SEDIMENT TRANSPORT AND CHANNEL MORPHOLOGY MODEL IN THE SAN JOAQUIN RIVER FROM FRIANT DAM TO MENDOTA DAM, CALIFORNIA

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Abstract An analysis of sediment transport and channel morphology was performed for the San Joaquin River between Friant Dam and Mendota Dam. The study was conducted in support of the San Joaquin River Restoration Program (SJRRP). The San Joaquin River is located in the Central Valley of California. The current study area covers Reach 1 from Friant Dam to Gravelly Ford (RM267.5 to RM 229.0), and Reach 2 from Gravelly Ford to Mendota Dam (RM 229.0 to RM 204.8). Gravelly Ford denotes the transition area from a gravel-dominated bed in Reach 1 to a sand-dominated bed in Reach 2. SRH-1D, which is a hydraulic and sediment transport model (Sedimentation and River Hydraulics – One Dimension), was used to simulate the erosion and deposition under baseline and alternative hydrologic conditions. Results were compared in regards to bed profiles, bed sediment gradation, and erosion and deposition volumes and can be used to understand the channel response to different restoration strategies.

INTRODUCTION

SRH-1D (Sedimentation and River Hydraulics – One Dimension; Huang and Greimann, 2007) is a hydraulic and sediment transport numerical model developed to simulate flows in river channels with or without movable boundaries. The program is able to compute water surface profiles in single, dendritic, and looped network channels. Both steady and unsteady flow and sediment models can be simulated. SRH-1D uses the standard step method to solve the energy equation for steady, gradually-varied flows. SRH-1D applies a modified “NewC” scheme to solve the de St Venant equations for unsteady, rapidly-varied flows. Two methods of sediment transport may be employed in SRH-1D. For a long term simulation, the unsteady term of the sediment transport continuity equation is ignored, and the non-equilibrium sediment transport method of Han (1980) is used. For a short term simulation, the governing equation for sediment transport is the convection-diffusion equation with a source term arising from sediment erosion/deposition. This equation is solved with an implicit finite-volume method and with the Lax-Wendroff TVD scheme for the convective term and the central difference scheme for the diffusion term. Internal boundary conditions, such as time-stage tables, rating curves, weirs, bridges, and radial gates are simulated. The notation of an active layer, which allows selective erosion, provides an appropriate framework to simulate the bed armoring. Non-cohesive sediment transport equations and cohesive sediment physical processes are applied to calculate the sediment deposition and erosion. The most recent version can be downloaded at: www.usbr.gov/pmts/sediment.

SRH-1D was applied to study the sediment transport and channel morphology of the San Joaquin between Friant Dam and Mendota Dam. The San Joaquin River is located in the Central Valley of California. It originates in the highest peaks of the Sierra Nevada Mountains above 11,000ft, and flows down to sea level at the delta. The San Joaquin River is bounded by the Sierra Nevada on the east and Coast Ranges on the west. The San Joaquin River Restoration area covers approximately 148 miles from Friant Dam, where the San Joaquin River leaves the Sierra Nevada foothills, to its confluence with the Merced River. This 148-mile reach was divided into five primary reaches that exhibit similar flows, geomorphology, and channel morphology. The current study area covers Reach 1 from Friant Dam to Gravelly Ford (RM267.5 to RM 229.0), and Reach 2 from Gravelly Ford to Mendota Dam (RM 229.0 to RM 204.8). The assessment presented herein was conducted in support of the San Joaquin River Restoration Program (SJRRP) and is part of a larger analysis that focuses on the sediment transport and geomorphic characteristics of the San Joaquin River.

While water resource developments within the San Joaquin River Basin have benefitted the economic growth, they have significantly altered flow in the river and have deteriorated wildlife habitat. Friant Dam and flood bypasses have regulated flows in the main channel and reduced the peak flows downstream of the dam. Levees along the river confine water and sediment in the main channel. Groundwater pumping has lowered the water table and increased the water loss by channel percolation. Resulting habitat changes have caused a general reduction of wildlife populations and specifically the extirpation of all anadromous salmonids in the San Joaquin River (Mussetter Engineering, Inc., 2002).

In this paper, SRH-1D was used to study erosion and deposition under Baseline and Alternative A hydrologic conditions. Baseline hydrology represents the current condition, and Alternative A represents one of the restoration and water supply strategies. The geometry and bed gradations were kept the same for all hydrologic conditions simulated. The model was used to predict the channel profile, sediment erosion and deposition volumes, and bed gradations. Sensitivity analyses were conducted on model inputs, including bed material layers, active layer thickness, transport formula, roughness coefficient, cross section numbers, and silt and sand gradations in Reach 1 (Huang and Greimann, 2009a). Model results could be used to understand the channel response to different restoration strategies.

NUMERICAL MODEL

SRH-1D solves hydraulics and both cohesive and non-cohesive sediment transport, for steady and unsteady flow problems and for single and interconnected channels. Some of its most notable features include:

- Computation of water surface profiles in a single channel or channel networks.
- Subcritical flows in steady hydraulic simulation.
- Subcritical, supercritical, and transcritical flows in steady hydraulic simulation
- Steady and unsteady flows.
- Steady and unsteady sediment transport models.
- Transport of cohesive and non-cohesive sediments simultaneously.
- Cohesive sediment aggregation, deposition, erosion, and consolidation.
- 13 different non-cohesive sediment transport equations with a wide range of hydraulic and sediment conditions.
- Floodplain simulation.
- Exchange of water and sediment between main channel and floodplains.
- Fractional sediment transport, bed sorting, and armoring.

- Computation of width changes using the theory of stream power minimization and other minimizations.
- Point and non-point sources of flow and sediments.
- Internal boundary conditions, such as time-stage tables, rating curves, weirs, bridges, and radial gates.

MODEL INPUT

Model input included flow rates, sediment loads, channel roughness, initial channel geometry, and initial bed material. In addition, several computational parameters were required, including the active layer thickness and sediment transport formula.

The upstream flow rate into the model was based on flows recorded at the gage station downstream of Friant Dam. Friant Dam was assumed to block all incoming sediment from upstream reaches, and therefore no sediment load was input at the upstream boundary. Four gages located in the study reach provided Historical Hydrology from a common period of January 1, 1980 through May 31, 1997, including the San Joaquin River below Friant Dam (USGS 11251000), the San Joaquin River near Gravelly Ford(USBR GRF, the Chowchilla Bypass downstream from the Chowchilla Bifurcation Structure(DWR CBP), and the San Joaquin River downstream from the Chowchilla Bifurcation Structure(USBR, SJB). These gages were used to develop the hydrology for historical conditions, denoted as Historical Hydrology. In addition to the Historical Hydrology, numerical simulations were conducted with the Baseline and Alternative A hydrology conditions. The simulated Baseline hydrology was computed by first using CALSIM II to simulate monthly average flows under current operational conditions. These monthly average flows were used as input into a daily operations model developed for the San Joaquin River Restoration Project. The period used in the CALSIM II simulations was from January 1, 1980 to September 31, 2003. Various water management alternatives were analyzed within CALSIM II, but only Alternative A was analyzed in this report. Details of the flow modeling will be documented in subsequent reports by Montgomery Watson Harza (MWH).

HEC-RAS geometry provided by a consulting firm (MEI, 2002) was transferred into SRH-1D format. To limit the computational time, one of every six cross sections was used in the sediment modeling. Based on previous hydraulic calculations the Manning’s roughness coefficient was set to 0.035 for the main channel and 0.15 for the floodplain in most cross sections (MEI, 2002). In other cross sections, the coefficient was calculated by averaging the depth-varied Manning’s roughness coefficients from the HEC-RAS model.

Non-uniform flow along the river was simulated with point and non-point sources in SRH-1D. Flow rates decreased significantly along the reach due to channel percolation and diversions. Hydrology data from four flow gage stations were used to interpolate the flow rates at the upstream and downstream ends of each sub-reach. The four gages stations are located downstream of Friant Dam (Cross Section #596 (XS596)), at Gravelly Ford (XSA213), on the Chowchilla Bypass downstream of Chowchilla Bifurcation Structure (CBP), and on the San Joaquin River downstream of Chowchilla Bifurcation Structure (XS94). Non-point flow sources were used to represent flow differences between the downstream and upstream ends of each sub-reach. Flow upstream of the Chowchilla Bifurcation structure was determined by combining flows from the gages on the Chowchilla Bypass and the San Joaquin River, both downstream of the structure. A negative point source was used to represent the flow routed through the Chowchilla Bypass.

Rating curve tables were applied to simulate internal boundary conditions, such as bridges and culverts. The previous Hec-Ras model (MEI, 2002) used 12 bridges and culverts as internal boundary conditions. Only 3 of these structures were found to significantly influence the hydraulics (i.e. resulted in a difference in water surface elevation of greater that 1 foot across the structure). Of the three structures, one was no longer physically present and therefore was not used as internal boundary condition. Rating curve tables were used to capture hydraulics through the Ledger Island Bridge and Chowchilla Bypass Structure. All other structures were identified as hydraulically insignificant for the purposes of this model and were not incorporated into the SRH-1D model.

Surface bed material data used in the sediment transport analysis were derived from surface samples collected in February 2008 (Reclamation, 2008a), 29 of which were located in Project Reaches 1 and 2. For cross sections where bed material samples were not available, SRH-1D automatically interpolates the surface bed material based upon linear channel distance from the nearest sediment samples.

Transport capacity was calculated with three different transport formulas: Parker's gravel transport equation (Parker, 1990) combined with Engelund and Hansen's sand transport equation (Engelund and Hansen, 1972), Wilcock and Crowe's gravel-sand-mixed transport equation (Wilcock and Crowe, 2003) combined with Engelund and Hansen's sand transport equation, and Wu et al.'s non-uniform sediment transport for gravel and sand (Wu et al. 2000).

A final required input parameter is the active layer thickness. The active layer concept is used to simulate channel armoring. In SRH-1D, the active layer thickness is equal to a constant times the diameter of the largest sediment size. The constant was set equal to 10 based on previous experience. A sensitivity analysis of the active layer thickness value was performed and documented in a previous analysis (Huang and Greimann, 2009).

RESULTS

The simulated daily average flows under Baseline and Alternative A conditions were obtained from MWH for the period from 1/2/1980 to 9/30/2003. SRH-1D was used to simulate the sediment transport and channel morphology with the 1998 channel geometry as the initial channel conditions. Water year 1997 was a wet year with a high peak discharge. The chance that a peak discharge of this magnitude will occur in the near future is low. Thus, the Baseline hydrology was simulated based upon the period from January 1, 1980 through September 30, 2003 with and without the water year 1997. Levee setbacks were considered in Alternative A Hydrology to contain flows exceeding 1,500cfs. Two options of levee setbacks are currently under consideration: (1) Average Levee Setback (ALS) and (2) Maximum Levee Setback (MLS). The levee setback options only affect the geometry in Reach 2B downstream of the Chowchilla Bifurcation Structure. In this analysis, the impacts of both the ALS and MLS options on sediment transport characteristics were investigated.

Figure 1 shows the bed profiles that were simulated under Baseline and Alternative A hydrology with Parker's (1990) gravel transport equation combined with Engelund and Hansen's (1972) sand transport equation. Very minimal erosion and deposition occurred upstream of Gravelly Ford in Reach 1. Reach 2A, from Gravelly Ford to Chowchilla Bypass, experienced erosion, which reached an average of 3.1 ft in 23 years under Baseline conditions. Hydrology without water year 1997 resulted in 11.3% less erosion (2.8ft) on average than with water year 1997 included. The erosion through this reach reduced to 2.1 ft under Alternative A Hydrology. Reach 2B, between Chowchilla Bypass and Mendota Pool, experienced deposition, which reached an average of 0.25 ft in 23 years under Baseline hydrology. Hydrology without water year 1997 shows similar deposition (0.35 ft on average). Under Alternative A hydrology, Reach 2B also experienced deposition, which reached an average of 0.4 ft and 0.2 ft in 23 years, for ALS and MLS, respectively. Compared with the Baseline hydrology, Alternative A hydrology increases the frequency of all flow ranges in Reach 2B. Within this reach, the SRH-1D model predicted nearly a five-fold increase in sand and small gravel transport capacity from Baseline conditions to Alternative A conditions (Huang and Greimann, 2009a). On a reach-average, Reach 2B has similar deposition in the main channel under Alternative A than under Baseline conditions. Compared with the ALS option, the MLS option experienced slightly more deposition in the first few cross sections downstream from the bifurcation structure since more flow is distributed onto the floodplain, and the channel has a reduced capacity to transport incoming sediment.

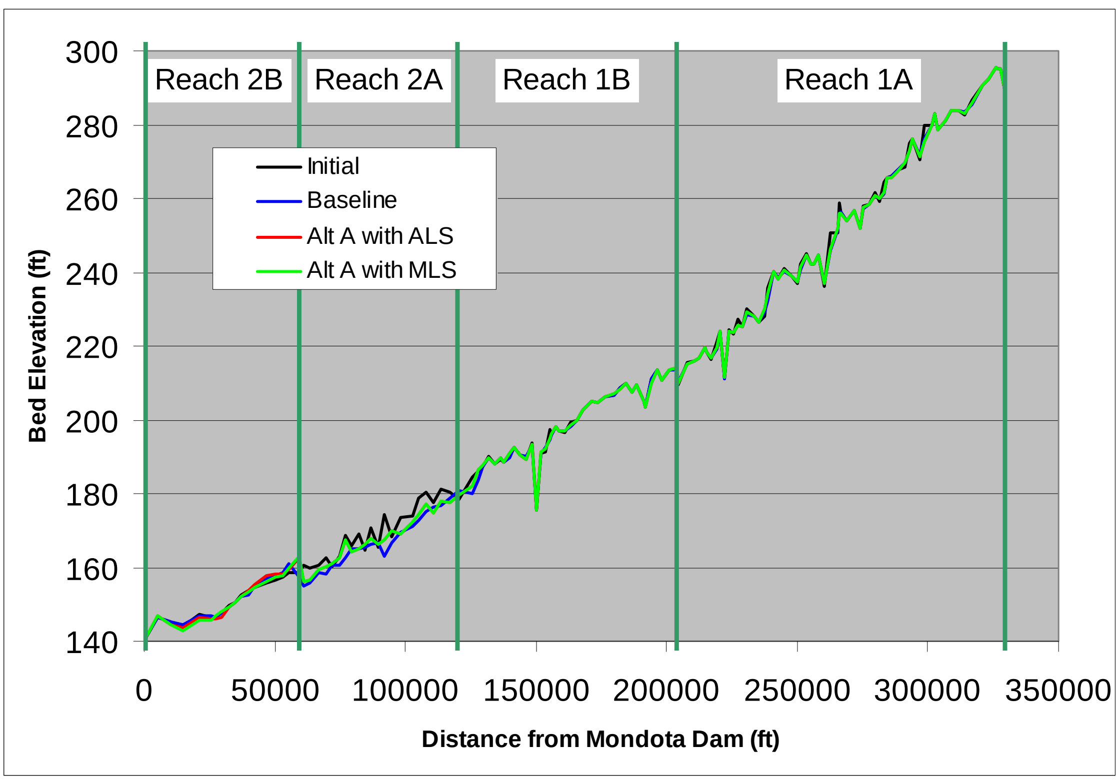

Figure 1 Bed profiles simulated under Baseline and Alternative A hydrology.

Figure 2 shows the simulated mean bed material sizes in each reach. No changes in sediment size were measured upstream of Gravelly Ford. Sediment became coarser in Reach 2A from Gravelly Ford to Chowchilla Bypass due to sediment erosion. Alternative A hydrology results in similar bed material in Reach 2A compared with Baseline hydrology. Just downstream of the Chowchilla Bypass, the sediment size increased slightly.

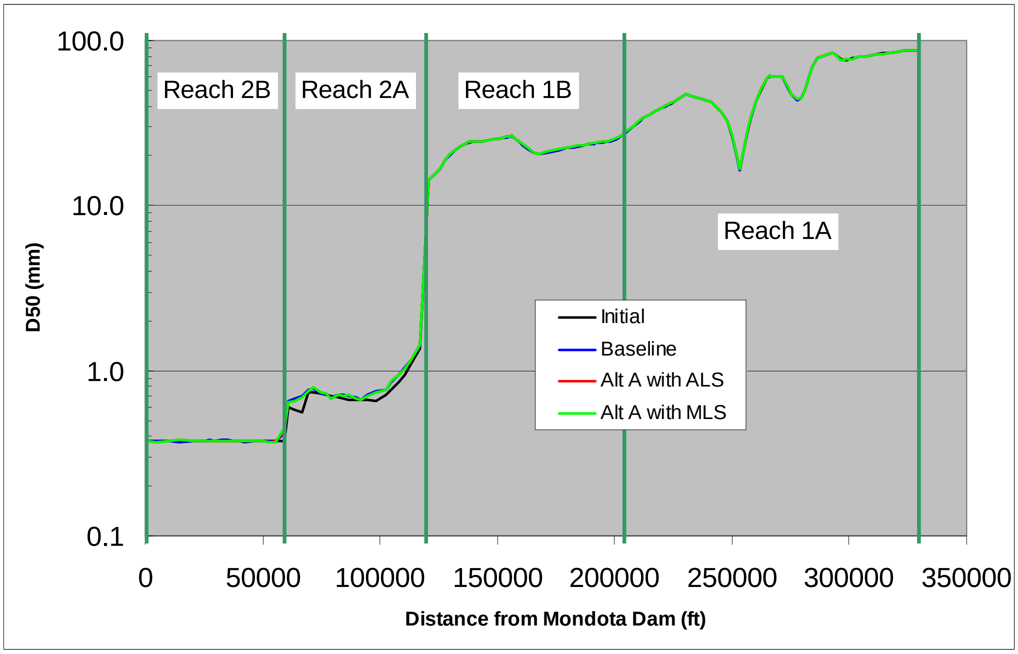

Figure 2 Median bed material size for Baseline and Alternative A hydrology.

Figure 3 depicts the locations of erosion and deposition of sand, small gravel, and large gravel at each cross section. Upstream of Gravelly Ford in Reach 1, erosion was generally observed in riffle locations, and deposition was noted in pool locations. One-Dimensional models generally cannot simulate the detailed sediment and hydraulic conditions that maintain pool-riffle complexes. Therefore, they commonly will predict erosion in riffles and deposition in pools, when in fact, the system is generally stable and no significant changes are expected. Compared with Baseline hydrology, Alternative A hydrology resulted in less transport of small gravel in Reach 1A; however, the trend was reversed in Reach 1B, where Alternative A hydrology resulted in more transport of small gravel. In regards to large gravel, Alternative A hydrology resulted in a small increase in transport relative to Baseline conditions.

Between Gravelly Ford and the Chowchilla Bypass in Reach 2A, sand erosion occurred in all cross sections; gravels were eroded in some cross sections and deposited in others. Compared to Baseline conditions, Alternative A caused less sand erosion in most of the cross sections in this reach. Also, Alternative A resulted in more small gravel erosion in riffle locations and deposition in pool locations. In regards to large gravels, Alternative A hydrology usually caused more deposition as compared with Baseline hydrology.

In Reach 2B downstream of the Chowchilla Bypass, sand deposition occurred at the cross section immediately downstream of the bypass. More deposition occurred in Reach 2B under Alternative A than under Baseline conditions. However, most of this deposition was restricted to the widened floodplain. The main channel bed elevations actually increased less under Alternative A than under Baseline conditions. Compared with the ALS option, the MLS scenario experienced a greater volume of deposition at the very upstream and downstream cross sections of Reach 2B. No gravel erosion or deposition was predicted in this reach. Table 3-1 summarizes the depths of erosion and deposition predicted with the Baseline and Alternative A hydrologic conditions.

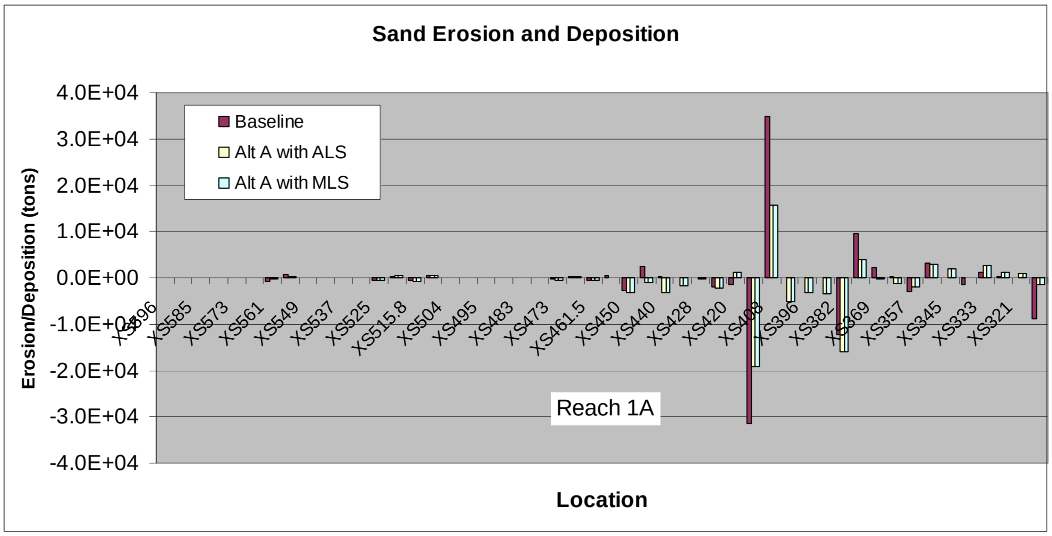

Figure 3(a) Sand Erosion and Deposition with upstream on the left.

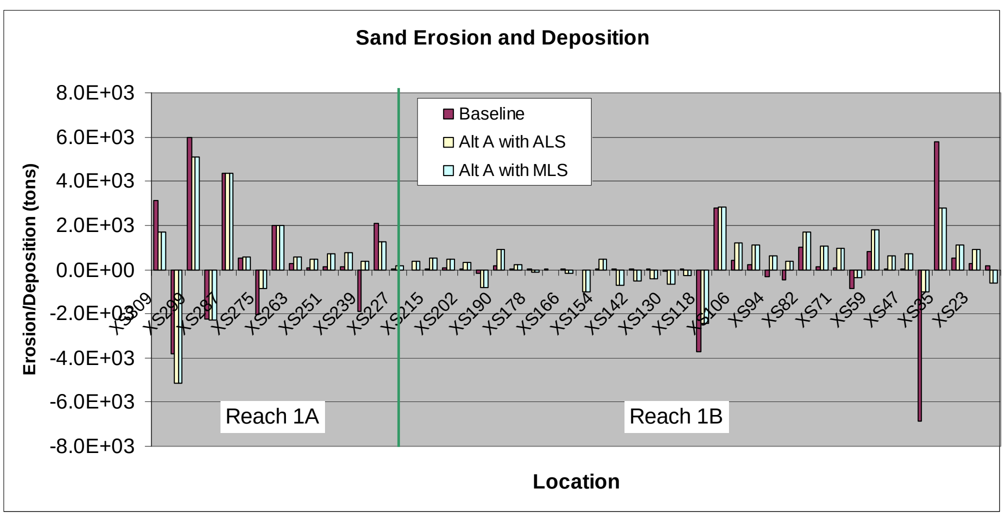

Figure 3(b) Sand Erosion and Deposition with upstream on the left (continued).

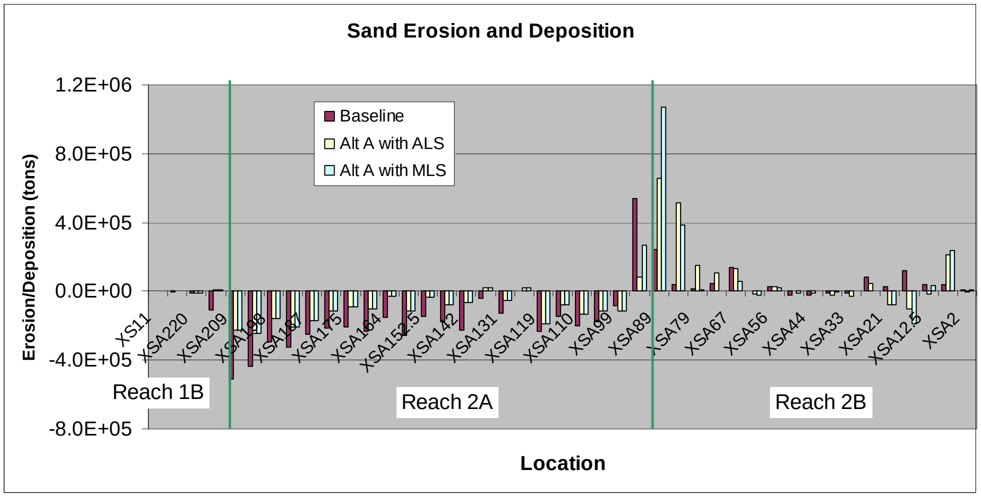

Figure 3(c) Sand Erosion and Deposition with upstream on the left (continued).

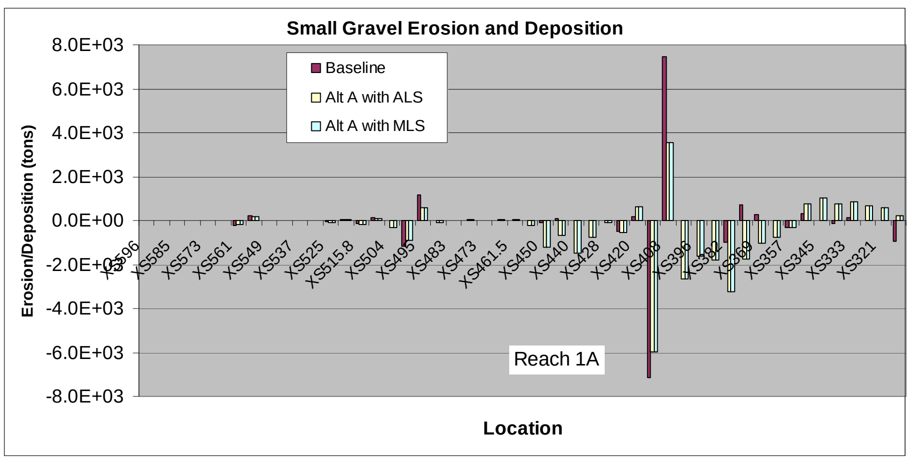

Figure 4 (d) Small Gravel Erosion and Deposition with upstream on the left (continued).

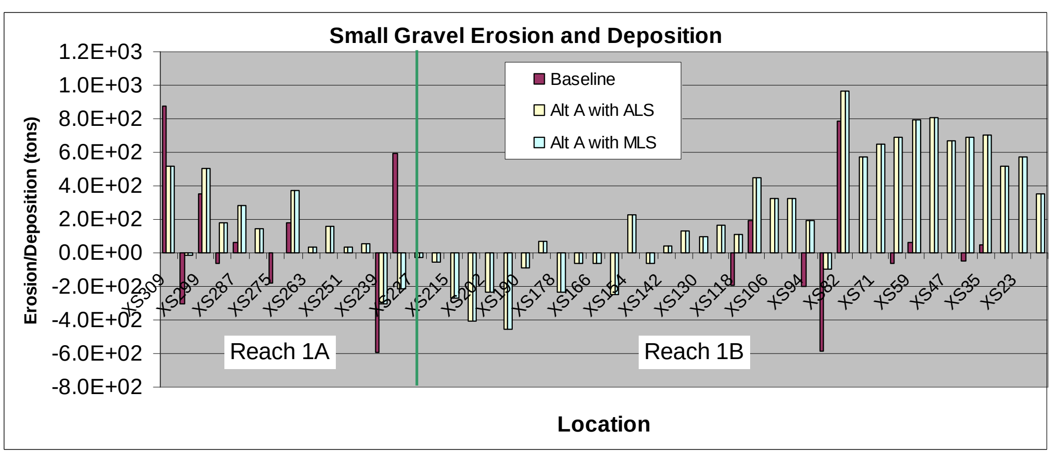

Figure 5 (e) Small Gravel Erosion and Deposition with upstream on the left (continued).

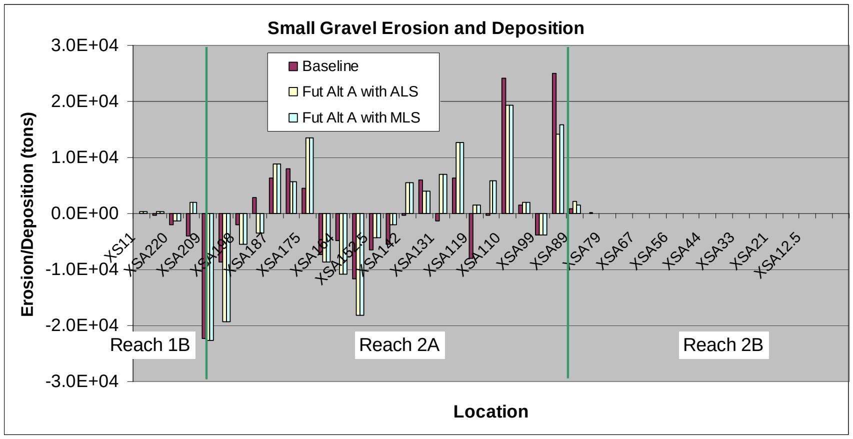

Figure 6 (f) Small Gravel Erosion and Deposition with upstream on the left (continued).

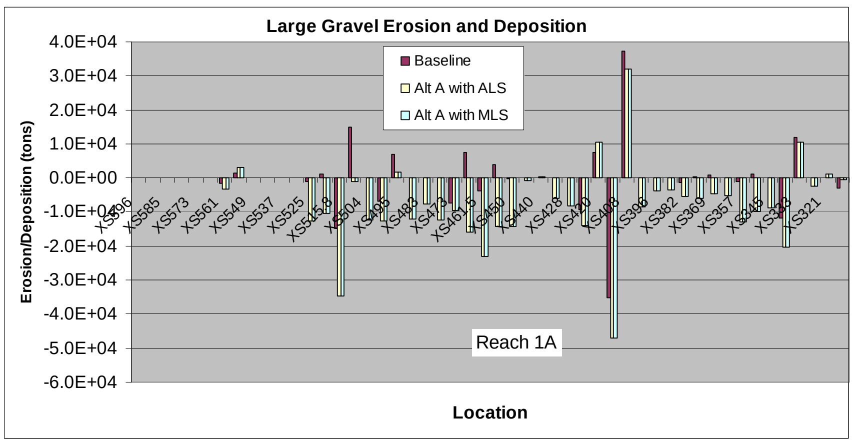

Figure 7 (g) Large Gravel Erosion and Deposition with upstream on the left (continued).

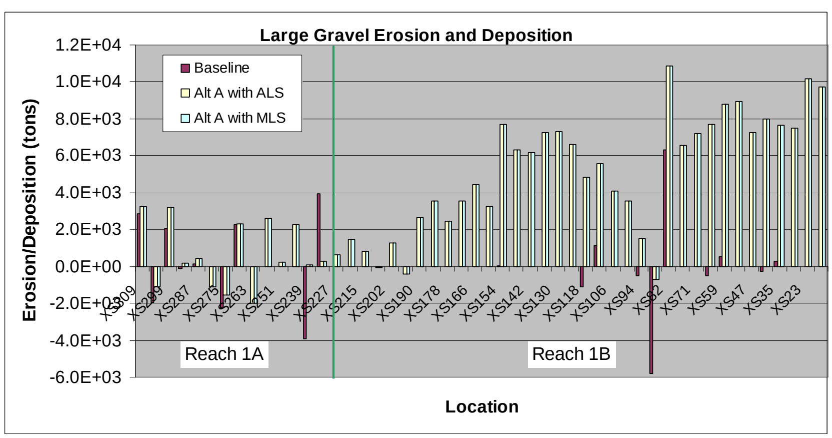

Figure 8 (h) Large Gravel Erosion and Deposition with upstream on the left (continued).

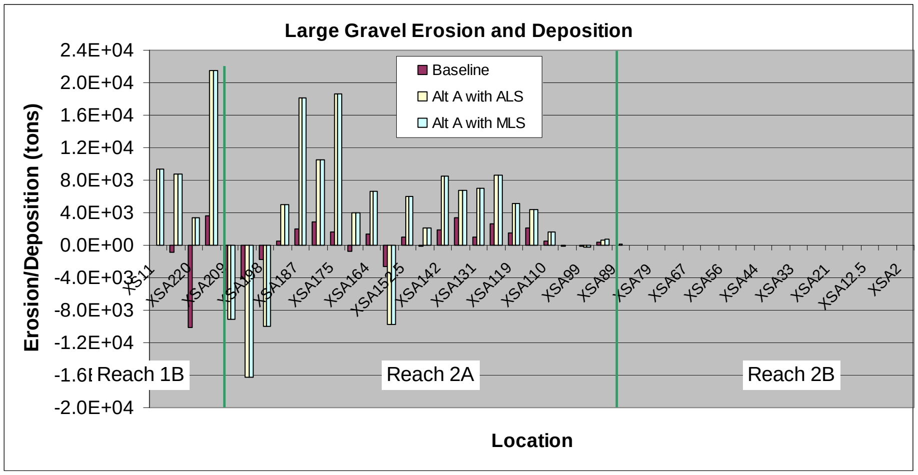

Figure 9 (i) Large Gravel Erosion and Deposition with upstream on the left (continued).

Table 1 Summary of results with Baseline and Alternative A conditions.

Hydrology	Baseline	Baseline without Year 1997	Future Alt A with ALS	Future Alt A with MLS
Reach 2A	Erosion 3.1 ft	Erosion 2.8 ft	Erosion 2.1 ft	Erosion 2.1 ft
Reach 2B	Deposition 0.25 ft	Deposition 0.35 ft	Deposition 0.37 ft	Deposition 0.22 ft

SUMMARY

SRH-1D was used to simulate the erosion and deposition under Baseline conditions and Alternative A hydrologic conditions. The geometry and bed gradations were kept the same for all hydrologic conditions. However, the levees were setback in Reach 2B to contain high flows in Alternative A hydrology. Other channel and sediment conditions are assumed identical between the scenarios.

Upstream of Gravelly Ford (Reach 1A and 1B), no erosion or deposition was notable under Baseline hydrology or Alternative A hydrology. Detailed investigation of the simulated erosion and deposition depths indicate that upstream of Gravelly Ford, some cross sections experienced erosion and some deposition, but this is due to the one-dimensional model's inability to simulate pool-riffle complexes. Overall, this reach is relatively stable, and the water surface profiles remain stable.

Under the Baseline conditions, the predicted erosion was 3.1 ft in 23 years in Reach 2A. Alternative A hydrology resulted in only 2.1 ft of erosion.

The model predicted deposition in the reach between Chowchilla Bypass and Mendota Pool (Reach 2B) under both scenarios. Compared with the ALS option, the MLS option experienced slightly more deposition in the first few cross sections downstream from the bifurcation.

Bed material gradations were also simulated. No change in sediment size occurred upstream of Gravelly Ford. The model predicted that the median sediment size in the bed increased from Gravelly Ford to Chowchilla Bypass due to erosion of the bed material for all scenarios. No substantial difference was present between the scenarios. Just downstream of the Chowchilla Bifurcations Structure on the San Joaquin River, the sediment size increased slightly due to the movement of coarser sands into that reach.

The results were presented to evaluate the channel response to different restoration strategies.

ACKNOWLEDGEMENTS

This study is funded by Reclamation's Mid-Pacific Regional Office (D. Mooney). The authors would also like to thank Tetra Tech Engineering who provided the HEC-RAS model of the San Joaquin River and colleague E. H. Gordon who contributed her insights and peer reviewed the paper.

REFERENCES

Ayres Associates, Inc., 1998. Topographic and Bathymetric Surveys for the San Joaquin River from Friant Dam to Gravelly Ford (RM 267 to RM 229). Prepared for U.S. Bureau of Reclamation, Fresno, California.

Ayres Associates, Inc., 1999. Topographic and Hydrographic Surveys for the Sacramento and San Joaquin Comprehensive Study, California - Topographic and Hydrographic Surveying and Mapping for San Joaquin River, RM 40 to RM 230, Including Tributaries and Distributaries. Prepared for U.S. Army Corps of Engineers, Sacramento District, Sacramento California.

Engelund, F., and Hansen, E. (1972). A monograph on sediment transport in alluvial streams, Teknish Forlag, Technical Press, Copenhagen, Denmark.

Han, Q. (1980). "A study on the non-equilibrium transportation of suspended load," Proc. of the Int. Symp. on River Sedimentation, Beijing, China, 793–802. (In Chinese.)

Huang, J., and Greimann, B.P., (2007). User's Manual for SRH-1D 2.0 (Sedimentation and River Hydraulics – One Dimension Version 2.0), Bureau of Reclamation, Technical Service Center (www.usbr.gov/pmts/sediment).

Huang, J., and Greimann, B.P., (2009a). Sediment Mobilization and Transport in the San Joaquin River from Friant Dam to Mendota Pool, California, Bureau of Reclamation, Technical Service Center, Denver, CO.

Huang, J., and Greimann, B.P., (2009b). Sediment transport and channel morphology model in the San Joaquin River from Mendota Dam to the Merced River confluence, California, Bureau of Reclamation, Technical Service Center, Denver, CO.

Mussetter Engineering, Inc. (2002). "Hydraulic and Sediment Continuity Modeling of the San Joaquin River from Friant Dam to Mendota Dam, California," U.S. Bureau of Reclamation, Contract No. 98-CP-20-20060.

Parker, G. (1990). "Surface based bedload transport relationship for gravel rivers," Journal of Hydraulic Research, Vol. 28(4), 417–436.

Wilcock, P.R., and Crowe J.C. (2003). “Surface-Based Transport Model for Mixed-Size Sediment,” Journal of Hydraulic Engineering, ASCE, 129(2):120-128.

Wu, W., S.S.Y. Wang, and Y. Jia (2000). "Nonuniform sediment transport in alluvial rivers," Journal of Hydraulic Research, Vol. 38(6):427-434.