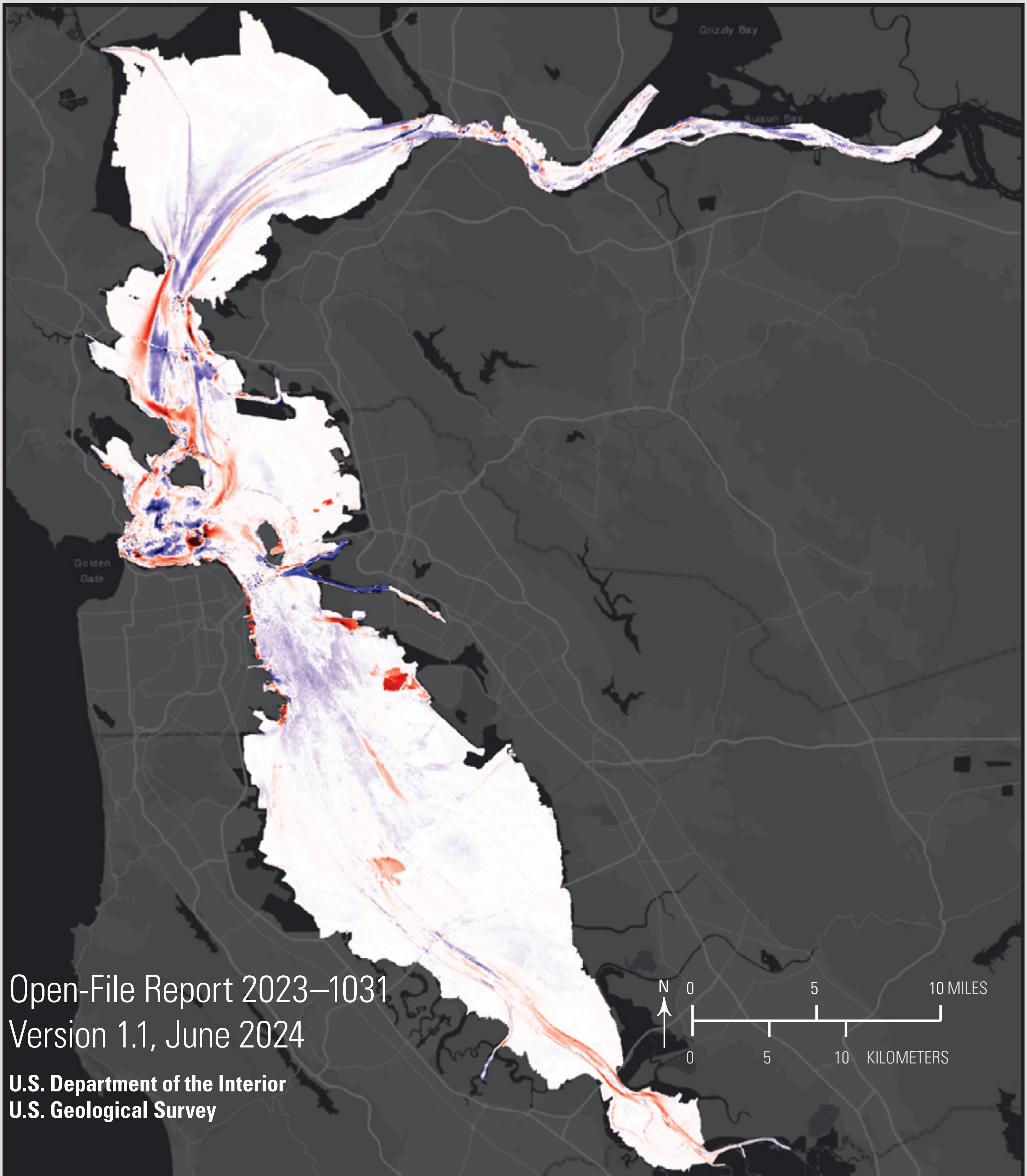
Prepared in cooperation with the Regional Monitoring Program for Water Quality in San Francisco Bay

Sediment Deposition, Erosion, and Bathymetric Change in San Francisco Bay, California, 1971–1990 and 1999–2020



Open-File Report 2023–1031
Version 1.1, June 2024

U.S. Department of the Interior
U.S. Geological Survey

Cover: Map showing bathymetric change in San Francisco Bay from the 1980s to 2010s.

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
centimeter per year (cm/yr)	0.3937	inch per year (in./year)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
Area		
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
Volume		
cubic meter (m^3)	6.290	barrel (petroleum, 1 barrel = 42 gal)
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
million cubic meters (Mm^3)	35.31	million cubic feet (Mft^3)
million cubic meters per year (Mm^3/yr)	35.31	million cubic feet per year (Mft^3/yr)

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) and Mean Lower Low Water (MLLW).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum NAVD 88.

Depth, as used in this report, refers to distance below MLLW.

Abbreviations

DEMs	digital elevation models
IDW	inverse distance weighting
IHO	International Hydrographic Organization
MHW	Mean High Water
MLLW	Mean Lower Low Water
NAD 83	North American Datum of 1983
NAVD 88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NTDE	National Tidal Datum Epoch
OLUs	Operational Landscape Units
OCM	Office for Coastal Management
USAC	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator

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Abstract

Bathymetric change analyses document historical patterns of sediment deposition and erosion, providing valuable insight into the sediment dynamics of coastal systems, including pathways of sediment and sediment-bound contaminants. In 2014 and 2015, the California Ocean Protection Council, in partnership with the National Oceanic and Atmospheric Administration (NOAA) Office of Coastal Management, provided funding for new bathymetric surveys of large portions of San Francisco Bay. A total of 93 bathymetric surveys were conducted during this 2-year period, using a combination of interferometric sidescan and multibeam sonar systems. These data, along with recent NOAA, U.S. Geological Survey (USGS), U.S. Army Corps of Engineers, and private contractor surveys collected from 1999 to 2020 (hereinafter referred to as 2010s), were used to create the most comprehensive bathymetric digital elevation models (DEMs) of San Francisco Bay since the 1980s. Comparing DEMs created from these 2010s surveys with USGS DEMs created from NOAA's 1971–1990 (hereinafter referred to as 1980s) surveys provides information on the quantities and patterns of erosion and deposition in San Francisco Bay during the 9 to 47 years between surveys. This analysis reveals that in the areas surveyed in both the 1980s and 2010s, the bay floor lost about 20 million cubic meters of sediment since the 1980s. Results from this study can be used to assess how San Francisco Bay has responded to changes in the system, such as sea-level rise and variation in sediment supply from the Sacramento-San Joaquin Delta and local tributaries, and supports the creation of a new, system-wide sediment budget. This report provides data on the quantities and patterns of sediment volume change in San Francisco Bay for ecosystem managers that are pertinent to various sediment-related issues, including restoration of tidal marshes, exposure of legacy contaminated sediment, and strategies for the beneficial use of dredged sediment.

Introduction

For decades, the U.S. Geological Survey (USGS) has developed and interpreted historical bathymetric digital elevation models (DEMs) of San Francisco Bay. These DEMs were based on surveys conducted from the 1850s to 1990 by the National Oceanic and Atmospheric Administration (NOAA) Office of Coast Survey and its predecessor, the U.S. Coast and Geodetic Survey. The present study is a continuation of previous work detailing the historical bathymetry and decadal-scale bathymetric change in each of four subembayments in San Francisco Bay (Suisun, San Pablo, Central, and South Bays) using NOAA data collected every 30 to 40 years from the 1850s to the 1990s (Jaffe and others, 1998; Cappiella and others, 1999; Foxgrover and others, 2004; Fregoso and others, 2008). Prior to this study, the last comprehensive, bay-wide bathymetric change analysis covered the period from 1971 to 1990.

This study presents the data sources and methods for creating bathymetric DEMs with surveys from 1971 to 1990 (hereinafter referred to as the 1980s because most surveys were in the 1980s) and from 1999 to 2020 (hereinafter referred to as the 2010s because most surveys were in the 2010s) in San Francisco Bay. The methods of DEM creation and calculation of bathymetric change from the 1980s to 2010s from DEMs are followed by an assessment of the uncertainty in bathymetric change. Sediment volume change from the 1980s to 2010s and, for comparison, from the 1950s to 1980s, are presented. The patterns and volumes of bathymetric change highlight trends through time and how natural processes and human activities have altered the bathymetry of San Francisco Bay.

Study Area

San Francisco Bay is composed of four subembayments (fig. 1), covering a total area of about 1,200 square kilometers (km^2). Suisun Bay, which is just west of the confluence of the Sacramento and San Joaquin Rivers, is the most directly affected by flows and sediment from the Sacramento-San Joaquin Delta. The main channel has a sand deposit and is regularly mined for sand. San Pablo Bay is to the west of Suisun Bay and connected to it by Carquinez Strait. The combination of San Pablo Bay, Carquinez Strait, and Suisun Bay is often referred to as North Bay. San Pablo Bay is fringed by expansive mudflats and marshes that support vital ecosystems and are surrounded by managed ponds and marsh restoration areas, which are sinks for sediment, as well as areas of dredge disposal. South of San Pablo Bay is Central Bay, which is the deepest of all subembayments and includes the connection to the Pacific Ocean. Central Bay has been subject to many anthropogenic changes from diking and draining of marshes, filling of San Francisco Bay, sand mining, dredging and dredge disposal, and sediment borrow pits. Lastly is South Bay, which here is defined as extending from Hunter's Point on the western shore and the Oakland Airport on the eastern shore, south to the City of San Jose following the definition used in Foxgrover and others (2004). South Bay is dominated by large mudflats and surrounded by former salt production ponds, many of which are undergoing restoration to mixed intertidal habitat. Starting in the early 1900s, oyster shell deposits were mined from the South Bay for cement production to be used as a calcium supplement in poultry and livestock feed, as well as a soil conditioner (Hart, 1966; Lind Marine, 2020).

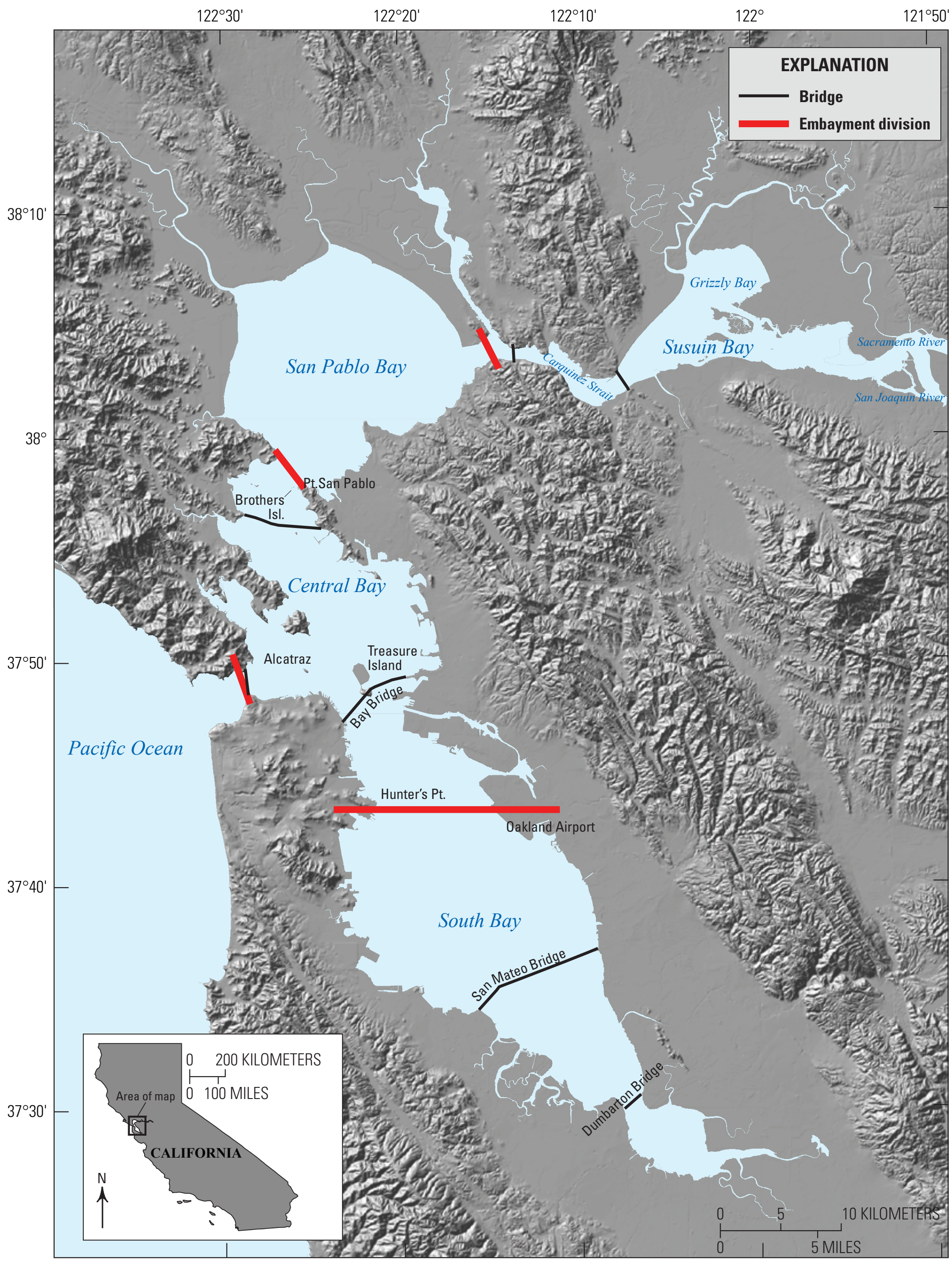

Figure 1. Location of study area, the entirety of San Francisco Bay, delineating subembayment divisions as used for this report.

Data Sources

1980s Bathymetric Surveys

The bathymetric surface models for the 1980s DEMs are documented in a series of USGS Open-File Reports produced beginning in the 1990s (Jaffe and others, 1998; Foxgrover and others, 2004; Fregoso and others, 2008). These historical bathymetric surface models were all created from single-beam hydrographic surveys collected by the NOAA National Ocean Service (NOS). NOAA generally completed surveys of each subembayment within a few years, with most soundings collected in a single year—1979 for Central Bay, 1983 for San Pablo and South Bays, and 1990 for Suisun Bay, with the entire San Francisco Bay mapped from 1971 to 1990 (fig. 2). A total of 31 surveys, comprising about 400,000 soundings, were used in the 1980s bathymetric surface model. Sounding density for these single-beam surveys varies but averages a sounding every 50 meters (m) along track with track-line spacing of approximately 100 m (Jaffe and others, 1998; Foxgrover and others, 2004; Fregoso and others, 2008). All data were referenced to the Mean Lower Low Water

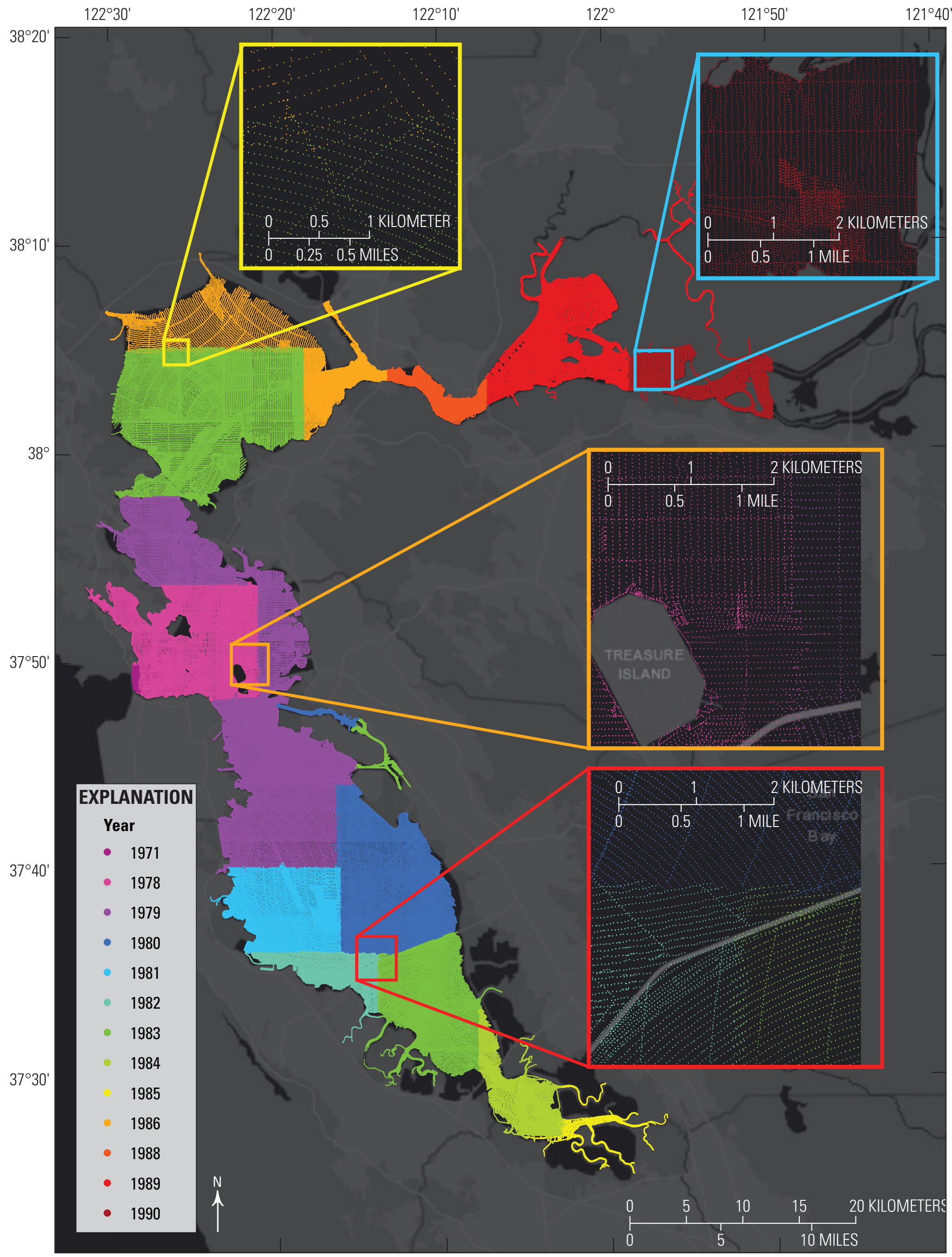

Figure 2. 1980s surveys by year collected with insets for each subembayment showing data density and the distribution of survey tracklines.

(MLLW) tidal datum (either the 1941–1959 or 1960–1978 National Tidal Datum Epoch [NTDE]) at the tide station nearest the survey area. The NTDE is a 19-year period of water level measurements used to calculate tidal datums (for example, MLLW). A 19-year period is used to ensure that tidal variations, including the 18.6-year cycle caused by the oscillation of the orbital surface of the Moon around the Earth, are accounted for in the observations. Depending on when a survey is collected, it is generally referenced to the proceeding 19-year tidal epoch. Tidal epochs are typically published and put into use a few years after the end of the previous epoch. This means that Suisun Bay (1990), San Pablo Bay (1983), and South Bay (1983) used the 1960 to 1978 tidal epoch, whereas Central Bay (1979) referenced the 1941 to 1959 epoch.

2010s Bathymetric Surveys

The bathymetric surveys used to create the 2010s DEMs were collected from 1999 to 2020 (fig. 3*A*; Office for Coastal Management, 2021a, 2021b, 2021c, 2021d, 2021e). Most of the 2010s data were collected in 2014 and 2015 under the direction of the California Ocean Protection Council, in cooperation with the NOAA Office for Coastal Management (OCM) (Esposito, 2016), using either multibeam or interferometric sidescan sonar systems (fig. 3*B*).

A total of 128 surveys, comprising millions of soundings, were conducted. Of those surveys, 22 were single beam, covering 19 percent of total survey area (fig. 3*B*). The largest single-beam survey was collected in South Bay in 2005 by Sea Surveyor, Inc., under contract with the California Coastal Conservancy (Foxgrover and others, 2007). These South Bay data have a sounding spacing of 1 m along track, with 100 m between tracklines and were gridded at a resolution of 25 m by Foxgrover and others (2007). The rest of the single-beam surveys were collected by the U.S. Army Corps of Engineers (USACE) in shipping channels and areas of routine dredging and have a sounding spacing of 5 to 10 m along a trackline, and 30 to 60 m between tracklines.

The remainder of the surveys (81 percent of total survey area) were collected with high resolution multibeam or sidescan sonar systems. Instead of recording individual soundings along the trackline (like the 1980s NOAA surveys), multibeam or interferometric side-scan systems collect numerous soundings per square meter in an along-trackline swath of varying width. The soundings generally are of a high enough density to generate a 1-m DEM without additional interpolation and are usually collected with overlap between adjacent tracklines, resulting in continuous data coverage. However, to decrease survey costs and maximize overall survey area, trackline spacing for many of the 2014 and 2015 surveys was intentionally increased, creating data gaps between

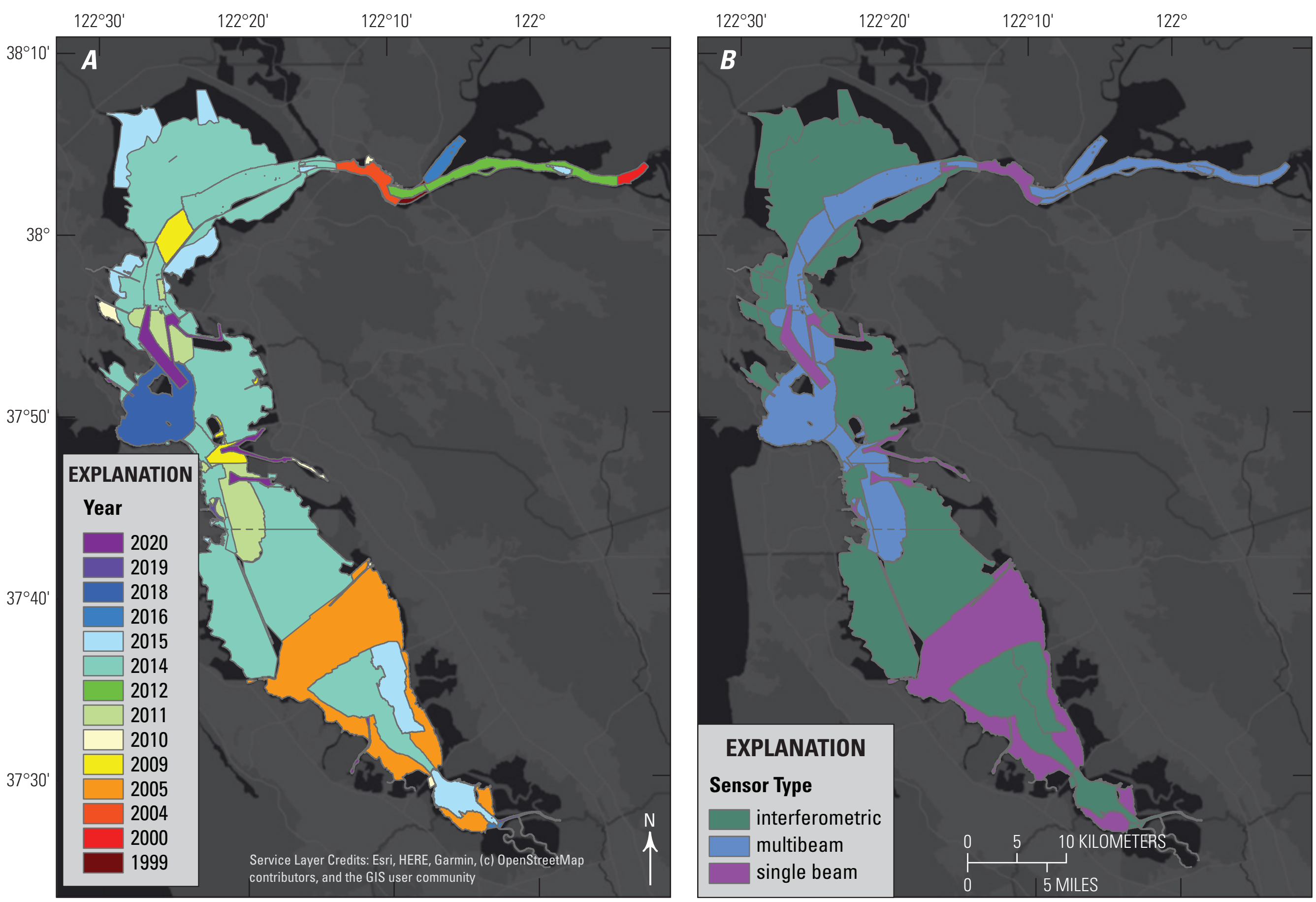

Figure 3. Year data were collected (*A*) and bathymetric survey sensor type (*B*) for the 2010s digital elevation model (DEM) surface.

adjacent tracklines. Few surveys had trackline spacing close enough to continuously map the bay floor; 86 percent of the surveys were collected in swaths that ranged in width from 18 m to greater than 100 m, with data gaps between adjacent tracklines ranging from 10 m to greater than 300 m. These tracklines are composed of clouds of data that cannot be depicted as a single point (like the 1980s single-beam data), the multibeam and swath surveys were provided in raster format with a native cell size of 50 centimeters (cm) to 2 m. All surveys were vertically referenced to either the MLLW tidal datum (1983–2001 NTDE) or the North American Vertical Datum of 1988 (NAVD 88) geodetic datum.

Owing to the challenges and expense of surveying in extremely shallow waters, many of the surveys did not extend all the way to the Mean High Water (MHW) shoreline (figs. 3, 4). Incomplete coverage of San Francisco Bay is most noticeable in the intertidal flats of San Pablo Bay and the shallows and intertidal flats of Suisun Bay.

Methods

To analyze bathymetric change throughout San Francisco Bay, the patchwork of 2010s surveys with varying data types, resolutions, collection years (1999–2020), and trackline

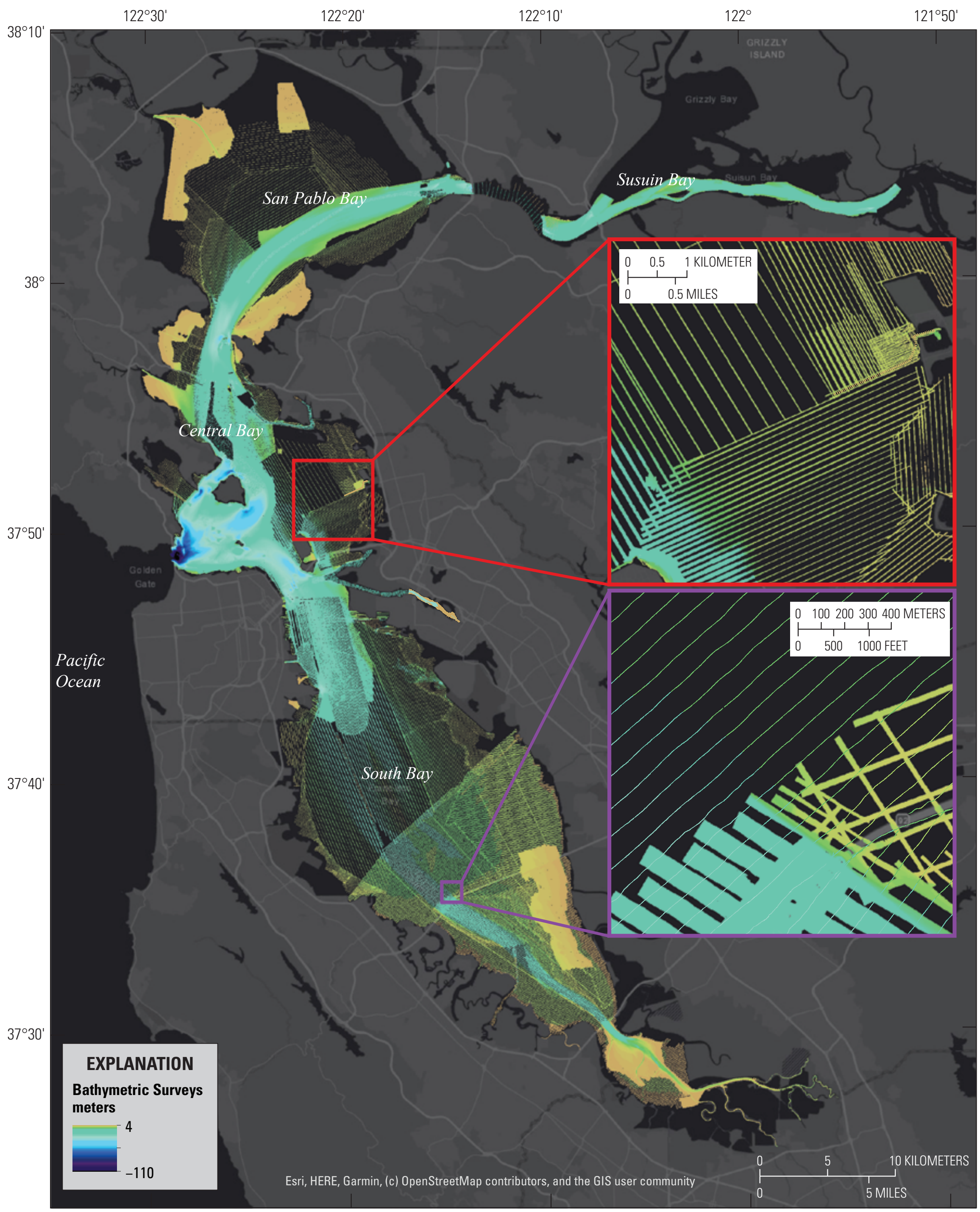

Figure 4. Soundings from the 2010s used to create the continuous surface digital elevation models (DEMs) showing data density and data gaps.

patterns were carefully modeled to create a continuous surface DEM representing each subembayment (Fregoso and others, 2020). To allow a meaningful comparison with the 1980s DEM, those continuous surfaces were resampled to the 25- or 50-meter (m) resolutions of the 1980s bathymetric surface models. After these subembayment DEMs were created and adjusted to account for differences in reference datums and grid cell resolutions, and corrected for grid interpolation bias, they were differenced (in other words, the 1980s surface was subtracted from the 2010s surface) to reveal patterns of bathymetric change throughout the system. These bathymetric change surfaces were then used to calculate sediment volume change throughout San Francisco Bay and individual subembayments. Normalized rates of change (in centimeters per year [cm/yr]) also were calculated to account for the varying time spans (9–47 years) of survey collection throughout the study area.

1980s Digital Elevation Model

The surface models for the 1980s DEM come from a series of USGS Open-File Reports produced beginning in the 1990s (Jaffe and others, 1998; Foxgrover and others, 2004; Fregoso and others, 2008). As stated in the “1980s Bathymetric Surveys” section, these surveys were all single-beam surveys originally collected by NOAA. Sounding densities varied by survey but averaged 50 m along track, with a trackline spacing of approximately 100 m. Depth contours were manually digitized based on sounding depths and the general seafloor geomorphology to help constrain the gridding algorithm in areas of sparse soundings.

DEMs created from these surveys during previous studies used what was Esri’s topogrid model and is now referred to as Topo to Raster (Esri, 2020). The Topo to Raster interpolation algorithm is designed to use both point (sounding) and contour data to generate a hydrologically correct DEM. This method essentially uses a discretized thin plate spline technique (Wahba, 1990) that has been modified to allow for abrupt changes in terrain (Esri, 2020). Using an iterative finite difference interpolation technique, the contours are initially used to build a generalized drainage model that is further refined using both soundings and contour values to determine elevation values at each cell. The resulting DEMs produced for Suisun, San Pablo, and Central Bays have a resolution of 25 m and for South Bay a resolution of 50 m. The DEMs were then evaluated to determine how well the interpolated surface agreed with the original sounding data. Grid bias was calculated by comparing each individual sounding to its coresponding cell value and the DEMs adjusted by the average amount of grid bias per subembayment.

Prior to comparison with the 2010 surveys, adjustments were made to the original bathymetric surface DEMs for each subembayment. All DEMs were brought into a common horizontal datum (North American Datum of 1983 [NAD 83]) and the rasters were aligned to their 2010s counterparts to ensure all cells lined up directly on top of each other.

2010s Digital Elevation Model

The starting point of these analyses was the Fregoso and others (2020) DEMs for North Bay (San Pablo Bay, Carquinez Strait, and Suisun Bay), Central Bay, and South Bay in which all data were brought into common horizontal (NAD 83) and vertical (NAVD 88) datums and data resolution (1 m). For the original DEM, 73 percent of the surveys were provided at 1-m resolution and referenced to NAVD 88. The remaining surveys were referenced to MLLW (1980–2001 NTDE) and were converted to NAVD 88 using NOAA’s Vertical Transformation tool (VDatum; National Oceanic and Atmospheric Administration, 2021). Using Esri’s ArcGIS software suite, grid cells ranging in size from 50 cm to 2 m for swath and (or) multibeam data, to 25 m (South Bay single beam), were resampled to 1-m using the resample tool and bilinear interpolation in ArcGIS (Fregoso and others, 2020).

In the 2010s continuous surface DEMs, interpolation was needed across data gaps between track lines and neighboring surveys. Data gaps were filled by adapting the same methodology used to interpolate between single-beam tracklines for the creation of the 1980s San Francisco Bay DEMs (Jaffe and others, 1998; Foxgrover and others, 2004; Fregoso and others, 2008). Contours were generated (fig. 5) and Esri’s Topo to Raster tool was used to interpolate across data gaps between swath tracklines (Esri, 2020). The use of contours in addition to soundings helps to better constrain the surface in areas of sparse sounding data or swath data gaps while helping to maintain geomorphic features. For this project, the original 1-m swath grids were mosaicked into small, manageable sections then converted to points to run Topo to Raster without the use of contours. This created a rough draft version of these sections of the final DEM, and from this, contours were generated using Esri’s contour tool in intervals of 20 cm across broad, shallow areas (generally in water depths less than 4 m), and in intervals of 1 m in deep areas. These contours were then examined and manually edited to better reflect the geomorphology of the bay floor by connecting obvious features such as channels, as well as smoothing contours between tracklines (fig. 5). In areas of complex geomorphology such as sand waves, as well as areas with unusual features such as furrows, the backscatter imagery collected in conjunction with the sidescan bathymetry for the OCM surveys (Office for Coastal Management, 2021a, 2021e) provided additional guidance when manually digitizing contours. For data gaps that could be connected logically by surrounding data using contours, those contours were added. The finalized contours and the point versions of the original sections were then rerun through Topo to Raster to create a continuous DEM for each part at a resolution of 1 m to better process the large amounts of data.

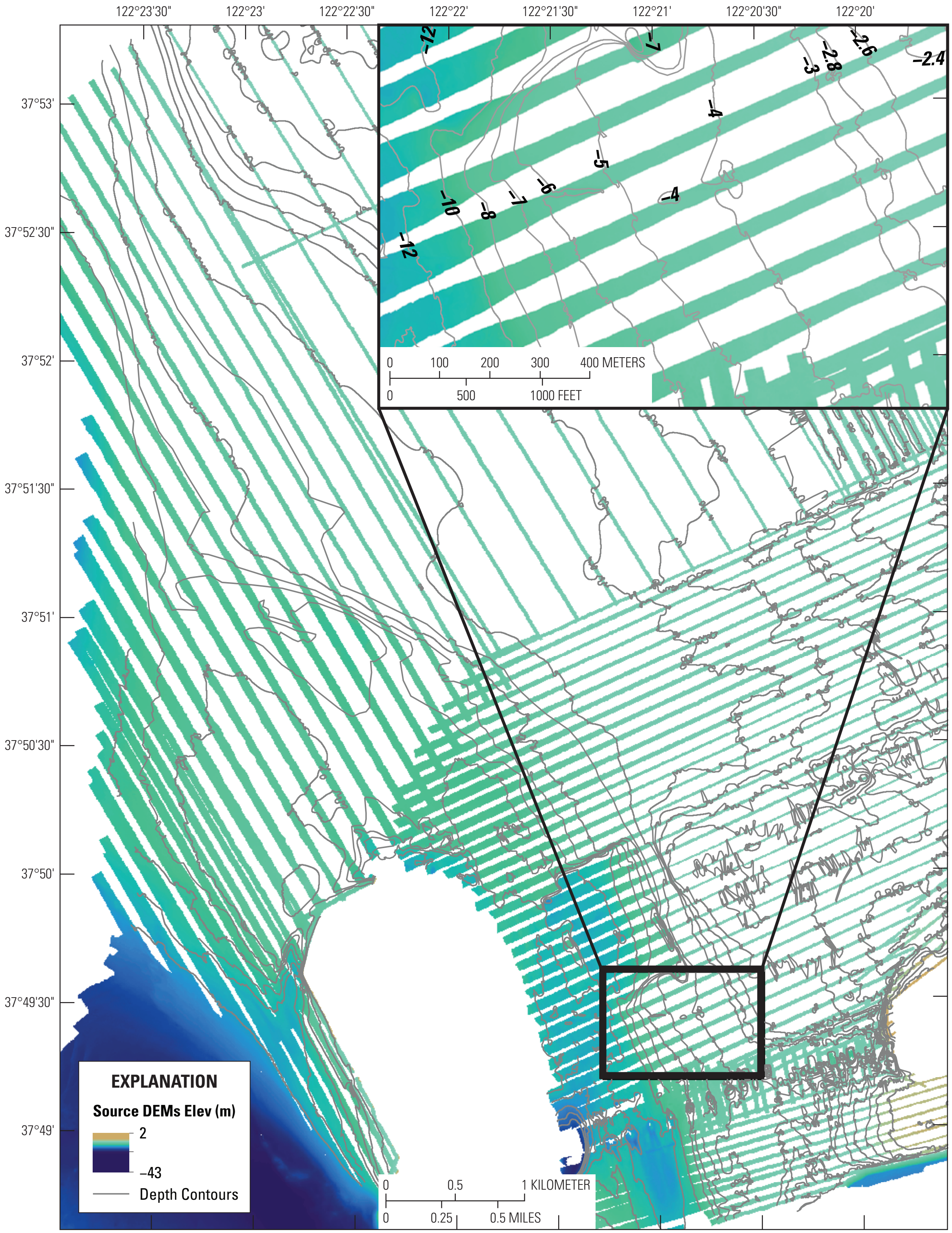

Figure 5. Example of computer-generated depth contours that were then corrected and smoothed for use in constraining interpolation.

The DEM sections were then examined for areas with small data gaps and (or) missed interpolation areas, as well as places showing edge discrepancies between adjacent and overlapping DEM sections. Additional contours were added to fill some larger gaps between surveys. For cases with discontinuities along the edges of adjacent and overlapping datasets, edges were smoothed by first deleting a narrow gap between DEMs. Then gaps for both edge issues and smaller data gaps (about 100 square meters [m^2]) were filled using the “Interpolate from Edges” or “Fill Voids” interpolation options in the ArcGIS Pro pixel editor tool. Decisions were made on a case-by-case basis as to which options were best suited to the gap being filled. Interpolate from Edges uses values from the edges of the selected area and allows for four different interpolation methods, nearest neighbor, linear tinning, natural neighbors, and inverse distance weighting (IDW). Fill Voids allows for specifying a maximum width to be filled using a short range IDW interpolation and can be applied to a larger area defined by the user, to fill a group of little gaps otherwise missed (Esri, 2021b). These sections were finally merged into seamless DEMs using the ArcGIS Mosaic to new Raster tool. Owing to the large size of San Francisco Bay, three DEMs were produced—a North Bay DEM, which includes San Pablo Bay, Carquinez Strait, and Suisun Bay, a Central Bay DEM, and a South Bay DEM that together are the 2010s San Francisco Bay DEMs.

The initial 2010s DEMs were all referenced to the NAVD 88 vertical datum. VDatum was then used to convert the 2010s NAVD 88 DEMs to MLLW (1983–2001 NTDE) for use in bathymetric change calculations. In regions where the VDatum tidal datum conversion did not extend to the shoreline, the conversions were extrapolated to the shoreline based on the closest available data using ArcGIS Pro Pixel Editor Interpolate from Edges option (Esri, 2021b). In South Bay, rather than using VDatum, the conversion to MLLW was done using a NAVD 88 to MLLW conversion created by NOAA for the 2005 bathymetric survey (Foxgrover and others, 2007). Because the 2010s DEMs were primarily derived from multibeam bathymetry, with many soundings per cell, no grid bias correction was applied. The 2010s 1-m resolution surface DEMs referenced to both MLLW and NAVD 88 and their associated source data are published as a USGS data release (Fregoso and others, 2020).

Bathymetric Change Grids

To create bathymetric change grids, the 1980s DEMs were adjusted to the same MLLW tidal epoch (1983–2001 NTDE) as the 2010s DEM to account for sea-level rise that occurred in the decades between surveys. Suisun, San Pablo, and South Bays were adjusted from the 1960 to 1978 NTDE and Central Bay from the 1941 to 1959 NTDE, to the one used by the 2010s, 1983 to 2001 NTDE, using measurements from the nearest primary tide station, following the methodology from Jaffe and Foxgrover (2006). Suisun, San Pablo, Central, and South Bay elevations were adjusted by 7, 4, 7, and 2 cm, respectively.

To better compare the two time periods, the 2010 DEMs needed to be modified. Comparing a 25- or 50-m grid to a 1-m cell resolution can give the impression of having a higher level of informative detail than exists. To combat this impression, the 1-m bathymetric surfaces were resampled to the same resolution as the 1980s DEMs (50 m for South Bay and 25 m for all others). ArcMap’s Aggregate Tool (Esri, 2021a) was used to calculate mean values within the specified 25×25 m or 50×50 m cell size and to export the reduced-resolution raster. The final processing step before performing the change calculations was to ensure that the 2010s and 1980s surfaces were properly aligned to avoid false change artifacts caused from a mismatch of data cells, and that the extents for the 2010s data matched those of the historical bathymetric change studies.(Jaffe and others, 1998; Foxgrover and others, 2004; Jaffe and Foxgrover, 2006; Fregoso and others, 2008).

Once the above adjustments were applied, bathymetric change grids were calculated by differencing the adjusted 1980s and 2010s MLLW (1983–2001 NTDE) bathymetric DEMs to reveal areas of sediment gains and losses over time. To make comparisons of the 1980s to 2010s change period with the previous change period (1950s–1980s), the two change surfaces were clipped to the same extent to confine comparisons to a common survey area.

Sediment Volume Change Calculations

Once the bathymetric change grid was created, volumes of erosion and deposition were calculated by multiplying the amount of bathymetric change on a cell-by-cell basis for each subembayment. However, owing to the large variation in timespans of the 2010s surveys, caution must be used when interpreting the volumetric calculations. To account for this, we also have normalized the bathymetric change data by time between surveys.

The range of timespans between the 1980s and 2010s surveys varies spatially throughout San Francisco Bay and must be considered when analyzing patterns and volumes of bathymetric change. Rates of bathymetric change were calculated based on the specific collection year of the individual surveys that comprise the DEMs, dividing change areas by their corresponding survey timespan, so that no one area has a stronger signal based on duration between surveys. Survey dates for the 1980s DEM were assigned by subembayment on the basis of when most soundings were collected (1979 for Central Bay, 1983 for South Bay and San Pablo Bay, and 1990 for Suisun Bay). For the 2010s DEM, the survey year polygons in figure 3 (ranging from 1999 to 2020) were converted to grids and differenced from the 1980s subembayment dates to create a grid of survey timespans. The bathymetric change grid was divided by the resulting timespan grid, with the number of years ranging from 9 to 47, to obtain a grid depicting rate of change in cm/yr for the entire bay.

Uncertainty in Bathymetric Change

Two types of uncertainty are associated with bathymetric change: random error and systematic biases (U.S. Army Corps of Engineers, 2002; Anderson, 2019). Random error is associated with sounding inaccuracy or noise and is generally randomly distributed in space (Adams, 1942; Shalowitz, 1964; Sallenger and others, 1975). Sounding errors are primarily low magnitude, lie both above and below the true value, and with enough data points, cancel to negligible levels when averaged or summed, as is the case in calculation of volume change (Anderson, 2019). Systematic biases, however, can enter surveys through various sources, including differences in horizontal or vertical datums (reference points), measurement inconsistencies, or during the creation of bathymetric grids. In comparing bathymetry from two time periods for an area with many soundings, random error cancels out and therefore does not significantly affect our estimates of deposition or erosion. However, systematic biases introduce false offsets between surveys and must be accounted for in bathymetric change estimates.

Random error can lead to large uncertainties in bathymetric change at a single point in space when calculating volume change in an area with sparse data. The magnitude of random error, as well as the corresponding uncertainties in bathymetric change or volumetric change in areas with enough data points for the random area to cancel out, are a function of the quality of the bathymetric survey. All bathymetric surveys used in this study are high quality and specific information on accuracy estimates can be found through the original source data (Jaffe and others, 1998; Foxgrover and others, 2004; Jaffe and Foxgrover, 2006; Fregoso and others, 2008; Fregoso and others, 2020). The 1980s surveys were collected using the International Hydrographic Bureau 1968 standards for collections of bathymetric data (International Hydrographic Bureau, 1968; Umbach, 1976) and using the National Geodetic Survey third order, class 1 standard for horizontal control (Federal Geodetic Control Committee, 1984). The 2005 South Bay single-beam survey by Sea Surveyor, Inc., was collected to meet International Hydrographic Organization (IHO) Order 1 specifications (International Hydrographic Organization, 1998; Foxgrover and others, 2007), and all Office for Coastal Management multibeam surveys met or exceeded IHO Order 1a specifications according to the latest IHO standards for hydrographic surveys (International Hydrographic Organization, 2008). Although the interferometric bathymetry collected as part of the OCM surveys were not required to meet the same uncertainty specifications, analyses performed by Esposito (2016) confirmed that the majority of bathymetry retained from the interferometric sonars met IHO Order 1a specifications as well.

Uncertainty in bathymetric change from systematic error in areas with enough soundings for random error to cancel out comes into play in aggregate measures such as sediment volume change. To minimize systematic error, efforts have been made to understand and account for any differences in horizontal and vertical datums as to not influence bathymetric change estimates. However, other sources of systematic errors are still present in our analysis, some of which are known and can be removed and others which are either unknown or difficult to remove.

The 1980s bathymetric grids have a measured source of one type of systematic error resulting from imperfect gridding algorithms. Gridding biases in the 1980s surfaces were estimated by comparing individual depth soundings to the cell value of the bathymetric grid at that specific location (Jaffe and others, 1998; Foxgrover and others, 2004; Fregoso and others, 2008). Negative values are when the sounding values are deeper than the grid cell, positive values are the opposite. In 1980s Central Bay, a gridding bias of −5.4 cm was removed from the final DEM surface (Fregoso and others, 2008). Gridding biases of −0.3, −1.4, and −6.4 cm were calculated for South, San Pablo, and Suisun Bays, respectively. In some previous studies, grid bias was calculated as part of the uncertainty assessment, but not removed from the source DEMs used for bathymetric change calculations (Jaffe and others, 1998; Cappiella and others, 1999; Foxgrover and others, 2004; Jaffe and Foxgrover, 2006). Here, these gridding biases have been removed prior to all bathymetric change calculations.

An uncertainty assessment was conducted by Esposito (2016) for the OCM surveys, which are the majority of the 2010s surveys, by comparing independent depth values collected by different sonars and survey vessels in areas of overlap between adjacent survey blocks. The mean difference of the 1-m grid cells in areas of overlap was 0.019 m and the standard deviation, a representation of random error, was 0.144 m (Esposito. 2016). This depth difference at overlap locations was greater than 0.5 m for 8.4 percent of the compared cells. The larger differences in depth values tended to be in deeper water or near bridge pilings or piers and (or) where sediment deposition or erosion may have occurred between surveys (Esposito, 2016). Even for the high-quality surveys used in this study, random error can result in an overestimate and (or) underestimate of bathymetric change greater than a meter for individual cells, especially in deeper water and where the bed surface is steeply sloping.

The total absence of data between interferometric swath tracklines in the 2010s surveys undoubtedly results in interpolation uncertainties, which have not been quantified here. However, the coherent bathymetric change patterns seen across these data gaps give some reassurance that the interpolation is reasonable.

Another approach we used to assess systematic bias in bathymetric change from the 1980s to 2010s for an area that did not use OCM surveys was to compare 1980s survey single-beam soundings to one of the 2010s multibeam surveys, after correcting to a common vertical datum at an unchanging (static) bedrock area. This approach was used by Barnard and Kvitek (2010) for surveys of west-central San Francisco Bay. Barnard and Kvitek (2010) calculated depth differences for static surfaces, primarily bedrock areas, identified in Central Bay through the habitat mapping of Greene and others (2009). Here, following the advice of Steve Sullivan (Farallon, written commun., 2022), we restricted our comparison of bathymetric change to Arch and Shag Rocks in central San Francisco Bay. Although the tops of these rocks have portions that are nearly flat, slopes can be 10 degrees or more. For slopes up to 10 degrees, the average and standard deviation of depth change on Shag and Arch Rocks from the 1980s to 2010s were 0.12±1.13 m (208 soundings), with positive values indicating the 2010s surface is deeper than the 1980s. For slopes up to 1 degree, the average and standard deviation of depth change on Shag and Arch Rocks from the 1980s to 2010s were 0.03±0.50 m (13 soundings). For the entirety of San Francisco Bay, the approach of assessing uncertainty caused by systematic error by comparing soundings at static (unchanging) locations is limited by the paucity of suitable static locations and the limited number of soundings at those locations.

Because our assessment of systematic error is not perfect and does not include all possible sources, and because systematic error likely varied for different parts of San Francisco Bay, a single value that we are confident characterizes the uncertainty from systematic error does not exist. However, based on the 2 cm found by Esposito (2016) in his uncertainty assessment of the OCM surfaces and our own similar finding of 2 cm less of vertical uncertainty in USGS bathymetric surveys (Foxgrover and others, 2011), we find it reasonable that the minimum uncertainty of this change surface would be ±4 cm, the sum of 2 cm of uncertainty for the 2010s surveys and an estimated "best case" 2-cm uncertainty for the 1980s surveys. Therefore, in the "Results" section, we present volume change associated with two different possible levels of uncertainty, a minimal value of 4 cm and a more conservative value of 8 cm that assumes uncertainty in the 1980s surveys is 6 cm. Depending on the application, we leave consideration of uncertainty level to the user.

Results

Bathymetric Change from 1980s to 2010s

The 1980s to 2010s bathymetric change grid (Fregoso and others, 2024) shows a system that is losing sediment (fig. 6). In all, approximately 40 percent of the area surveyed deepened by more than 10 cm and 35 percent shoaled by more than 10 cm. The remaining 25 percent of San Francisco Bay was relatively stable with less than 10 cm of bathymetric change. The dark reds and dark blues in figure 6 are areas with large (> about 1 m) of sediment gain (7 percent by area) or loss (8 percent by area), respectively. These areas coincide with deposition and erosion associated with natural processes such as channel migration, as well as with human-induced changes such as dredged channels, sand mining, active borrow areas (areas where bay sediment is removed for various purposes), the placement of dredged sediments, and (or) filling of inactive borrow areas by natural processes. The maximum sediment loss was 17 m and occurred in a small area off the coast of Point San Pablo, south of The Brothers Islands by about 400 m and east of Point San Pablo by about 700 m. This area existed as a depression in the 1980s at approximately 16 m deep, in the 2010s this area deepened even more. This is not a known dredging area, so sediment loss in this depression may be the result of a natural process. The maximum sediment gain of 23 m was located within the Alcatraz Island dredged sediment-disposal site. The areas of maximum bathymetric change attributed to natural processes were in regions where channels migrated, resulting in both erosion and deposition that ranged from 1 to 5 m.

Because the timespan between surveys included in the 1980s and 2010s surveys varies spatially throughout San Francisco Bay, a time-normalized approach for examining bathymetric change is desirable. Figure 7 shows bathymetric change depicted as rates. This image still shows the same areas of gain and loss of sediment as in figure 6, but the strength of those signals and corresponding colors have been adjusted to remove differences caused by varying timespans between the 1980s and 2010s surveys. The maximum rates of sediment gain and loss were 109 and −67 cm/yr, respectively. The highest rates of sediment gains and losses are associated primarily with human activities and are mostly in Suisun Bay, except for an area located within the SF 11, Alcatraz Island dredged sediment-disposal site. In general, the highest rates of sediment loss attributed to natural processes range from −10 to −20 cm/yr and are located within or on the margins of the channels passing from San Pablo Bay to Central Bay. The highest rates of sediment gain, excluding areas associated with channel migration, channel narrowing or widening, in-bay dredged sediment disposal, or infilling of areas where sediment was previously taken from San Francisco Bay, are on the order of 1 to 2 cm/yr and occur in lower South Bay, south of the Dumbarton Bridge, and in the shallows of San Pablo Bay and eastern Central Bay. The areas with the highest rates of sediment loss, not including the same areas mentioned above (about −2 to −3 cm/yr), are predominantly between the San Francisco-Oakland Bay and San Mateo Bridges and a small area just north of the main channel in San Pablo Bay.

Sediment Volume Change

The volumes of sediment gain and loss help to improve understanding of the sediment transport processes in the system and to construct a sediment budget. The net loss for San Francisco Bay from the 1980s to 2010s was about 20 million cubic meters (Mm^3) of sediment (table 1). The greatest net loss was in the Suisun Bay region with 18 Mm^3, followed by San Pablo Bay with 13 Mm^3, and South Bay with 8 Mm^3. Central Bay was the only area with a net sediment

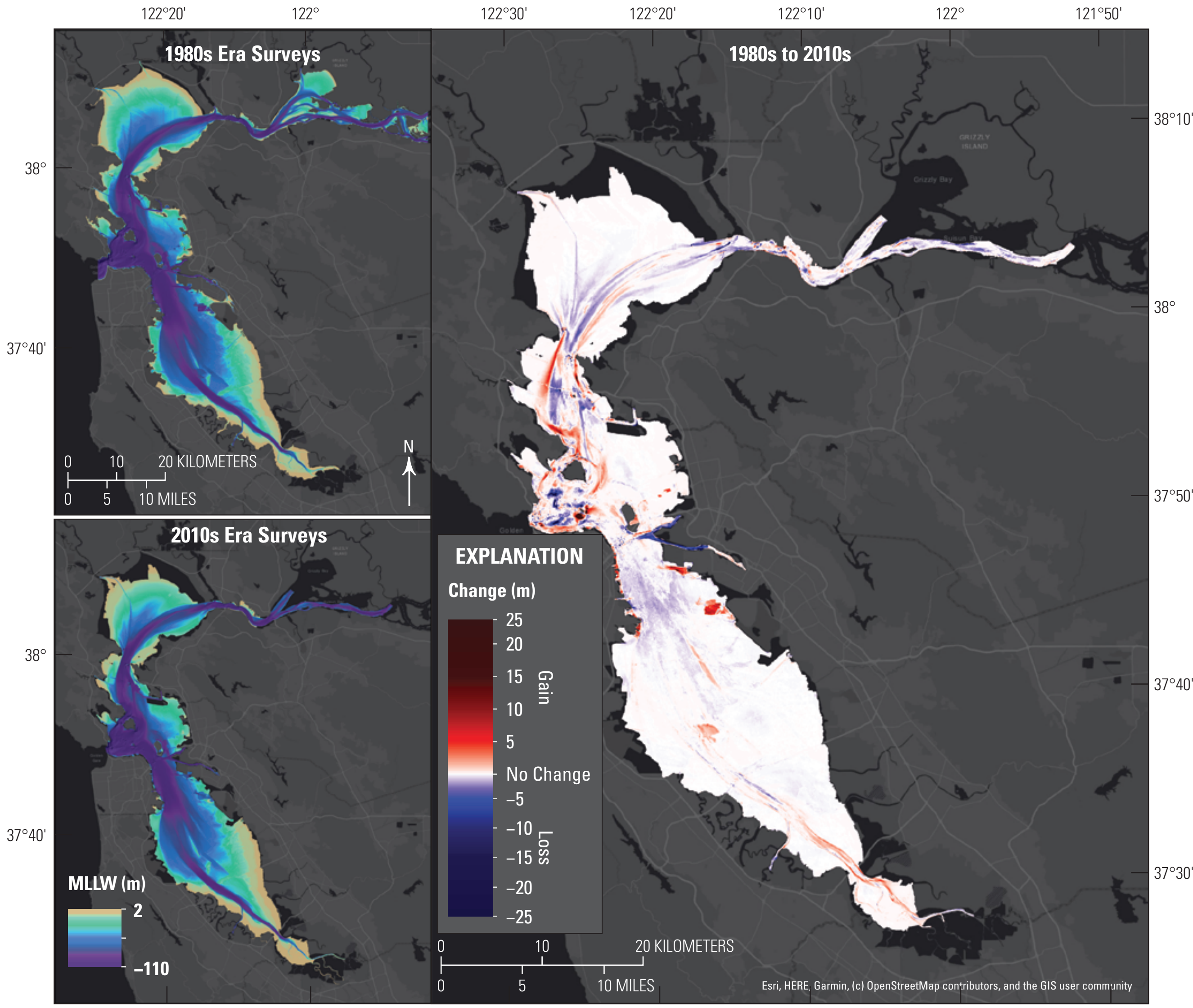

Figure 6. 1980s and 2010s bathymetric digital elevation models (DEMs) (left panels) and bathymetric change from the 1980s to 2010s showing areas of sediment gain and loss (right panel).

gain, 18 Mm^3. However, because these net volume change calculations do not account for the varying timespan between surveys, rate-derived metrics were calculated as well.

The mean rate of rate-derived bed-level change is the average rate of bathymetric change per subembayment when accounting for the varying time spans from the 2010s to 1980s surveys. This rate is largest in Suisun Bay at −2.1 cm/yr, and the smallest in South Bay at −0.1 cm/yr, both are net erosional. The rate-derived volume change rate is simply the mean rate of rate-derived bed-level change multiplied by the area surveyed. The projected volume change from 1983 to 2014, which ranges from −28 to 16 Mm^3 for subembayments and is −34 Mm^3 entire 882 km^2 surveyed, is a simple, illustrative calculation multiplying the rate-derived volume change rate by the fixed number of 31 years.

Table 2 presents the bathymetric change volumes associated with specific uncertainty values, which is calculated as the uncertainty multiplied by surveyed area for each subembayment for 4 and 8 cm. This uncertainty is from systematic error, not random error (see section, “Uncertainty in Bathymetric Change”). The numbers in this table apply for the complete area of each subembayment; they cannot and should not be applied to smaller areas in the subembayments. These numbers will need to be recalculated for each new

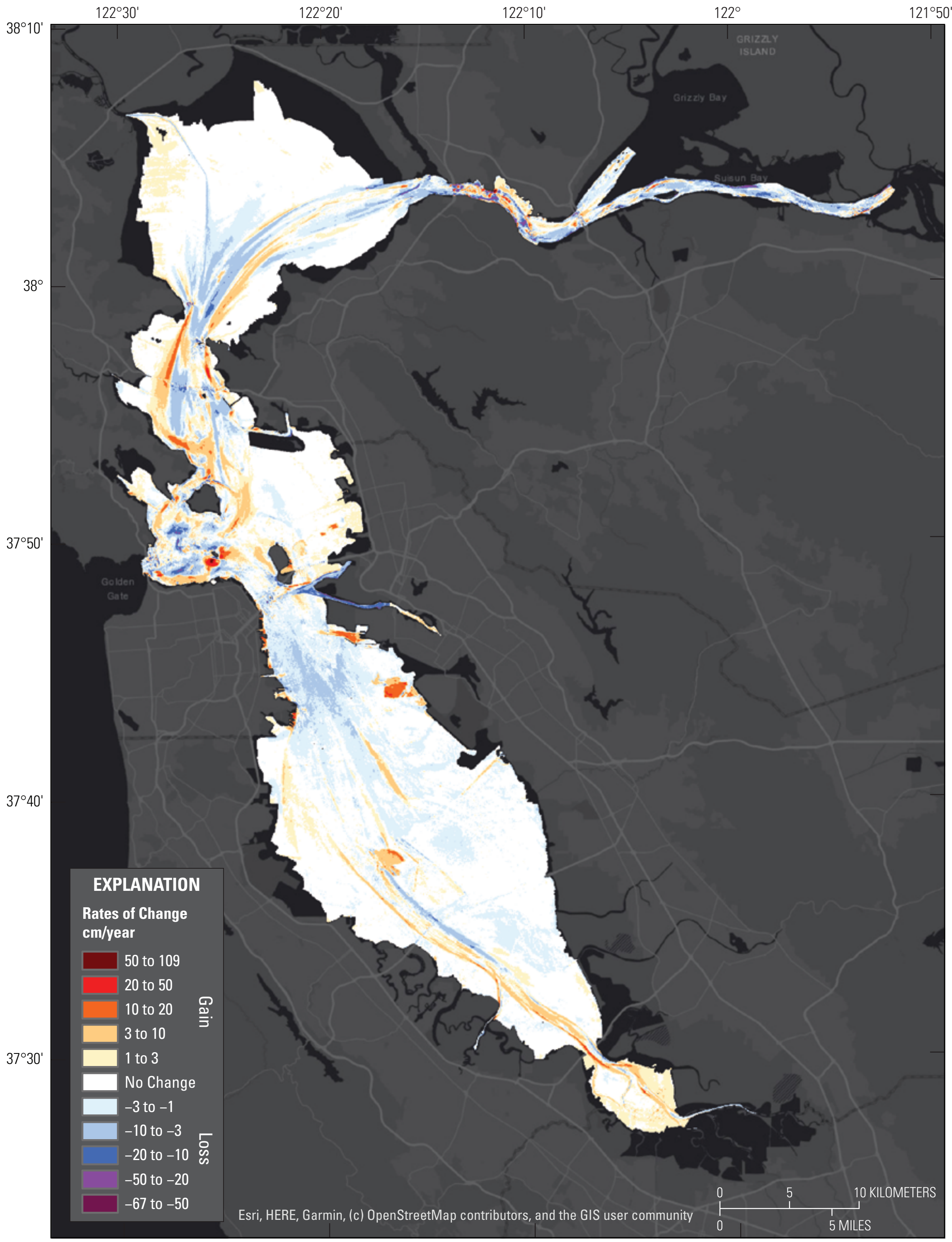

Figure 7. Bathymetric change rates from the 1980s to 2010s.

Table 1. Sediment volume change statistics, 1980s to 2010s.

[Subembayments are shown in figure 1. **Net volume change:** Time between surveys varies spatially in each subembayment. Abbreviations: cm/yr, centimeter per year; km², square kilometer; m, meter; Mm³, million cubic meters; Mm³/yr, million cubic meters per year, NA, not applicable]

Subembayment	Cell size (m)	Survey area (km²)	Total area (km²)	Percentage of subembayment surveyed	Net volume change (Mm³)	Mean rate of rate-derived bed level change (cm/yr)	Rate-derived volume change rate (Mm³/yr)	Projected volume change for 1983–2014 (Mm³)
						Accounts for differences in time between surveys		
Suisun	25	44	107	42	−18	−2.1	−0.91	−28
San Pablo	25	208	275	76	−13	−0.2	−0.44	−14
Central	25	256	295	87	18	0.2	0.52	16
South	50	373	407	92	−8	−0.1	−0.28	−9
Total	NA	**882**	**1,084**	NA	**−20**	NA	NA	**−34**

Table 2. Potential sediment volume change for two examples of varying uncertainty levels from the 1980s to 2010s.

[Subembayments are shown in figure 1. **Net volume change of uncertainty**: Does not account for varying time spans between surveys. Volume change associated with uncertainty: Example only—not a definitive measure of uncertainty for this study; values rounded to million cubic meters. Abbreviations: cm, centimeter; km², square kilometer; Mm³, million cubic meters]

Subembayment	Area surveyed (km²)	Net volume change (Mm³)	Sediment volume change associated with uncertainty (Mm³)	
			4 cm	8 cm
Suisun	44	−18	2	4
San Pablo	208	−13	8	16
Central	256	18	10	20
South	373	−8	15	30

study area of interest. This table is meant to allow end users of the volume change data contained in this report to evaluate bounds on volume changes for the entirety of the bathymetric change grids for Suisun, San Pablo, Central, and South Bays, respectively. For example, if South Bay is thought to have 4 cm of uncertainty in the change values, this results in 15 Mm³ of volume change, which is nearly twice the magnitude of the net volume change, −8 Mm³, measured from the 1980s to 2010s. Therefore, accounting for a 4 cm uncertainty results in a volume change in the range from −23 Mm³ (−8 Mm³ measured − 15 Mm³ uncertainty) to 7 Mm³ (−8 Mm³ measured + 15 Mm³ uncertainty). For values of uncertainty greater than 2 cm, South Bay could be net depositional within error bounds. For San Pablo Bay, uncertainty of 4 cm has less of an impact on the direction of the net sediment volume change. For example, San Pablo Bay is still net erosional at an uncertainty in bathymetric change of 4 cm (measured volume change of 13 Mm³ is still erosional when accounting for 4 cm of uncertainty; 13 ± 8 Mm³). However, an uncertainty value of 8 cm, which equates to 16 Mm³ for the area of San Pablo Bay, allows for a change in sign of the net change in San Pablo Bay from an area losing sediment, −29 Mm³, to an area gaining sediment, +3 Mm³.

Uncertainty associated with systematic error likely varied with location in San Francisco Bay and with the survey. There is not a single value that we are confident characterizes the uncertainty from systematic error. Depending on how the bathymetric volume change data are used determines how conservative the uncertainty level needs to be.

Bathymetric Change from Human Activities

In addition to sediment erosion and deposition from natural processes, San Francisco Bay is directly impacted by human activities such as dredging channels, sediment extraction for development, sand mining, and dredged sediment disposal. A thorough analysis of such activities is beyond the scope of this report; however, their impacts may be significant and possibly be one of the largest influences on change in sediment volume in San Francisco Bay. Examples of different types of human activities that have influenced bathymetric change are shown in figure 8. Five areas are highlighted—a regularly dredged area, a disposal site for dredged sediments, and three sediment borrow areas (areas where sediment is removed from San Francisco Bay for uses such as land fill) of varying ages. The dredged channel along

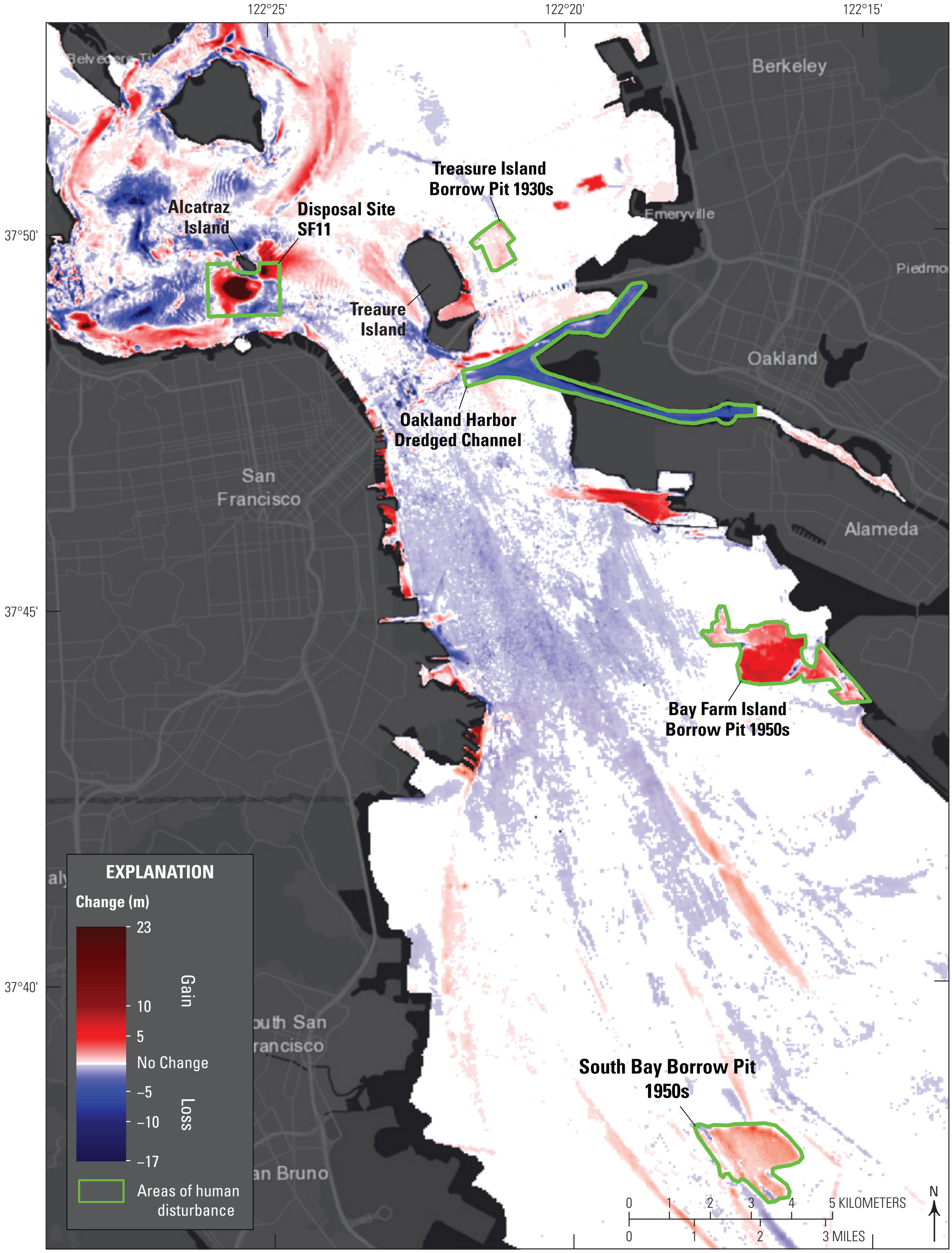

Figure 8. Areas of bathymetric change, with areas of human-induced bathymetric change outlined.

the Oakland Harbor had a net sediment loss of 15 Mm^3. The Oakland Harbor in the early 2000s underwent a major deepening project, so this loss of sediment was not a regular event (Port of Oakland, 2009). The SF11 disposal site of dredged and other sediment-removal projects near Alcatraz Island is defined on the basis of the official boundary, which includes some areas of erosion, and had a net gain of 7 Mm^3. The oldest sediment borrow site in Central Bay highlighted in figure 8, the one from which sediment was taken to make Treasure Island in the 1930s, is still filling in and had a net gain of 1 Mm^3 from the 1980s to 2010s. The site where sediment was extracted for Bay Farm Island in the 1950s shows a net gain of 11 Mm^3. Lastly, the South Bay borrow pit that was present in the 1950s had a net gain of 16 Mm^3 from the 1980s to 2010s. These sites demonstrate the impact of human-induced change and are important to consider when accounting for the sediment balance in the system.

Bathymetric Change from 1950s to 1980s

Net sediment loss from the 1980s to 2010s follows the general erosional trend documented in the 1950s to 1980s volume change analyses, but the volume of sediment loss was less (table 3; Jaffe and others, 1998; Foxgrover and others, 2004; Fregoso and others, 2008). From the 1950s to 1980s, about 200 Mm^3 of sediment loss was from the same area of San Francisco Bay surveyed in the 2010s. This equates to a loss of more than 6 Mm^3/yr, which is a mean rate of bed-level change of −0.7 cm/yr. From the 1980s to 2010s, sediment loss for the study area was just greater than 1 Mm^3/yr, which is a mean rate of bed-level change of −0.1 cm/yr. Table 3 shows the comparisons of mean bed-level change in cm/yr and by net volume change in Mm^3/year by subembayment for the 1950s to 1980s and 1980s to 2010s clipped to the common survey area for all three time periods.

Discussion

How the trends in sediment deposition and erosion measured in this study will be altered in the future by climate change and sea-level rise is a key question. Although the trends observed are comparable to those from the 1950s to the 1980s, the rate of sediment loss in areas surveyed during both periods decreased fourfold from more than 6 million cubic meters per year (Mm^3/yr) approximately 1.1 Mm^3/yr. From the 1950s to 1980s, all four subembayments had a net loss of sediment (table 3). In contrast, only three of the four subembayments had a net loss of sediment from the 1980s to 2010s, with Central Bay gaining 18 Mm^3 of sediment. This comparison should not be mistaken as a whole San Francisco Bay analysis. The volume change comparison excluded much of Suisun Bay and many shallow and intertidal areas because of the limited extent of the 2010s survey. The inclusion of the missing areas in Suisun Bay, Grizzly Bay for one, likely would not change Suisun Bay from being an area of sediment loss; every historical change period for that area has been one of sediment loss (Cappiella and others, 1999). However, for San Pablo Bay, a faint hint of sediment gain exists in the mudflat in this current change analysis, and an even stronger gain closer to shore could have occurred. If so, the certainty that San Pablo Bay lost sediment during this time period is reduced. Nevertheless, this latest analysis of change could be usefully compared to past measurements and estimates of sediment supply that have been published for water years 1995 to 2021 (McKee and others, 2006, 2013; Schoellhamer and others, 2018). To describe how San Francisco Bay will change in the future will require a combination of approaches, including detailed analysis of trends, patterns, and volumes of historical deposition and erosion, forecasts of sediment supply from the Sacramento-San Joaquin Delta and local tributaries (Dusterhoff and others, 2021), and numerical modeling studies of future hydrodynamics and sediment transport that include climate change and sea-level rise.

Table 3. Bathymetric change from 1950s to 1980s and 1980s to 2010s using a common clip area where both change periods have been clipped to a common and (or) equal extent, and the original extents are based on data available from the 1950s to 1980s and the 1980s to 2010s.

[Subembayments are shown in figure 1. Abbreviations: km^2, square kilometer; cm/yr, centimeter per year; Mm^3/yr, million cubic meters per year]

Sub-embayment	Common survey area (km^2)	1950s to 1980s					1980s to 2010s				
		Full survey area (km^2)	Mean rate of rate-derived bed level change (cm/yr)		Net volume change (Mm^3/yr)		Full survey area (km^2)	Mean rate of rate-derived bed level change (cm/yr)		Rate-derived volume change rate (Mm^3/yr)	
			Common area	Full extent	Common area	Full extent		Common area	Full extent	Common area	Full extent
Suisun	42	107	−3.22	−1.42	−1.17	−1.30	44	−2.23	−2.06	−0.94	−0.91
San Pablo	208	275	−0.25	−0.29	−0.51	−0.79	208	−0.21	−0.21	−0.43	−0.44
Central	251	295	−0.61	−0.55	−1.54	−1.62	256	0.21	0.20	0.52	0.52
South	373	407	−0.79	−0.65	−2.93	−2.64	373	−0.07	−0.07	−0.26	−0.28

The sediment volume changes documented in this study will inform a sediment budget for San Francisco Bay. However, because the 2010s surveys did not cover the entire San Francisco Bay, estimates of sediment volume change will have to be made for unsurveyed areas. Previous studies (Jaffe and others, 1998; Foxgrover and others, 2004; Jaffe and Foxgrover, 2006; Fregoso and others, 2008) provide information on trends and patterns of change that can guide these estimates, but with an associated increase in uncertainty.

A potentially useful future analysis is to link sediment losses and gains in San Francisco Bay with changes on land, including alterations of the shoreline (Beagle and others, 2015) and restoration or loss of wetlands (San Francisco Estuary Institute, 2022). San Francisco Estuary Institute (SFEI) has divided the baylands into Operational Landscape Units (OLUs) that help to manage the physical and jurisdictional complexity of the San Francisco Bay shoreline (Beagle and others, 2019). The relation of these OLUs to the bathymetric change documented in this study is shown in appendix 1 (fig. 1.1).

Summary

Bathymetric surfaces generated from surveys made in the 1980s (1971–1990) and 2010s (1999–2020) indicate that San Francisco Bay lost approximately 20 million cubic meters (Mm^3) of sediment from 1971 to 2020. The following are observations made through bathymetric surface change analyses in San Francisco Bay:

1. The rate of net sediment loss in San Francisco Bay in areas surveyed in the 1950s, 1980s, and 2010s decreased from more than 6 million cubic meters per year (Mm^3/yr) for the 1950s to 1980s to less than 1.1 Mm^3/yr for the 1980s to 2010s. Much of Suisun Bay and parts of shallows and intertidal flats in other bays are not included in this estimate owing to the limited extent of the 2010s survey. Therefore, the total bay net sediment volume change will be different than in our analysis because of the exclusion of areas of sediment loss or gain.

2. The patterns of bathymetric change indicate that sediment loss is caused by both natural processes and human activities.

3. Human activities caused the largest depth changes in San Francisco Bay and many millions of cubic meters of sediment gains and losses. These activities are a significant influence on sediment gains and losses in San Francisco Bay.

4. The areas of maximum bathymetric change attributed to natural processes were in regions where channels migrated, widened, or narrowed. Changes associated with channels, both gains and losses, were typically from 1 to 5 meters.

5. The rates of bathymetric change for most of San Francisco Bay were less than 1 centimeter per year for gains and losses. The greatest rates of bathymetric change, more than 1 meter per year, were associated with dredging and dredge disposal.

6. This study underscores that the San Francisco Bay sediment system is dynamic and complex. Bathymetric change, and rates of bathymetric change varied across and in subembayments.

The patterns and volumes of bathymetric change in this study indicate that the delivery, transport, deposition, and erosion of sediment in San Francisco Bay has changed from the 1950s to 1980s and from the 1980s to 2010s. Additional research is needed to fully understand the causes for these changes and to enable accurate forecasts of future change.

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Appendix 1. Operational Landscape Unit boundary extents

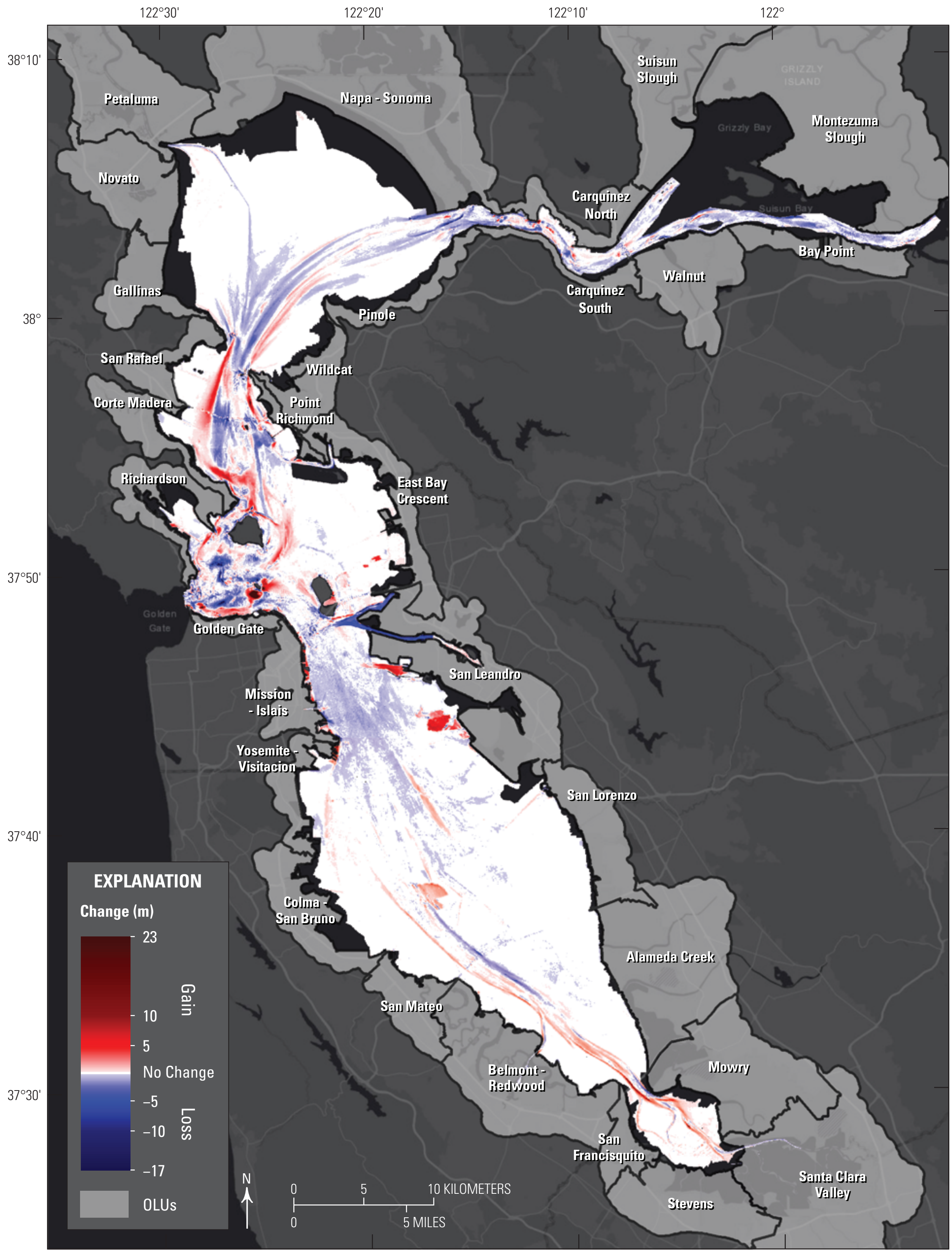

Figure 1.1. Operational Landscape Units (OLUs) and how they correspond with the bathymetric change from the 1980s to 2010s.

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