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Anthropogenic Influence on Recent Bathymetric Change in West–Central San Francisco Bay

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ABSTRACT

Two multibeam sonar surveys of west–central San Francisco Bay, California, were conducted in 1997 and 2008. Bathymetric change analysis between the two surveys indicates a loss of 14.1 million m^3 (–3.1 cm yr^{-1}) of sediment during this time period, representing an approximately three-fold acceleration of the rate that was observed from prior depth change analysis from 1947 to 1979 for all of Central Bay, using more spatially coarse National Ocean Service (NOS) soundings. The portions of the overlapping survey areas between 1997 and 2008 designated as aggregate mining lease sites lost sediment at five times the rate of the remainder of west–central San Francisco Bay. Despite covering only 28% of the analysis area, volume change within leasing areas accounted for 9.2 million m^3 of sediment loss, while the rest of the area lost 4.9 million m^3 of sediment. The uncertainty of this recent analysis is more tightly constrained due to stringent controls on vertical and horizontal position via tightly coupled, inertially aided differential Global Positioning Systems (GPS) solutions for survey vessel trajectory that virtually eliminate inaccuracies from traditional tide modeling and vessel motion artifacts. Further, quantification of systematic depth measurement error can now be calculated through comparison of static surfaces (e.g., bedrock) between surveys using seafloor habitat maps based on acoustic backscatter measurements and ground-truthing with grab samples and underwater video. Sediment loss in the entire San Francisco Bay Coastal System during the last half-century, as estimated from a series of bathymetric change studies, is 240 million m^3, and most of this is believed to be coarse sediment (i.e., sand and gravel) from Central Bay and the San Francisco Bar, which is likely to limit the sand supply to adjacent, open-coast beaches. This hypothesis is supported by a calibrated numerical model in a related study that indicates that there is a potential net export of sand-sized sediment across the Golden Gate, suggesting that a reduction in the supply of sand-sized sediment within west–central San Francisco Bay will limit transport to the outer coast.

KEYWORDS

bathymetry, multibeam sonar, estuary, anthropogenic, dredging, aggregate mining, sediment transport

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INTRODUCTION

Multibeam sonars use swaths of sound pulses focused perpendicular to the direction of a ship to measure depths of the seafloor. Within the last decade, multibeam sonar system technology has advanced to enable imaging of the seafloor with increased spatial coverage (sub^{-1} m grid resolution) and angular resolution, allowing a greater number of beams per swath, increased ping frequency (5 Hz in 30 m of water) and speed (3,000 soundings/sec), and the potential of measuring depths with resolution of a few centimeters. Modern systems can collect data at boat speeds of up to 16 km hr^{-1} while still maintaining density of up to 10 soundings per m^2 in 50 m water depth, a four-fold increase in the last decade. By combining sub-meter resolution multibeam data with the sub-decimeter positioning accuracy of differential GPS surveying, the seafloor position can now be mapped with unprecedented detail and precision. The goal of this paper is to report the results of bathymetric change analysis in west–central San Francisco Bay, California, using the first multibeam surveys performed with differential GPS covering this region. This information is critical for the sediment-management community who must assess the impact of anthropogenic influences such as aggregate mining and dredging on the regional sediment supply.

STUDY AREA

San Francisco Bay is a large estuary with a number of economically significant harbors in one of the most developed regions of the United States (Figure 1). The San Joaquin and Sacramento rivers had, from the period 1938 to 2005, an annual mean fresh-water discharge rate into the San Francisco Bay of 800 m^3 s^{-1} (DWR 2007). Despite this accounting for 40% of California's drainage area, fresh-water input represents less than 1% of the tidal prism of 2 x 10^9 m^3 served by the Golden Gate tidal inlet, the only point of exchange with the Pacific Ocean. Tidal currents in the inlet throat peak at over 2.5 m s^{-1}, and can exceed 1 m s^{-1} even on the edge of the San Francisco Bar (i.e., ebb tidal delta), which is more than 10 km seaward of the inlet throat (Barnard and others 2007) (Figure 1). Landward of the Golden Gate, west–central San Francisco Bay is the deepest part of the entire estuary, containing the coarsest sediment, and the strongest currents. Bedrock pinnacles and sandy shoals focus currents and produce a wide range of bedform morphologies (Rubin and McCulloch 1980; Barnard and others, in press). Wave energy in the Bay is primarily generated by local winds, and plays only a minor role in sediment transport throughout the deeper portions of the bay. However, the impact of local, wind-generated waves and deep ocean swell can induce significant turbulence and sediment transport in the shallow, inter-tidal areas, where fine sediment dominates the substrate (Talke and Stacey 2003).

PRIOR WORK

Major anthropogenic changes to the San Francisco Bay Coastal System (which incorporates the San Francisco Bay, the mouth of the Sacramento–San Joaquin Delta, and the mouth of the San Francisco Bay, including the adjacent open coast) began during the Gold Rush in the 19th century and have continued to the present. The influx of an estimated 1.15 x 10^9 m^3 of sediment from hydraulic mining during the Gold Rush (Gilbert 1917) in concert with major building development in the coastal wetlands in San Francisco Bay has exerted a strong influence on San Francisco Bay evolution during the last 150 years. Anthropogenic activities in the San Francisco Bay Coastal System have permanently removed at least 200 million m^3 of sediment in the last century from borrow pit mining (54 million m^3), aggregate mining (26 million m^3), and dredging (120 million m^3) (USACE 1996; Friends of the Estuary 1997; Chin and others 1997, 2004; Dallas 2009; Dallas and Barnard 2009). However, this is a minimum estimate because not all records have been compiled. For instance, records are missing from 1976 to 1996 for dredging and borrow pit mining for the San Francisco waterfront, Alameda Air Base, BART tunnel, and Oakland Airport, and other 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%). Grain sizes were not recorded for most of the documented

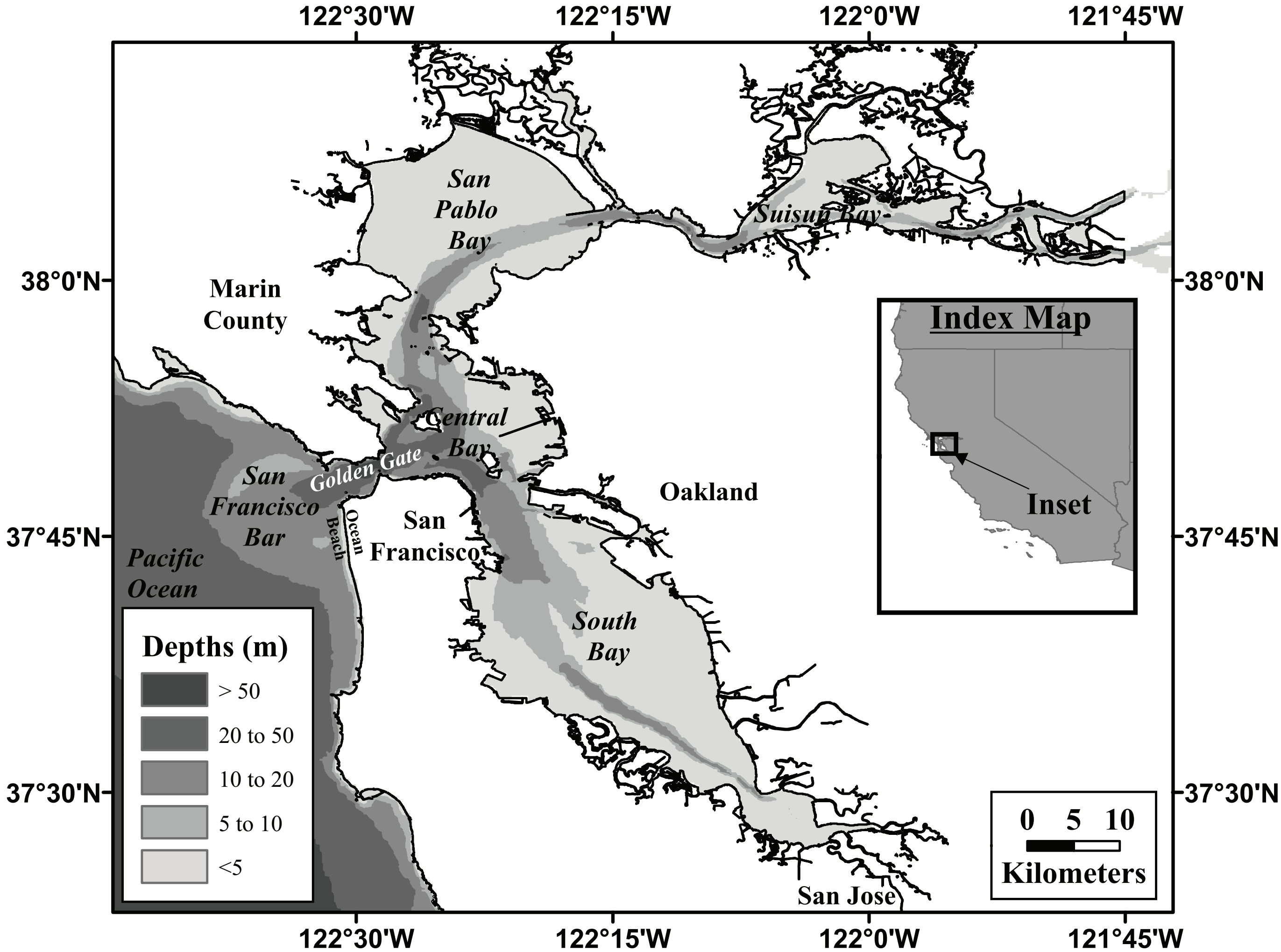

Figure 1 Study area: San Francisco Bay, California, USA

events, but 75 million m^3 of sediment was reported to be coarser than fine sand (Dallas 2009). The largest single removal event on record was the extraction of 22 million m^3 of sand from Central Bay for the building of Treasure Island from 1936 to 1938 (Scheffauer 1954). The impact of these disturbances on the San Francisco Bay Coastal System has not been quantified, although it was recently determined that the mouth of San Francisco Bay lost over 90 million m^3 of sediment between 1956 and 2005 (Barnard and others 2006; Hanes and Barnard 2007), and Central Bay lost 52 million m^3 of sediment between 1947 and 1979 (Fregoso and others 2008). Additionally, Wright and Schoellhamer (2004) demonstrated that modifications in the Delta have resulted in a ~50% reduction in suspended sediment flux to San Francisco Bay from 1957 to 2001. Since the mid-1950s, sediment-loss trends have been documented in North Bay (i.e., San Pablo Bay and Suisun Bay by Jaffe and others [1998] and Capiella and others [1999]); Central Bay by Fregoso and others [2008]; and San Francisco Bar (i.e., mouth of San Francisco Bay) by Hanes and Barnard (2007) (Table 1). Applying these rates over the last 50 years would result in an estimated sediment loss of 240 million m^3 from the entire San Francisco Bay Coastal System. It is highly probable that the majority of sediment lost from Central Bay and on the San Francisco Bar is coarse sediment (i.e., sand and gravel) because mud only accounts

Table 1 Summary of historical bathymetry changes in the San Francisco Bay Coastal System

Location	Reference	Dates of Analyzed Data	Rate of Change (m^3 yr^{-1} x 10^6)	Total Volume Change Projected from 1959 to 2009 (m^3 yr^{-1} x 10^6)
San Francisco Bar	Hanes and Barnard (2007)	1956 – 2005	–1.9	–95
Central Bay	Fregoso and others (2008)	1947 – 1979	–1.6	–80
San Pablo Bay	Jaffe and others (1998)	1951 – 1983	–0.7	–35
Suisun Bay	Cappiella and others (1999)	1942 – 1990	–1.1	–55
South Bay	Jaffe and Foxgrover (2006)	1983 – 2005	0.5	25
			Total	–240

for ~10% and 0.1% of the mapped substrate, respectively (Greene and others 2009). Barnard and others (in press) used a calibrated hydrodynamic model to demonstrate that there is a net potential export of sand-sized sediment from San Francisco Bay to the ocean. Therefore, limits on the sand supply to the San Francisco Bay Coastal System, especially west–central San Francisco Bay, can limit the sand supply to open-coast beaches such as Ocean Beach, portions of which have been experiencing severe erosion over the last several decades (Barnard and others 2009).

METHODS

In 1997, the U.S. Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA) mapped west–central San Francisco Bay at a 4-m horizontal resolution using a Simrad EM-1000 multibeam sonar system (Dartnell and Gardner 1999). The vertical uncertainty of each sounding in this survey is reported as 10 to 20 cm (Chin and others 1997).

In April 2008, the footprint of the 1997 multibeam survey was re-surveyed by the Seafloor Mapping Lab at California State University, Monterey Bay, aboard the R/V VenTresca (Kvitek 2008; Figure 2). The study area was mapped using a Reson 8101 multibeam sonar system, which operates at 240 kHz and measures relative water depths within a 150° swath consisting of 101 1.5° x 1.5° beams. The Reson 8101 can provide up to 3,000 soundings per second with a swath coverage of up to 7.4 times the water depth. A C-Nav 2050 RTG GPS system supplied real-time position data to an Applanix Position and Orientation System, Marine Vessel (POS/MV 320v4). Horizontal positional accuracy of this system is typically ±15 cm. Attitude (pitch, roll, yaw, and heave) data were generated at 200 Hz by the POS/MV with an average pitch, roll and yaw accuracy of ±0.03°, while heave accuracy was maintained at ±5% or 5 cm. Water surface-to-seafloor profiles of the speed of sound through the water were collected periodically during the surveys to correct for variations in sound velocity resulting from salinity and temperature changes throughout the water column.

Sonar data were post-processed using CARIS Hydrographic Information Processing System (HIPS) 6.1 software, after being combined with the vessel trajectory and sound velocity data. Vessel trajectory data from the Applanix POS/MV were processed with local L1/L2 GPS reference-station data using Applanix POSPac 5 software and a tightly coupled Inertially Aided Post-Processed Kinematic (IAPPK) technique to generate a smoothed best estimate of trajectory (SBET) file at 200 Hz. The SBET solution includes rotational motion about all three axes as well as heave from surface waves and tidal variation over the survey period, all tied directly to the ellipsoid, virtually eliminating positional and motion-related artifacts traditionally found in multibeam data that tended to obscure fine, sub-meter geomorphic detail, particularly when data from adjacent track lines are superimposed. Applying the new IAPPK SBET approach to existing multibeam sonar data yields more co-registered data points per unit area with less noise, bringing fine features into much sharper focus than previously was possible (see Figure 2). The maximum vertical uncertainty of the individual soundings in this survey was reported at 12 cm.

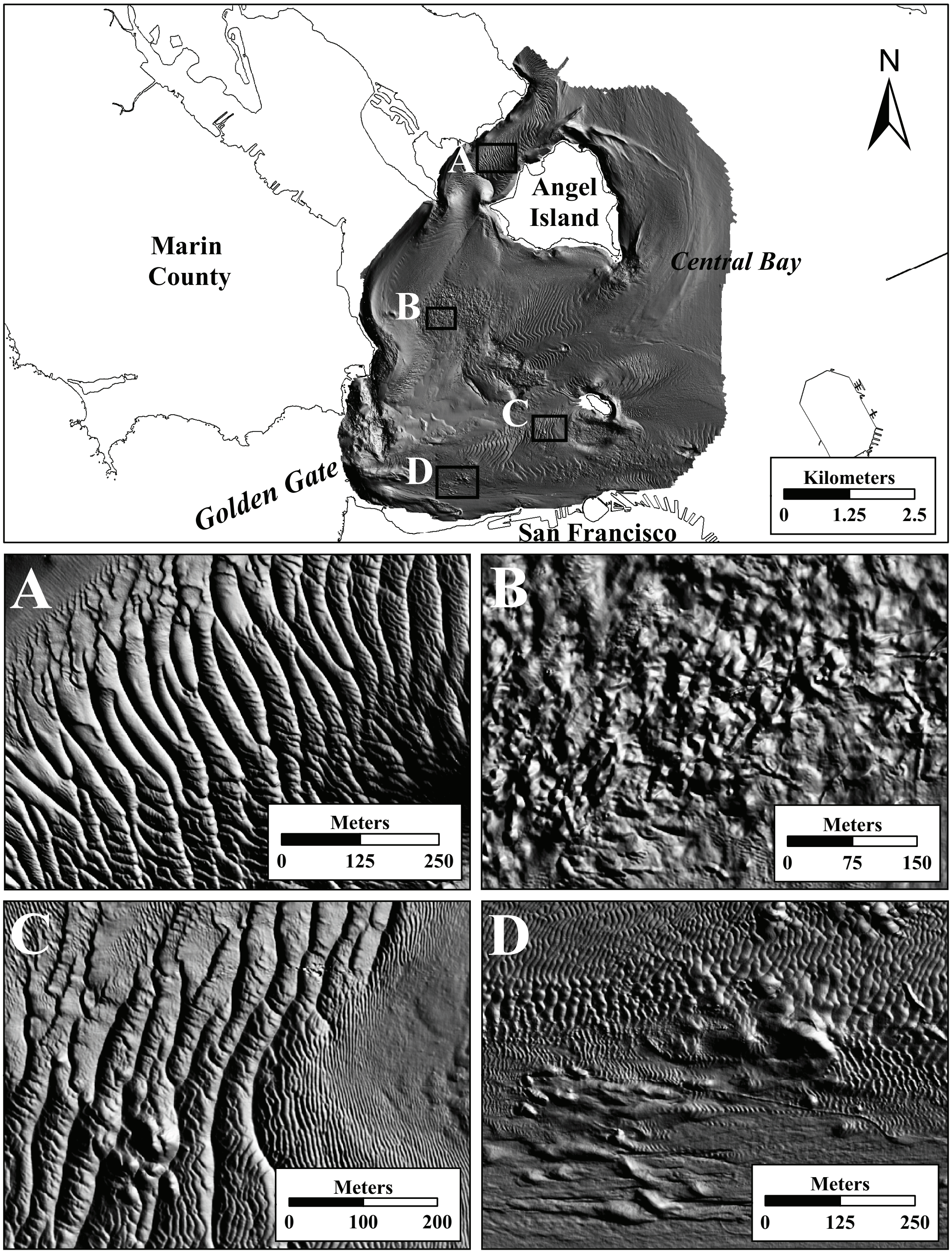

Figure 2 Shaded relief bathymetry of west-central San Francisco Bay from the 2008 multibeam sonar survey with selected close-ups of seafloor details. All bathymetry presented at 1-m resolution with a sun azimuth of 240° and vertical angle of 25°. (A) Bi-directional flow patterns in Raccoon Strait. (B) Apparent significant bottom disturbance due to aggregate mining activities on Pt. Knox Shoal. (C) Transitions to different flow regimes west of Alcatraz. (D) Large-scale flute marks due to dredge mound evolution under largely uni-directional (i.e., seaward, right to left on map) transport.

Prior to change-detection analysis, the cleaned soundings for the 2008 survey were gridded to 4-m cells using a standard inverse distance-weighting procedure. The 1997 survey data was only available as 4-m grids. The gridding accuracy for the 2008 survey was verified by spatially joining each of the cleaned soundings with the nearest gridded sounding and calculating the difference. The mean difference for over 2.8 million sounding pairs (gridded and point data) showed no significant gridding error (mean value = –0.001 m). The grids were then converted to the same horizontal coordinate system (Universal Transverse Mercator Zone 10 North) using ArcGIS transformation tools, and a common vertical datum (North American Vertical Datum of 1988 [NAVD 88]). The 1997 survey soundings were measured relative to the mean lower low water (MLLW) tidal datum (1960 to 1978 epoch) and then converted to NAVD 88 based on the datum offsets published on the Bench Mark Sheet page for the NOAA San Francisco Tide Gauge Station ID: 9414290 (NOAA 2009). The height of the geoid varies by ~±0.02 m in the study area (NOAA 2010), but it was unclear whether the soundings from the 1997 survey were mapped relative to MLLW based only on the San Francisco Tide Gauge Station or if corrections were applied using a regional tide model. Therefore, given the relatively insignificant amount of geoid height variation and to avoid potentially introducing additional vertical uncertainty, no geoid adjustments were made to the 1997 survey. The soundings from the 2008 survey were mapped directly to the North American Datum (NAD) 83 ellipsoid (Continuously Operating Reference Station [CORS] 96) and then converted to NAVD 88 on a sounding by sounding basis using the Geoid03 model (i.e., the sonar head trajectory was computed in NAD 83 height above the reference ellipsoid (HAE) and the elevations were then converted to NAVD 88 via Geoid03). Bathymetric change was then calculated by subtracting the 1997 survey grid from the 2008 grid.

RESULTS

For the total overlapping survey areas of 40.56 km^2 between the 1997 and 2008 surveys, the mean vertical change was –0.13 m (–1.2 cm yr^{-1}), which equates to a total sediment loss of 5.4 x 10^6 m^3. To assess systematic depth-measurement error, we performed a grid subtraction between the two surveys for the static surfaces (i.e., primarily bedrock surfaces that could be expected to show negligible change between surveys) as defined by the habitat mapping of Greene and others (2009) that utilized acoustic backscatter from the 2008 multibeam sonar survey, grab samples, and underwater video (Figure 3). This analysis resulted in a systematic vertical offset of +0.21 m; the 1997 survey was too low relative to the 2008 survey that showed no statistical correlation ($r^2 \leq 0.01$) with depth, slope, easting position or northing position (Figure 4). Because there was no spatial or slope bias to the offset, we applied this value to the entire data set, although it should be noted that these static surfaces only accounted for ~4% of the total survey areas. After applying the offset, the corrected mean vertical change was –0.35 m (–3.2 cm yr^{-1})[1], equating to a total sediment loss of 14.1 x 10^6 m^3 for the 11-year span between surveys. Using the seafloor characterization of Greene and others (2009), 5% (~750,000 m^3) of the total volume loss detected from 1997 to 2008 was from substrates that are mud-dominated.

DISCUSSION

The area for the change detection from 1947 to 1979 performed by Fregoso and others (2008) only overlapped with the recent analysis by ~50%. However, they reported a rate of –1.1 cm yr^{-1} (–31 x 10^6 m^3) for the area that most closely approximates the 1997 to 2008 change-detection analysis region. Additionally, the rate of change calculated for the mouth of San Francisco Bar from 1956 to 2005 was –1.3 cm yr^{-1} (Hanes and Barnard 2007). A comparison of these values and the 1997 to 2008 average of –3.2 cm yr^{-1} indicates that west-central San Francisco Bay is losing sediment at approximately two to three times the rates of both the historical Central Bay rate (1947 to 1979) and the recent rate (1956 to 2005) calculated for the San Francisco Bar.

Figure 5 shows the bathymetric change map overlain with aggregate mining lease sites as designated

1 Due to carrying over of the third decimal place, not reported in the text, the rounded value after adding 0.21 and 0.13 is in fact 0.35.

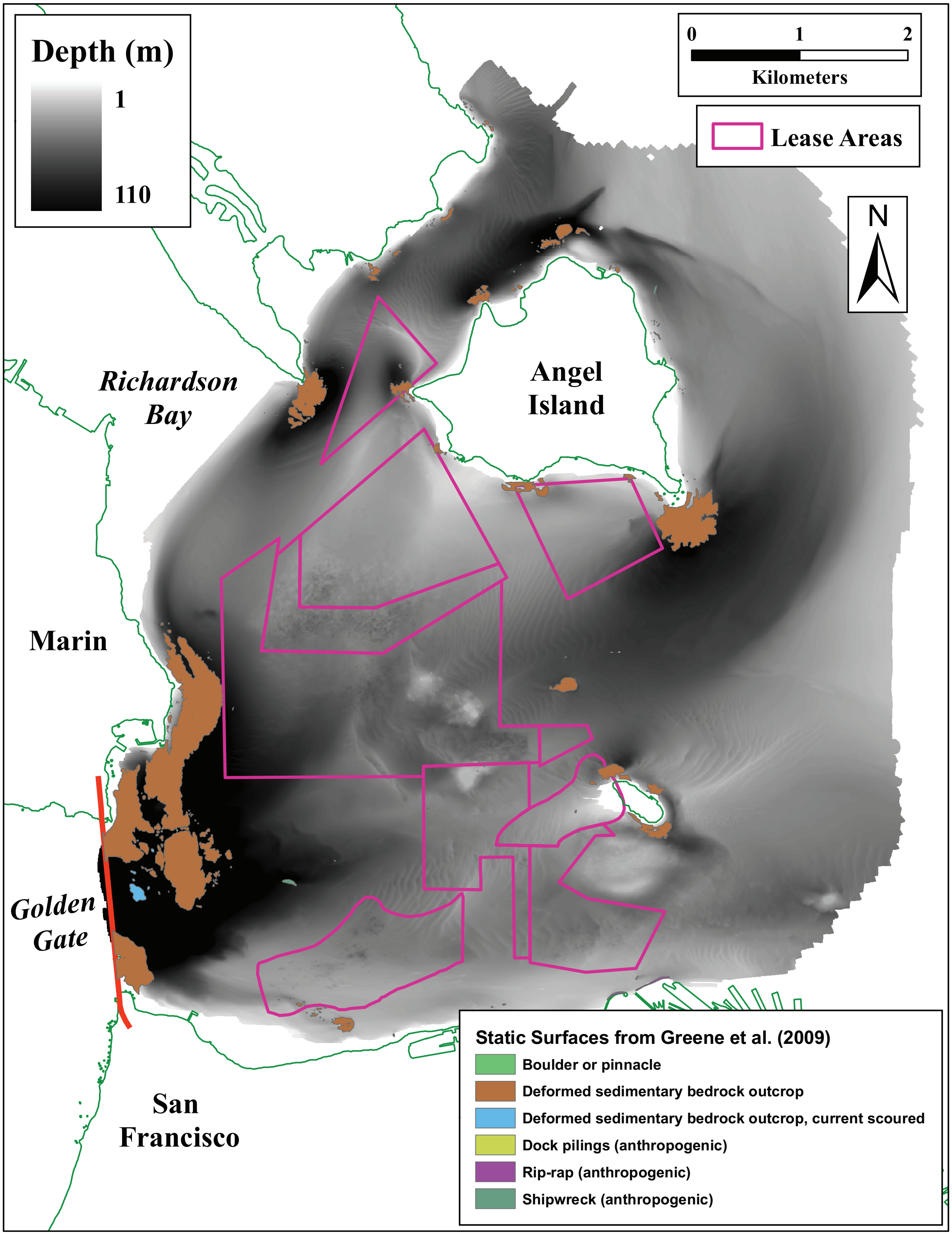

Figure 3 Location of static surfaces in west-central San Francisco Bay as defined by Greene and others (2009), with depth from the 2008 multibeam sonar survey. Note that ~95% of the static surfaces are identified as "deformed sedimentary bedrock outcrop" and that most features in the legend are barely visible due to their limited extent.

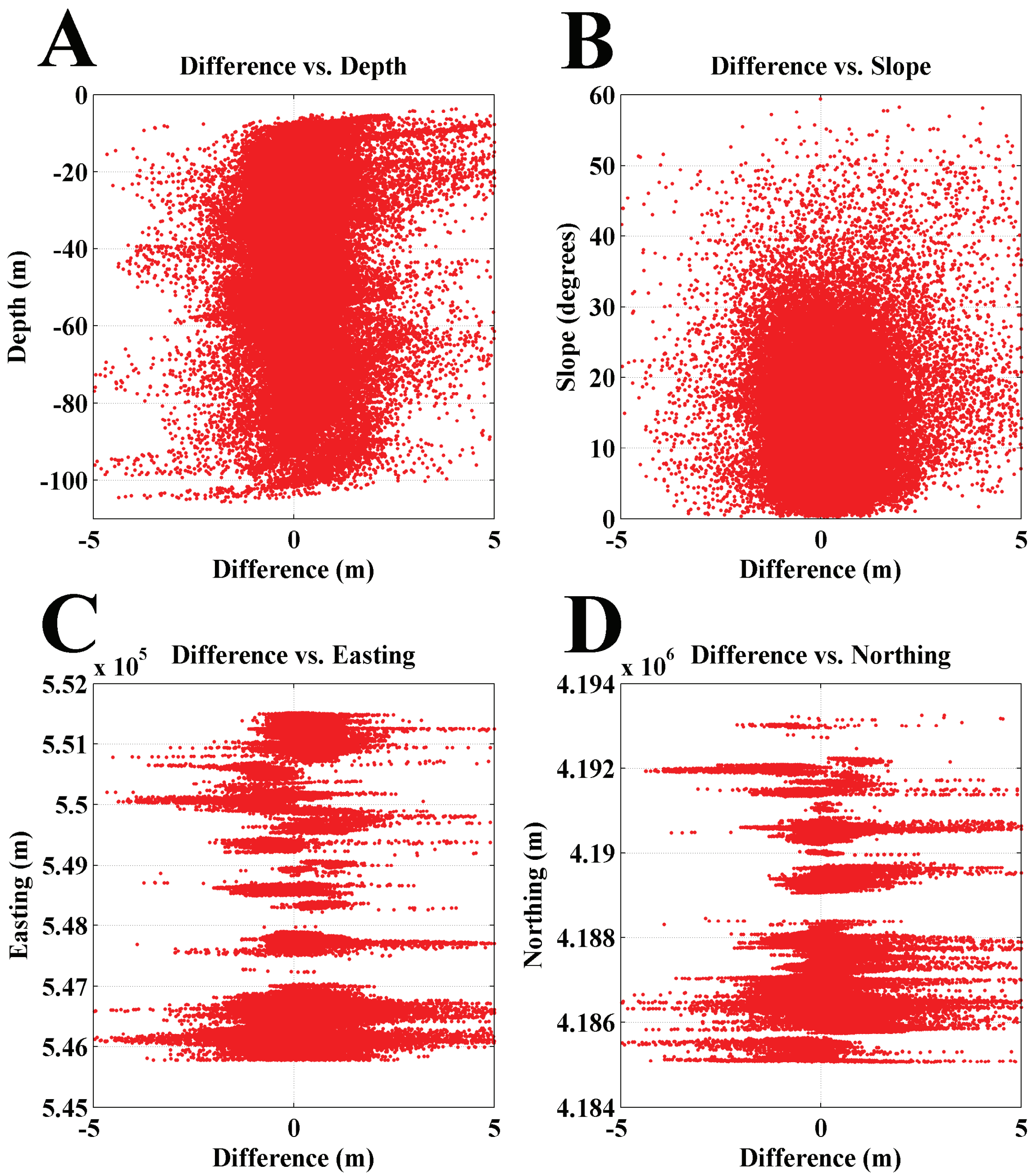

Figure 4 Plots of depth difference between the 1997 and 2008 multibeam surveys for the static surfaces identified by Greene and others (2009) vs. other spatial and slope parameters, indicating no significant correlations

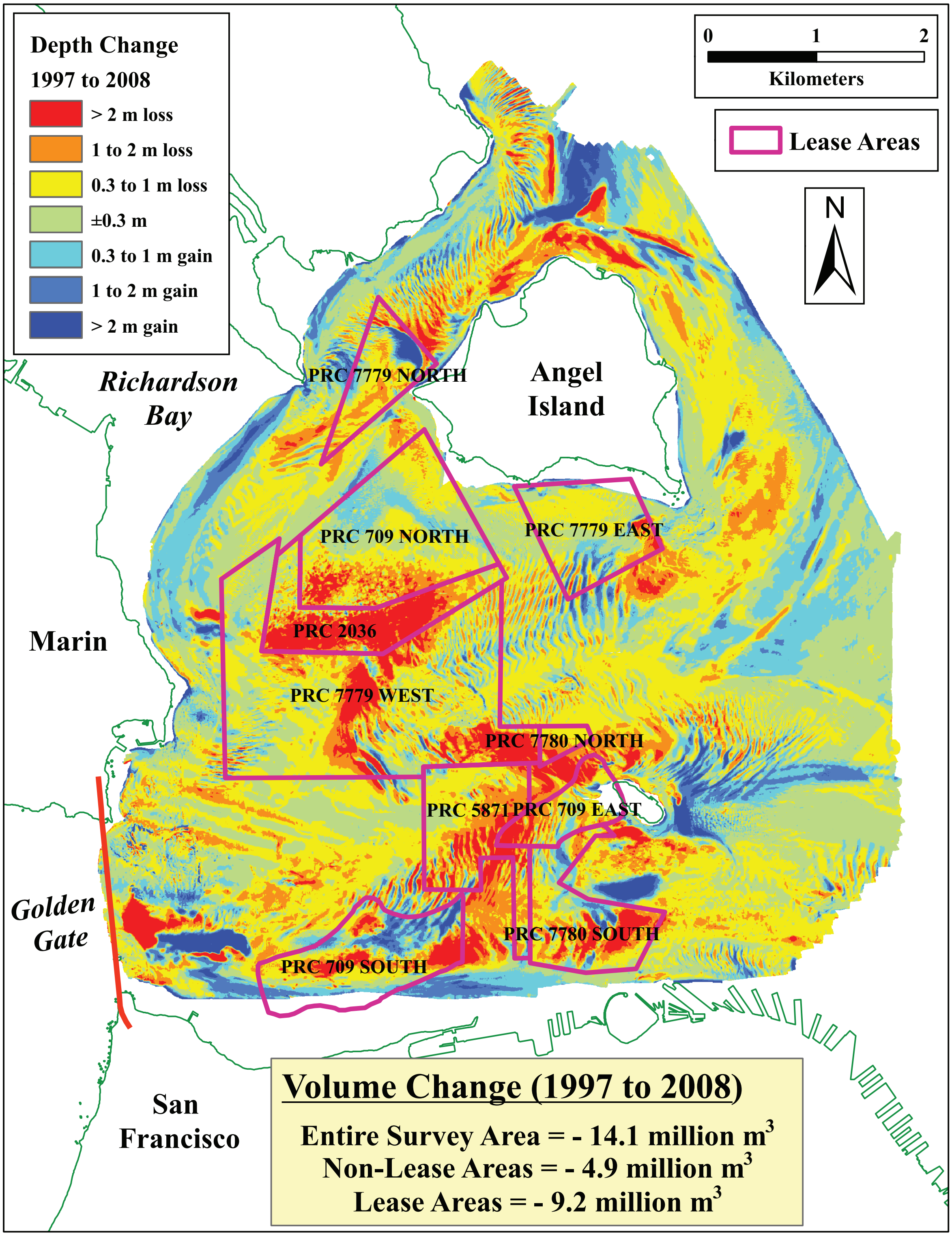

Figure 5 Bathymetric change in west-central San Francisco Bay from 1997 to 2008 with location of aggregate mining lease sites

by the California State Lands Commission and the San Francisco Bay Conservation and Development Commission (BCDC). Net sediment loss was detected within each of the ten aggregate mining lease sites in west–central San Francisco Bay (Table 2), peaking with a mean vertical change of >2 m at Public Resources Code (PRC) 2036, near Pt. Knox Shoal. Bathymetric change, in terms of volume loss, was nearly double within the aggregate mining lease sites compared to non-lease sites (-9.2×10^6 m^3 vs. -4.9×10^6 m^3), although lease areas account for only 28% of the study area. Additionally, there is an almost five-fold difference in the rate of sediment loss between the lease and non-lease areas (-7.2 cm yr^{-1} vs. -1.5 cm yr^{-1}).

The rate of sediment loss for the non-lease areas in west–central San Francisco Bay from 1997 to 2008 (-1.5 cm yr^{-1}) appears to approximate the background rate of sediment loss over the last half-century, because it is broadly consistent with rates for the adjacent San Francisco Bar (-1.3 cm yr^{-1}, 1956 to 2005) and the prior change detection for west-central San Francisco Bay (-1.1 cm yr^{-1}, 1947 to 1979). Therefore, the 1997 to 2008 rate of change in the lease areas (-7.2 cm yr^{-1}) must be largely attributable to anthropogenic sediment removal by aggregate mining and/or dredging, given that the rate of loss is at least 5.7 cm yr^{-1} higher than the background rate. The slightly higher background rate from 1997 to 2008 in west–central San Francisco Bay may result from the cumulative impacts of sediment removal in this region, especially in leasing areas, which can effectively limit sediment supply/replenishment to adjacent, non-lease areas. The background rate of sediment loss and local patterns of sediment gain/loss from the San Francisco Bar and west-central San Francisco Bay are likely attributable to a combination of natural (e.g., flood and ebb tidal delta deposition, tidal-channel incision, submarine landslides, bedform migration, etc.) and anthropogenic influences (e.g., hydraulic mining signal reduction, drainage damming, bay sediment removal, bay development, etc., see "Prior Work"). Given that an estimated one-quarter of a billion cubic meters of sediment has been lost from the San Francisco Bay Coastal System in the last 50 years (Table 1), most of which is sand and due to anthropogenic activities (Dallas 2009), and that a direct potential sediment transport link from San Francisco Bay to the outer coast (Barnard and others, in press) has been established, it is not surprising that over 90% of the 13-km-long shoreline south of the San Francisco Bar has been eroding during this same period (Dallas 2009).

Table 2 Summary of bathymetric change analysis in west-central San Francisco Bay from 1997 to 2008, differentiated by aggregate mining lease sites. The geographical extent of each lease site is shown in Figure 5.

Sample Area	Area (m^2)	Mean Vertical Change (m)	Volume Change (m^3)
Total Survey Area	40,564,490	–0.35	–14,087,792
Non-lease Areas	29,032,349	–0.17	–4,861,591
All Lease Areas	11,532,142	–0.80	–9,226,201
Individual Lease Sites:			
PRC 7779 NORTH	569,432	–0.27	–152,999
PRC 7779 EAST	888,764	–0.22	–199,647
PRC 2036	918,573	–2.17	–1,991,812
PRC 709 NORTH	1,791,064	–0.52	–926,317
PRC 7779 WEST	3,699,923	–0.81	–3,015,028
PRC 7780 NORTH	114,594	–1.08	–123,648
PRC 709 EAST	424,550	–1.09	–464,579
PRC 7780 SOUTH	930,381	–0.81	–757,307
PRC 709 SOUTH	1,099,743	–0.40	–437,086
PRC 5871	1,053,022	–1.07	–1,124,425

Dallas (2009) reports that 50 million m^3 of sand-sized or coarser sediment has been removed through dredging, aggregate mining, and borrow pit mining from Central Bay since 1900. However, neither borrow pit mining nor dredging was performed in the bathymetric change analysis area (Figure 5) from 1997 to 2008, although there were minor amounts of dredging of predominantly fine-grained material (i.e., mud) in small marinas adjacent to the study area (B. Goeden, BCDC, pers. comm.). During this same period, 10.8 million m^3 of sediment was reported to be permanently removed by aggregate mining from the lease sites in west–central San Francisco Bay, while 9.2 million m^3 of sediment loss was recorded by the bathymetric change analysis within these same lease sites (Table 3). Therefore, within the lease sites, 85% of the sediment that was extracted by aggregate mining from 1997 to 2008 was not "replenished," based on the bathymetric change analysis. However, a closer inspection of Table 3 and Figure 5 indicates areas where sediment loss values were heavily influenced by natural processes and/or other anthropogenic factors. For example, the amount of sediment loss in PRC 5871 is approximately double the amount extracted by aggregate mining, suggesting that other processes play a significant role in sediment loss. Further, although Table 3 indicates that ~50% of the sediment extracted from PRC 709 by aggregate mining was naturally replenished, the spatial distribution of bed-level change in Figure 5 shows extensive mining impact in the southwest section of PRC 709 North, while the northeast section is naturally accreting, suggesting that the local impact of mining on the 11-year sediment loss values may still be substantial. Regardless of the aforementioned nuances and relatively minor uncertainties of the bathymetric change analysis, the data presented here demonstrates a clear anthropogenic influence on sediment loss in west–central San Francisco Bay from 1997 to 2008.

Table 3 Sediment volume loss by leasing block based on the depth change analysis and volume of sediment reported to be extracted by aggregate mining (Dallas, 2009; B. Goeden, pers. comm.) during the 1997 to 2008 analysis period. Volumes of sediment extracted were only reported by leasing block (i.e., not by individual lease site; see Table 2 and Figure 5).

Leasing Block	Sediment Loss (10^6 m^3)	Sediment Extracted (10^6 m^3)	Loss/ Extracted
PRC 7779	3.4	3.3	101%
PRC 2036	2.0	2.3	85%
PRC 709	1.8	3.8	49%
PRC 7780	0.9	0.8	106%
PRC 5871	1.1	0.5	211%
Total	9.2	10.8	85%

CONCLUSIONS

From 1997 to 2008, west–central San Francisco Bay lost over 14 million m^3 of sediment, the majority of which was located within aggregate mining lease sites. The rate of sediment loss is nearly three times the rate determined between surveys from 1947 to 1979, indicating a rapid acceleration of sediment loss from the region during the last decade. As only 10% of the mapped substrate is dominated by mud, and only 5% of the measured sediment loss is from mud-dominated substrates, the majority of the sediment lost from west–central San Francisco Bay was coarse sediment, material that would otherwise have been available for transport to eroding, open-coast beaches. While it is difficult to establish the precise contribution of the various potential anthropogenic influences to the observed sediment loss from 1997 to 2008 in west–central San Francisco Bay, the timing, spatial distribution, and magnitude of sediment loss suggests a strong correlation with sediment removal by aggregate mining activities.

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