

COMPREHENSIVE GEOMORPHIC AND SEDIMENTATION ANALYSES OF LOWER SACRAMENTO RIVER FOR FLOOD MANAGEMENT, EROSION MITIGATION AND HABITAT ENHANCEMENT DESIGN

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INTRODUCTION

This paper presents the results from a geomorphic and sediment transport study of the lower Sacramento River, conducted by Northwest Hydraulic Consultants (NHC) and Mobile Boundary Hydraulics (MBH) for the Sacramento District of the U.S. Army Corps of Engineers (USACE). The study was undertaken to support the ongoing bank protection, flood control system, and aquatic and riparian habitat enhancement design programs. The intent of the study was to collect and review available historic and present-day data related to geomorphology and sediment transport of the Sacramento River system and assess the implications of channel evolution trends and sediment transport regime on riparian habitat and long-term levee repair requirements for the Sacramento River Flood Control System. Specific objectives of this study were: (1) evaluate the risk of future river channel shift to erode project levees; (2) evaluate the historic change in the riparian habitat and floodplain (overbank berms located between river channel and levees); (3) determine current trends in evolution of channel longitudinal profile (degradation or aggradation); and (4) assess historic and current sediment transport conditions in the study reach of the river.

STUDY AREA

General Setting: The study reach of the Sacramento River is approximately 98 miles long and extends from River Mile (RM) 144 at Colusa downstream to RM 46 at Freeport (Figure 1). Bed material in the Sacramento River changes from a sand-gravel mixture in the upper part of the study reach to predominantly sand in the lower reach. Channel slope ranges from about 0.0001 at Colusa to about 0.00008 in the vicinity of Sacramento. The major tributaries are the Feather and American Rivers, entering the study reach at RM 80 and 60, respectively. The study reach of the Sacramento River is completely constrained by flood control levees, which restrict the natural channel planform evolution. Approximately 85 miles (87%) of the study reach is bordered by levees located less than 200 ft away from the river channel (Figure 2, left photo). Along about 13 miles (13%) of the reach (mainly upstream of the Feather River confluence), one or both levees are set back a few hundred feet from the river channel (Figure 2, right photo).

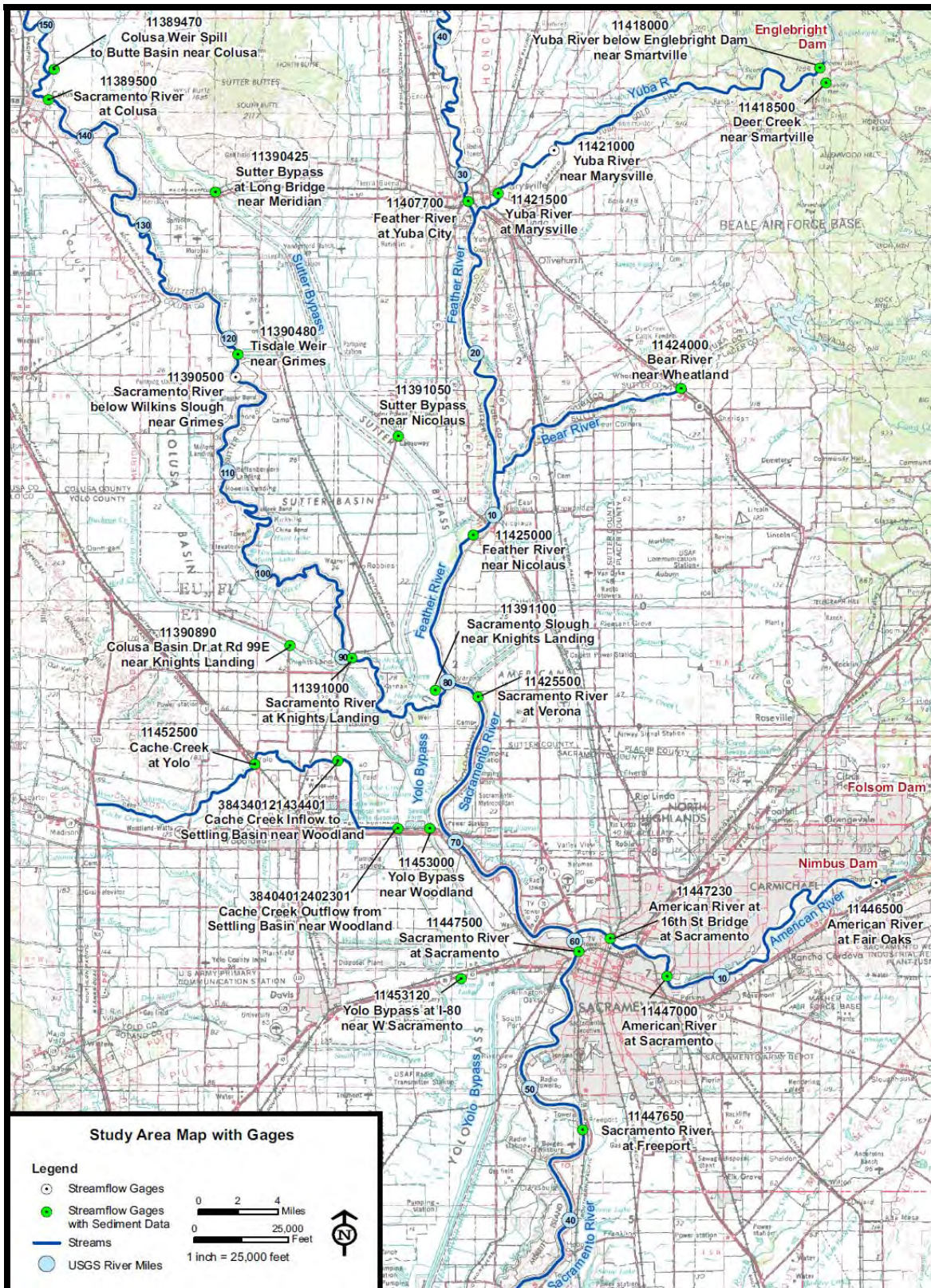


Figure 1 Study area map with U.S. Geological Survey gages.

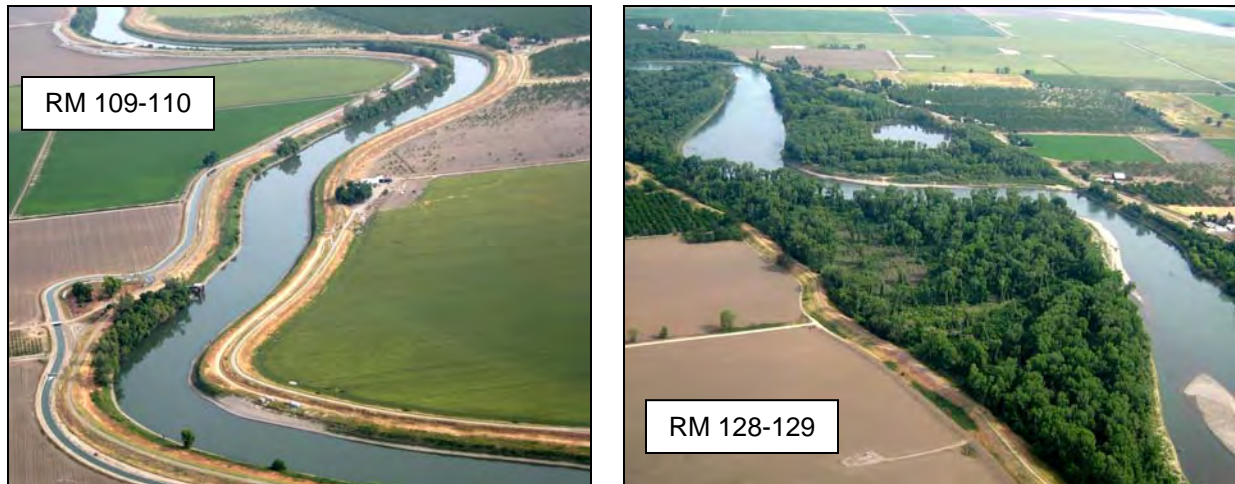


Figure 2 Typical examples of close proximity of levees to Sacramento River channel in study area (left photo) and setback levees with large overbank berms (right photo).

During summer low water periods, flow is contained within the river channel. During winter high water periods, flows in excess of channel capacity are conveyed through a system of overbank leveed bypasses which include the Colusa, Tisdale, Sutter, Yolo, and Sacramento Bypasses. Downstream of Sacramento, the river is influenced by tides.

Anthropogenic Impacts: The Sacramento River system has been significantly affected by historic human activities over the last century and a half (NHC and MBH 2009). Hydraulic and dredge mining for gold, building of levees for land reclamation and flood control, bank protection works, land use changes, construction and operation of upstream reservoirs, water export projects, and dredging of alluvium for navigation and levee maintenance purposes have all had an impact on river hydrology, channel pattern, and sediment transport. Uncontrolled hydraulic mining for gold in the mid-1800s caused a massive influx of sediment into the Sacramento River system, which caused rapid aggradation (up to 10-25 ft) of the river channel. In the 1900s, sediment loads started to decline and the river began to incise into the mining debris as hydraulic mining was stopped, dams were built that captured sediment and reduced flood flows, levees were constructed which confined flows to the river channel and overbank bypasses, and water diversion facilities were constructed that reduced flows and affected sediment transport pattern. In-channel sediment dredging for levee construction and navigation purposes contributed to channel degradation of the lower Sacramento River. The transportation of residual mining debris into the Delta of the Sacramento River and further to the bay system probably continued until the mid-1900s. Many researchers believe that present sediment loading on the Sacramento River is approaching its pre-gold rush value.

RIVER CHANNEL SHIFT ANALYSIS

Historic Bankline Shift: This analysis was conducted using digitized georeferenced historic topographic maps and aerial photographs collected for the period from the early 1950s to present. This period represents the contemporary hydrologic era for the Sacramento River, defined by the start of Shasta Dam operations in 1945. Historic bankline shift maps were

developed in ArcGIS for the entire study reach. Typical examples of such maps are shown for a closely leveed reach and a reach with setback levees in Figure 3. Oblique aerial photographs for the mapped reaches in Figure 3 are shown in Figure 2. Analysis of the bankline shift maps indicate that from the 1950s to 2005, 86.5 miles (88%) of the 98-mile long study reach show less than 150 ft of bankline shift, 6.1 miles (6%) show bankline shift between 150 ft and 300 ft, and the remaining 5.4 miles (6%) show more than 300 ft of bankline shift. Most of bankline shifting occurred upstream of the Feather River confluence in reaches where levees are setback from the river channel. For most of the study reach, however, the river channel is closely bordered by extensively revetted levees and lateral channel evolution is limited.

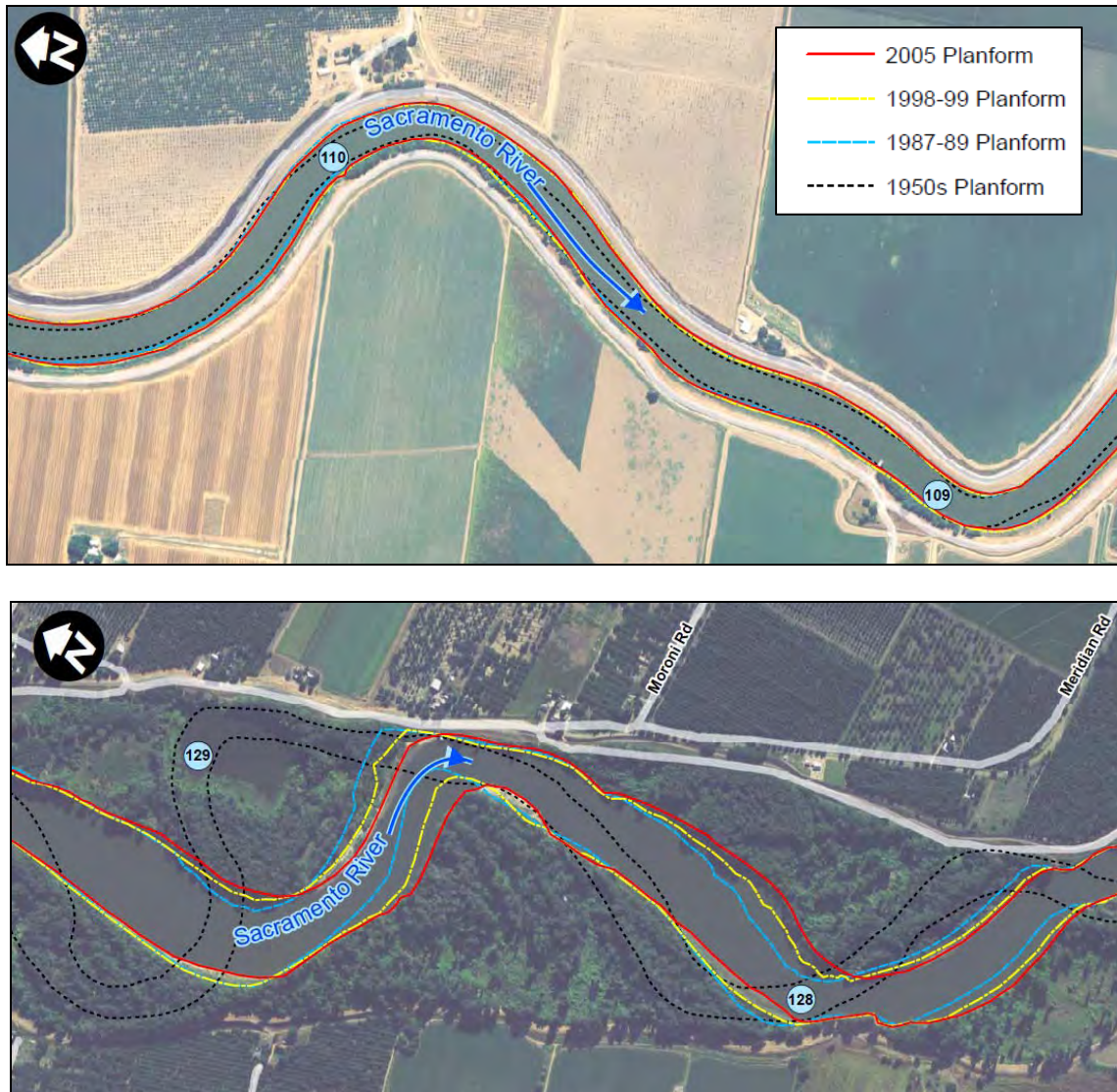


Figure 3 Historic bankline shift maps: RM 109-110 (top) and RM 128-129 (bottom).

The historic bankline shift maps show an increase in average channel width over time, primarily upstream of the Feather River confluence. Average channel width increased 10% to 39% from the 1950s to 1987, then changed no more than 4% from 1987 to 2005. The observed channel

enlargement may be related to changes in hydrologic conditions caused by Shasta Dam and reduction of sediment supply into the Sacramento River system.

Overbank Berms: Overbank berms are relatively flat floodplain terraces located between the river channel and adjacent levees. The largest 40 representative overbank berm sites were selected for analysis of historic trends in spatial evolution of overbank berms in the study reach. In the fall of 2009, NHC conducted a field inspection of the selected overbank berm sites to document current bankline conditions and identify eroding or accreting reaches. Historic rates of bankline shift at the overbank berms and changes in their surface area were determined in ArcGIS using the compiled historic aerial photographs. For river sections with a continuous sequence of overbank berms and significant historic channel shifts (such as on the bottom map in Figure 3), the bankline shift rates and change in surface area were determined for the entire sequence of all the overbank berms in this section. Average and maximum rates of bankline shift (erosion and accretion) at the overbank berm sites during the 1952-2005 period are shown in Figure 4. Maximum rates of bank erosion varied from 0.7 ft/yr to 67.3 ft/yr, with an average maximum rate of 9.6 ft/yr. Maximum bank accretion rates varied from zero to 63.3 ft/yr, with an average maximum rate of about 7.7 ft/yr. Calculated long-term average bank erosion rates range from 0.1 ft/yr to 31.3 ft/yr (4.4 ft/yr on average), while average accretion rates range from zero to 29.1 ft/yr (3.6 ft/yr on average). In many locations bank erosion was accompanied by accretion at the opposite bank. However, bank erosion was the dominant process at 36 overbank berm sites whereas bank accretion dominated only at 4 of the 40 overbank berm sites. The highest rate of erosion and accretion occurred in the overbank berm sequence from RM 126 to RM 131.

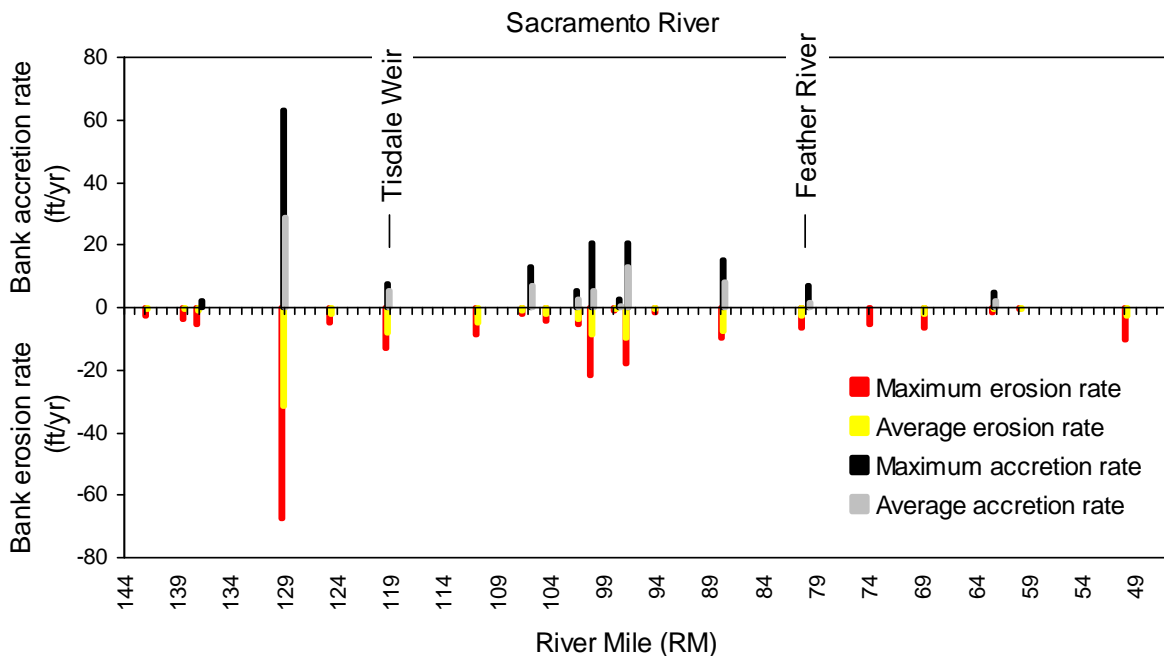


Figure 4 Average and maximum rates of bankline shift (erosion and accretion) at overbank berm sites from 1952 to 2005.

Net changes in surface area of the overbank berms from 1952 to 2005 are shown in Figure 5. The results show that from 1952 to 2005, there was a net reduction by 84 acre (4%) in the total surface area of the analyzed overbank berms. The overbank berm sequence from RM 126 to RM 131 accounts for more than half of this change. Most of the berm erosion occurred upstream of the Feather River confluence. The observed net erosion of the overbank berms is mainly the result of channel enlargement in response to changes in hydrology and sediment transport rather than lateral channel shifting. In addition to bank erosion, bank accretion also occurred at 30 of the 40 overbank berm sites and accounted for net growth of 4 overbank berm sites from 1952 to 2005.

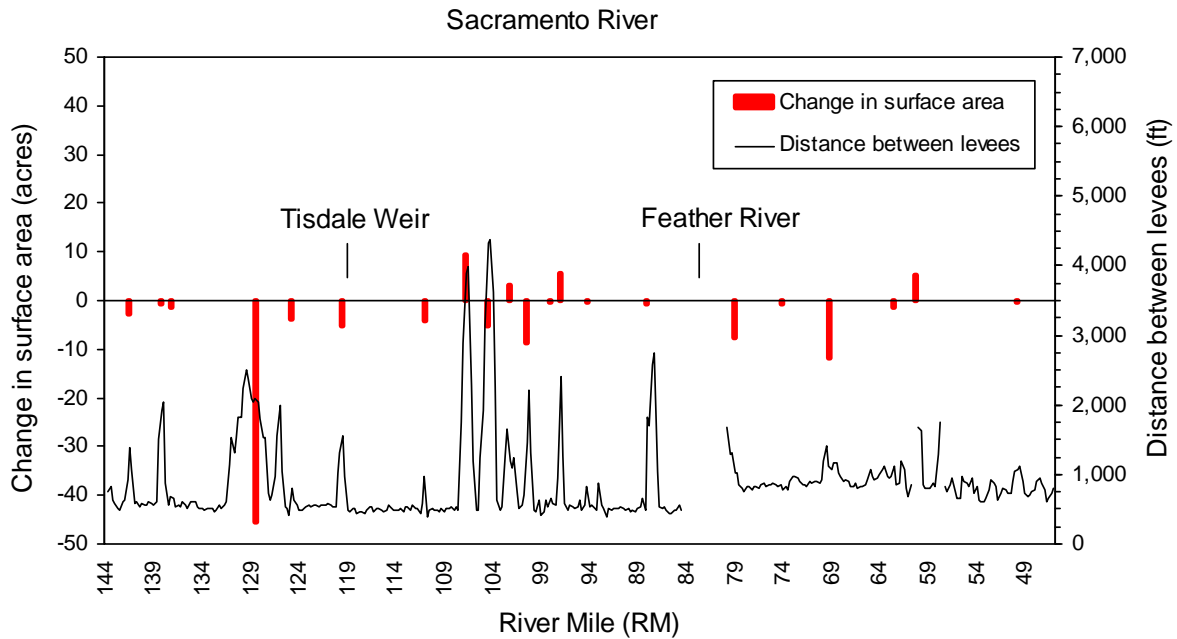


Figure 5 Net changes in surface area at overbank berm sites from 1952 to 2005.

Levee Erosion Risk: The potential for future (in the next 50 years) river channel shifting to pose a risk to project levees was assessed using the results of the historical bankline analysis, overbank berm analysis, and an assessment of regional soils and geologic information (location of resistant geologic materials in the area). The assessment was based on the assumption that future rates of river channel shifting would be similar to historical rates. It was determined that approximately 35 miles (19%) of the 185 miles of project levees in the study reach are at risk of erosion due to future river channel shifting, flanking of existing revetment, river avulsion or the formation of secondary channels over the next 50 years. The remaining 150 miles (81%) are either protected from future river channel shift by bankline revetment or are set back far enough from the bankline to be outside the maximum river channel shift expected within the next 50 years. The analysis of levee risk only accounts for risk due to river channel shifting and does not account for the adequacy of bank protection (revetment) design and long-term maintenance, geotechnical condition of the levees and subsurface soils, and local hydraulic effects such as frequent boat wakes or a large snag or pier scour on the bank.

STREAMBED EROSION ANALYSIS

Historic Channel Profiles: Since the cessation of hydraulic mining for gold in the late 1800s, the lower Sacramento River channel has been in an overall degradational state. Comparison of historic thalweg profiles conducted by WET (1990) revealed significant bed degradation (by up to about 10 ft) in the reach extending from Tisdale Bypass (RM 118) to Verona (RM 78) during the 1909-1938 period and localized channel scour upstream of Tisdale Bypass during the same period. No system-wide variation in thalweg profiles was observed between 1938 and 1980, which suggested that degradational trend was generally arrested after 1938.

Specific Gage Data: To quantify recent geomorphic effects on the Sacramento River hydraulics, long-term specific gage plots (showing temporal variation of gage heights for a given flow) were developed for the U.S. Geological Survey (USGS) gages at Colusa (RM 144) and Verona (RM 78) (Figure 6). The specific gage plots were developed using current and historic stage-discharge rating curves and measured streamflow data and were supplemented by the specific gage data from the WET (1990) study. Analysis of the specific gage plots reveals a distinct decrease in high flow gage heights from the mid-1960s to the mid-1980s and a very small degradational trend during the last two decades. This suggests that the channel of the Sacramento River at Colusa and Verona is approaching a stable state.

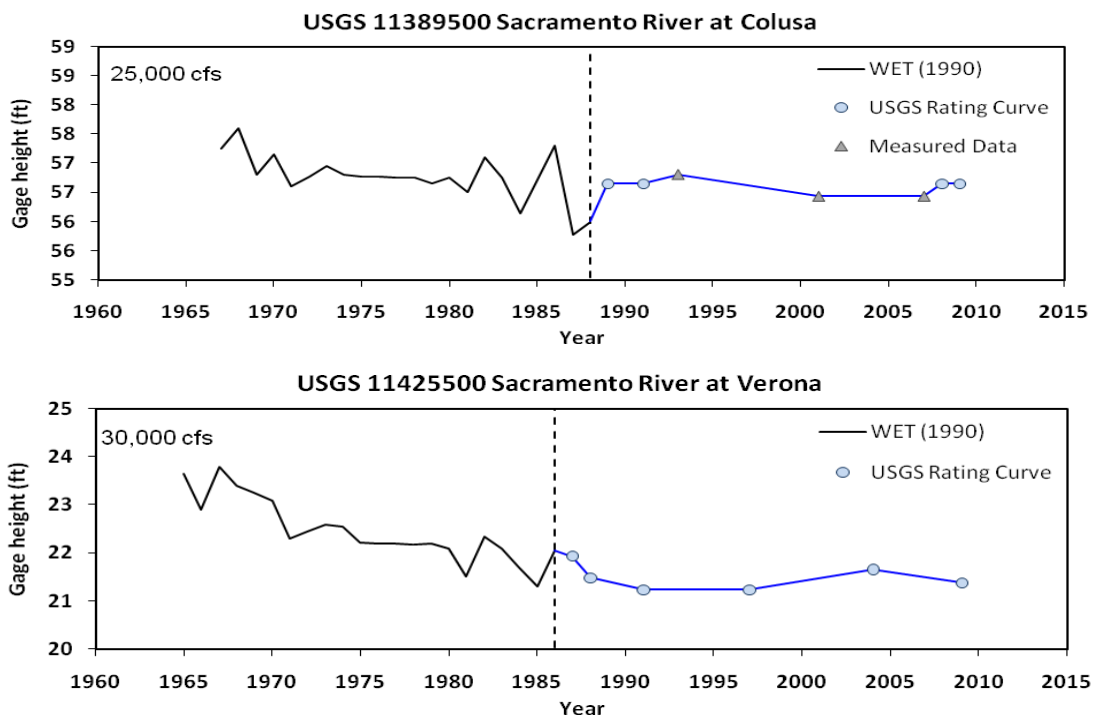


Figure 6 Specific gage plots for Sacramento River at Colusa and at Verona.

Recent Bathymetry Data: Current trends in channel bed evolution below the confluence with the Feather River were evaluated by comparing the 1997 and 2008 bathymetries of the Sacramento River. The 1997 bathymetry is available for the entire study reach, while the 2008 bathymetry extends from Verona (RM 78) to Freeport (RM 46). The 1997 and 2008

bathymetries were compared in ArcGIS to determine spatial changes in streambed elevations and to calculate aggradation and degradation volumes along the river reach covered by both bathymetries. An example of the map comparing the two bathymetries is shown in Figure 7. Comparison of the 1997 and 2008 thalweg profiles extracted from the bathymetries is shown in Figure 8. Calculated aggradation and degradation volumes are shown in Figure 9.

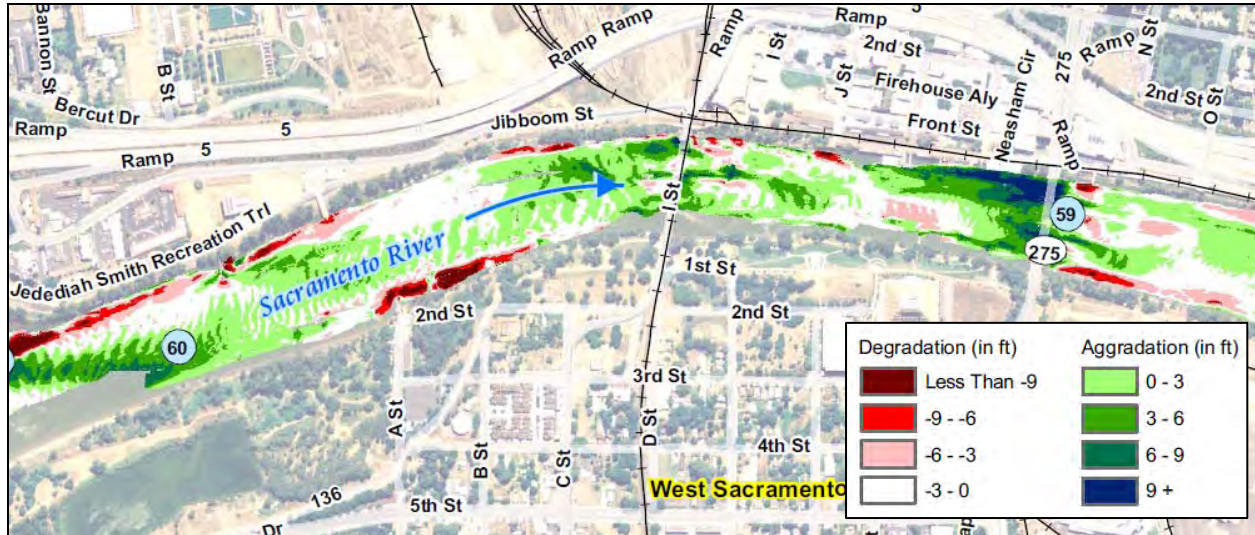


Figure 7 Example of map comparing 1997 and 2008 bathymetries (RMs 59-60).

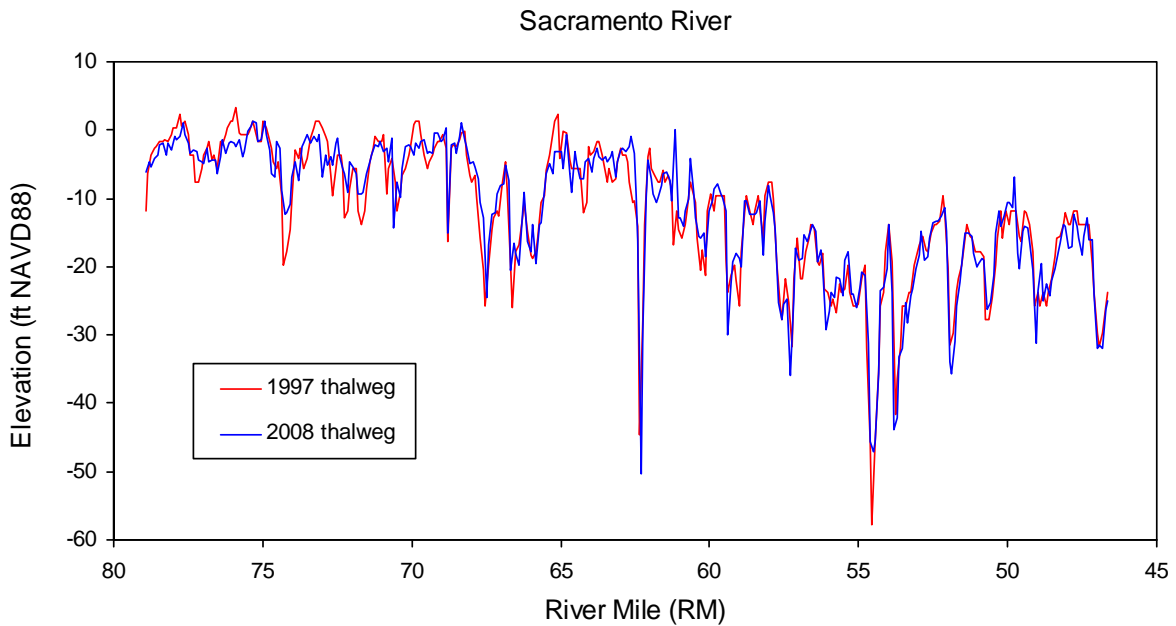


Figure 8 Comparison of 1997 and 2008 thalweg profiles.

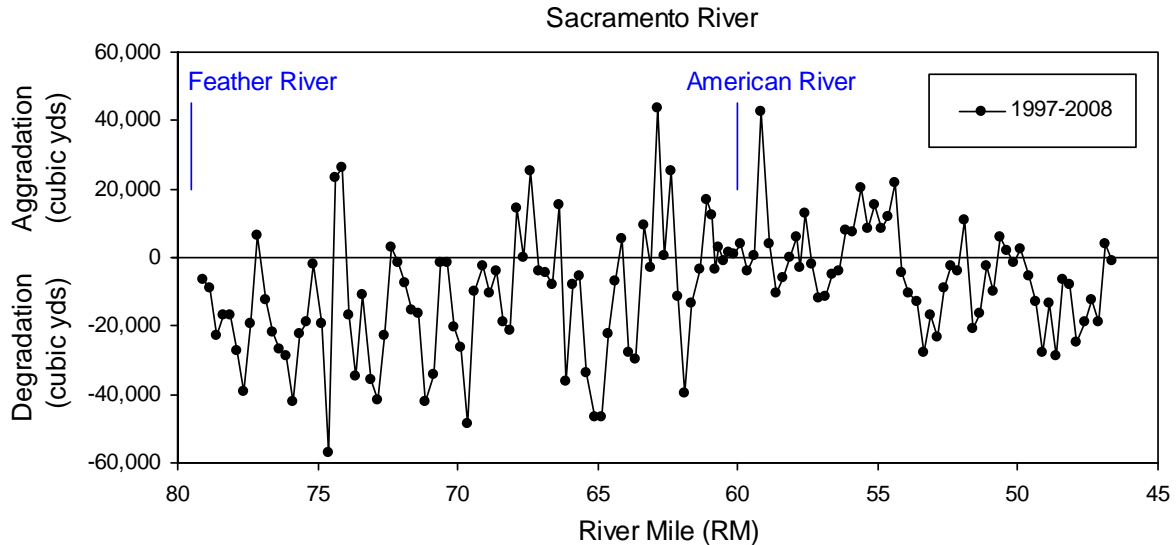


Figure 9 Aggradation and degradation volumes for Sacramento River between 1997 and 2008.

Comparison of the 1997 and 2008 bathymetries reveals a highly non-uniform, patchy distribution of aggradation and degradation areas (with up to 5-10 ft of elevation differences), which is likely related to local channel adjustments during high flow events and spatial evolution and propagation of various bed features (such as dunes and bars). However, despite the generally noisy channel bed evolution pattern, there is a predominantly degradational trend in the Sacramento River between approximately RM 79 and RM 61 and between RM 54 and RM 47 (see Figure 9). A predominantly aggradational trend is observed between RM 61 and RM 54. In general, the channel of the Sacramento River below the confluence with the Feather River appears to be in an overall degradational state.

SEDIMENT TRANSPORT

Bed Material: The primary source of historic bed material data are streamflow gages operated in the study area by the USGS. Most of the USGS bed material data were collected between 1977 and 1980. The only gage where regular bed material sampling is being currently undertaken is Freeport (RM 46). Recent bed material data for the Sacramento River (collected between 2002 and 2004) are available from Singer (2008). In 2009, NHC collected bed material data at a number of locations throughout the study reach. Longitudinal variations of bed material median sizes as determined from the USGS 1977-1980 data, Singer 2002-2004 data, and NHC 2009 data are compared in Figure 10. It is seen that the past and recent bed material data are in overall agreement and show no obvious trend with time in bed material sizes in the study reach of the river.

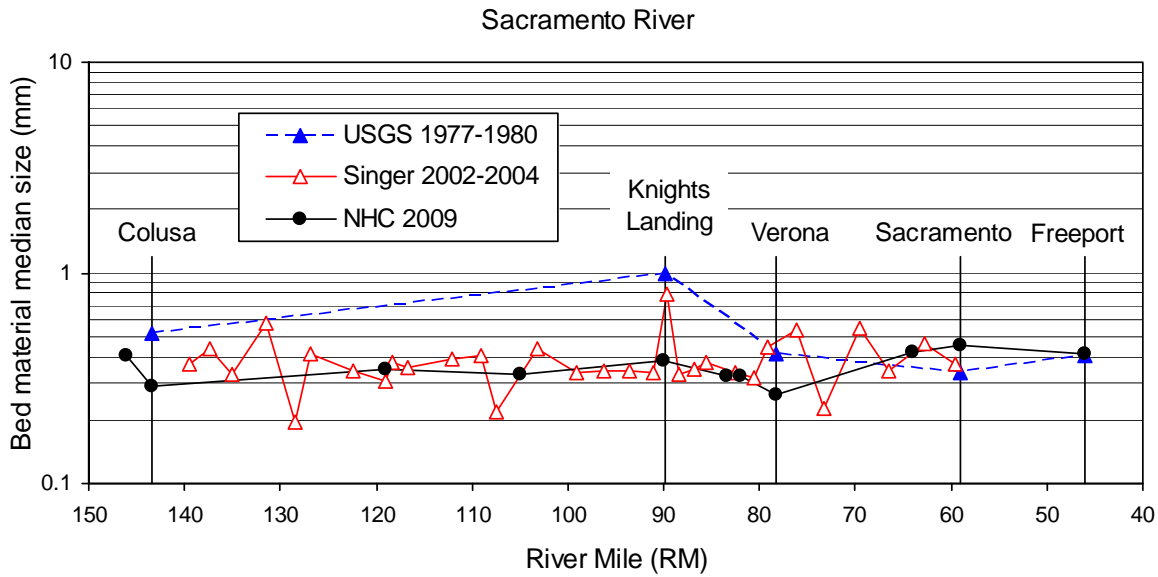


Figure 10 Longitudinal variation of bed material median size in study reach of Sacramento River.

Suspended Sediment: Suspended sediments have been sampled by the USGS at a number of gages within the study area. Most of the suspended sediment data were collected in the 1970s and 1980s and are limited to just a few measurements. Relatively recent episodic measurements of suspended loads were undertaken in the late 1990s and early 2000s on the Sacramento River at Colusa (RM 144) and at Verona (RM 78). The most substantial suspended load record is available for the Sacramento River at RM 59.5 at Sacramento (measured during 1957-1979) and at RM 46 at Freeport (measured during 1973-2008). At present, suspended sediment measurements are continued by the USGS at the Freeport gage only.

According to the published USGS data, suspended sediments in the study reach are mostly composed of clay, silt, and fine sand. The proportion of wash load (clay and silt) in the measured total suspended sediment load is typically greater than 50-80%. Suspended sand loads (for particles coarser than 0.062 mm) were calculated from the measured total suspended load data and are plotted versus flow for selected gages in Figure 11. Comparison of the USGS suspended sand data measured during different time periods at Colusa, Verona, and Freeport indicate a decline in suspended sediment transport at Colusa and no obvious long-term trends at the other gages. For most of the gages, suspended load records are too short to draw a definite conclusion as to whether the suspended bed material load in the study streams has stabilized or not. Present-day suspended sediment data are programmed to be collected on the Sacramento River by NHC in winter 2010 and compared with the historic USGS data to quantify current sediment transport conditions of the Sacramento River system.

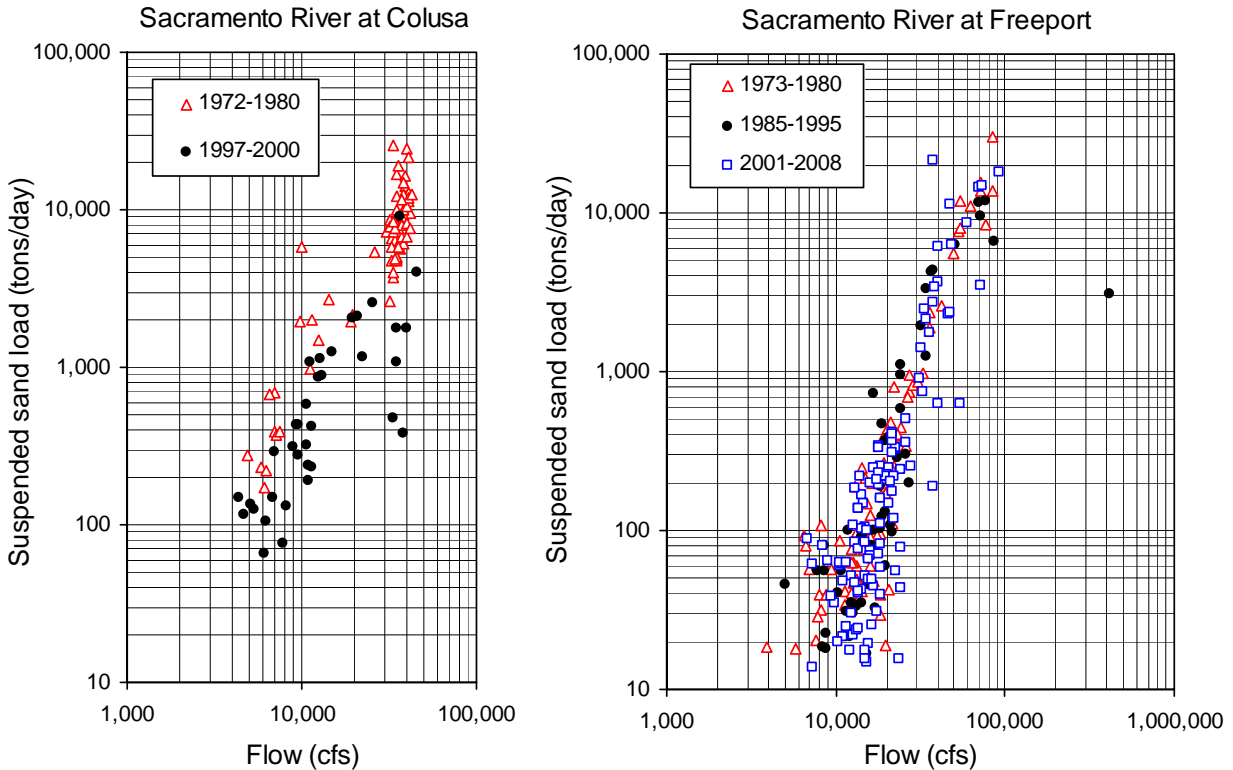


Figure 11 Historic suspended sand loads for Sacramento River at Colusa and at Freeport.

Bed Load: Bed load data for the study area are extremely sparse due to the difficulty of bed load transport measurements. A few bed load measurements were undertaken by the USGS at the Colusa gage (RM 144) in 1976 and 1977. The measured bed load mainly consisted of medium to coarse sand, with small amounts of fine gravel. In 1998-2008, the USGS measured movement of dunes and bed form transport at Garcia Bend (about 4 miles upstream of Freeport) using repeated bed form mapping with an array of echo-sounders (Dinehart 2002). All the bed load data available for the study reach of the Sacramento River were collected during low flow periods with relatively inactive sediment transport, are sparse and rather scattered, and are insufficient to determine any temporal trends in bed load transport conditions.

SUMMARY

A comprehensive study of historic and present-day geomorphic and sediment transport conditions in the lower Sacramento River was conducted to support the ongoing bank protection, flood control system, and aquatic and riparian habitat enhancement design programs. The study included a historical bankline shift analysis, streambed erosion analysis, and assessment of sediment transport conditions in the river reach extending between RM 144 at Colusa and RM 46 at Freeport. Results of the study were used to evaluate risk of future channel shift to erode flood control levees, to evaluate potential future reduction of riparian habitat, and to assess current trends in streambed profile evolution and sediment transport conditions in the study reach of the river.

Comparison of historic maps and aerial photographs indicates that historic river channel shift and bank erosion are most significant in reaches with setback levees (mostly upstream of the Feather River confluence). For most of the study reach, however, the river channel is closely bordered by extensively revetted levees and lateral channel evolution is limited. Bank erosion analysis indicates that approximately 35 miles (19%) of the 185 miles of project levees in the study reach are at risk of erosion over the next 50 years. The remaining 150 miles (81%) are either protected from future river channel shift by bankline revetment or are set back far enough from the bankline to be outside the expected maximum river channel shifts.

Comparison of recent bathymetric data indicates that the streambed of the Sacramento River below the confluence with the Feather River is in an overall degradational state, which may have implications for toe scour and levee stability in this reach. Analysis of historic and most recent sediment data does not reveal significant changes in sediment transport characteristics over the last few decades, which suggests that the transportation of residual mining debris through the Sacramento River system has generally completed.

REFERENCES

- Dinehart, R. L. (2002). Bedform movement recorded by sequential single-beam surveys in tidal rivers. *Journal of Hydrology* 258, p. 25-39.
- NHC and MBH (2009). Sacramento River basin sediment study, Phase I – Data review and work plan. Report prepared for the U.S. Army Corps of Engineers, Sacramento District by Northwest Hydraulic Consultants (NHC) and Mobile Boundary Hydraulics (MBH), 24 July 2009.
- Singer, M.B. (2008). Downstream patterns of bed material grain size in a large, lowland alluvial river subject to low sediment supply. *Water Resources Research*, Vol. 44, W12202, doi:10.1029/2008WR007183.
- WET (1990). Geomorphic analysis and bank protection alternatives report for Sacramento River (RM 78-194) and Feather River (RM 0-28). Report prepared for U.S. Army Corps of Engineers, Sacramento District, Sacramento, California. Contract No. DACW05-88-D-0044, Delivery Order #5. Water Engineering and Technology Inc. (WET) Project No. 82-505-89, Fort Collins, Colorado, 277 p.