of Water Resources, personal communication). Fourth, we analyzed cores located in a region of the bypass more than 1 km downstream of the weir and the previously identified deposits—an area that has never undergone sediment removal. It suggests ~10 cm accumulation during a single flood in the last decade [Fig. 6(c)].

As was the case for Colusa Bypass, such sediment build up impairs the conveyance of flows over Fremont Weir (Fig. 8). However, these flow data indicate that sediment removal tends to mitigate this effect (c.f. flow data for 1986 and 2004 in Fig. 8). The downstream extent of deposition in the upper portion of Yolo Bypass (associated with flow over Fremont Weir) is limited.

Gully-type erosion tends to occur at the downstream end of this deposit, presumably due to sediment-poor flow conditions, and thus remobilizes sediment deposited in prior floods (Singer and Aalto 2008).

Farther downstream near the outlet of Cache Creek, our core data suggest another area of net accumulation. We document at least 60 cm of deposition during recent major floods originating in Cache Creek [Fig. 6(d)]. Although it is equipped with a sediment retention basin, Cache Creek drains a sediment rich basin (Lustig and Busch 1967) and has peak sediment concentrations up to an order of magnitude higher than those in the Sacramento (~10,000 versus ~1000 mg/L). Such a sediment-rich basin led to the creation of a large fan in a former geologic epoch (Fig. 1) and currently delivers high sediment loads to the bypass downstream of a weir that forms the boundary between the settling basin and Yolo Bypass. It is possible and indeed likely that such overflow and sediment delivery at this location causes a backwater effect in Yolo Bypass, augmenting the signal of net accumulation.

Although at this time no detailed estimates of sediment accumulation systematically over the bypass can be made with our limited sample set, the most rapid sedimentation appears to be concentrated in deposits associated with delivery from other water courses. Net deposition is also likely at local areas of bypass widening, where flow velocities decline rapidly. Our cores and observations suggest that deposition is occurring many km from the weirs.

Implications

Since its construction, the bypass system has been accumulating sediment consistently, albeit in spatially heterogeneous patterns. The primary controls on its delivery to bypasses are dictated by the natural geomorphic setting of the basin. In particular, sediment enters the system through natural overflow points and former levee breaks and crevasse splays, which were fixed by prevailing geology, tectonics, and sedimentary history and are now cemented into position by the flood control system. Once sediment enters the bypass system, its deposition is controlled by bypass capacity and hydrology. When bypasses were constructed within natural flood basins, their dominant floodplain function changed from storage to conveyance, capable of transporting relatively fine ($<63\ \mu m$) sediment as long as water surface slopes remained high and constant. However, breaks in slope associated with overflow weirs, topographic depressions, and river confluences induce backwater effects and local sedimentation of all suspended grain sizes, leading to significant local accumulation over time, both near the weirs and throughout the system. This appears to be what has happened in various locations of the Sacramento Valley in the period since bypass construction. Such accumulation has implications for flood conveyance and (where fine deposition occurs) the fate and transport of contaminants such as mercury.

In addition to natural sources of sediment, the bypass system inherited anthropogenic sources of sediment (and mercury) from hydraulic mining in the Sierra Nevada foothills. The first wave of sediment delivered from mine sites built great fans and impaired navigation in the lower Sacramento Valley (James and Singer 2008). For example, the ~1 m tidal range at the Sacramento delta head was reduced to zero (Jones 1967). Gilbert (1917) noted that of the $\sim 1.1 \times 10^9$ m^3 of mining debris delivered downstream of mine sites between 1850 and 1914, 398×10^6 m^3 was stored in piedmont fan deposits, including 252×10^6 m^3 in the Yuba River alone. These fans were subsequently bisected by the primary rivers draining the Sierra bringing their bed elevations back to their prior levels (Gilbert 1917; Graves and Eliab 1977; Meade 1982), but leaving large terrace deposits available for future mobilization in large floods. For example, James (1989) documented continued storage of 106×10^6 m^3 in the Bear River piedmont, suggesting very slow evacuation of fan terrace deposits. However, the remobilization of historical mining sediment appears to occur during episodic flooding, forming large deposits in the bypass system. For example, comparison of Fig. 6 of James (1993) with Fig. 7 from this paper suggests the evacuation of huge volumes of sediment from the piedmont and delivery to Sutter Bypass during the flood of 1986.

Mercury was used in the gold mining process to separate gold from surrounding material. However, in part due to poor contemporary understanding of its impact on the downstream environment, up to 4×10^6 kg of mercury was lost to mining (Alpers et al. 2005). Much of this mercury was likely to be adsorbed to fine sediment particles and is stored in piedmont tailings fans. Our research suggests that, in addition to sediment accumulation in flood bypasses, there is a risk of mercury delivery to the lowland environment during large floods. Since bypasses serve as important ecological areas (Sommer et al. 2001), in addition to flood conveyors, there is concern where deposition sites for mercury-laden sediment intersect with ecologically important locations where there is a high risk for methylation, the conversion of the mercury to a bioavailable form. This generally occurs in the reducing conditions that prevail near the delta (Compeau and Bartha 1985). Therefore, remobilization of selectively finer sediment from prior deposits, which occurs in Yolo Bypass downstream of Fremont Weir, could deliver mercury to zones favorable to methylation.

Once sediment arrives in the bypass system, it poses problems for flood conveyance. In addition to impairing the operation of weirs that divert flow into the bypasses (e.g., Figs. 5 and 8), sediment accumulation in the middle of a bypass causes a progressive loss of conveyance capacity. While the thick, sand-rich deposits near the weirs have been recognized and excavated, the deposits elsewhere have not been studied or removed. The delivery of relatively coarse sediments may also precipitate growth of woody vegetation that affect roughness, thereby creating backwater effects and promoting further deposition. Indeed, the surveyed Sutter Bypass deposit has been colonized by large cottonwood trees and other woody vegetation that noticeably emerge from an area of primarily rice fields. This is in part due to the arrival of seedlings that can successfully germinate in sandy substrates where there is a slowly declining water table (Mahoney and Rood 1998; Singer and Dunne 2004a).

Conclusion

We have documented patterns of sediment accumulation in the bypass system, which are consistent with the inherited controls on sediment movement and storage in the Lower Sacramento Valley. The exogenous geology, tectonics, and sedimentary history created the sediment transfer template upon which the flood control system was superimposed. Compiled data from various sources suggest the historic and ongoing delivery of sediment to and storage within flood bypasses, which may affect their roles in flood conveyance and ecological habitat. Sediment delivery to the bypass system appears to be compounded by the legacy of hydraulic mining in the Sierra Nevada foothills, raising the downstream risk of episodic sediment delivery and floodplain contamination. Such effects may be exacerbated by increasingly large floods associated with climate change in California (Knowles and Cayan 2002; Singer 2007).

We close with the relevant words of Kelley (1966):

> "The essential characteristic of the Sacramento Valley as a floodplain still remains."

Acknowledgments

The writers recognize support from the National Science Foundation (Grant Nos. 0521663 and 0521774) and the CALFED Bay-Delta Program (Grant No. 4600002659). Part of this research was performed while Singer held a National Research Council Research Associateship Award at USGS Menlo Park. Development and refinement of the 210-Pb dating technique was supported in part by NSF Nos. EAR-0310339 and EAR-0403722. The writers also acknowledge Trevor Greene of the California Department of Water Resources for his initiative and follow through on the sediment pad study. The writers thank two anonymous reviewers for helpful comments, Eric Buer and Jeff Nittrouer for their field and lab assistance, Eliza Ghitis and Carrie Schaff for lab assistance, Douglas Allen for elevation data processing, Graeme Sanderman for graphics assistance, Dane Lowry for providing access to the Sutter Bypass site, and John Nosacka and Marianne Kirkland of the Department of Water Resources for providing information on sediment removal.

References

Aalto, R., Lauer, W., and Dietrich, W. E. (2008). "Spatial and temporal dynamics of Strickland River floodplains during the past century." *J. Geophys. Res.*, *[Earth Surface]*, 113, F01S04.

Aalto, R., Maurice-Bourgoin, L., Dunne, T., Montgomery, D. R., Nittrouer, C. A., and Guyot, J. L. (2003). "Episodic sediment accumulation on Amazonian flood plains influenced by El Nino/southern oscillation." *Nature (London)*, 425, 493–497.

Alpers, C. N., Hunerlach, M. P., May, J. T., and Hothem, R. L. (2005). "Mercury contamination from historic gold mining in California." *Fact Sheet FS2005-3014*, U.S. Geological Survey.

Baugher, J. E. (1984). "Determination of channel capacity of the Knights Landing Ridge Cut." Division of Flood Management, California Dept. of Water Resources, Sacramento, Calif.

Bridge, J. S. (2003). *Rivers and floodplains, forms, processes, and sedimentary record*, Blackwell Publishing, Oxford, U.K.

Bryan, K. (1923). "Geology and groundwater resources of Sacramento Valley, California." *Water Supply Paper No. 495*, U.S. Geological Survey, Washington, D.C.

California Dept. of Water Resources. (1991). "Fremont weir sediment removal." *Specification No. 91–20*, Contract No. C50933.

Compeau, G. C., and Bartha, R. (1985). "Sulfate-reducing bacteria: Principal methylators of mercury in anoxic estuarine sediment." *Appl. Environ. Microbiol.*, 50, (2), 498–502.

Dettinger, M. D., and Cayan, D. R. (2003). "Interseasonal covariability of Sierra Nevada streamflow and San Francisco Bay salinity." *J. Hydrol.*, 277(3–4), 164–181.

Ellis, W. T. (1939). *Memories: My seventy-two years in the romantic county of Yuba, California*, J. H. Nash, ed., San Francisco.

Fischer, K. J. (1994). "Fluvial geomorphology and flood control strategies: Sacramento River, California." *The variability of large alluvial rivers*, S. A. Schumm and B. R. Winkley, eds., ASCE Press, New York, 115–138.

Gilbert, G. K. (1917). "Hydraulic-mining debris in the Sierra Nevada." *Professional Paper No. 105*, U.S. Geological Survey, Menlo Park, Calif.

Graves, W., and Eliab, P. (1977). "Sediment study: Alternative delta water facilities—Peripheral canal plan." California Dept. of Water Resources, Sacramento, Calif.

Harwood, D. S., and Helley, E. J. (1987). "Late Cenozoic tectonism of the Sacramento Valley, California." *Professional Paper No. 1359*, U.S. Geological Survey, Washington, D.C.

Ikehara, M. E. (1994). "Global positioning system surveying to monitor land subsidence in Sacramento Valley, CA, USA." *Hydrol. Sci. J.*, 39, (5), 417–429.

James, L. A. (1989). "Sustained storage and transport of hydraulic gold mining sediment in the Bear River, California." *Ann. Assoc. Am. Geogr.*, 79(4), 570–592.

James, L. A. (1993). "Sustained reworking of hydraulic mining sediment in California: G.K. Gilbert's sediment wave model reconsidered." *Z. Geomorphol. N.F.*, 88 (Suppl. Bd. 88), 49–66.

James, L. A., and Singer, M. B. (2008). "Early development of the lower Sacramento Valley flood-control system." *Nat. Hazards Rev.*, 9(3), 125–135.

Jones, G. (1967). *Alteration of the regimen of the Sacramento River and tributary streams attributable to engineering activities during the past 116 years*, American Society of Civil Engineers, Sacramento Section, California State Archives, Sacramento, Calif.

Jones, W. L. (1926). "Flood control in the Sacramento and San Joaquin River systems." *Committee on commerce*, War Department, ed., Government Printing Office, Washington, D.C., Doc. No. 23, 39.

Kelley, R. (1966). "The Sacramento River from Colusa to Butte City 1850 to 1920." Prepared for the Office of the Attorney General, State of California.

Kelley, R. (1972). "Flooding and the development of flood control systems: Colusa region: Sacramento River: 1850 to 1940." Prepared for the Office of the Attorney General, State of California.

Kelley, R. (1998). *Battling the Inland Sea*, Univ. of California Press, Berkeley, Calif.

Knowles, N., and Cayan, D. R. (2002). "Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary." *Geophys. Res. Lett.*, 29(18), 1891.

Knowles, N., and Cayan, D. R. (2004). "Elevational dependence of projected hydrologic changes in the San Francisco estuary and watershed." *Clim. Change*, 62(1–3), 319–336.

Lustig, L. K., and Busch, R. D. (1967). "Sediment transport in Cache Creek drainage basin in the Coast Ranges west of Sacramento, California." *Professional Paper No. 562-A*, U.S. Geological Survey, Washington, D.C.

Mahoney, J. M., and Rood, S. B. (1998). "Streamflow requirements for cottonwood seedling recruitment—An integrative model." *Wetlands*, 18(4), 634–645.

McClure, W. F. (1927). "Sacramento flood control project." Dept. of Public Works, Sacramento, Calif.

Meade, R. H. (1982). "Sources, sinks, and storage of river sediment in the Atlantic drainage of the United States." *J. Geol.*, 90(3), 235–252.

Robertson, K. G. (1987). "Paleochannels and recent evolution of Sacramento River, California." MS thesis, Univ. of California, Davis, Davis, Calif.

Singer, M. B. (2007). "The influence of major dams on hydrology through the drainage network of the Sacramento Valley, California." *River Research and Applications*, 23, 55–72.

Singer, M. B., and Aalto, R. (2008). "Floodplain development in an engineered setting." *Earth Surf. Processes Landforms* (in press).

Singer, M. B., and Dunne, T. (2001). "Identifying eroding and depositional reaches of valley by analysis of suspended-sediment transport in the Sacramento River, California." *Water Resour. Res.*, 37(12), 3371–3381.

Singer, M. B., and Dunne, T. (2004a). "An empirical-stochastic, event-based model for simulating inflow from a tributary network: Theoretical framework and application to the Sacramento River basin, California." *Water Resour. Res.*, 40, W07506.

Singer, M. B., and Dunne, T. (2004b). "Modeling decadal bed-material flux based on stochastic hydrology." *Water Resour. Res.*, 40, W03302.

Sommer, T., et al. (2001). "California's Yolo bypass: Evidence that flood control can be compatible with fisheries, wetlands, wildlife, and agriculture." *Fisheries*, 26(8), 6–16.

State of California Resources Agency. (1973). "Study of sediment storage in Colusa weir bypass and sediment basin during 1972–73 flood season." Prepared for the California Reclamation Board.

State of California Resources Agency. (1974). "Study of sediment storage in Colusa weir bypass and sediment basin during 1973–74 flood season." Prepared for the California Reclamation Board.

Thompson, K. (1960). "Historical flooding in the Sacramento Valley." *Pacific Historical Review*, 29(4), 349–360.

United States Army Corps of Engineers (USACE). (1985). "Sacramento River and tributaries bank protection and erosion control investigation, California." Sacramento, Calif.

United States Army Corps of Engineers (USACE). (1998). "Post-flood assessment for 1983, 1986, 1995, and 1997, Central Valley, California." Sacramento District, Sacramento, Calif.

United States Geological Survey (USGS). (1910). "Knights Landing quadrangle (1:24,000)."

Water Engineering and Technology. (1990). "Geomorphic analysis and bank protection alternatives for the Sacramento River (RM 0-78), Feather River (RM 28-61), Yuba River (RM 0-17), Bear River (RM 0-17), American River (RM 0-23)." Water Engineering and Technology, Fort Collins, Colo.