

## Draft Science Synthesis

Issue 2. Sediment management: Creating desired habitat while preserving existing habitat

David Schoellhamer, Jessica Lacy, Neil Ganju, Greg Shellenbarger, and Megan Lionberger

February 14, 2005

This synthesis is neither a complete literature review nor a conceptual model. The purpose of the synthesis is to answer six questions regarding the sediment management issue and restoration of the South Bay salt ponds. The Consultant Team is developing a conceptual model of sediment transport in South Bay.

### **What is the importance of the issue as it relates to the Project Objectives?**

Project objective 1 is to create, restore, or enhance habitats of sufficient size, function, and appropriate structure to promote restoration and support increased abundance and diversity of native species in South San Francisco Bay. These species utilize either tidally-influenced aquatic habitats or vegetated marsh habitats (Goals Project 2000). In order to create these habitats, the Project must convert existing nontidal submerged salt ponds. The levees around the ponds will be breached to connect the ponds to the estuary and allow the water level in the ponds to vary with the tides. Most of the ponds are below intertidal marsh elevation (Siegel and Bachand 2002). Thus, the bed elevation of the ponds must be raised before it can be colonized by marsh vegetation. Natural deposition of sediment is the most cost effective method to accomplish this. Placement of dredged sediment is a faster alternative but increases costs and regulatory impediments. Once established, vegetation helps the marsh develop by trapping additional sediment and providing organic material. As land subsides and sea level rises, sedimentation is needed to maintain the elevation of the marsh relative to sea level. The rate of sedimentation will determine whether and when the project objectives will be met.

Natural sedimentation is dependent upon:

- Sediment supply from local tributaries and Bay waters.
- Transport of sediment from the Bay and sloughs into the pond by tidal currents.
- Deposition and retention of sediment in the pond.

Restoration actions have the potential to destroy valuable habitat. One effect of breaching a pond to a tidal slough or Bay is to increase the tidal prism of South Bay and the slough. Tidal prism is the change in water volume between low and high tide for a given region. If tides were reintroduced to an area equal to the area of the Alviso ponds (9.4 km<sup>2</sup>), the tidal prism south of the San Mateo Bridge would increase by about 10%. If the tidal prism increases, tidal velocities must increase. Increased velocity can cause erosion in the slough and in the Bay (Shellenbarger et al. in review). This erosion may cause loss of existing marsh or tidal flats. Tidal flats are critical habitat for shorebirds and waterfowl, produce nutrients necessary for a healthy food web, and protect the shoreline from erosion (San Francisco Bay Joint Venture 2001). An example that is similar to the proposed salt pond restoration is marshes in the Medway Estuary that had been

enclosed by levees beginning about 1700 and were breached by tides in the 1880s. Recently, the marshes have been accreting while the salt marsh creeks and cliffs and tidal flats have eroded (Kirby 1990). Restoration essentially undoes what the original diking of tidal marsh did: reduce tidal prism and allow remaining tidal channels to fill with sediment (Hood 2004). The project should be designed to maximize sediment deposition and habitat creation in the ponds while minimizing erosion and loss of existing habitat.

Another effect of restoration will be to alter the sediment budget of South Bay. Some of the sediment supplied by South Bay tributaries will deposit in breached ponds. To compensate for the loss of sediment to the breached ponds, erosion must increase or the amount of sediment leaving South Bay must decrease. The relative change in erosion and sediment export will determine the extent of habitat loss. Thus, the future sediment budget of South Bay is a key issue that will determine how well the project meets its objectives.

The primary concern with sediment is the creation and loss of desired habitat, but sediment affects other project objectives. Deposition or erosion in sloughs could affect flood control (objective 2, flood control) and boat access to the ponds and sloughs (objective 3, public access). Potentially toxic substances, such as metals and pesticides, adsorb to sediment particles (Kuwabara et al. 1989, Domagalski and Kuivila 1993, Flegal et al. 1996). The transport and fate of suspended sediments are important factors in determining the transport and fate of constituents adsorbed on the sediments. Suspended sediments limit the availability of light in San Francisco Bay, which, in turn, limits photosynthesis, primary photosynthetic carbon production, and phytoplankton blooms (Cole and Cloern, 1987; Cloern, 1987, 1996). Project activities that alter sediment transport and suspended-sediment concentration can affect the transport and fate of adsorbed constituents (objective 4, water and sediment quality), primary production, and phytoplankton blooms (objective 1, habitat). This synthesis will focus on the creation and loss of desired habitat, but it is also applicable to other objectives.

### **What do we know about this issue as it relates to the Project?**

The Consultant Team is developing a conceptual model of sediment movement and deposition in restored sites. To avoid duplication of effort, this section is a summary of what we know about sediment transport specific for this Project rather than a conceptual model of sediment transport and restoration in South Bay.

Several factors determine whether and how rapidly marsh habitat is created.

- *Pond elevations:* 61 percent of salt ponds have bottom elevations between mean tide level and mean higher water (Siegel and Bachand 2002). 22 percent of the ponds, all within the Alviso system where subsidence has been greatest, are below mean tide. As of summer 2004 USGS is collecting more detailed bathymetric data for numerical modeling (Takekawa et al. 2003). Sea-level rise or subsidence would slow the rate of pond accretion relative to water level. The rate of sea level rise in San Francisco Bay from 1900-1999 was 2.17 mm/year (Flick et al., 2003). Subsidence in South Bay from 1934 to 1967 ranged from 0 m at Ravenswood Point to 2.2 m (65 mm/yr) at the southern extent of South Bay (Poland and Ireland 1988). Groundwater pumping that caused much of the

subsidence has since decreased and land elevations in Santa Clara Valley are now rebounding upward at rates up to about 30 mm/year (Ferretti et al. 2004).

- *Sediment supply from tributaries:* The USGS measures sediment load on the Guadalupe River, Alameda Creek, and Coyote Creek (Smithson et al. 2004). Sediment sources, transport pathways, and loads of streams tributary to San Francisco Bay are reviewed by McKee et al. (2003).
- *Suspended-sediment concentration in the Bay:* USGS has continuously monitored suspended-sediment concentrations in the deep channel of South Bay for over a decade (Buchanan and Ganju 2004). South Bay is most turbid in spring and early summer when a strong seabreeze generates wind waves and resuspends bottom sediment on the shoals (Schoellhamer 1996). The wind generates a tidally-averaged current to the south along the shoals that carries sediment (Lacy et al. 1996). The annual maximum of suspended-sediment concentration in South Bay is typically during the spring tide following the end of the spring phytoplankton bloom (Ruhl and Schoellhamer 2001).
- *Sediment loss to the Ocean:* The wind also generates a return flow moving toward the ocean in the deeper parts of the main channel (Walters et al. 1985). This is believed to be the pathway by which sediment leaves South Bay during summer. Some of the sediment delivered by large tributary inflow during winter flows out of South Bay. A sediment budget for water years 1995-2002 based on a simple numerical model calibrated to bathymetric change data (Foxgrover et al. 2004) indicates that sediment is exported from South Bay to Central Bay at a rate of 1.2 million metric tons per year (Shellenbarger et al. 2004). On average, South Bay eroded downward from 1956 to 1983 (Foxgrover et al. 2004) and therefore must have exported sediment. A new bathymetric survey is being conducted to determine bathymetric change from 1983 to 2004. A related factor is the potential for sediment from the Central Valley of California to enter South Bay via the Sacramento and San Joaquin Rivers and Central Bay. During turbid and high River discharge, plumes of sediment from Central Bay can enter South Bay during flood tide and travel at least 10 miles south of the Bay Bridge (McCulloch et al. 1970). The mineralogy of bottom sediment in South Bay, however, matches that of the South Bay watershed, not the Central Valley (Yancey and Lee 1972). Thus, the primary source of South Bay sediment is the local watershed, not the Central Valley.
- *Transport of sediment to ponds:* Suspended-sediment concentration on the shoals is greater than in the deep channel (Schoellhamer 1996). This turbid water enters the deep channel during ebb tides. During flood tides, it is likely that this turbid water enters the sloughs adjacent to the ponds. Tidal sloughs, especially those for which tidal prism has been reduced such as in South Bay, can trap sediment resulting in a tidally oscillating mass of sediment that deposits every tidal cycle near the slough mouth and up in the slough (Ganju et al. 2004). Propagation of tides up sloughs varies between sloughs depending on the location of their mouth in the Bay and their depth. When sloughs connect, such as in the Napa/Sonoma Marsh, this difference in tidal propagation can create complex hydrodynamics, transport, and a zone of flow convergence and sediment deposition (Warner et al. 2003).
- *Deposition at restored sites in South Bay:* Expected rates of sedimentation, and their spatial variability, need to be taken into account in planning phasing and/or location of breaches. Rapid deposition at the Warm Springs (also called Coyote Creek Lagoon) restoration site in Fremont filled the 4 m deep borrow pit to intertidal mudflat within 10

years (Williams 2001, Faber 2003). Tides were restored to a salt pond at Cooley Landing in Menlo Park in December 2000 and post-breach monitoring was conducted during the initial period of rapid site evolution (Orr et al. 2001). Wind waves can resuspend sediment that had deposited in a pond and reduce the net deposition rate (Williams and Orr 2002). Bathymetric change data show that South Bay as a whole is, on average, erosional, but that the region south of the Dumbarton has been depositional, over the period 1858-1983 (Foxgrover et al. 2004). This suggests that there may be significant spatial variability in rates of deposition in restored ponds within the Project Area, and particularly between south and north of the Dumbarton Bridge. There will also be significant spatial variability in deposition rates within restored ponds, as described in the tidal marsh and associated habitats synthesis by Collins et al.

- *Vegetation colonization at restored sites in South Bay: *Spartina foliosa* is typically the first vegetation to colonize depositing mudflats in San Francisco Bay. The mud flat elevation should be 0.2 to 0.4 m above mean tide for colonization. Once colonized, vegetation can expand to lower elevations (Williams and Orr 2002).*

Project-induced erosion of existing habitat will be determined by changes in sediment supply and tidal prism. As impounded lands are opened to connect with the estuary, there is an increase in the volume of water required to fill South Bay (i.e., the South Bay tidal prism). This volume increase does not affect the tidal period, therefore the tidal currents in the bay and slough must increase to handle the increased water volume during the same tidal period or the tidal range must decrease. Increased water velocities create increased bed shear and a greater potential for bed and channel erosion, especially in channels adjacent to the restoration site. Channels under the pressure of an increased tidal prism will first downcut (i.e., get deeper), thus increasing the steepness of the channel banks and leading to subsequent bank slumping and channel widening (Williams 2001; Orr et al. 2003). The scour of these channels is an equilibrium process that approaches a steady state when the water velocity is decreased enough by the widening and deepening channel to prevent additional erosion. Steady state empirical relationships have been developed for estimating tidal prism based on the channel width, depth and cross-sectional area (Williams et al. 2002; Pontee 2003). The process of channel downcutting has been noted in San Francisco Bay restorations such as Sonoma Baylands and Coyote Slough (Williams et al. 2002) and Napa Pond 3 (Shellenbarger et al. in review). The relative increase in tidal prism and thus the likelihood of habitat loss decreases with distance from the project (Federal Aviation Administration 2003). As the restoration progresses, the ponds will begin to fill with sediment. This leads to a decreased tidal prism and reduced water velocities in the channels and bay, thereby promoting sedimentation and infilling of the channels (Williams et al. 2002, Hood 2004). It is important to note that the time scale to the equilibrium condition is quite large, so erosion is likely to occur for many years (Kirby 1990, Ellery & McCarthy 1998, Williams et al. 2002).

Seaward of the slough channels are the tidal flats of South Bay. Tidal flats occur between mean lower low water and mean tide level, and have less than 10 percent vegetation cover, except eelgrass (Goals Project 1999). These areas of mud and fine sands are exposed at low tide and flooded at high tide. South Bay currently has 58 km<sup>2</sup> of tidal flats, down from 92 km<sup>2</sup> in the 1850s (Foxgrover et al. 2004). This constitutes over half of the existing tidal flat area in the bay (Goals Project 1999).

## What is the level of certainty of our knowledge?

The certainty of our knowledge of the factors that determine whether and how rapidly marsh habitat is created varies by factor:

- *Pond elevations*: Pond elevations will be well known upon completion of USGS surveys. Present rates of sea level rise and subsidence or rebound are well known.
- *Sediment supply from tributaries*: The USGS presently measures sediment load in the 3 largest tributaries above the extent of tidal influence. Changes in sediment load downstream from the gauges and sediment load from minor tributaries are not measured and are uncertain. Sediment load measurements on South Bay tributaries began in 1957, stopped by 1973, and began to be resumed in 2000. During the 30 to 40 year hiatus, the South Bay watershed became much more urbanized, so the historical records may not reflect present conditions. The recent period of record is not long enough to 1) evaluate whether the historical records represent present conditions and 2) remove interannual variability and accurately estimate what the present average annual load is. A back-of-the-envelope estimate of uncertainty of the local tributary sediment inflow can be made. A good sediment gage will have an uncertainty of  $\pm 10\%$ . Most of the sediment discharge data from local tributaries were collected before urbanization (assume uncertainty increases 5%). Even then, the majority of sediment inflow to the Bay was ungaged and had to be estimated (assume uncertainty increases another 5%). And the tidal reach of rivers between the gage and the Bay is an ungaged source or sink that is neglected (assume uncertainty increases another 5%). Thus, sediment discharge from local tributaries is not known better than  $\pm 25\%$ .
- *Suspended-sediment concentration in the Bay*: Certainty decreases as one moves from the deep channel into the shoals and into the sloughs because monitoring programs have historically focused on the deep channel. Our conceptual model of sediment transport in the open Bay waters is fairly well-developed (Consultant Team), but it is based on relatively scant data in the shoals and no data in the intertidal flats.
- *Sediment loss to the Ocean*: Although the southern part of South Bay was depositional and the northern part erosional, we are certain that there was net export of sediment from South Bay 1956-1983, and we do not expect that this trend will change 1983-2004. The available sediment export rate estimate is akin to a fancy back of the envelope calculation so the certainty is less. In addition, it is for a relatively wet period and probably would overestimate export for restoration design. Interannual variability, and thus uncertainty for a given year, is large. There has been no direct measurement of sediment transport at the seaward boundary of South Bay.
- *Transport of sediment to ponds*: There has been no direct measurement or quantification of sediment transport from the Bay to the sloughs or restored sites. Transport between South Bay and the sloughs is particularly uncertain because of the logistical, analytic, and numerical difficulties associated with the large tidal range relative to water depth.
- *Deposition at restored sites in South Bay*: Data from restored sites can and has been used to determine overall deposition rates, but these rates are probably site specific for specific hydrologic conditions not likely to be repeated. Thus, measured deposition rates are certain and instructive, but they have limited predictive value.

- *Vegetation colonization at restored sites in South Bay:* The basic process of vegetation colonization is known. The qualitative effect of vegetation on sedimentation is known but quantification is less certain. Invasive species introduce additional uncertainty.

Whether and how much existing habitat will erode is uncertain. Changes in tidal prism and tide range can be estimated with certainty, but geomorphic changes in response to tidal prism changes are uncertain. The possibility that restoration could decrease tide range thus reduce the increase in tidal prism could be investigated with a numerical model. Empirical relations between tidal prism and channel properties are uncertain. Numerical models are difficult to apply because erosion takes place at the turbulent time scale (seconds) while the time frame of interest is decades over which the landscape will evolve. In addition, process models of erosion and quantification of erosion parameters are uncertain. Besides tidal prism, sediment supply affects habitat erosion and is uncertain. Watershed changes, climate change, sea level rise, and sediment trapping by restored wetlands all make the future sediment supply uncertain.

Historical changes to South Bay marshes and mudflats can be determined with certainty for past tidal prism, sea level, and sediment supply conditions. While past changes are not predictive of future changes, they provide understanding of the processes that are likely to cause future changes and they provide data to test predictive models.

### **What predictive tools exist for gaining an understanding of this issue and what tools are needed to reduce uncertainty to an acceptable level?**

The tools available for predicting sediment transport and geomorphic response to restoration actions (including sediment transport and geomorphic modeling and analytical methods) are much less accurate than hydrodynamic or hydrologic models. While numerical modeling will be very important for comparing the relative outcomes for different restoration scenarios, we expect that the uncertainty in predictions of how long establishment of tidal marsh will take or how much erosion of mudflats will take place will not be low enough to ensure that the selected scenario will attain the goals of the Project. For this reason the Project must utilize adaptive management. For adaptive management to succeed, the Project needs to focus efforts on determining the best ways to monitor whether the project is proceeding as predicted, including detecting changes in bathymetry and sediment cycling, determining what levels of change in these parameters is acceptable, and distinguishing between change caused by the project and other sources of change.

Specific suggestions for predictive tools are given below and application of multiple approaches is often the best way to reduce uncertainty. Pontee (2003) states ‘the complexity of processes within estuary systems means that it is often beneficial to use a range of techniques and synthesise the results to reduce uncertainties.’

- *Pond elevations:* Well known upon completion of USGS surveys. Sea level is expected to rise 0.3 to 0.5 m by 2100 (IPCC 2001). A groundwater and land surface elevation model is needed to predict future land surface elevation.
- *Sediment supply from tributaries:* Continued or expanded measurement of sediment supply from tributaries and adding or transferring measurements into the tidal reaches of

channels closer to the ponds would improve our database. A longer period of record would help determine existing conditions and hydrologic variability. The data also can be used to improve sediment budgets and to determine relations between water flow and sediment supply. If this relation is assumed to remain constant, it can be used to predict sediment supply for a given flow. The historical data can be used to evaluate whether the relation has been constant. Numerical models of the watershed (with appropriate data) can be used to predict channel flow, and the relations can be used to predict sediment load. Alternatively, a numerical model of sediment transport in the watershed can be developed, but water yield can be predicted more easily than sediment supply. Sediment load and water discharge data are needed to develop reliable numerical models.

- *Suspended-sediment concentration in the Bay:* Numerical models, similar to those developed for other restoration projects in San Francisco Bay (e.g. Bair Island, Napa/Sonoma marsh) are used to predict suspended-sediment concentration. The greatest source of uncertainty is typically the parameterization of erosion (McDonald and Cheng 1997). Field data are needed to calibrate and validate the models to reduce uncertainty. Specifically, collection of suspended-sediment concentration data from mudflats and sloughs would be most helpful. Process studies to determine erosive characteristics would also reduce uncertainty. Other sources of uncertainty are watershed sediment input and sediment exchange with the ocean.
- *Sediment loss to the Ocean:* Multidimensional numerical models are the best predictive tool available. Field data are needed to calibrate and validate the models to reduce uncertainty. Specifically, direct measurement of sediment flux passing through the boundary between South and Central Bays would improve our understanding of sediment loss to the ocean, reduce uncertainty of sediment budgets, and provide data for model calibration and validation.
- *Transport of sediment to ponds:* Multidimensional numerical models are the best predictive tool available. Field data are needed to calibrate and validate the models to reduce uncertainty. Specifically, direct measurement of sediment transport from the Bay to the sloughs or restored sites is needed. Such measurements greatly improved our understanding of the Napa/Sonoma marsh sloughs (Warner et al. 2003) and provided data for developing models used to design the restoration.
- *Deposition at restored sites in South Bay:* Numerical models are the best predictive tool available. Zero-dimensional models that calculate deposition from an average sediment concentration have reasonably predicted deposition at restoration sites (Krone and Hu 2001). Field data are needed to calibrate and validate the models to reduce uncertainty. Specifically, long-term (decadal) average suspended sediment concentration and deposition rate data are needed.
- *Vegetation colonization at restored sites in South Bay:* A vegetation expert would be better suited to evaluate prediction of vegetation colonization. The empirical observations that have been developed for San Francisco Bay can be used to predict future vegetation colonization. The relations appear to be qualitatively reasonable but quantitatively uncertain, especially regarding the rate of colonization, which would be needed for a numerical model of a restoration site. The behavior of invasive species is uncertain and perhaps not predictable.

Geomorphic evolution, in response to tidal prism change, may be predicted with empirical relations and numerical models. Existing empirical relations are dependent on the quality of monitoring data. Comparison of sequential bathymetric surveys has proven valuable in quantifying evolution of channels and mudflats on decadal timescales (Jaffe et al. 1998), but such surveys are infrequent. Conversely, marsh accretion studies can be performed with high temporal resolution, but are usually limited to a few sites for a given marsh complex (Cahoon et al. 1996, Leonard 1997). Detailed surveying of breaches, adjacent sloughs and mudflats, and elevated marsh would improve empirical relations, if done with appropriate spatial and temporal density. More importantly, our understanding of the linkages between these four regimes and their response to tides, waves, and anthropogenic activity would be greatly enhanced (Yang et al. 2003).

Monitoring of geomorphic responses to breaches would also provide data for development and testing of numerical models. Decadal geomorphic simulations in estuaries are not as well-developed as hydrodynamic simulations at the tidal timescale. Researchers have begun modifying hydrodynamic code to run at decadal timescales, along with sediment transport routines (Hibma et al. 2003). Preliminary results with idealized estuaries show promise, but applications for real estuaries are not common as yet. Because these approaches are still in their infancy, the lack of spatial and temporal resolution for calibration data may be a future obstacle. Improving the quality of calibration data now may assist future modeling efforts. In addition, field or lab experiments may be needed to better specify the erosion process in the models.

**What are potential restoration targets and performance measures, linked to the Objectives, for evaluating the progress of the restoration project and what management measures might be used to reduce negative impacts?**

The Consultant Team is experienced in designing restoration projects and they would probably have additional valuable suggestions.

Performance measures:

- Deposition rates and volumes in breached ponds
- Breached pond elevations
- Vegetation colonization in breached ponds
- Erosion of slough channels
- Change in existing marsh area
- Change in mudflat area, elevation, and sediment volume
- Ecosystem function of ponds, breached ponds, sloughs, and mudflats

Possible management measures to reduce negative impacts:

- Dredged materials placement to accelerate restoration and reduce new tidal prism
- Time breaches (seasonal, wet years) for maximum initial deposition
- Phased breaches to increase tidal prism slowly
- Locate breaches to minimize damage to sloughs most susceptible to erosion from increased tidal prism
- Limit additional tidal prism by keeping ponds isolated or developing muted tidal ponds



- Temporary or permanent barriers to control which channels have increased tidal prism
- Connect adjacent sloughs to create a zone of flow convergence and sediment deposition
- Monitor slough and mudflat erosion and alter breaches if necessary

**What key questions essential to the success of the restoration need to be addressed through further studies, monitoring, or research?**

1. How much sediment is needed for each restoration alternative? The answer to this question depends on:
  - a) existing bathymetry of ponds
  - b) projected sea-level rise over the life of the Project
  - c) projected subsidence
  - d) contribution of internally generated organic material.
2. What will the rate of sediment supply to the restored ponds be? The answer to this question depends on:
  - a) existing bathymetry of ponds
  - b) projected sea-level rise over the life of the Project
  - c) projected subsidence
  - d) contribution of internally generated organic material
  - e) sediment supply from tributaries and Bay
  - f) hydrodynamic connection between pond, slough, and Bay
3. How will South San Francisco Bay evolve as tides are restored to the salt ponds? The answer to this question depends on:
  - a) Whether and how existing mudflats and tidal wetlands will be lost.
  - b) How opening up the ponds to tidal action, thereby creating additional tidal prism and a substantial new sediment sink, alters the cycling of sediment in South Bay.
  - c) How much of the sediment depositing in the breached ponds will be from existing desirable habitats and how much would otherwise exit South Bay.
  - d) How the South Bay sediment budget changes over time.
  - e) How pond levee breaches affect tidal currents, circulation patterns, and residence time in the sloughs and South Bay and how will these effects change in time as the pond bed elevation and breach geometry approach equilibrium conditions.

**References**

Buchanan, P.A., and Ganju, N.K., 2004. Summary of suspended-sediment concentration data, San Francisco Bay, California, Water Year 2002: U.S. Geological Survey Open File Report 2004-1219. <http://pubs.water.usgs.gov/ofr2004-1219/>

Cahoon, D.R., Lynch, J.C., and Powell, A.N., 1996. Marsh vertical accretion in a southern California estuary, USA, *Estuarine, Coastal and Shelf Science*, 43, p. 19-32.

- Cloern, J.E., 1987, Turbidity as a control on phytoplankton biomass and productivity in estuaries: *Continental Shelf Research*, v. 7, no. 11/12, p. 1367–1381.
- Cloern, J.E., 1996, Phytoplankton bloom dynamics in coastal ecosystems: a review with some general lessons from sustained investigation of San Francisco Bay, California: *Reviews of Geophysics*, v. 34, no. 2, p. 127–168.
- Cole, B.E. and Cloern, J.E., 1987, An empirical model for estimating phytoplankton productivity in estuaries: *Marine Ecology Progress Series*, v. 36, p. 299–305.
- Domagalski, J.L. and Kuivila, K.M., 1993, Distributions of pesticides and organic contaminants between water and suspended sediment, San Francisco Bay, California: *Estuaries*, v. 16, no. 3A, p. 416–426.
- Ellery, W.N. and T.S. McCarthy. 1998. Environmental change over two decades since dredging and excavation of the lower Boro River, Okavango Delta, Botswana. *Journal of Biogeography* 25:361-378.
- Faber, P.M., 2003, What are we learning from long-term monitoring: Proceedings of the 6th biennial State-of-the-Estuary Conference, Oakland, California, October 21-23, 2003, p. 9.
- Federal Aviation Administration, 2003, Proposed SFO runway reconfiguration project, Predicted changes in hydrodynamics, sediment transport, water quality, and aquatic biotic communities associated with SFO runway reconfiguration alternatives BX-6, A3, and BX-R: Final Technical Report.
- Ferretti, A., F.Novali, R.Bürgmann, G.Hilley, and C.Prati, 2004, InSAR Permanent Scatterer Analysis Reveals Ups and Downs in San Francisco Bay Area: *Eos*, v. 85, no. 34, p. 317.
- Flegal, A.R., Rivera-Duarte, I., Ritson, P.I., Scelfo, G.M., Smith, G.J., Gordon, M.R., and Sanudo-Wilhelmy, S.A., 1996, Metal contamination in San Francisco Bay waters: Historic perturbations, contemporary concentrations, and future considerations: *San Francisco Bay: The Ecosystem*, Hollibaugh, J.T. (ed.), Pacific Division of the American Association for the Advancement of Science, San Francisco, p. 173–188.
- Flick, R.E, J.F. Murray and L.C. Ewing. 2003. Trends in United States tidal datum statistics and tide range. *J. Waterway, Port, Coastal and Ocean Eng.*, 129(4): 155-164.
- Foxgrover, A.C, Higgins, S.A., Ingraca, M.K., Jaffe, B.E. and Smith, R.E., 2004, Deposition, erosion and bathymetric change in South San Francisco Bay: 1858-1983, U.S. Geological Survey Open-file Report 2004-1192, 25 p.  
<http://pubs.usgs.gov/of/2004/1192/of2004-1192.pdf>
- Ganju, N.K., Schoellhamer, D.H., Warner, J.C., Barad, M.F., and Schladow, S.G., 2004, Tidal oscillation of sediment between a river and a bay: a conceptual model: *Estuarine, Coastal and Shelf Science*, v. 60, no. 1, p. 81-90.

Goals Project. 1999. Baylands Ecosystem Habitat Goals. A report of habitat recommendations prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project. U.S. Environmental Protection Agency, San Francisco, Calif./S.F. Bay Regional Water Quality Control Board, Oakland, Calif.

<http://www.sfei.org/sfbaygoals/docs/goals1999/final031799/pdf/sfbaygoals031799.pdf>

Goals Project. 2000. Baylands Ecosystem Species and Community Profiles: Life histories and environmental requirements of key plants, fish and wildlife. Prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project. P.F. Olofson, editor. San Francisco Bay Regional Water Quality Control Board, Oakland, Calif.

Hibma, A., de Vriend, H.J., and Stive, M.J.F., 2003. Numerical modeling of shoal pattern formation in well-mixed elongated estuaries, *Estuarine, Coastal and Shelf Science*, 57, p. 981-991.

Hood, W.G., 2004, Indirect environmental effects of dikes on estuarine tidal channels: thinking outside of the dike for habitat restoration and monitoring: *Estuaries*, v. 27, no. 2, p. 273-282.

Intergovernmental Panel on Climate Change (IPCC), 2001, *Climate Change 2001: The Scientific Basis*: Cambridge University Press.

Jaffe, B.E., Smith, R.E, and Zink Torresan, L., 1998, Sedimentation and bathymetric change in San Pablo Bay 1856 – 1983, US Geological Survey, Open-File Report 98-0759.

Kirby, R., 1990, The sediment budget of the erosional intertidal zone of the Medway Estuary, Kent: *Proceedings of the Geological Association*, v. 101, no. 1. p. 63-77.

Krone, R.B., and Hu, G., 2001. Restoration of subsided sites and calculation of historic marsh elevations: *Journal of Coastal Research*, Special Issue, 27:162-169.

Kuwabara, J.S., Chang, C.C.Y., Cloern, J.E., Fries, T.L., Davis, J.A., and Luoma, S.N., 1989, Trace metal associations in the water column of South San Francisco Bay, California: *Estuarine, Coastal and Shelf Science*, v. 28, p. 307–325.

Lacy, J.R., Schoellhamer, D.H., and Burau, J.R., 1996, Suspended-solids flux at a shallow-water site in South San Francisco Bay, California: *Proceedings of the North American Water and Environment Congress*, Anaheim, California, June 24-28, 1996.

Leonard, L.A., 1997. Controls of sediment transport and deposition in an incised mainland marsh basin, southeastern North Carolina, *Wetlands*, 17 (2), p. 263-274.

McCulloch, D.S., Peterson, D.H., Carlson, P.R., and Conomos, T.J., 1970, A preliminary study of the effects of water circulation in the San Francisco Bay Estuary – Some effects of fresh-water inflow on the flushing of South San Francisco Bay: U.S. Geological Survey Circular 637-A, 27 p.

McDonald, E.T., and Cheng R.T, 1997, A Numerical Model of Sediment Transport Applied to San Francisco Bay, California, *Journal of Marine Environmental Engineering*, Vol.4, pp. 1 – 41.

McKee, L., Leatherbarrow, J., Newland, S., and Davis, J., 2003. A review of urban runoff processes in the Bay Area: Existing knowledge, conceptual models, and monitoring recommendations. A report prepared for the RMP Sources, Pathways and Loading Workgroup. San Francisco Estuary Regional Monitoring Program for Trace Substances. SFEI Contribution Number 66. San Francisco Estuary Institute, Oakland, Ca.  
[http://www.sfei.org/rmp/reports/splwg/Urban\\_runoff\\_literature%7E000.pdf](http://www.sfei.org/rmp/reports/splwg/Urban_runoff_literature%7E000.pdf)

Orr, M., Haltiner, J., Battalio, R., Kulpa, J., and Rafferty, M., 2001, A pilot project for South Bay salt pond restoration: Proceedings of the 5th biennial State-of-the-Estuary Conference, San Francisco, California, October 9-11, 2001, p. 139.

Orr, M., S. Crooks and P.B. Williams. 2003. Will restored tidal marshes be sustainable? In: Larry R. Brown, editor. *Issues in San Francisco Estuary Tidal Wetlands Restoration*. San Francisco Estuary and Watershed Science. Vol. 1, Issue 1, Article 5.  
<http://repositories.cdlib.org/jmie/sfews/vol1/iss1/art5>

Poland, J.F., and Ireland, R.L. 1988, Land Subsidence in the Santa Clara Valley, California, as of 1982: U.S. Geological Survey Professional Paper 497-F, 61 p.

Pontee, N.I. 2003. Designing sustainable estuarine intertidal habitats. *Engineering Sustainability* 156(ES3): 157-167.

Ruhl, C.A., and Schoellhamer, D.H., 2001, Time series of SSC, salinity, temperature, and total mercury concentration in San Francisco Bay during water year 1998: Regional Monitoring Program for Trace Substances contribution number 44, San Francisco Estuary Institute, Richmond, California. URL [http://www.sfei.org/rmp/reports/time\\_series/timeseries\\_cont43.pdf](http://www.sfei.org/rmp/reports/time_series/timeseries_cont43.pdf)

San Francisco Bay Joint Venture, 2001, Restoring the estuary: An implementation strategy for the San Francisco Bay Joint Venture.  
<http://www.sfbayjv.org/estuarybook.html>

Schoellhamer, D.H., 1996, Factors affecting suspended-solids concentrations in South San Francisco Bay, California: *Journal of Geophysical Research*, v. 101, no. C5, p. 12087-12095.

Shellenbarger, G.G., Schoellhamer, D.H., and Lionberger, M.A., 2004, A South San Francisco Bay Sediment Budget: Wetland Restoration and Potential Effects on Phytoplankton Blooms: Proceedings of the 2004 Ocean Research Conference, Honolulu, Hawaii, February 15-20, 2004.  
<http://www.sgmeet.com/aslo/honolulu2004/viewabstract2.asp?AbstractID=569&SessionID=SS9.01>

Shellenbarger, G.G., K.M. Swanson, D.H. Schoellhamer, J.Y. Takekawa, N.D. Athearn, A.K. Miles, S.E. Spring and M.K. Saiki. In Review. Desalinization, Erosion, and Tidal and

Ecological Changes Following the Breaching of a Levee between a Salt Pond and a Tidal Slough. Submitted to Restoration Ecology.

Siegel, S. W., and P. A. M. Bachand. 2002. Feasibility analysis of South Bay salt pond restoration, San Francisco Estuary, California. Wetlands and Water Resources, San Rafael, California. 228pp.

Smithson, J.R., Webster, M.D., Pope, G.L., Friebel, M.F., and Freeman, L.A., 2004, Water resources data, California, water year 2003, vol. 2, Pacific slope basins from Arroyo Grande to Oregon state line except Central Valley: U.S. Geological Survey Water-Data Report CA-03-2. <http://water.usgs.gov/pubs/wdr/wdr-ca-03-2/WDR.CA.03.vol2.pdf>

Takekawa, J., Demers, S., Woo, I., Athearn, N., Ganju, N., Shellenbarger, G., Schoellhamer, D., and Perry, W.M., 2003, A bathymetry system for measuring sediment accumulation in tidal marsh restoration projects: Proceedings of the 6th biennial State-of-the-Estuary Conference, Oakland, California, October 21-23, 2003, p. 157.

Walters, R.A., Cheng, R.T., and Conomos, J.T., 1985, Time scales of circulation and mixing processes of San Francisco Bay waters: *Hydrobiologia*, v. 129, p.13-36.

Warner, J.C., Schoellhamer, D.H., and Schladow, G.S., 2003, Tidal truncation and barotropic convergence in a channel network tidally driven from opposing entrances: *Estuarine, Coastal and Shelf Science*, v. 56, p. 629-639.

Williams, P. 2001. Restoring physical processes in tidal wetlands. *Journal of Coastal Research*, Special Issue, 27:149-161.

Williams, P.B., and Orr, M.K., 2002, Physical evolution of restored breached levee salt marshes in the San Francisco Bay estuary: *Restoration Ecology*, v. 10, no. 3, p. 527-542.

Williams, P.B., M.K. Orr and N.J. Garrity. 2002. Hydraulic geometry: a geomorphic design tool for tidal marsh channel evolution in wetland restoration projects. *Restoration Ecology* 10:577-590.

Yang, S.L., Friedrichs, C.T., Shi, Z., Ding, P., Zhu, J., and Zhao, Q., 2003. Morphological response of tidal marshes, flats, and channels of the outer Yangtze River mouth to a major storm, *Estuaries*, 26 (6), p. 1416-1425.

Yancey, T.E., and Lee, J.W., 1972, Major heavy mineral assemblages and heavy mineral provinces of the central California coast region: *Geological Society of America Bulletin*, v. 83, p. 2099-2104.