Journal of Coastal Research	SI 56	713 - 716	ICS2009 (Proceedings)	Portugal	ISSN 0749-0258

Linking Human Impacts within an Estuary to Ebb-tidal Delta Evolution

K. L. Dallas† and P. L. Barnard‡

†Department of Earth & Planetary Sciences
University of California, Santa Cruz
CA 95064, USA
kldallas@usgs.gov

‡ Coastal and Marine Geology Program
United States Geological Survey, Santa Cruz,
CA 95060, USA
pbarnard@usgs.gov

ABSTRACT

DALLAS, K.L. and BARNARD, P.L., 2009. Linking Human Impacts within an Estuary to Ebb-tidal Delta Evolution. Journal of Coastal Research, SI 56 (Proceedings of the 10th International Coastal Symposium), 713 – 716. Lisbon, Portugal, ISSN 0749-0258

San Francisco Bay, California, USA is among the most anthropogenically altered estuaries in the entire United States, but the impact on sediment transport to the coastal ocean has not been quantified. Analysis of four historic bathymetric surveys has revealed large changes to the morphology of the San Francisco Bar, an ebb-tidal delta at the mouth of the San Francisco Bay. From 1873 to 2005 the bar eroded an average of 80 cm, which equates to a total volume loss of 100 $\pm$ 65 x 10^6 m^3 of sediment. Comparison of the surveys indicates the entire ebb delta has contracted radially while its crest has moved landward an average of 1 km. Compilation of historic records reveals that 130 x 10^6 m^3 of sediment has been permanently removed from the San Francisco Bay and adjacent coastal ocean. Constriction of the bar is hypothesized to be from a decrease in sediment supply from San Francisco Bay, a reduction in the tidal prism of the estuary, and/or a reduction in the input of hydraulic mining debris. Changes to the morphology of the San Francisco Bar have likely altered wave refraction and focusing patterns on adjacent beaches and may be a factor in persistent beach erosion occurring in the area.

ADITIONAL INDEX WORDS: *San Francisco Bay, San Francisco Bar, long-term changes, bathymetry, sedimentation, erosion*

INTRODUCTION

Anthropogenic activities within coastal estuaries may affect sediment delivery to the coastal ocean. Because beaches and nearshore bars are supplied in part from this material, activities that alter sediment delivery are important to quantify. Ocean Beach, California, USA (Fig. 1) is located near the mouth of the San Francisco Bay estuary and has been eroding along its southern reach for decades. Modeling results and bedform analysis for the area show distinct pathways for the seaward transport of bed load and suspended load out of San Francisco Bay (BARNARD et al., in press). Sediment management practices inside the bay, therefore, at least partly influence the amount of sediment transported to the coastal ocean.

San Francisco Bay is one the largest estuaries in the United States and has been continuously altered by a range of activities, including influx by hydraulic mining debris, mining of fill for bay development, dredging of harbors and waterways, and mining of sand and gravel for use as construction aggregate. The bay is connected to the Pacific Ocean by the narrow Golden Gate Inlet, where during peak ebb flow depth-averaged currents can exceed 2.5 m/s (BARNARD et al., 2007). After the ebb jet emerges from the inlet throat the velocity decreases and coarse sediment is dropped. This sediment, and sediment supplied by littoral drift, accumulates to form the San Francisco Bar, a 100 km^2 ebb-tidal delta (Fig. 1). The bar is shaped by tidal currents and waves and exerts a strong influence on wave refraction and focusing patterns on adjacent beaches (BARNARD et al., 2007). This in turn, impacts beach morphology, a critical issue at Ocean Beach where erosion threatens valuable infrastructure.

The objective of this study is to quantify the impact of anthropogenic activities within San Francisco Bay on the amount of sediment delivered to the coastal ocean. To assess this impact, dredging and mining records were compiled and historic bathymetric models of the San Francisco Bar were generated. This study builds on previous work in the area by GILBERT (1917), MOFFATT AND NICHOL (1995), BATTALIO AND TRIVEDI (1996), BARNARD et al. (2007), JAFFE et al. (2007), FREGOSO et al. (2008) and others, but is the most comprehensive study on long-term bathymetric change of the San Francisco Bar to date.

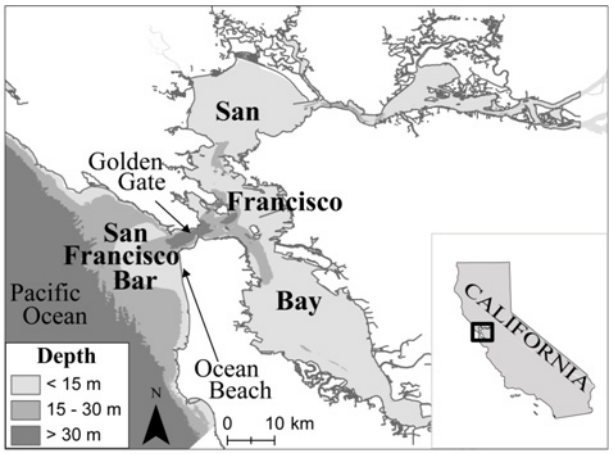

Figure 1. Location of study area near the San Francisco Bay estuary, California.

METHODS

Volumes for historic dredging and borrow pit mining events in San Francisco Bay were compiled by a thorough literature search (e.g. MARKWART, 1973, US ARMY CORPS OF ENGINEERS, 1975, SCHEFFAUER, 1954). Volumes reported represent only those sediments that were permanently removed from the system either through beneficial reuse, disposal on land, or disposal in the deep ocean. Sand mining volumes were collected from annual reports submitted to the Bay Conservation and Development Commission.

Sounding data from four historic bathymetric surveys were used to create continuous bathymetric grids of the San Francisco Bar. Creation of accurate surface grids involved several steps. For the 1873 and 1900 grids, soundings were digitized from hydrographic sheets obtained from the National Ocean Service (NOS). Sounding data were then registered to a common horizontal datum using latitude/longitude graticules. For the 1956 and 2005 grids, registered soundings were obtained directly from NOS and the California State University, Monterey Bay Sea Floor Mapping Lab, respectively. Bathymetric TIN grids with a horizontal resolution of 25 meters were generated for each survey. Grids were adjusted to a common vertical datum (NAVD88) to account for changes in sea-level rise (i.e. tidal epoch and tidal datum) and differenced to create bathymetric change grids. To improve comparability of all surveys, bathymetric change maps were limited to a 125 km^2 area that contained data for all four surveys. Net sediment volume change for each survey period was calculated by multiplying the average depth change between surveys by the surface area of the grid. Crest location was determined for each survey by extracting the shallowest depth along 40 transects cast roughly perpendicular to the crest.

Error and Uncertainty Analysis

The total bathymetric grid uncertainty is a combination of potential errors and uncertainties, including sounding measurement uncertainty, vertical tidal inconsistencies, and gridding bias errors. While some uncertainties/errors can be assessed with high precision, others can only be estimated. It is noted that the total grid error is believed to be far less than the grid uncertainty. For example, grid bias was calculated by comparing every sounding to its associated grid value and finding the mean difference. Grid bias was small (0.1 cm to 0.52 cm) and is included in the uncertainty calculation even though it was removed from the grids. On the other hand, measurement uncertainties of individual soundings from the 1873 and 1900 surveys can only be estimated. An average uncertainty can be estimated by using the error criteria employed during surveying. In the early surveys sounding error was determined in the field by comparing separate measurements at trackline crossings and was not to exceed 3% of the water depth (SCHALOWITZ, 1964). Visual observations of trackline crossings and observations of the pinching out of profiles from different years on the inner continental shelf indicate sounding error is not systematic. The same long-term morphological trends were also found in Central San Francisco Bay by FREGOSO et al. (2008) and provide further support for sounding error being non-systematic. Due to the complexity of error assessment, uncertainties could only be estimated. As a conservative estimate, $\pm$0.4 m was applied for the 1873 and 1900 surveys, $\pm$0.2 m for 1956, and $\pm$0.12 m for 2005. Volume change uncertainties were calculated by multiplying the sum of uncertainties of both surveys by the surface area of the grid. For example, the volume change uncertainty from 1956 and 2005 is $\pm$0.32 m (0.2 m + 0.12 m) times the surface area of the grid. These estimates assume a systematic error throughout the surveys, but there is no evidence that the error is this large for any of the volume calculations. Future research will explore options for reducing these uncertainties.

RESULTS

Anthropogenic impacts

The greatest single impact to the San Francisco Bay floor was the influx of hydraulic mining debris. GILBERT (1917) estimated that approximately 1.15 x 10^9 m^3 of sediment was transported to the bay from 1849 to 1909. This pulse of sediment, in tandem with widespread development and loss of wetlands, caused a ~30% reduction in the tidal prism (BARNARD et al., 2007).

Since 1900 a minimum of 130 million m^3 (Mcm) of sediment has been permanently removed from the San Francisco Bay and adjacent coastal ocean through borrow pit mining (27 Mcm), aggregate mining (26 Mcm), and dredging (77 Mcm) (Fig. 2). This is a minimum estimate because not all records have been compiled (missing 1976-1996 dredge records and borrow pit mining records for the San Francisco waterfront, Alameda Air Base, BART tunnel, and Oakland Airport) and some records are incomplete. A majority of the sediment was removed from Central Bay (52%), with lesser amounts removed from the North Bay (28%), San Francisco Bar (18%), and South Bay (2%). The largest single event was the removal of 22 Mcm of sand from Central San Francisco Bay for the building of Treasure Island from 1936-1938 (SCHEFFAUER, 1954).

Historical bathymetric change to the San Francisco Bar

The San Francisco Bar has experienced periods of erosion and deposition since the first detailed survey in 1873. From 1873 to

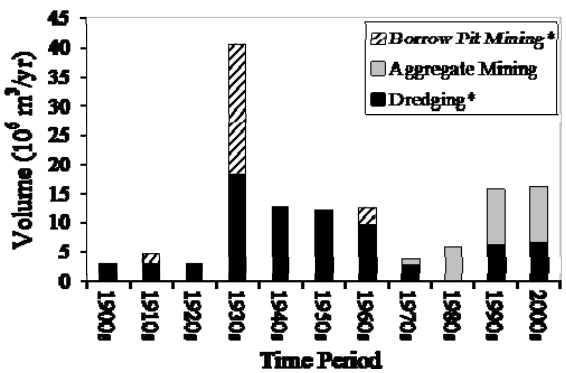

Figure 2. Volume of sediment permanently removed from the San Francisco Bay and coastal ocean. *incomplete data

1900 a net volume of 78 $\pm$ 124 Mcm was eroded across the bar, with an average depth change of -0.63 m (Fig. 3). During this time, erosion occurred along the entire length of the crest and within the inner most portion of the bar. From 1900 to 1956 a net volume of 52 $\pm$ 75 Mcm of sediment was deposited on the bar, with an average depth change of +0.42 m (Fig. 3). Significant changes include accretion landward of the crest, initiation of channel dredging, and migration of the crest landward. Comparison of the 1956 and 2005 surveys reveals net erosion of 75 $\pm$ 40 Mcm of sediment, with an average depth change of -0.60 m (Fig. 3). During this period erosion of the crest was widespread with additional erosion in the ship channel from modified

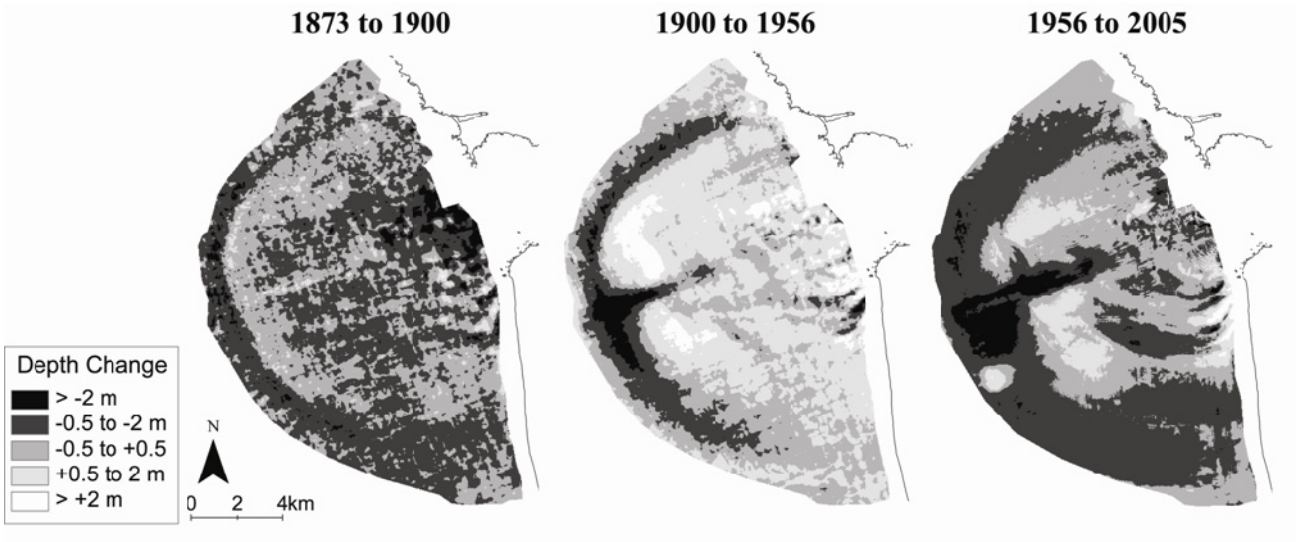

Figure 3. Bathymetric change maps of the San Francisco Bar from 1873 - 2005.

dredging practices to deepen and widen the channel. A distinct accretionary mound can also be seen south of the ship channel as a result of dredge disposal in this location since 1973. Accretion is also evident along the peripheral flood channels and may represent a decrease in flow through these channels as a result of increased hydraulic efficiency of the main channel due to dredging (HANES AND BARNARD, 2007). Comparison of the 1873 and 2005 surveys reveals net erosion of 100 ± 65 Mcm of sediment, with an

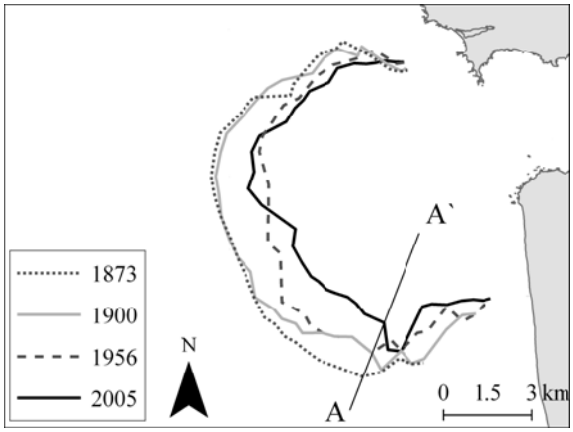

Figure 4. Location of the crest of the San Francisco Bar from 1873 – 2005.

average increase in depth of -0.8 m.

Consistent across all surveys is a landward migration of the crest through time (Fig. 4). Cross sections through the ebb delta demonstrate continued radial shrinking throughout the study period despite overall accretion between 1900 and 1956 (Fig. 5). In the northern and central sections of the bar, where the crest is narrow and well defined, the crest has moved landward an average of ~1 km since 1873, with a maximum landward movement of ~1.6 km.

DISCUSSION

The general shape of any ebb-tidal bar is determined by a balance between tidal currents, waves, and the amount of sediment supplied (HAYES, 1980). Previous studies indicate any modification in the factor(s) listed above can produce significant morphological response (see ELIAS AND SPEK, 2006; FAN et al., 2006; SYVITSKI AND SAITO, 2007). Results presented here reveal large changes in the morphology of the San Francisco Bar and suggest a change in the forcing factors or boundary conditions. Although waves are highly variable over short timescales, it is assumed that the average wave strength remained constant over the 132 years encompassed in this study. Continued radial shrinking of the bar would result from a decrease in sediment supply, reduction in the tidal prism of the estuary, and/or a reduction in the input of hydraulic mining material.

Damming of rivers that drain into the San Francisco Bay and dredging, borrow pit mining, and aggregate mining within the estuary have changed sediment dynamics from its natural state. WRIGHT AND SCHOELLHAMER (2004) found that the three largest reservoirs in the watershed have impounded over 60 Mcm of sediment, while results from this study indicate a minimum of 130 Mcm of sediment has been removed from the estuary. It is noted that the specific median grain sizes of the trapped or

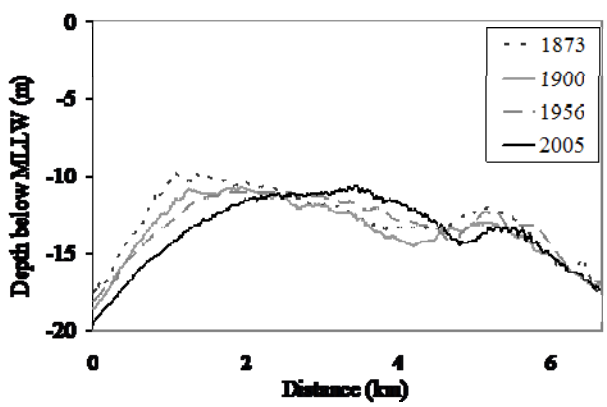

Figure 5. Profile of San Francisco Bar along line A-A` (Fig 4) from 1873 – 2005.

removed sediments are unknown, so it is impossible to know what fraction would affect morphology of the ebb delta (median grain size 0.19 mm) (BARNARD et al., 2007). However, from sand mining reports and sampling of the bay floor in areas formerly used for dredging and borrow pit mining, we know that each of these activities did utilize sediment that is compatible with grain sizes on the bar, so each are important to consider.

The second hypothesis to explain contraction of the ebb delta is a change in the tidal prism of the San Francisco Bay. A reduction in the tidal prism of the estuary due to development, sedimentation, and infilling of marshes has been recorded by previous studies (see GILBERT,1917 and KRONE,1979). In this case, tidal currents would be reduced and the ebb-tidal delta would be shrinking to reach a new equilibrium.

The last hypothesis is a decrease in the amount of hydraulic mining debris supplied to the coast. GILBERT (1917) estimated that the effects of mining would persist for roughly 50 years after 1914, and MEADE (1982) showed that the main pulse of mining debris passed through the watershed prior to 1950. In this case, the ebb-tidal delta may still be adjusting to a large input of hydraulic mining debris and slowly evolving back to its equilibrium size. In the future we plan to investigate each of these hypotheses, all of which have likely contributed toward morphological changes of the San Francisco Bar.

CONCLUSIONS

Analysis of historical bathymetric surveys has revealed erosion of 100 $\pm$ 65 Mcm of sediment to the San Francisco Bar in the past 130 years. In addition, the bar crest has retreated landward an average of ~1 km. Changes to the morphology of the bar have likely caused changes to wave refraction and focusing patterns and altered sediment transport pathways. The erosional trend observed on the ebb-tidal delta is hypothesized to be linked to a decrease in sediment supply from San Francisco Bay, a reduction in the tidal prism of the estuary, and/or a reduced input of hydraulic mining material. Compilation of historical records indicates a minimum of 130 Mcm of sediment has been permanently removed from the system. A similar pattern of bathymetric change was found for Central San Francisco Bay by FREGOSO et al. (2008) and suggests a sediment supply link between Central Bay and the San Francisco Bar. With new management plans calling for an increase in out of bay dredge disposal, and aggregate companies lobbying to extract greater volumes, it is likely these activities will further limit the available sediment supplied to the bar. Future sediment management decisions made within San Francisco Bay should therefore consider the impacts to coastal sediment delivery.

LITERATURE CITED

BARNARD, P.L.; HANES, D.M.; ERIKSON, L.H.; RUBIN, D.M.; DARTNELL, P., and KVITEK, R.G, in press. Analyzing bedforms mapped using multibeam sonar to determine regional bedload sediment transport patterns in the San Francisco Bay Coastal System: Bedform patterns in the San Francisco Bay coastal system. International Association of Sedimentologists, Special Issue, 36pp.

BARNARD, P.L.; ESHLEMAN, J.L.; ERIKSON, L.H., and HANES, D.M., 2007. Coastal processes study at Ocean Beach, San Francisco, CA: summary of data collection 2004-2006. U.S. Geological Survey Open-File Report 2007-1217, 160p.

BATTALIO, R.T. and TRIVEDI, D., 1996. Sediment transport processes at Ocean Beach, San Francisco, CA. Proceedings of the 25th International Conference on Coastal Engineering (Orlando, Florida, USA), pp. 2691-2707.

ELIAS, E.P.L. AND SPEK, A.J.F., 2006. Long-term morphodynamic evolution of Texel Inlet and its ebb-tidal delta (The Netherlands). Marine Geology, 225, 5-21.

FAN, H.; HUANG, H., and ZENG, T., 2006. Impacts of Anthropogenic Activity on the Recent Evolution of the Huanghe (Yellow) River Delta. Journal of Coastal Research, 22(4), 919-929.

FREGOSO, T.A.; FOXGROVER, A.C., and JAFFE, B.E., 2008. Sediment deposition, erosion, and bathymetric change in Central San Francisco Bay: 1855-1979: U.S. Geological Survey Open-File Report 2008-1312, 47p.

GILBERT, G.K., 1917. Hydraulic-mining debris in the Sierra Nevada. U.S. Geological Survey Professional Paper 105, 154p.

HANES, D.M. and BARNARD, P.L., 2007. Morphological Evolution in the San Francisco Bight. Proceedings of the 9th International Coastal Symposium. Journal of Coastal Research Special Issue No. 50, pp. 469-473.

HAYES, M.O., 1980. General morphology and sediment patterns in tidal inlets. Sedimentary Geology, 26, 139–56.

JAFFE, B.E.; SMITH, R.E., and FOXGROVER, A.C., 2007. Anthropogenic influence on sedimentation and intertidal mudflat change in San Pablo Bay, California: 1856-1983. Estuarine Coastal and Shelf Science, 73, 175-187.

KRONE, R.B., 1979. Sedimentation in the San Francisco Bay System. In: CONOMOS, T.J. (ed.), San Francisco Bay: The Urbanized Estuary. San Francisco, California: American Association for the Advancement of Science, pp. 85-96.

MARKWART, A.H., 1915. Engineering problems of the Panama-Pacific Exposition. Engineering News-Record, 73(7), 329-336.

MEADE, R.H., 1982. Sources, sinks, and storage of river sediment in the Atlantic drainage of the United States. Journal of Geology, 90(3), 235-252.

MOFFATT and NICHOL ENGINEERS, 1995. Sediment transport processes study, Ocean Beach, San Francisco, California, Final Report, 69p.

SYVITSKI, J.P. and SAITO, Y., 2007. Morphodynamics of deltas under the influence of humans. Global and Planetary Change, 57, 261-282.

SCHALOWITZ, A.L., 1964. Shore and sea boundaries. U.S. Coast and Geodetic Survey Publication, 749p.

SCHEFFAUER, F.C., 1954. The hopper dredge, its history, development, and operation. U.S. Army Corps of Engineers, pp. 366-369.

U.S. ARMY CORPS OF ENGINEERS, 1975. Maintenance dredging, existing navigation projects, San Francisco Bay Region, California. San Francisco, California: U.S. Army Corps of Engineers, San Francisco District, 70p.

WRIGHT, S.A. and SCHOELLHAMER, D.H., 2004. Trends in the sediment yield of the Sacramento River, California, 1957-2001. San Francisco Estuary and Watershed Science (online serial) 2 (Issue 2, Article 2). http://repositories.cdlib.org/ jmie/sfews/ vol2/iss2/art2.

ACKNOWLEDGEMENTS

This research was supported by the United States Geological Survey, the Wiegel Scholarship Committee, and Friends of Long Marine Lab. The manuscript was improved by reviews from Dan Hanes and Theresa Fregoso. Special thanks goes to Theresa Fregoso for her help throughout the project.