



Inventory of Coastal Engineering Projects in Golden Gate National Recreation Area

Natural Resource Technical Report NPS/NRSS/GRD/NRTR—2013/734



ON THE COVER

Great Highway Seawall and magnetite-rich sand at Ocean Beach, San Francisco.
Photograph by: Kate Dallas

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Abstract

A reconnaissance-level investigation, analysis and inventory of coastal engineering projects in eight coastal national parks were completed by Oregon State University with funding provided by the National Park Service Geologic Resources Division. The coastal national parks inventoried in this study include:

1. Cape Hatteras National Seashore
2. Colonial National Historical Park
3. Fort Matanzas National Monument
4. Fort Raleigh National Historic Site
5. Gateway National Recreation Area
6. Golden Gate National Recreation Area
7. Olympic National Park
8. San Francisco Maritime National Historical Park

This report includes information on coastal engineering projects identified in, or immediately adjacent to, Golden Gate National Recreation Area (GOGA). The report serves as a supplement to a Geographic Information Systems (GIS) database (the GIS data are available online at <http://irma.nps.gov>).

One hundred and sixteen coastal engineering projects were found in and adjacent to GOGA. Of this total, 94 are coastal structures that together extend 26 km (16 mi). Coastal structures armor roughly 79% of the park's northern San Francisco shoreline from the Golden Gate Bridge to Fort Mason and approximately 46% of the shoreline along Ocean Beach's 7-kilometer (4.3 mi) long beach.

Dredge and fill projects have altered over 5.7 km² (1,400 ac) of submerged and sub-aerial lands within and adjacent to GOGA. The most significant project (by size and volume) is the Main San Francisco Ship Channel, offshore and outside of GOGA. Since 1931, channel dredging has removed nearly 41 million m³ (53 million yd³). Aggregate mining within central San Francisco Bay and on Ocean Beach has removed over 19 million m³ (24 million yd³) of sediment between 1953 and 2008.

Modifications to sediment input combined with coastal engineering projects have changed the natural sediment transport dynamics within San Francisco Bay. These projects have directly affected much of GOGA's 95 km (59 mi) of coastline.

Crissy Field was historically a salt marsh and estuary, and its filled wetlands have contributed to a system-wide trend of ecosystem degradation, habitat loss and tidal prism alteration. Recent efforts have restored this site to a more natural state. However, new hydrodynamic and sediment transport impacts related to tidal impoundment and water quality exist.

Ocean Beach represents a heavily engineered system with a long history of filling, beach and dune nourishment, and hard structure installation. Anthropogenic impacts within San Francisco Bay have changed sediment delivery to the outer coast, impacting the ebb-tidal delta as well as shoreline change rates along Ocean Beach.

Acknowledgments

This research would not have been possible without the help from many different individuals and agencies. Jodi Eshleman, formerly of the NPS, helped establish the project, shared resources, and arranged meetings with local experts. Park staff at GOGA were extremely helpful and shared numerous resources and references. Stephen Skartvedt, Kristen Ward, Tamara Williams, and Steve Ortega accompanied us in the field during our visit and shared great local knowledge. They also helped us to obtain many historic references and answered our numerous questions. Darren Fong provided information on dredging at Fort Baker and Danny Collman shared maintenance information for the O'Shaughnessey Seawall.

Frank Filice, at the San Francisco Department of Public Works, met with us during our visit and shared detailed historical information related to Ocean Beach and the San Francisco Marina. Doug George with ESA PWA shared references on Crissy Field. Patrick Sweetland, of Daly City, provided background information for the outfall structures at Fort Funston. United States Geological Survey scientists, Patrick Barnard and Dan Hoover, met with us to discuss their work at Ocean Beach and shared references and figures. Jessie Burton Evans and Alyssa Moore at the U.S. Army Corps of Engineers provided GIS data of federal channels and dredge disposal areas.

Introduction

The Coastal Engineering Inventory (CEI) project aims to inventory, catalog and map coastal engineering projects in and adjacent to coastal units of the National Park Service (NPS). The primary projects that were inventoried include coastal structures, dredge and fill projects, and beach nourishment and dune construction projects. In this phase of the inventory coastal engineering projects were identified in seven coastal national parks. Prior to this study another report (Coburn et al. 2010) documented coastal engineering projects in ten additional coastal national parks. The report and GIS data are available online at <http://irma.nps.gov>.

In this phase of the NPS CEI project, a qualitative impacts analysis was also performed to help better understand the extent of human-altered coastal areas within each respective park. This section describes the impacts of coastal engineering projects and their influence on natural sediment transport processes. In addition to highlighting major engineering projects that are impacting local and regional sediment transport, we have also included related information pertaining to current park management concerns as expressed during the site visit in February 2012.

Coastal engineering projects are usually motivated by a desire to protect the backshore environment from erosion or alter the coastal zone for a particular purpose (i.e. maintain a navigation channel, develop roadways, or restore wetlands). In order to fulfill project objectives, a suite of engineering solutions are available that are typically categorized into hard and soft engineering projects. Coastal engineering solutions often combine both hard and soft engineering approaches, such as when beaches are nourished following breakwater construction.

Hard engineering solutions include the construction of seawalls, revetments, breakwaters, sills, and bulkheads to protect the backshore from coastal erosion and sometimes flooding (see the Glossary in Appendix A for definitions). Jetties and groins are also classified as hard engineering projects and are used to alter the sediment transport regime by trapping sediment. Impacts from hard structures are highly site dependent, but may include the loss of sediment supplied to downdrift areas, localized scour in front of and at the downdrift end of structures, visual impacts, placement losses, reduction in beach access, and the alteration or reduction of habitat.

Soft engineering solutions include non-structural means of stabilizing the backshore or changing coastal environments through beach nourishment, dune construction, dredging, or filling. These methods add or redistribute sediment within the system and are used to widen sediment-starved beaches, maintain navigable waterways, protect coastal infrastructure, and restore wetlands. As with hard solutions, impacts vary significantly by project and location. Soft engineering projects may impact hydrodynamic and sediment transport processes, beach morphology, aquatic ecosystems, and/or beach habitats.

The overall goal of this project is to develop a greater understanding of the coastal engineering modifications in the National Park System. Along coastlines expected to be impacted by climate change, structurally modified shorelines will likely respond differently than natural coastlines, which may have a more dynamic response to coastal erosion and sea level rise. An inventory of coastal engineering modifications will provide information to allow resource managers to make better decisions about how to preserve NPS resources, establish baselines, develop desired future

conditions, and balance the protection of historic resources and infrastructure with the preservation of natural systems. All of these actions will improve the ability of the NPS to manage coastal park units in accordance with NPS policies. The main NPS policies relevant to coastal engineering projects are summarized below (see *NPS Management Policies 2006* for more detail).

Maintenance of Natural Processes

Generally, NPS policy requires that natural coastal processes in parks, such as erosion, shoreline migration, deposition, overwash, and inlet formation, be allowed to continue without interference (*NPS Management Policies* § 4.8.1.1 2006). The NPS may intervene in these processes only in limited circumstances, such as when there is no other feasible way to protect natural resources, park facilities, or historic properties (*NPS Management Policies* § 4.8.1 2006).

Restoration of Natural Processes

In parks where pre-existing or new activities or structures have altered and/or are currently altering coastal dynamics, ecosystems, tidal regimes, and sediment transport rates, the NPS policy is to investigate, in consultation with appropriate state and federal agencies, alternatives for mitigating the effects of such projects and for restoring natural conditions (*NPS Management Policies* § 4.8.1.1 2006). NPS restoration actions in human-disturbed areas seek to return the area to the natural conditions and processes characteristic of the ecological zone in which the damaged resources are situated, as called for by park management plans (*NPS Management Policies* § 4.1.5 and § 4.4.2.4 2006). An example would be the restoration of shoreline processes.

Park landscapes disturbed by natural events, such as hurricanes, are allowed to recover naturally unless manipulation is necessary to 1) mitigate for excessive disturbance caused by past human effects, 2) preserve cultural and historic resources as appropriate based on park planning documents, or 3) protect park developments or the safety of people. (*NPS Management Policies* § 4.1.5 and § 4.4.2.4 2006).

Construction of Facilities

Generally, the NPS must avoid the construction of buildings, roads, and other development that will cause unacceptable impacts on park resources and values (*NPS Management Policies* § 9.1 2006). Development will not compete with or dominate park features or interfere with natural processes (*NPS Management Policies* § 9.1.1.2 2006). In shoreline areas, this means that new developments will not be placed in areas subject to wave erosion or active shoreline processes unless 1) the development is required by law; or 2) the development is essential to meet the park's purposes, as defined by its establishing act or proclamation, and

- no practicable alternative locations are available;
- the development will be reasonably assured of surviving during its planned life span without the need for shoreline control measures; and
- steps will be taken to minimize safety hazards and harm to property and natural resources (*NPS Management Policies* § 4.8.1.1 2006).

Replacement of Facilities

Park development that is damaged or destroyed by a hazardous or catastrophic natural event will be thoroughly evaluated for relocation or replacement by new construction at a different location.

If a decision is made to relocate or replace a severely damaged or destroyed facility, it will be placed, if practicable, in an area that is believed to be free from natural hazards (NPS *Management Policies* § 9.1.1.5 and § 4.1.5 2006).

Cooperative Conservation

Under NPS policy, park superintendents are required to monitor state government programs for managing state-owned submerged lands and resources within NPS units. When there is potential for such programs to adversely impact park resources or values, superintendents will make their concerns known to appropriate state government officials and encourage compatible land uses that avoid or mitigate potential adverse impacts. When federal acquisition of state-owned submerged lands and resources within NPS units is not feasible, NPS will seek to enter into cooperative agreements with state governments to ensure the adequate protection of park resources and values (NPS *Management Policies* §3.4 2006).

In addition, the NPS has the authority under 36 C.F.R. §1.2(a)(3) to apply general NPS regulations, such as special use permit requirements, on or in waters that are subject to the jurisdiction of the United States, or in areas within their ordinary reach up to the mean or ordinary high water line, even if the submerged lands are non-federally-owned and regardless of whether the park has exclusive, concurrent, or proprietary jurisdiction. Waters subject to the jurisdiction of the United States refers to three types of waters: (1) navigable (as defined in 33 C.F.R. § 2.36(a), (2) non-navigable but located on lands for which the U.S. has acquired title or control and has accepted or retained exclusive or concurrent jurisdiction, and (3) waters made subject to U.S. jurisdiction by certain international agreements and statutes (33 C.F.R. § 2.38).

Methods

Coastal engineering terminology was adapted from the NPS Coastal Engineering Inventory pilot project (Coburn et al. 2010) and through discussion with the NPS Geologic Resources Division. The NPS selected eight coastal national parks in which coastal engineering projects were identified, inventoried and mapped. Projects in the inventory include coastal structures, dredging, filling, beach nourishment, and dune construction.

A digital park boundary shapefile for all of the inventoried parks was downloaded from the NPS Integrated Resources Management Applications Portal (<https://irma.nps.gov>). Georeferenced digital orthophoto imagery was obtained from each park and added to ArcMap 10.0 to create a basemap.

A visual inspection of the orthophoto imagery was completed and locations of all discernible coastal structures were digitized using ArcMap. A site visit to the park, along with staff correspondence, was used to complement and confirm initial findings based on examination of the imagery and to identify other coastal engineering projects. A comprehensive online and hardcopy literature search was undertaken to obtain attribute data for each project (year of construction, material, year of maintenance, cost, lead construction agency, and volume). Unless otherwise specified, costs presented in the report are in project-year dollars.

A coastal engineering project was considered distinct if there was any discernible, physical separation between it and an adjacent engineering project. A series of bulkheads constructed by individual interests, for example, would be classified as one structure as long as no identifiable gaps were observed between them. Some projects, such as dredge projects that place dredge spoil on the beach, serve multiple purposes (i.e., dredging and beach nourishment). In these cases, the primary reason for the project was ascertained and the project was classified accordingly. Projects that occurred repeatedly in one place (e.g. inlet dredging) were counted as one project.

Overview statistics were calculated to summarize the coastal engineering projects within each park. The percentage of shoreline armored by coastal structures was found by totaling the length of bulkheads, breakwaters, groins, revetments, seawalls, and sills and dividing it by the total length of shoreline. Structure length and shoreline length were determined using ArcMap. The structure length used in calculating the percentage of shoreline armored for individual structures was merely the length of the structure. For groin fields (defined here as three or more groins) the length was set as the length of the groin field along the shoreline, while for jetties the width of the mouth of the inlet was used.

An ArcGIS 10.0 file geodatabase for each park was compiled using ArcMap. Each geodatabase includes a park boundary feature class and identified coastal engineering projects separated into three feature classes: 1) coastal structures 2) dredge and fill projects and 3) beach nourishment and dune construction projects. The GIS projects also contain an ArcMap document for data viewing (.mxd), data layer files (.lyr), FGDC-compliant metadata (.xml and .txt), FAQ metadata (.html), a table attribute file (.pdf), and a README file (.pdf). Location information for dredge, fill, beach nourishment, and dune construction projects was often non-existent or vague.

Therefore, not all of these projects are included in the GIS data, and those that are included have only approximate locations.

Results

One hundred and sixteen coastal engineering projects were identified in and adjacent to Golden Gate National Recreation Area (GOGA) (Table 1). Ninety-four coastal structures were found that together span 26 km (16 mi) (Figure 1 & Table 2). Coastal structures along the park's northern San Francisco shoreline, which extends roughly 6 km (3.7 mi) from the Golden Gate Bridge to Fort Mason, armor approximately 79% of the shore. At Ocean Beach, the 7-kilometer (4.4 mi) long beach is roughly 46% armored.

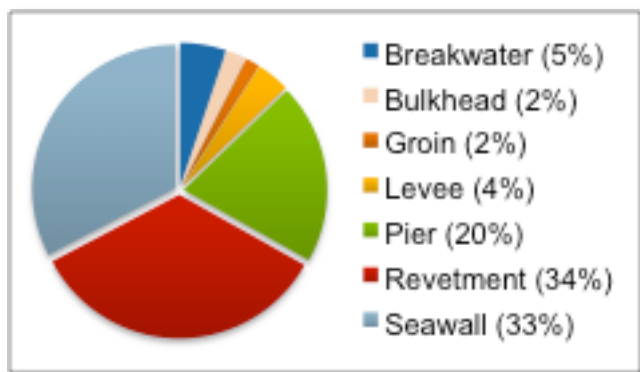


Figure 1. Percent of total length of structures in and adjacent to GOGA (by structure type).

Eight beach nourishment projects placed a minimum of 2.7 million m³ (3.5 million yd³) on park beaches during 17 nourishment episodes from 1872–2012 (minimum because not all projects had volume information). Dredge and fill projects between 1851 and 2011 have disturbed over 5.7 km² (1,400 ac) of submerged and sub-aerial land within and adjacent to the park. A majority of this area (4.9 km² [1,200 ac]), is within the Main San Francisco Ship Channel, which is offshore and outside of GOGA. Since 1931, dredging within the channel has removed over 40 million m³ (53 million yd³) of sediment.

Between 1851 and 1917, roughly 775,000 m² (190 ac) of the park's northern San Francisco shoreline was filled with debris and sand dredged from the Bay. In addition, aggregate mining within central San Francisco Bay and along Ocean Beach has removed over 19.5 million m³ (25 million yd³) of sediment during 103 mining episodes from 1956–2008. Summaries of the coastal engineering projects identified within GOGA are presented in Appendices B–D and Table 1.

Table 1. Coastal engineering projects in and adjacent to GOGA. Numbers in parentheses reflect the number of episodes of the project.

# Coastal Structures	# Beach Nourishment Projects	¹ Beach Nourishment Volume (million m ³)	Beach Nourishment Year	² # Dredge/Fill Projects	³ Dredge/Fill Area (m ²)	Dredge/Fill Year	# Mining Projects	⁴ Mining Volume (million m ³)	Mining Year
94	8 (17)	2,714,527	1872–2012	4 (93)	5,710,000	1851–2011	10 (103)	19,561,428	1953–2008

¹Nourishment volume is a minimum value because not all projects had volume information.

²Dredge/Fill episodes are a minimum value because it is unknown how many episodes of filling occurred along the northern San Francisco shoreline.

³Dredge/Fill area is very approximate. Most of the area (over 4.8 million m²) is offshore of GOGA in the San Francisco Main Ship Channel.

⁴Mining volume is a minimum value because no volumes exist for sand mining at Ocean Beach from 1953–1962, and the volume does not include any aggregate mining that has likely occurred in central San Francisco Bay since 2009.

Table 2. Coastal structures in and adjacent to GOGA. Note, some of these structures overlap.

¹ Structures	Total	Total Length (m)
Breakwater	8	1,351
Bulkhead	3	600
Groin	8	² 416
Levee	1	974
Pier	34	5,300
Revetment	21	8,905
Seawall	19	8,525
TOTAL	94	26,071

¹See Appendix A for structure definitions.

²Groin length does not include the full extent of the Southwest Ocean Outfall Pipe at southern Ocean Beach (#85 Figure 24) or the Vista Grande Outfall at Fort Funston (#88 Figure 24). Only the sub-aerial, beach sections of these outfalls were mapped.

Background

Golden Gate National Recreation Area (GOGA) contains 326 km² (80,624 ac) (NPS 2013a) along the northern coast of California (Figure 2), and includes two additional National Park Areas under its management: Fort Point National Historic Site and Muir Woods National Monument. The park was established in 1972 with the intent of bringing the national park experience to urban residents and is one of the largest urban national parks in the world. Each year 16 to 20 million visitors explore the park, accounting for nearly 50% of all visits to the 29 national parks in California (NPS 2011). GOGA is not one continuous park, but a group of distinct areas, which includes 95 km (59 mi) of bay and ocean shoreline (Figure 2).



Figure 2. Map of GOGA (dark green) and the surrounding public lands (light green) (from NPS 2012).

Setting

GOGA is at the mouth of San Francisco Bay, the largest estuary on the west coast of the United States (Chin and Graymer 2001). The Bay is an urbanized estuary, and with the surrounding area home to over 7 million people, is widely considered to be the estuary most impacted by human activities in the United States (Nichols et al. 1986). Hydraulic gold mining in the Sierra Nevada from 1852–1884 discharged over 350 million m³ (460 million yd³) of sediment into watersheds that drain into San Francisco Bay, dramatically altering the morphology of the Bay (Gilbert 1917). In addition, dredging, aggregate mining, and borrow pit mining have removed large volumes of sediment from San Francisco Bay since the first dredged waterway in 1878 (USACE 1975).

Bathymetric change surveys indicate that over 150 million m³ (196 million yd³) of sand-dominated sediment has been lost in the last 50 years from Central San Francisco Bay, the Golden Gate Inlet, and the ebb-tidal delta (Hanes and Barnard 2007, Fregoso et al. 2008, Barnard and Kvitek 2010). Projects addressed in this report include only those that are located within or adjacent to GOGA. For a more detailed discussion of dredging and mining projects within the greater San Francisco Bay, and their related impacts, see Dallas and Barnard (2011) and Barnard et al. (2013).

The area's geology is complex due its position along the boundary of the North American Plate and the Pacific Plate. The plates move past each other at an average rate of about 5 cm/yr (2 in/yr) (Pendleton et al. 2005). However, earthquakes can cause sudden, large displacements, such as the magnitude 7.7 Great 1906 San Francisco Earthquake that moved the Pacific Plate 6 m (20 ft) to the northwest along the San Andreas Fault (Waldo et al. 1993). Rocks and sediments along the park's coast include chert, pillow basalts, mélanges, volcanic rocks and ash, ocean floor sediments, and sediments actively being deposited as dunes, alluvium, and stream deposits (Chin and Graymer 2001).

The open coast of GOGA is part of the San Francisco Littoral Cell that extends 75 km (47 mi) from Pt. Reyes in the north (~50 km [31 mi] north of the Golden Gate) to Pt. San Pedro in the south (~23 km [14 mi] south of the Golden Gate). Within the cell, alongshore sediment transport is from north to south as a result of the dominant waves approaching from the northwest. Results from sediment transport models and examination of bedform asymmetry around the mouth of San Francisco Bay by Barnard et al. (2013) indicate transport is dominantly seaward at the mouth of San Francisco Bay. However, narrow flood-directed transport does occur from northern Ocean Beach, along Baker Beach, and into the Bay along the northern shoreline of San Francisco (Barnard et al. 2013).

The Golden Gate Bar, a roughly 15 km² (3,700 ac) ebb-tidal delta, lies just offshore of the Golden Gate Inlet (Figure 4). The bar extends about 10 km (6 mi) from east to west and 14 km (9 mi) from north to south and is only 7 m (23 ft) below the surface at its shallowest point. The ebb-tidal delta has a horseshoe shape with a dredged shipping channel across its central crest. Modeling by Barnard et al. (2007) indicates that the delta plays an important role in dissipating and focusing wave energy in the region.

Most of the ocean shoreline within GOGA has experienced long-term (1880–1998) shoreline change rates of -1 to +1 m/yr (-3.3 to +3.3 ft/yr) (Pendleton et al. 2005, Hapke et al. 2006).

However, the shorelines near Stinson Beach, , Fort Funston and Pacifica have experienced higher rates of long-term shoreline recession at -1 to -2 m/yr (-3.3 to -6.6 ft/yr). At Ocean Beach there has been a trend of accretion in the northern and central portions of the beach and erosion in the south since 1997 (Barnard et al. 2007, 2012). Between 2004 and 2010 the shoreline at southern Ocean Beach eroded as much as -5.3 m/yr (-17.4 ft/yr) (Barnard et al. 2012).

Mean significant wave heights in GOGA range between 0.1 and 2.5 m (0.3 to 8.2 ft), reflecting both the sheltered and open ocean shorelines within the park. The open coast is exposed to large Pacific swells, with annual maximum offshore significant wave heights regularly exceeding 8 m (26 ft) (Barnard et al. 2013). Mean tidal range in the park is between 1.1 and 1.3 m (3.6 to 4.3 ft) (Pendleton et al. 2005).

Tides in the region are mixed, semi-diurnal with a maximum tidal range of 1.78 m (5.84 ft) (Barnard et al. 2011). Due to the large surface area of the Bay, the spring tidal prism, which is the volume of water that enters and exits the bay through the Golden Gate Inlet four times a day, is roughly 2 billion m³ (528 billion gallons) (Barnard et al. 2013). The Fort Point tide gauge shows a 2.01 ± 0.21 mm/yr (0.8 ± 0.01 in/yr) rise in sea level from 1897 to 2006 (NOAA 2012), in comparison to the 20th century global average of 1.7 mm/yr (0.07 in/yr) (Church and White 2006).

North of the Golden Gate

Stinson Beach

Stinson Beach is a 6 km (3.7 mi) long spit that separates Bolinas Lagoon from the Pacific Ocean, located roughly 18 km (11 mi) north of the Golden Gate Inlet (Figures 3, 4, 5). Northward-flowing longshore currents have extended the Stinson Beach spit northwestward over time. Winter storm waves frequently inundate the beach, threatening homes built on the spit (Hapke et al. 2006).



Figure 3. Stinson Beach with homes built on stilts on the back beach. View is to the northwest (image by Kate Dallas).

Following the damage or destruction of over 65 homes in the winter of 1982, a 7.5-kilometer (4.7 mi) long revetment was built along the beach just to the north of GOGA (#1 Figure 5) at a cost that exceeded \$525,000 (in 2005 dollars) (Savoy et al. 2005). Since the early 1990s the NPS has maintained the dunes along the southern section of the beach (within GOGA) periodically to store sand that has blown into the parking lot (NPS 2009).

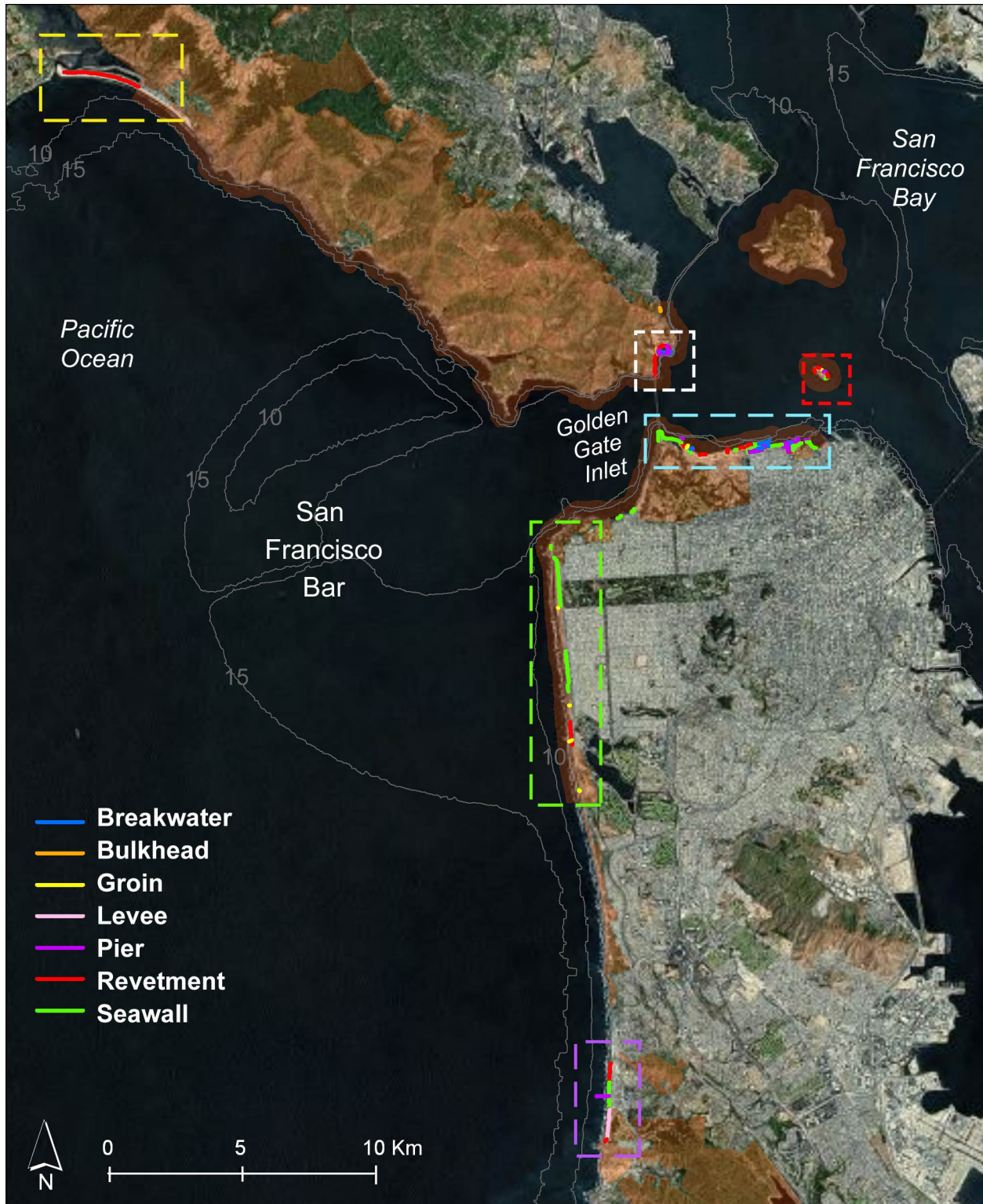


Figure 4. GOGA structure map with the 10 and 15 m bathymetric contours. Orange shading shows park property. Areas enlarged are as follows: Yellow Box (Stinson Beach) in Figure 5, White Box (Fort Baker) in Figure 7, Red Box (Alcatraz) in Figure 11, Blue Box (San Francisco shoreline) in Figure 13, Green Box (Ocean Beach/Fort Funston) in Figure 24, Purple Box (Pacifica) in Figure 31 (image from ESRI Bing Maps basemap layer 2012).



Figure 5. Stinson Beach structure map. Orange shading shows park property (image from ESRI Bing Maps basemap layer 2012).

Fort Baker

Fort Baker is a historic army post located on the north side of the Golden Gate Bridge on Horseshoe Cove. Prior to construction of the fort, the natural harbor had a curving sand beach and brackish marshlands (Figure 6). Fort Baker was built between 1902 and 1910 to provide housing for the soldiers manning the seacoast defense batteries. Requiring more space for the fort, the U.S. Army Corps of Engineers (USACE) filled 28,330 m² (7 ac) of marshland in 1903 with 61,160 m³ (80,000 yd³) of sediment (NPS no date a, NPS 2004).



Figure 6. Horseshoe Cove circa 1905 (from NPS no date a).

The original timber wharf was built in 1867 and repaired or extended in 1893, 1903, and in the 1920s (NPS 2004). In 1937 an L-shaped concrete wharf (#6 Figure 7) was built by the USACE immediately to the north of the older timber wharf in order to load mines during World War II (NPS 2005a). The timber wharf was observed on a 1946 aerial image (Google Earth 2012), but was eventually removed at a later (unknown) date.

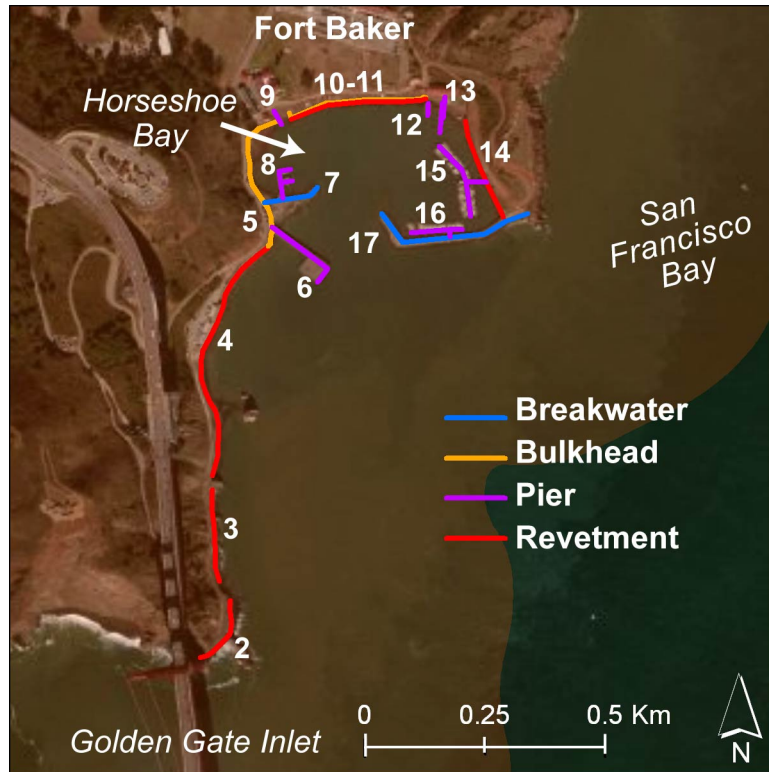


Figure 7. Fort Baker structure map. Orange shading shows park property (image from ESRI Bing Maps basemap layer 2012).

The shoreline within the cove and towards the Golden Gate has been stabilized nearly continuously with bulkheads and revetments (Figure 7). In 1929 a concrete bulkhead was built along the western shoreline by the Quartermaster Department and it was extended eastward along the cove in 1932 (#5 Figure 7) (NPS 2004). A timber bulkhead fronting the Fort was installed in 1942 to stabilize the shoreline, and was repaired and extended in the 1980s (#10 Figure 7 & Figure 8) (NPS 2004). A revetment composed of concrete debris protects the bulkhead and was installed sometime prior to 2000 (#11 Figure 7 & Figure 8).

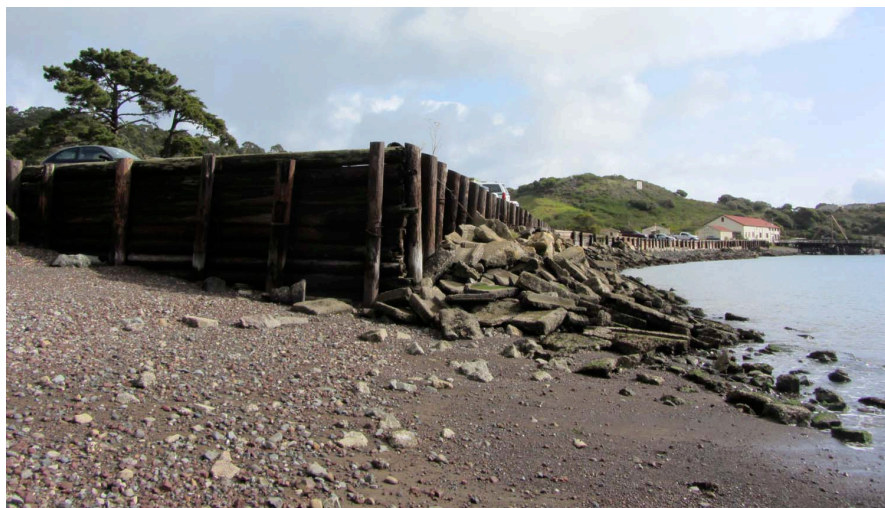


Figure 8. Timber bulkhead and revetment at Fort Baker (#10–11 Figure 7). View is to the northeast.

The concrete boat ramp on the west side of the cove was built in 1958 (#9 Figure 7), followed by a concrete retaining wall west of the ramp in 1960 (east end of #5 Figure 7) (NPS 2004). A concrete block revetment armors the eastern edge of the cove and was constructed sometime before 1987 (#14 Figure 7). Additional rock and concrete debris revetments protect Moore Road as it runs south towards the Golden Gate (#2–4 Figure 7), but no background could be found on their history.

Two rock breakwaters provide shelter within the cove. The Moore Breakwater (#7 Figure 7) was constructed between 1937 and 1945 and was widened by the U.S. Coast Guard in the 1990s (NPS 2005a). The 237-meter (778 ft) long Satterlee Breakwater (#17 Figure 7 & Figure 9) was built in 1943 by the Army, and was improved and repaired from 1951 to 1984 (NPS 2004).



Figure 9. The Satterlee Breakwater and the Ft. Baker wharf (right middle) (#6 & #17 Figure 7) in front of the Golden Gate Bridge. View is to the southwest (image by Kate Dallas).

Two piers are present within the cove at the Travis Marina. The eastern pier was originally used to access a refueling dock and was built in 1937 (#13 Figure 7) (NPS 2004). The western pier was installed between 1943 and 1946 and served as a marine hoist (#14 Figure 7) (NPS 2004). This pier is no longer connected to land and is in poor condition. The marina's boat docks were installed circa 1969 (#15–16 Figure 7) (NPS 2005a).

The U.S. Coast Guard has operated its Golden Gate station out of Horseshoe Cove since 1990 when it moved the station from Fort Point (USCG 2012). The Coast Guard constructed the pier and floating docks on the west side of the cove in 1988 (#8 Figure 7) (NPS 2004).

North of Fort Baker, just inside GOGA, is a 380-meter (1,247 ft) long concrete bulkhead (Figure 4) at the Sausalito-Marin City Sanitation District's Wastewater Treatment Plant. The plant is on a NPS easement and treats NPS influent in exchange (Cola 2007). Historic imagery from Google Earth shows the plant and bulkhead were constructed sometime between 1946 and 1987.

Alcatraz

Alcatraz Island is a 0.09 km² (22.5 ac) island (Figure 10) that has been used as a Civil War military fortification, army post, military prison, federal prison, abandoned federal land, Native American occupation, and in its current use, as a National Park (NPS 2005b). The federal prison closed in 1963 and the island opened to the public ten years later as the first unit of GOGA (NPS 2005b).



Figure 10. Alcatraz Island viewed from the southeast end of the island. The southern seawall and revetment (#24–25 Figure 11) are visible on the left and the ferry pier (#23 Figure 11) is in the middle right of the image (image by Kate Dallas).

The landscape of the island has been significantly modified through blasting and filling (Kleinfelder 2011). The island was altered in order to build roads, create a large plateau on top of the island, construct batteries, and create terraces (NPS 2005b). Rock that was excavated during construction was used for fill on the island or was deposited over the cliffs, extending the island's shoreline (NPS 2005b). Significant amounts of fill are present on the north and south ends of the island, on the northeast side, and within the area previously known as Pirates Cove (near #19 Figure 11). Based on an assessment of historic topographic data, Kleinfelder (2011) reports that Pirates Cove and the south end of the island may have been filled with over 12 m (40 ft) of material.

The island is accessed by ferry with its dock facility located on the southeast end of the island (#24 Figure 11). The original timber dock was built in 1854 and was repaired and modified over time, including documented work in 1884 and 1887 (NPS 2005b). In 1907 the pier was reinforced with steel and in 1934 the Bureau of Prisons installed a concrete dock (NPS 2001). Recently, the dock pilings were repaired in the 2000s (NPS 2001).

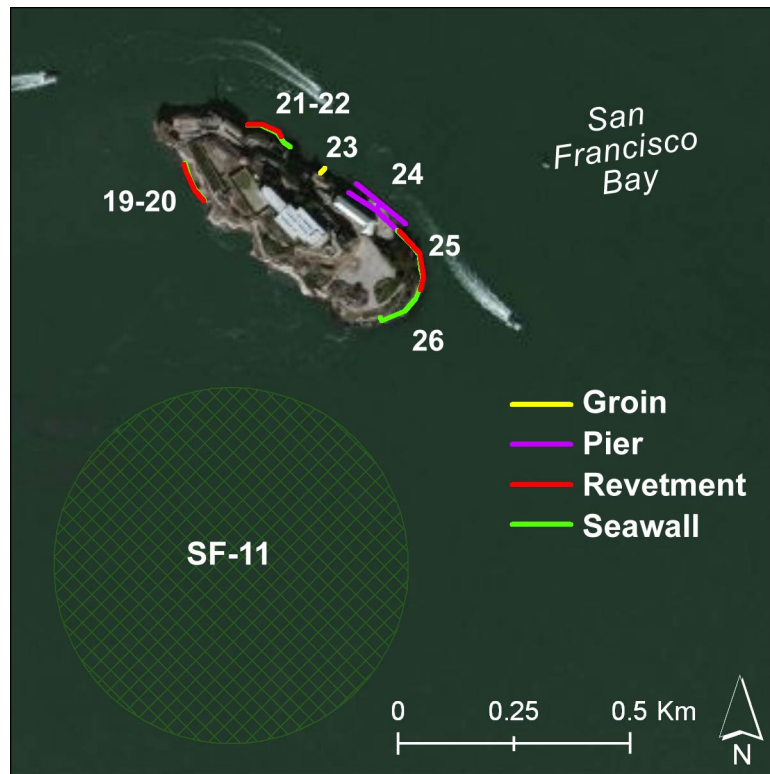


Figure 11. Alcatraz Island structure map and location of SF-11, a federal dredge disposal site (image from ESRI Bing Maps basemap layer 2012).

Three seawalls exist on the northwest, northeast, and south sides of the island (#19, 21, 26 Figure 11). The northeastern and southern seawalls (#21 & 26 Figure 11) were built during the military prison era from 1907 to 1933 as part of the Perimeter Sentry walk, a path that encircled the island (NPS 2005b). The southern stone seawall was built circa 1920s and is nearly 700 m (2,300 ft) long. The northeastern seawall is made of concrete (Figure 12) and was improved in 1937 (Bishop 2010).

The northwestern concrete seawall and fronting rock revetment (#19–20 Figure 11) were installed to stem erosion after a severe storm in 1935 (Bishop 2010). Concrete piles and debris were placed on top of the seawall's southern end in 1997–1998 to mitigate a slope failure (Kleinfelder 2011). A pier used to ship rock quarried on the island existed in this location until 1937 when it was demolished by the Bureau of Prisons (Bishop 2010).



Figure 12. Northeast seawall and revetment on Alcatraz Island (#21–22 Figure 11) (image by Kate Dallas).

On the eastern side of the island a submerged, concrete structure extends roughly 40 m (130 ft) perpendicular to the shore (labeled as a groin, #23 Figure 11). No background information could be found on this structure.

Following the establishment of aquatic bay disposal sites in 1972, most of the material dredged within the Bay was placed at the disposal site southwest of Alcatraz Island (SF-11, Figure 11), based on the false expectation that tidal currents would carry the material out to sea (Chin et al. 2004). Instead, a mound of sediment grew and rose to within 10 m (33 ft) of the water surface in 1997, creating a navigational hazard (Chin et al. 2004).

Northern San Francisco Shoreline

The northern San Francisco shoreline of GOGA stretches from Fort Point in the west to Fort Mason in the east (Figure 13). Nearly the entire northern San Francisco shoreline of GOGA is composed of fill placed in the mid-late 1800s and early 1900s. This area of the park is highly developed, with coastal structures armoring roughly 75% of the shoreline from Fort Point to Fort Mason.

Fort Mason

Filling of submerged land from 1909–1912 at Lower Fort Mason created 0.05 km² (13 ac) of reclaimed land for buildings, piers, and rail access (ARG 2009). A concrete seawall was built at the same time around the area to maintain the fill (#29 Figure 13) (ARG 2009) and was armored with revetment along its western side at a later date (Figure 13). The three concrete piers at Lower Fort Mason (#30–32 Figure 13, Figure 14) were built in 1912 as part of the Army’s shipping center, and later served as the San Francisco Point of Embarkation during World War II (Hoke and Foulds 2004). Piers 2 & 3 (#30–31 Figure 12) were extended in 1933 (Hoke and Foulds 2004) and Pier 2 was retrofitted to withstand earthquakes and repaired from 2002–2004 (ARG 2009).



Figure 13. San Francisco structure map. Area in orange box is enlarged in Figure 16. Orange shading shows GOGA property and blue shading shows the boundary of the San Francisco Maritime National Historical Park (image from ESRI Bing Maps basemap layer 2012).



Figure 14. Fort Mason's Pier 1, seawall, and revetment (#29, 32, 33 Figure 13). Piers and a breakwater (middle left) in the San Francisco Marina's East Harbor are also visible (#35, 40, 41 Figure 13). View is to the north (image by Kate Dallas).

Pier 4 (#28 Figure 13), sometimes called the Alcatraz Pier, was built by the city of San Francisco in 1931 and used by the Army as a supply and transport dock (Hoke and Foulds 2004). After 1934, the concrete and timber pier was used to transport prisoners to Alcatraz (Hoke and Foulds 2004). The curving Municipal Pier, located to the east of Pier 4 (Figure 13), was also built in 1934 and is part of the San Francisco Maritime National Historical Park (SAFR). (For more information on the coastal structures in SAFR see the SAFR Coastal Engineering Inventory report, available at <http://irma.nps.gov>.)

A concrete seawall begins behind Pier 4 (#27 Figure 13) and continues southeastward into SAFR's Aquatic Park. The original seawall was built in 1931 when Van Ness Avenue was extended northward (NPS 2010a). Works Progress Administration (WPA) laborers built the current concrete and stone seawall between 1931 and 1933, removing the original 1931 seawall (NPS 2010a).

Panama-Pacific International Exposition Fill

Historically, the northern San Francisco coast had an irregular, marshy shoreline and a shallow bay called Marina Cove (Figure 15) (Bonilla 1991). Filling occurred along the northern San Francisco shoreline between 1869 and 1917, primarily in 1912 in preparation for the 1915 Panama-Pacific International Exposition that celebrated the completion of the Panama Canal (Figure 15) (Bonilla 1991). Fill placed from 1869 to 1906 likely included beach sands and debris from the 1906 earthquake and fire (Bonilla 1991). To accommodate the exposition, 0.7 km² (184 ac) were filled in 1912 with 1.3 million m³ (1.7 million yd³) of fill (70% sand and 30% mud) mined from Presidio Shoal at a cost of \$302,000 (Markwart 1915).



Figure 15. Comparison of nautical charts of the northern San Francisco shoreline in 1869 (top) and 1915 (bottom) illustrate the significant filling that occurred during this time period (from U.S. Coast Survey (1869) and U.S. Geological Survey (1915)).

San Francisco Marina

The James Fair Seawall was completed in 1894 to contain the newly placed fill by dumping rock from a railroad trestle (Bonilla 1991). The rock seawall was ultimately replaced with a concrete seawall (#43 Figure 13 & Figure 16) that was constructed in phases until 1938. The seawall was extended an additional 335 m (1,100 ft) to the west of Scott Street in 1934 by WPA laborers (Treadwell & Rollo 1997, SFPD 2007). The 1934 addition is commonly referred to as the Marina Boulevard Seawall and is composed of concrete with a basalt rock facing. Today the Fair & Marina Boulevard Seawalls extend seamlessly for 1,890 m (4,230 ft) from the East Harbor to the St. Francis Spit (Figures 13 & 17).



Figure 16. James Fair Seawall along the Marina Green (#43 Figure 13). View is to the southwest (image by Kate Dallas).

The San Francisco Small Craft Yacht Harbor (also called the San Francisco Marina) has over 700 boat slips in two harbors, West Harbor and East Harbor (also known as Gashouse Cove) (Figure 13). The West Harbor was developed for the 1915 Panama-Pacific Fair and expanded in the late 1920s with construction of an outer breakwater (the western side of the spit), extended seawall (including the western mole (large stone structure), labeled as a breakwater [#47 Figure 17]), revetment on the inside harbor, and harbor dredging (SFPD 2007). These original structures were eventually removed or incorporated into later construction projects at the marina.

The St. Francis Spit (Figure 17) was filled during the early 1900s through the 1930s (SFPD 2007). A seawall surrounds the spit (#53 Figure 17 & Figure 18) and was likely constructed near the end of filling in the 1930s. The spit was extended in 1958 by the Recreation and Park Department with construction of the 335-meter (1,100 ft) long rubble breakwater (#60 Figure 17 & Figure 18), changing the location of the harbor entrance (SFPD 2007). The Scott St. mole (labeled as a breakwater, #46 Figure 17), is a remnant of the pre-1958 breakwater that served as part of the earlier entrance channel. A 138-meter (453 ft) long rock revetment was built in front of the St. Francis Yacht Club building circa 1940 and was recently repaired (#61 Figure 17) (Frank Filice, SFDPW, email, 2-22-13).



Figure 17. West Harbor structure map (image from ESRI Bing Maps basemap layer 2012).



Figure 18. St. Francis Spit seawall and rubble breakwater (#53, 60 Figure 17). View is to the east (image by Kate Dallas).

The East Harbor was created by the Recreation Park Department between 1964 and 1966 (#34–42 Figure 12), and the seawall and piers in the West Harbor were also repaired at the same time (SFPD 2007). Historic nautical charts from NOAA (2012) show that the eastern end of sheet pile and concrete East Harbor breakwater was initially detached from the shore, and that it was connected to the shore in the mid 1970s.

The current marina structures in both harbors have existed in their present configuration since 1963 (SF Marina 2013). The West Harbor has required periodic maintenance dredging to prevent shoaling. Between 1994 and 2012 nearly 394,000 m³ (515,000 yd³) was dredged from the West

Harbor's berthing areas, entrance channel, and outer jetty (Table 3). The West Harbor was likely dredged periodically before 1994, but no records were found. The East Harbor was dredged in 1994 (Table 3, exact volume unknown), but no further records of dredging could be found.

Table 3. Dredging data for the San Francisco Marina.

Year	Volume (m³)	Area	Source
1994	38,228	West & East harbors	SFPD 2009
1995	19,114	West Harbor Entrance Channel	SFPD 2009
1996	15,291	West Harbor	SFPD 2009
1997	38,228	West Harbor	SFPD 2009
1998	74,926	West Harbor	SFPD 2009
1999	34,634	West Harbor & Entrance Channel	SFPD 2009
1999	38,228	West Harbor Outer Jetty	SFPD 2009
2000	12,004	West Harbor Entrance Channel	SFPD 2009
2001	10,704	West Harbor Outer Jetty	SFPD 2009
2004	19,114	West Harbor Outer Jetty	SFPD 2009
2005	3,364	West Harbor Entrance Channel	SFPD 2009
2005	5,413	West Harbor Outer Jetty	SFPD 2009
2010	27,753	West Harbor	Frank Filice (SFDPW)
2011	50,007	West Harbor	Frank Filice (SFDPW)
2012	6,881	West Harbor	Frank Filice (SFDPW)
TOTAL	393,889		

The City of San Francisco began a \$38 million renovation project in April 2011 that will include installation of two new breakwaters, revetment repair, dock removal and repair, and harbor dredging. Maintenance dredging associated with the renovation project occurred in the West Harbor in summer 2010 and summer 2011 (SF Marina 2013). The exact volume of sediment dredged is unknown, but proposed dredging called for the removal of roughly 66,500 m³ (87,000 yd³) from the West Harbor (not included in Table 3) (SFPD 2007). Dredging of 71,870 m³ (94,000 yd³) from the East Harbor was also proposed, but as of February 2013, this project is still in the pre-planning phase (Frank Filice, SFDPW, email, 2-22-13).

In 2011, a 56-meter (185 ft) long steel sheet-pile breakwater was installed in the West Harbor (#44 Figure 17). The breakwater was built offset from the seawall to avoid construction impacts to the historic Fair Seawall and enhance current circulation (Coast & Harbor Engineering 2010).

Crissy Field

Crissy Field was originally a 0.5 km² (130 ac) salt marsh and estuary and was used as a dumping ground when the U.S. Army took control of the Presidio army base in 1846 (NPS 2013b). Diking and filling began in the 1870s (Boland 2003) and from 1912 to 1915 roughly 305,800 m³ (400,000 yd³) of sand dredged from the Bay was pumped onto 0.5 km² (114 ac) of shoreline in preparation for the Panama-Pacific Exposition (Markwart 1915). By 1916, the once irregular shoreline had been filled and straightened (Figure 19). After the Exposition the army used Crissy Field as an airfield intermittently to 1974. When the NPS took control in 1994, 0.3 km² (70 ac) were covered with asphalt and hard-packed dirt and most of the shoreline was lined with rubble (Boland 2003).

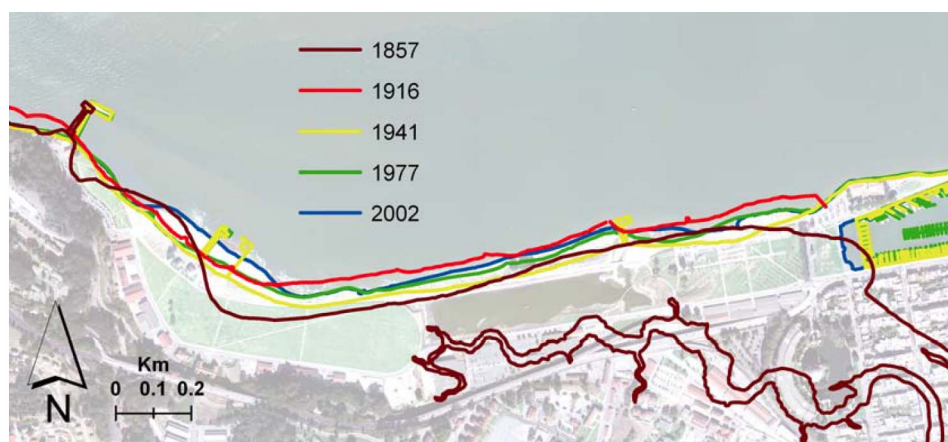


Figure 19. Shoreline change along Crissy Field from 1857 to 2002 (from Dallas 2009).

Beginning in the 1990s, Crissy Field was restored into an urban park. In 1998, about 175,850 m³ (230,000 yd³) of soil and rubble was removed from the site to restore 0.08 km² (20 ac) of tidal salt marsh (Porter 2003). In November 1999 an entrance channel was dug, connecting the marsh to San Francisco Bay. The restoration project also included the removal of rubble from the beach and restoration of the dunes. The \$32 million restoration project was managed and funded by the Golden Gate National Parks Association of San Francisco in cooperation with GOGA (Porter 2003).

Circa 2000, 1,910 m³ (2,500 yd³) of sand was placed on East Beach (Figure 13) (Porter 2003). A low, roughly 170 m (558 ft) long seawall was built under the sand using concrete highway barriers in December 2000 (#64 Figure 13) (Porter 2003). The seawall fronts a low, concrete seat wall that was built in 1998 or 1999 as a place for visitors to sit (Figure 20A). A rock revetment is also present on the east end of the beach (#63 Figure 13), but its installation date is unknown.



Figure 20. Crissy Field's (A) seat wall and location of buried (i.e. non-visible) concrete seawall and (B) rock groin (#64–65 Figure 13) (images by Kate Dallas).

The marsh channel regularly migrates and sometimes closes completely. From May 2001 to January 2013 the entrance channel closed approximately 55 times (Hanes et al. 2011, Kristen Ward, NPS, email, 4-26-13). During this period the channel usually re-opened naturally, but mechanical excavation was required 19 times (Hanes et al. 2011, Kristen Ward, NPS, email, 4-26-13). At the mouth of the marsh inlet there is a concrete storm drain (age unknown) and a rock groin that was placed circa 1999 on top of the drain to stabilize the marsh channel (#65 Figure 13 & Figure 20B). Moving westward, there is some broken concrete riprap located in the central, narrow region of the beach (labeled as a revetment, #67 Figure 13). Erosion in this location in the winter of 2002–2003 motivated the installation of the riprap in 2003 (Kristen Ward, NPS, email, 2-13-13). Prior to Crissy Field's restoration project, much of the shoreline was littered with rubble, and riprap may have existed in this location before the clean up in 1998–2000.

The original Fort Point Lifeboat Station was built east of the current station in 1890 and moved in 1915 to the west end of Crissy Field for the Panama-Pacific International Exposition (NPS 2006a). A timber bulkhead was constructed seaward of the new site in February 1915 and replaced with a concrete seawall (#69 Figure 13) circa 1935 (NPS 2006a). The timber pier fronting the historic Lifeboat Station (#68 Figure 13) is home to the San Francisco tide station, the oldest continually operating tide gauge in the United States. The pier was built from 1915–1919, and in 1928 the buoy house and tide gauge house were added and the pier was reduced in width (NPS 2006a). The pier was repaired by NPS in 2003 (Kristen Ward, NPS, email, 3-26-13).

The timber breakwater to the north of the pier (#70 Figure 13) was built in 1938 to provide shelter to the Coast Guard operations (NPS 2006a). Northward of the breakwater is a concrete ramp (labeled as a groin, #71 Figure 13) that is usually buried in the beach. The seaplane ramp was built in 1921 by the Army and connected the bayshore with the aircraft hangers at Crissy Field (Haller 1994). This section of beach has experienced a significant increase in width in recent years, with shoreline accretion of +8.4 m/yr (+28 ft/yr) measured between 1993 and 2000 (Erikson et al. in review).

The concrete Crissy Field Fishing Pier, also known as Torpedo Wharf, is 115-meters (377 ft) long with an L-shape that is 60 m (197 ft) long (#73 Figure 13). Bishop (2012) documents that a pier has existed in this location since 1854. Torpedo Wharf was constructed in 1907–1910 at a cost of \$6,782 and was originally used to load submarine mines (Thompson 1997, Bishop 2012). In 1943 the wharf was rebuilt of reinforced concrete (Bishop 2012).

Fort Point

Fort Point was built between 1853 and 1861 by the U.S. Army Engineers as part of a system of forts that protected San Francisco Bay during the California Gold Rush (Martini no date, NPS 2013a). Fort Point National Historic Site was established in 1970 and is administered by GOGA (Martini no date).

The Fort Point Seawall extends for nearly 1,120 m (3,670 ft) from southwest of the fort to past Torpedo Wharf (#74 Figure 13 & Figure 21). The seawall was built in stages between 1861 and 1933 and has been repaired numerous times (Table 4). From roughly 1861 to 1869 a 610 m (2,000 ft) long granite seawall, called the DeRussy Seawall, was completed around the tip of Fort Point at a cost of \$400,000 (Martini no date, Bearss 1973, Bishop 2012). A second seawall, named after Major Elliot, was built adjacent to the DeRussy Seawall and extended the seawall an additional 183 m (600 ft) to the east.

Further eastern extensions were made in 1909, 1915, and 1933 (Bishop 2012). To preserve the Fort's seawall, the northern and western portions of the wall were dismantled, stored, and rebuilt during construction of the Golden Gate Bridge in the mid 1930s (NPS 2006b, Bishop 2012). Various sections of the seawall were repaired in 1963, 1979, and in the 1980s (Table 4). Revetment was added to the front of the seawall beginning as early as 1870 (NPS 2006b). In the 1980s the NPS rebuilt the wall and placed rock revetment seaward (#71 Figure 13) to deflect wave energy (NPS no date c).

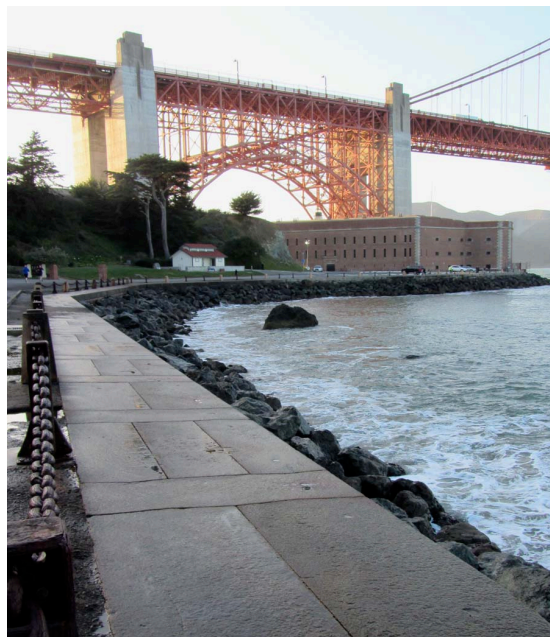


Figure 21. Fort Point's seawall and revetment (#71–72 Figure 13) adjacent to the Golden Gate Bridge. View is to the northwest (image by Kate Dallas).

Table 4. History of the Fort Point Seawall.

Description	Length (m)	Year	Project-Year Cost	Source
DeRussy Seawall built	610	circa 1861–1869	\$400,000	NPS (2006)
Elliot Seawall built	183	1860s		Bishop (2012)
Revetment added	216	1870	\$18,000	Bishop (2012)
Seawall repair		1890		NPS (2006)
Seawall extended	173	1909		NPS (2006)
Seawall extended	252	1915		Bishop (2012)
Seawall extended	38	1933		Bishop (2012)
Seawall rebuilt – north and west sections		1933		Bishop (2012)
Seawall repair		1963		Bishop (2012)
Seawall repair – east portion	207	1979	\$217,854	NPS (2006)
Revetment and seawall repairs		1983	\$118,000	NPS (2006)
Revetment added for entire seawall		1984	\$800,000	NPS (2006)
Seawall repair	27	1984	\$162,832	NPS (2006)
Seawall repair – east portion		1985	\$518,955	NPS (2006)
Revetment and seawall repairs		1988	\$564,670	NPS (2006)
Seawall repair – west portion		1988	\$30,188	NPS (2006)

Aggregate Mining

Coarse sand and gravel have been permanently removed from central San Francisco Bay for use as construction aggregate. Aggregate mining began in the 1930s and continues within designated lease areas of the bay. Within these areas, sand and gravel are removed from the bay floor with a suction pump lowered from a hopper barge. In central San Francisco Bay, a total of over 19 million m³ (25 million yd³) of sediment has been removed from 1978–2008 during 98 mining episodes (Table 5 & Figure 22) (Dallas 2009).

Table 5. Central San Francisco Bay aggregate mining data. See Figure 22 for mining lease locations (from Dallas 2009).

Shoal	¹ BCDC Lease #	Year	Episodes	Volume (m ³)
Presidio, Alcatraz, & Point Knox shoals	709 N, S, E,	1978–2008	31	9,987,100
Point Knox Shoal	2036	1980–2008	29	4,462,450
Alcatraz Shoal	5871	1995–2008	14	586,166
Point Knox Shoal	7779 N, E, W	1995–2004	14	3,616,806
Alcatraz Shoal	7780 N, S	1999–2008	10	832,896
TOTAL			98	19,485,418

¹San Francisco Bay Conservation and Development Commission (BCDC) lease numbers.

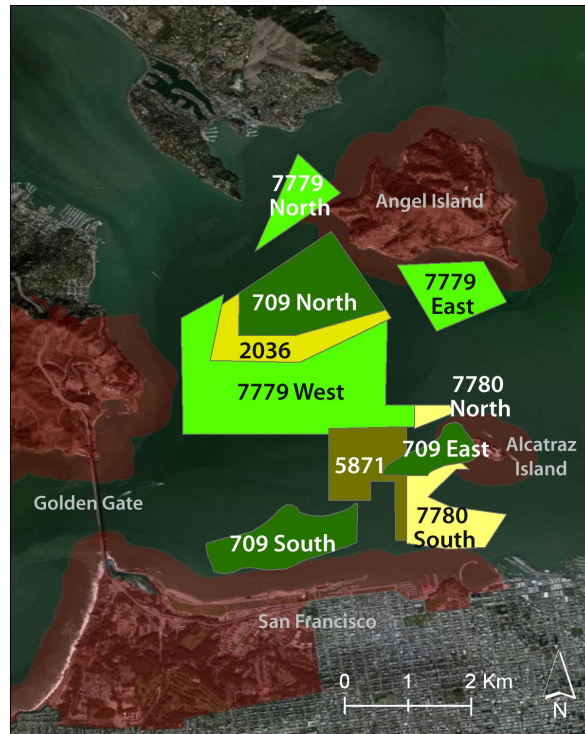


Figure 22. Location of mining leases in central San Francisco Bay. Red shading shows park property (image from ESRI Bing Maps basemap layer 2012).

Baker Beach & China Beach

Baker Beach and China Beach lie on the northwest coast of San Francisco facing the Golden Gate Inlet (Figure 24). Modeling results by Barnard et al. (2013) demonstrate that Baker Beach and China Beach are fed with sediment that is transported around Pt. Lobos from northern Ocean Beach. Recent shoaling inside the San Francisco Bay at Crissy Field and the West Harbor entrance further indicate that these beaches may be pathways for sediment feeding the northern shoreline of San Francisco (Barnard et al. 2007).

The very southern end of Baker Beach has a low, concrete seawall that protects a sloping hillside with private homes (#75 Figure 24). At China Beach, a tall concrete seawall constructed circa 1951 armors nearly the entire beach (Figure 23 & #76 Figure 24).



Figure 23. China Beach seawall (#76 Figure 24) (image by Kate Dallas).



Figure 24. Baker, China, and Ocean Beach structure map. Orange shading shows park property. Groin #85, the Southwest Ocean Outfall pipe, extends 7.2 km (4.5 mi) offshore (not shown) and Groin #88, the Vista Grande Outfall, extends 762 m (2,500 ft) offshore (not shown) (image from ESRI Bing Maps basemap layer 2012).

Sutro Baths

To the north of Ocean Beach lie the ruins of the Sutro Baths, an extravagant bathhouse that opened in 1895 and was destroyed by fire in 1966 (NPS no date d). The concrete and rock seawall and fronting rock revetment (#77–78 Figure 24 & Figure 25) were built in the fall of 1889 by Adolph Sutro (NPS 2005c).



Figure 25. Sutro Baths' ruins with its concrete and rock seawall and revetment (#77–78 Figure 24). View is to the south (image by Kate Dallas).

Ocean Beach

Ocean Beach is a 7 km (4.4 mi) long sandy beach located south of the Golden Gate Inlet (Figure 2). Historically, this area had a wide dune field that stretched eastward toward downtown San Francisco. Today, roughly 46% of the beach is armored by coastal structures. Construction of the Great Highway in the late 1800s and early 1900s moved the shoreline seaward roughly 61 m (200 ft) (Moffat & Nichol 1995). The southern portion of the beach has been eroding for decades (Hapke et al. 2006), with a recent mean shoreline retreat of -1.1 m/yr (-3.6 ft/yr) from 1997 to 2007 (Barnard et al. 2007). Between 2004 and 2010 areas of the southern shoreline eroded by as much as -5.3 m/yr (-17.4 ft/yr) (Barnard et al. 2012).

Since 1997 there has been a pronounced trend of accretion in the northern and central portions of the beach and erosion in the southern portion (Barnard et al. 2007). Between 2004 and 2012, the mean beach width at the north end of the beach exceeded 160 m (525 ft), while the mean beach width in the south was only about 30 m (98 ft) (Barnard et al. 2012).

Ocean Beach is in the shadow of the San Francisco Bar, a large ebb-tidal delta, which significantly focuses incident waves and increases alongshore variability (Eshleman et al. 2007). Erosion in the southern section of Ocean Beach has claimed portions of two parking lots (North & South Lot Figure 24), has damaged the Great Highway, and currently threatens valuable wastewater infrastructure. A combination of seawalls, artificial dunes, revetments, beach nourishment, and nearshore dredge placement has been used to mitigate the erosion hazard. Table 6 presents a timeline of human-induced changes at Ocean Beach and is followed by a description of the events in more detail.

Table 6. Timeline of anthropogenic changes at Ocean Beach. See Appendix E for dredging data for the Main Channel Ship. See Figure 24 for locations.

Year	Location	Activity (Volumes in m ³)		Notes	¹ Source
		Structure	Beach/Dune Nourishment		
1872–1882	North of Lincoln Way		Unknown	Dune stabilization and road building. Shoreline extended 46-61 m (150–200 ft) seaward north of Lawton St.	1
1890–1900	Northern end		Unknown	Fill for road building and dune stabilization.	1
1890–1900	South of Sloat Blvd.		Unknown	Lake Merced outlet filled.	1
1915–1927	All reaches		750,000	From O'Shaughnessey Seawall construction.	1
1927–1929	All reaches	O'Shaughnessey Seawall	963,400	O'Shaughnessey Seawall (#79 Figure 24) and Great Highway finished, with 61-meter (200 ft) wide dunes built along beach.	1
1931–1935	Between Lincoln Way & Taraval St.		107,000	Placed as beach fill.	1
1940–1941	Between Santiago St. & Taraval St.	Taraval Seawall		Taraval Seawall constructed (#82 Figure 24) and concrete debris placed on beach and behind seawall.	2
Early 1940s	Rivera St.	Concrete rubble		Rubble, including tombstones, placed on dunes.	2
1942–1946	Between Rivera St. & Ulloa St.		Unknown	Fill moved shoreline about 12 m (40 ft) seaward.	1
1953–1963	Beach			Unknown	1
1963	Beach			11,090	1
1964	Beach			17,200	1
1965	Beach			19,500	1
1966	Beach			5,280	1
1967	Beach			22,940	1
early 1970s	South of Sloat Blvd.		Unknown	Fill placed south of Sloat Blvd. to extend the Great Highway.	1
1972	Southern reach	Concrete rubble		Concrete blocks and rubble placed in front of southern dunes.	1
1976	Beach			Sand from highway and seawall moved back onto the beach.	1
1980–1981	Dunes		458,730	Sand that was excavated for the Westside Sewage Transport Box was placed on the dunes.	1
1982–1983	Southern reach	Revetment		Revetment installed to protect transport box detour road.	1
1986–1992	Between Noriega St. & Santiago St.	Great Highway Seawall	267,590	Great Highway Seawall built (#81 Figure 24), sand excavated during construction was placed on the beach and dunes.	1
	Noriega St. & Santiago St. to South Lot			Sand excavated during seawall construction was placed north and south of seawall (7,645 m ³ [10,000 yd ³]) and at South Lot (19,110 m ³ (25,000 yd ³)).	
1994					3

Year	Location	Activity (Volumes in m ³)			Notes	¹ Source
		Structure	Beach/Dune Nourishment	Mining (from beach)		
Fall 1997	Between North and South Lot	Revetment			Revetment placed at the toe of the bluff (#84 Figure 24).	4
Feb 1998	Between North and South Lot	Revetment addition			Additional rock placed on top of the Fall 1997 revetment.	4
Oct 2000	Sand Barrier South of South Lot		15,290		113-meter (370 ft) long sand barrier constructed south of South Lot.	4
Jan 2001	Sand Barrier South of South Lot		9,170		Sand barrier nourished.	4
2003–2009	Great Highway Seawall to south of South Lot		45,870		Sand barrier nourished with about 7,650 m ³ /yr (10,000 yd ³ /yr).	4
2005–2011	Offshore southern Ocean Beach		1,673,350		Sand dredged from the Main Ship Channel was placed in 9–14 m (30–36 ft) water depth at the OBDS (see Figure 29).	5
Feb–Apr 2010	South of ocean outfall pipe	Revetment			Revetment installed (#86 Figure 24).	3
Fall 2012	O'Shaughnessey Seawall to south of South Lot		95,570		Trucked from in front of the O'Shaughnessey Seawall.	6

¹Source: 1: Moffat & Nichol (1995), 2: McLaughlin (2012), 3: DPW (2010), 4: USACE (no date), 5: USACE (2012). 6: NPS (no date d).

Coastal Structures

The 1.5 km (0.9 mi) long curved, concrete O'Shaughnessey Seawall (#79 Figure 24) was built from 1915–1929 along northern Ocean Beach and was accompanied by extensive beach and dune nourishment (see next section) (Moffat & Nichol 1995). The seawall has had minor repairs over time, including repairs circa 2006/2007 and in 2012 (Danny Collman, NPS, email, 4-29-13). Since the 1970s, sand has steadily accreted in front of the seawall (Figure 26) (McLaughlin 2012). Beginning in 2012 excess sand was moved from the seawall to south of Sloat Boulevard (Figure 24) (NPS no date e).



Figure 26. Oblique aerial imagery of northern Ocean Beach and the O'Shaughnessey Seawall (#79 Figure 24) in 1972 (left) and 2009 (right) illustrates the significant progradation that has occurred on the northern section of the beach (from Adelman and Adelman 2012).

The low Taraval Seawall extends for 203 m (665 ft) between Santiago and Taraval Streets (#82 Figure 24 & Figure 27) and was built in 1940–1941 to protect a historic pedestrian underpass (USACE no date). Constructed of steel sheet piling with a concrete cap, the Taraval Seawall is typically buried in the beach (Olmsted and Olmsted 1979). A third seawall, the Great Highway Seawall, extends for 964 m (3,162 ft) and was constructed from 1986–1993 to protect the Great Highway and underlying sewer box between Noriega Street and Santiago Street (#81 Figure 24) (USACE 1996). Sand excavated during seawall construction was placed on the fronting beach (see next section).



Figure 27. Jodi Eshleman and Mike Berry at the buried Taraval Seawall (#82 Figure 24). Concrete rubble is also visible on the dune face. View is to the north (image by Kate Dallas).

The Ocean Beach neighborhood supports an extensive stormwater management system. Two concrete outfall structures discharge stormwater runoff onto the beach when the main system's capacity is exceeded during storms (labeled as groins #80 & 83 Figure 24). At the southern end of the beach, the concrete Southwest Ocean Outfall pipe extends 7.2 km (4.5 mi) into the Pacific Ocean and transports one-third of San Francisco's treated sewage out to sea (#85 Figure 24) (Barnard et al. 2009, SPUR 2012). The outfall was constructed in 1984 at a cost of \$170 million (Moffat & Nichol 2007).

The 1996–1997 storm season eroded a large gully in the bluffs between the two southern parking lots that ended 4.6 m (15 ft) from the Great Highway (USACE no date). The City of San Francisco responded by constructing a 183-meter (600 ft) long revetment in 1997 (#84 Figure 24). The 1997–1998 El Nino season caused further erosion, resulting in placement of additional rock on top of the 1997 revetment in February 1998.

Storms in winter 2009–2010 caused erosion in excess of 20 m (70 ft) in some locations south of Sloat Boulevard. In January 2010 the San Francisco Department of Public Works (SFPDWP) closed the Great Highway's southbound lanes south of Sloat Blvd. for almost a year (SFPDWP 2012). In February–April 2010 the DPW installed a 130-meter (425 ft) long rock revetment (#86 Figure 24 & Figure 28) and removed 600 metric tons (660 ton) of debris, including asphalt, concrete, steel, rubber, and wood from the site during construction (SFPDWP 2012). Some of this debris may have eroded out of the bluffs and been part of the fill placed in the late 1800s. Debris associated with historic fill was observed at the base of the bluffs near South Lot in February 2012. To provide temporary bluff protection to the unarmored section north of the 1997 revetment, large sandbags were placed in December 2011–May 2012.



Figure 28. Revetment at southern Ocean Beach installed in 2010 (#86 Figure 24). View is to the south towards Fort Funston (image by Kate Dallas).

Beach & Dune Nourishment

In the late 19th and early 20th centuries sand was pushed westward to create level ground for construction of the Great Highway and adjacent neighborhoods. An unknown volume of sand was used to stabilize the dunes and develop the highway along the entire beach, such that the shoreline was extended 45–60 m (150–200 ft) seaward north of Lawton Street. Lake Merced’s outlet to the ocean was also filled by 1900 (Moffat & Nichol 1995). Beach nourishment continued with placement of 750,000 m³ (980,000 yd³) of sand along the beach between 1915 and 1927 (Moffat & Nichol 1995). During final construction of the O’Shaughnessey Seawall and Great Highway in the late 1920s, 963,300 m³ (1.26 million yd³) of sand was used to create dunes 61-meters (200 ft) wide along Ocean Beach (Moffat & Nichol 1995). Further to the south, 107,000 m³ (140,000 yd³) of sand was placed on the beach between Lincoln Way and Taraval Street from 1931–1935 (Moffat & Nichol 1995).

Sand excavated during construction has regularly been used to nourish the beach and dunes along Ocean Beach. In 1980–1981, 458,730 m³ (600,000 yd³) of sand excavated for construction of the Westside Sewage Transport Box was placed on the beach (Moffat & Nichol 1995), but was short-lived due to the 1982/83 El Niño storms (Leslie Ewing, CCC, 3-5-13). Similarly, construction of the Great Highway Seawall resulted in placement of 267,590 m³ (350,000 yd³) of sand on the beach from 1986–1992.

Following severe erosion in 1997–1998, approximately 15,290 m³ (20,000 yd³) of sand was placed in October 2000 along 113 m (370 ft) of bluffs south of the South Lot to form a sand barrier (Moffat & Nichol 2007). An additional 9,175 m³ (12,000 yd³) was placed at the sand barrier again in January 2001. Sand for this project was barged from a shoal offshore of Angel Island in San Francisco Bay (DBW & SCC 2002). Beginning in 1994, the City of San Francisco started an annual program of moving sand from in front of the Great Highway Seawall to the sand barrier (Moffat & Nichol 1995). The USACE (no date) documents that approximately 7,645 m³ (10,000 yd³) was placed each year from 2003 to 2009. In Fall 2012, approximately 76,455–114,680 m³ (100,000–150,000 yd³) of sand was excavated from in front of the O’Shaughnessey Seawall and transported with dump trucks to the erosion hotspot south of Sloat Boulevard (NPS no date e).

Sand Mining

Sand mining occurred on Ocean Beach from 1953 to 1967 (Moffat & Nichol 1995). Volume information from 1963–1967 indicates that at least 76,010 m³ (99,400 yd³) of sand was removed from the beach (Table 6).

Offshore Dredging & Nearshore Placement

Dredging also occurs annually outside the Golden Gate at the San Francisco Main Ship Channel (MSC) (Figure 29). Construction of the channel began in 1921 and it was periodically deepened until 1975 when it reached its authorized depth of 17 m (55 ft) Mean Lower Low Water (USACE 2012). The USACE maintains the federal channel and has dredged nearly 41 million m³ (54 million yd³) since 1931 (see Appendix E for annual data) (Moffat & Nichol 1995, USACE 2012).

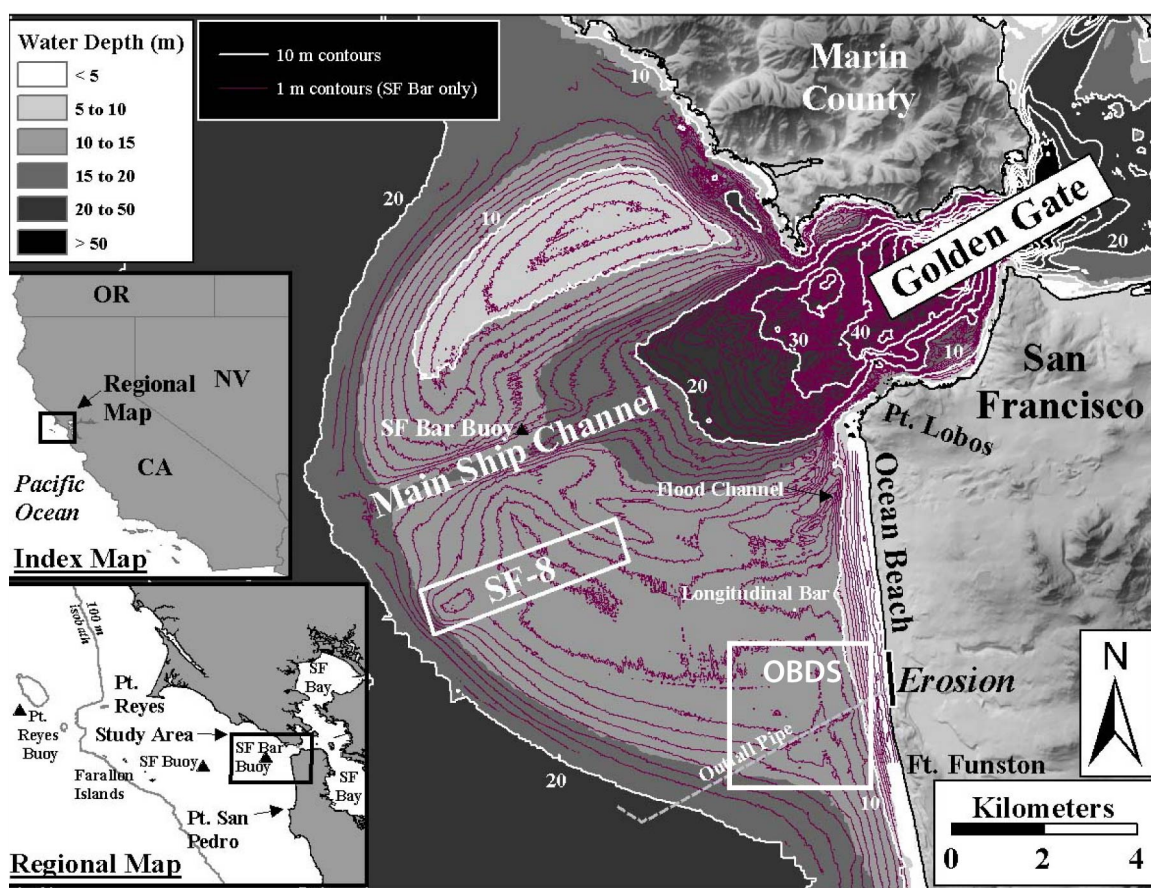


Figure 29. Map of the San Francisco Bar area. SF-8 and OBDS (Ocean Beach Demonstration Site) are federal dredge disposal sites (modified from Barnard et al. 2012).

Prior to 1971 sediment dredged from the MSC was placed in deep water. From 1971 to 2004, disposal of over 18 million m³ (23 million yd³) occurred at SF-08, a disposal site located south of and parallel to the channel (Figure 29) (USACE 2012). However, shoaling at SF-08 has created hazardous conditions for its continued use as a placement site. Since 2005, dredged sediment has been placed at the Ocean Beach Demonstration Site (OBDS, Figure 29) offshore of southern Ocean Beach in depths between 9 and 14 m (30 and 46 ft) (USACE 2012). This location was

chosen to fill in scour holes on the Southwest Ocean Outfall Pipe, provide wave sheltering to the adjacent eroding beach, and establish a nourishment site that might feed sediment into the littoral zone (Barnard et al. 2009). From 2005 to 2011 approximately 1.7 million m³ (2.2 million yd³) of sediment dredged from the MSC was placed at the OBDS. Modeling results by Barnard et al. (2009) indicate that disposal in the nearshore site increases wave dissipation, but that sediment is placed too deep to feed the beach.

Fort Funston

Fort Funston is a former harbor defense installation south of Ocean Beach (Figure 24). This section of the park has steep 60-meter (200 ft) high bluffs that are susceptible to erosion (Kristen Ward, NPS, email, 3-26-13). Two concrete wastewater management outfalls exist on Fort Funston's beach (#87 & 88 Figure 24). The northern outfall was built in 1955–1956 (Patrick Sweetland, City of Daly City, email, 2-6-13) and is the City and County of San Francisco's Lake Merced combined sewer overflow outfall (labeled as a seawall, #87 Figure 24). The southern outfall, called the Vista Grande Outfall, was built in 1950–1951 and is operated by Daly City (Patrick Sweetland, City of Daly City, email, 2-6-13). This structure discharges stormwater and treated sewage through an outfall that extends 762 m (2,500 ft) into the ocean (labeled as a groin, #88 Figure 24 & Figure 30) (RMC 2006).



Figure 30. Vista Grande Outfall at Fort Funston (#88 Figure 24). View is to the south (image by Kate Dallas).

Mori Point

Mori Point is the newest acquisition to GOGA (added in 2000) and encompasses 0.4 km² (105 ac) in Pacifica, California (KellerLynn 2008). Mori Point was previously mined for limestone and sand during World War II and has been restored to create habitat for threatened and endangered species (KellerLynn 2008).

To the north of Mori Point there are various coastal structures at Sharp Park and in the town of Pacifica (Figure 31). Sharp Park is a multiple use park facility owned by the City of San Francisco and includes a 970-meter (3,180 ft) long levee, constructed in the 1980s (#93 Figure 31 & Figure 32) (ESA PWA 2011). Two sections of revetment exist at the north and south ends of the levee, but no background information could be found on their history (#92, 94 Figure 31).

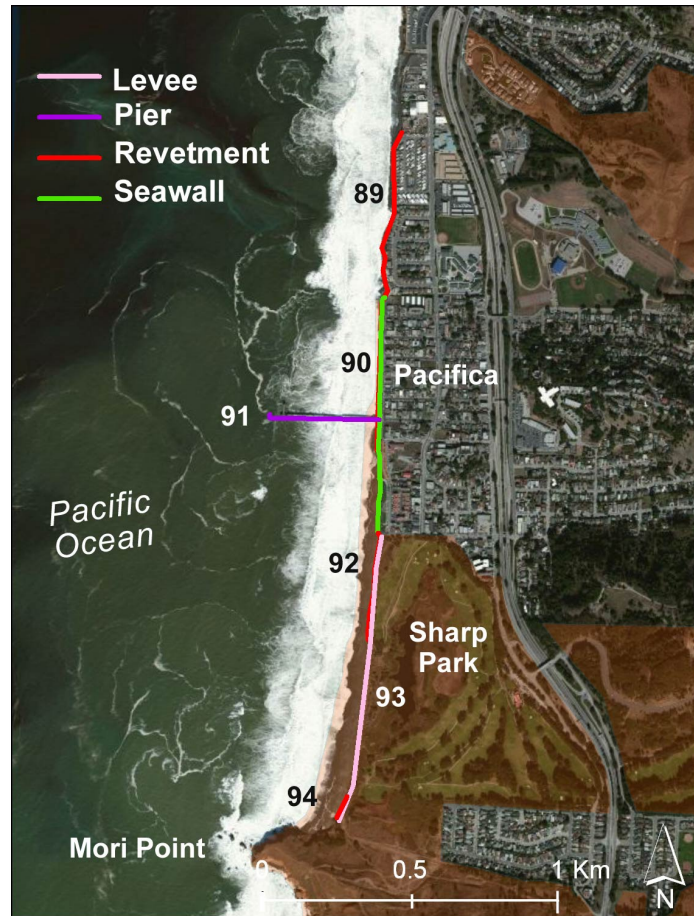


Figure 31.. Mori Point structure map. Note, map does not accurately reflect the extent of revetment #89, which extends to the southern end of the seawall. Orange shading shows park property (image from ESRI Bing Maps basemap layer 2012).



Figure 32. Levee and revetment at Mori Point/Sharp Park (#93–94 Figure 31). View is to the northeast (image by Kate Dallas).

The Pacifica Pier was built in 1973 as a cooperative project between the City of Pacifica and the Department of Fish and Game (#91 Figure 31) (Pacifica Pier 2010). Pacifica's concrete seawall and fronting rock revetment (#89–90 Figure 31) were constructed in the mid-1980s, with the revetment likely extended to the north at a later date.

Impacts

Golden Gate National Recreation Area is unique within the National Park system because it is a large urban park. The San Francisco Bay Delta is considered to be one of the most diverse and productive ecosystems in the world (Weeks 2006), while also being considered the estuary most impacted by anthropogenic activities in the United States (Nichols et al. 1986). The San Francisco Bay Estuary was recently designated as a Wetland of International Importance under the Ramsar convention of wetlands (Ramsar 2013). The park's landscape has been heavily altered through dredging, filling, sand mining, beach and dune nourishment, and the installation of coastal structures. Below we review some of the major alterations to the natural system and subsequent impacts to sediment transport processes on a local and regional scale.

Regional Sediment Trends affecting GOGA

Human activities within the San Francisco Bay, and its watershed, have significantly affected sediment transport within the system (Table 7). Hydraulic gold mining activities in the late 19th century are thought to have released nearly 850 million m³ (1.1 billion yd³) of sediment into the system, artificially inflating sediment delivery into the 20th century (Table 7) (Gilbert 1917). Later, primarily as a consequence of damming and a depletion of erodible hydraulic mining sediment, the delivery of suspended sediment from the Sacramento River to San Francisco Bay decreased by 50% from 1957 to 2001 (Wright and Schoellhamer 2004). Similarly, estimated mean sediment loads from the Sacramento and San Joaquin Rivers have decreased from a high of greater than 9 million metric tons/yr (10 million tons/yr) in the late 19th century (Ganju et al. 2008) to present day values ranging from 1.1 to 3.6 metric tons/yr (1.2 million to 4 million tons/yr) (Shvidchenko et al. 2004). This reduction in sediment supply has an apparent linkage to the disappearance of over 150 million m³ (200 million yd³) of sand-sized sediment from the central San Francisco Bay Coastal System during the last 50 years (Figure 33) (Barnard et al. 2013). This reduction, coupled with sediment extraction (i.e. aggregate mining and dredging) and extensive bay development, has altered the sediment dynamics of the region (Table 7).

Table 7. Historical overview of activities affecting sediment dynamics within the San Francisco Bay system.

Years	Activity	Impacts
1850–1900	Hydraulic mining released about 850 million m ³ (1.1 billion yd ³) of sediment into the system (Gilbert 1917).	This supply of sediment is thought to have made its way through the system by the mid 20 th century with deposition of over 350 million m ³ (450 million yd ³) in the Bay between 1856 and 1887 (Capiella et al. 1999, Foxgrover et al. 2004, Jaffe et al. 2007, Fregoso et al. 2008).
1850–2000	Extensive bay development included the filling and diking of 90% of the tidal marshes within the Bay. This reduced the tidal exchange surface area by 66% (Atwater et al. 1979) and the tidal prism by nearly 10% (Dallas and Barnard 2011).	These reductions likely reduced tidal currents and limited the sediment exchange capacity from the Bay to the outer coast.
1900– Present	Over 200 million m ³ (261 million yd ³) was removed through dredging, mining and borrow pit mining within the SF Bay (Figure 33) (Barnard et al. 2012).	At least 54 million m ³ (71 million yd ³) was removed from central San Francisco Bay, which may limit sand supply to the ebb-tidal delta and open coast beaches (Figure 34) (Dallas and Barnard 2011).
1950– Present	Damming within the Sacramento and San Joaquin rivers reduced sediment supply through impoundment of over 80 million m ³ (105 million yd ³) at the three largest dams within the watershed (Wright and Schoellhamer 2004).	A reduction in sediment supply within the Bay and a 50% decrease in suspended sediment was observed over this time period (Wright and Schoellhamer 2004).

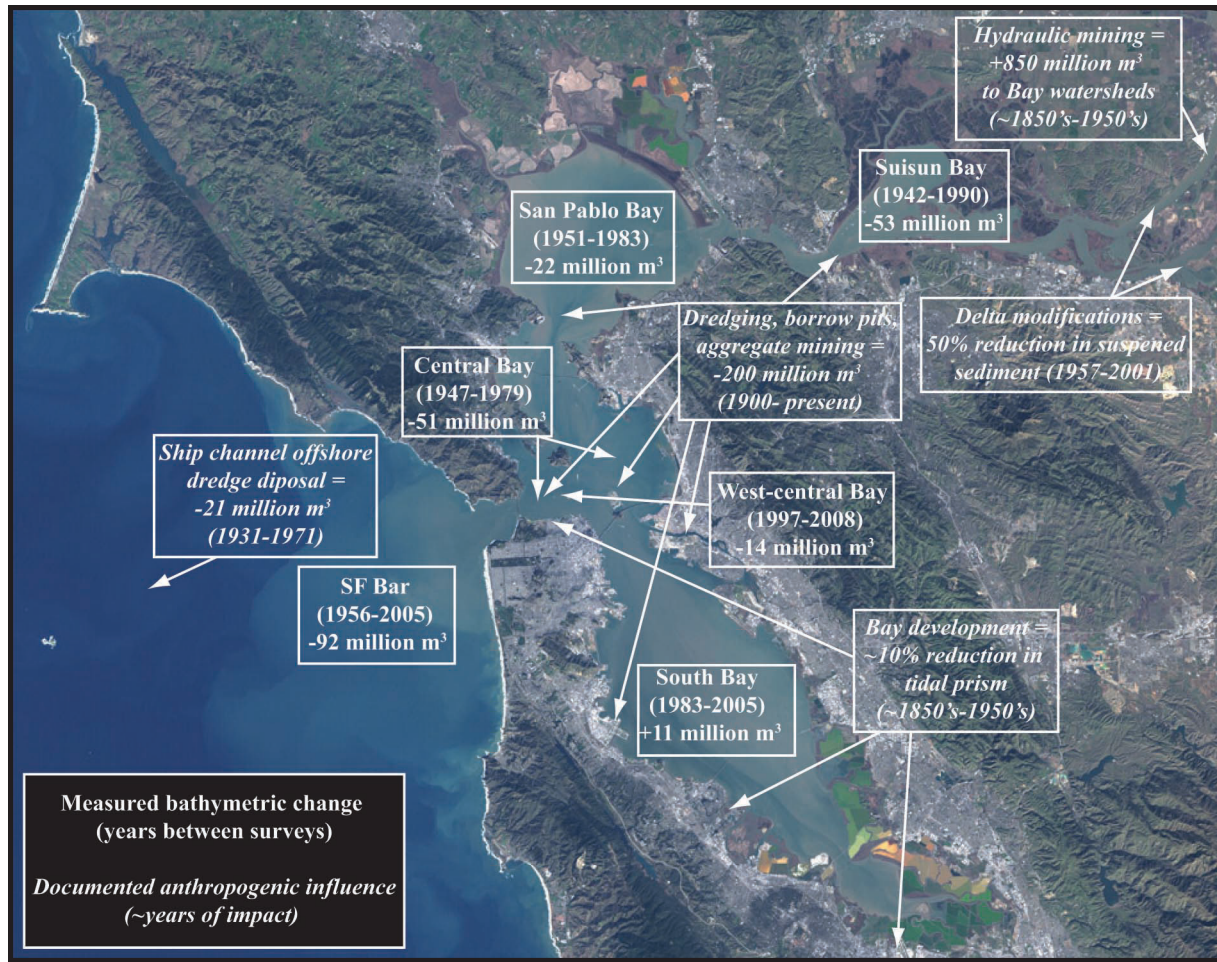


Figure 33. Overview of historical changes in the San Francisco Bay Coastal System incorporating estimated quantities and location of dredging, mining, borrow pits and diking activities within the region (from Barnard et al. 2012).

Anthropogenic activities within San Francisco Bay and its watershed have likely contributed to high volumes of erosion of the San Francisco Bay ebb-tidal delta (ETD) at the mouth of San Francisco Bay (Figure 33). The ETD has lost approximately 100 million m³ (131 million yd³) of sediment, with an average depth change of -0.64 m (-2.1 ft) between 1873 and 2005 (Dallas and Barnard 2011). During this time period the ETD progressively contracted, with implications for hydrodynamic and sediment transport patterns (Figure 34) (Dallas and Barnard 2011).

As noted within the inventory, changes to the morphology of the ETD have influenced alongshore variations in incident waves, with wave focusing impacting shoreline change rates along Ocean Beach (see Ocean Beach Impacts). Southern Ocean Beach has been eroding for decades, with accelerated erosion of up to -5.3 m/yr (-17.4 ft/yr) observed between 2004 and 2010 (Barnard et al. 2012).

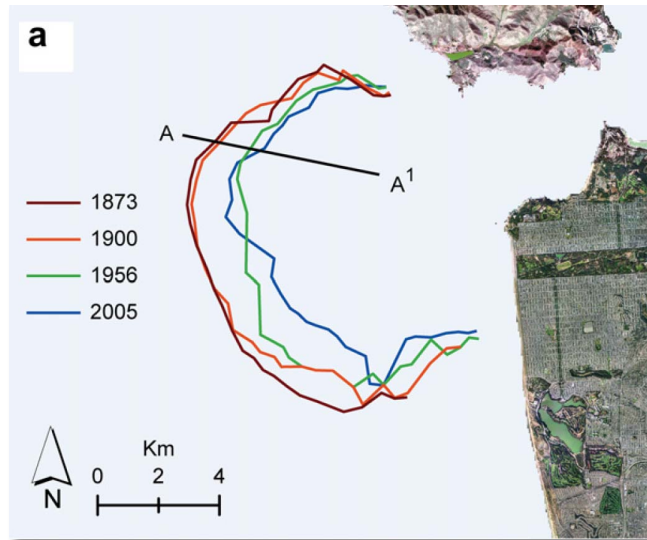


Figure 34. Location of the crest of the San Francisco ebb-tidal delta from 1873 to 2005 (from Dallas and Barnard 2011).

San Francisco Bay Filling and Diking Operations

The San Francisco Bay (SF Bay) is the largest estuary on the west coast of the United States and serves as a drainage basin for over 40% of California. The Bay provides resting areas, feeding grounds and wintering habitat for millions of birds while supporting nearly 500 species of fish, invertebrates, birds, mammals, insects and amphibians (BCDC 2013). The local marine, estuarine and terrestrial ecosystems support outstanding examples of native biodiversity and provide refuge for one of the largest concentrations of rare, threatened and endangered species within the entire national park system (Weeks 2006). Over the last 200 years, diking and filling operations have reduced the size of the Bay from about 2,038 km² (787 mi²) to approximately 1,144 km² (442 mi²), a 44% reduction in area (Figure 35) (Weeks 2006, BCDC 2013).

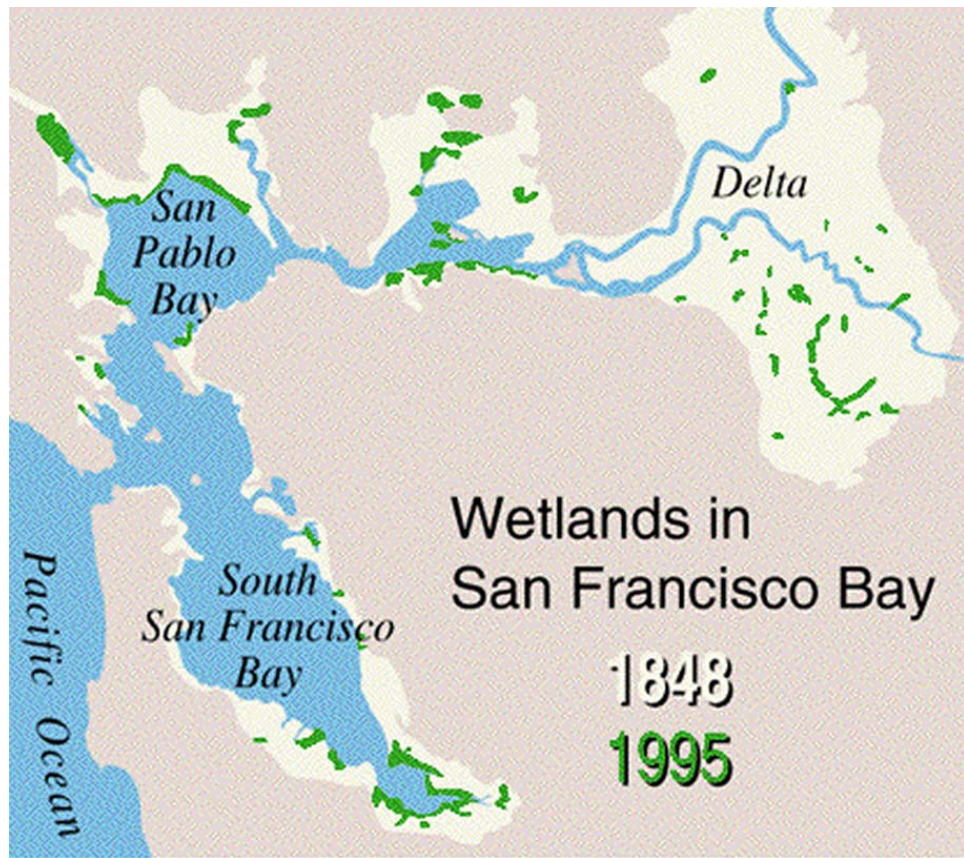


Figure 35. Schematic of San Francisco Bay wetlands lost between 1848 and 1995 (from Hostettler et al. 2006).

Healthy wetlands have natural mechanisms for water quality control, flood mitigation, erosion control, groundwater recharge, and support for native food webs and diverse aquatic and terrestrial species (Weeks 2006). However, 90% of the historic tidal wetlands within the Bay have been cut off from tidal influence, resulting in an approximately 92% loss of habitat within the coastal environment (Figure 35) (Goals Project 1999). The reduction in wetlands has decreased the Bay's tidal prism and tidal flushing capabilities, and reduced the Bay's ability to take up oxygen, resulting in increased pollution concentrations (BCDC 2013). Filling and diking have fragmented the remaining tidal marshes resulting in further habitat degradation, species loss and altered ecosystem community structures (BCDC 2013). The habitat that remains is thought to be heavily infested with invasive plants and exotic animals that further alter the natural system (Goals Project 1999); the Bay is considered to be one of the most invaded ecosystems in the world (Cohen and Carlton 1998). Since 1850, approximately 170 species have invaded the Bay with an average of one new, non-native species establishing itself every 14 weeks (BCDC 2013). Losses of aquatic surfaces are also related to increases in air pollution contributing to smog within the Bay area (BCDC 2013).

Crissy Field

Crissy Field (Figure 36) was originally part of a 0.5 km² (127 ac) marsh that drained into the San Francisco Bay. This area was filled from the 1870s to 1915 to provide for commercial and government interests (Figure 15) (Markwart 1915, Boland 2003). Impacts due to the elimination

of sensitive marsh habitats at Crissy Field are consistent with the broader Bay region where filling and diking activities have degraded both ecosystem and Bay functionality (see Dike/Fill Impacts section). The filling of this area, along with upland modifications (dams, tunnels, fills) within the 1.09 km² (270 ac) Tennessee Hollow Watershed, has forced the historic network of freshwater tributaries underground, disconnecting the natural riparian ecosystem from the Bay (NPS 2010b).

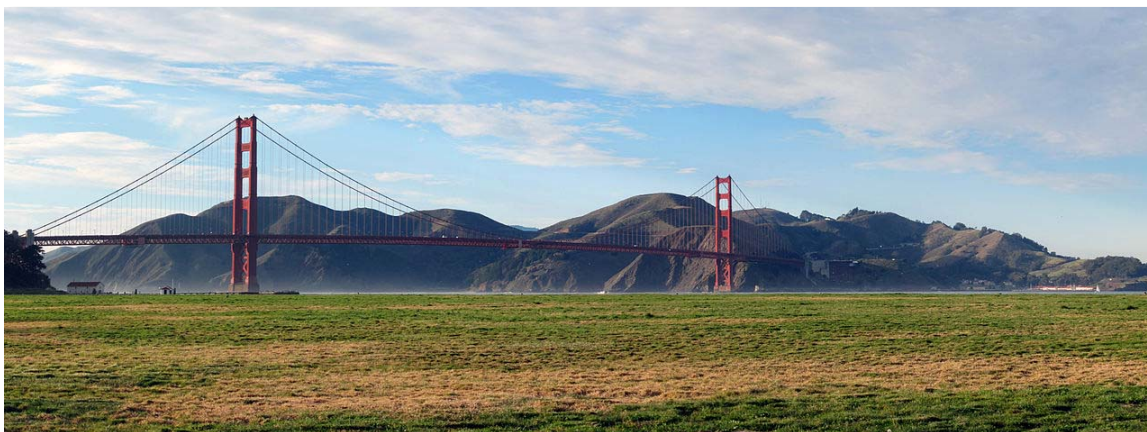


Figure 36. Crissy Field with the Golden Gate Bridge and Marin Headlands in the background (from Wikipedia 2013).

Originally a marsh, the Crissy Field area has hosted Spanish and Mexican ships, a Grand Prix raceway, a historic army field, and a U.S. Coast Guard station (Hargreaves 2013). Today it is a popular urban park that is visited by more than 1 million people per year. As noted within the inventory, Crissy Field was the site of a restoration project that began in the 1990s with an aim to restore a portion of the Bay's native wetlands. The \$34 million dollar restoration project included the removal of 0.3 km² (70 ac) of asphalt, 78,925 metric tons (87,000 tons) of hazardous material, 175,850 m³ (230,000 yd³) of material, and the planting of 100,000 plants (Hargreaves 2013). The restored setting now includes 0.16 km² (40 ac) of natural habitat, including a 0.07 km² (18 ac) tidal wetland (with a 12.2 m [40 ft] wide entrance to the Bay) and 0.09 km² (22 ac) of dune and dune swale habitat, along with a grassy field, shoreline promenade and education facility (Figure 37) (Ward and Ablog 2006). The current landscape provides foraging and nursery habitat for 25 fish species, supports more than 100 invertebrates, and is utilized by nearly 100 species of birds (Ward and Ablog, 2006).



Figure 37. Aerial images of Crissy Field before (1995) and after (2012) the 1998–1999 restoration project. Arrow represents location of restored marshlands, circle indicates area of the restored tidal outlet (from NPS 2013b & Google Earth 2012).

Engineers originally recommended a 0.12 km^2 (30 ac) wetland to maintain continual tidal action and retention of a natural inlet within the reconstructed wetland system (PWA 2004). Due to site constraints, the project was only able to create a 0.07 km^2 (18 ac) wetland, resulting in the need for periodic mechanical excavation of the tidal inlet (PWA 2004). To counteract sediment deposition, the wetland's tidal prism was maximized by keeping the majority of the wetland at sub-tidal elevations (Windham-Myers et al. 2013). Unfortunately, a reduction in the tidal prism has occurred due to more rapid sedimentation than predicted (Windham-Myers et al. 2013).

The inlet first closed 1.5 years after project completion and has since closed at least twice per year (Windham-Myers et al. 2013). Modeling efforts completed in 2004, based on data from the first several years of monitoring data, indicate that the system is in a state of dynamic equilibrium and is expected to continue as an intermittent open water lagoon for the next several decades (PWA 2004). Inlet closure results from interactions between waves, tides and lagoon size with closures more likely occurring during neap tides when tidal scour is minimal. Natural inlet reopening occurs following spring tides, higher lagoon water levels and ebb tidal scouring (PWA 2004). Hanes et al. (2011) suggest that a primary cause of closure is likely due to the high rate of littoral sand transport driven by ocean swells breaking along the shoreline at oblique angles.

Periodic and prolonged closures of the inlet have impacted local vegetation and biota. These events, which inhibit tidal flushing, have likely caused a dieback and inability of native cordgrass (*Spartina foliosa*) to colonize and may also limit the possibilities for replanting (Windham-Myers et al. 2013). Closures have also caused increased total reduced sulfur (TRD) concentrations in sediment and pore water and increased toxic methylmercury production, which may be linked to the dieback of recolonized plants (Windham-Myers et al. 2013).

A groin that was built as part of this restoration project along the western flank of the marsh inlet disrupts littoral transport and limits inlet migration. The groin is comprised of a concrete outfall topped with rock revetment (#65 Figure 13). The natural west to east sediment transport has resulted in sand being transported into the marsh inlet, rather than continuing alongshore to East Beach (Porter 2003).

The new marsh channel increased currents locally and resulted in severe erosion (7.6 m [25 ft]) at East Beach, necessitating beach nourishment and installation of a low 67 m (220 ft) long seawall buried in the beach in 2000 (#63 Figure 13). Since this time, the beach width has recovered (Porter 2003, PWA 2006). The inlet mouth is dynamic and its location varies nearly 200 m (656 ft) alongshore depending on the season and local conditions.

Ocean Beach & the San Francisco Ebb-Tidal Delta

Ocean Beach and the San Francisco ETD have experienced numerous anthropogenic modifications including beach and dune nourishment, installation of coastal structures, sand mining, and dredging dating back to the 1800s (Table 6). Some of the most significant historical changes to the beach are the result of the construction of the Great Highway and O'Shaughnessey Seawall in the late 1920s (Figure 38). Highway completion moved the shoreline seaward nearly 61 m (200 ft), while the seawall hardened 1.5 km (0.9 mi) of shoreline (Moffat & Nichol 1995). During the construction phase of these projects (1900 to 1929) at least 1.5 million m³ (2 million yd³) of sediment was placed on the beach (Moffat & Nichol 1995).



Figure 38. Comparison of Northern Ocean Beach in (A) 1865 and (B) 2012 illustrates the extensive residential development, construction of the O'Shaughnessey Seawall, and progradation of the shoreline due to artificial fill and natural processes (top image from the San Francisco Library 2012, photo AAB-9721, bottom image from SPUR 2012).

Additional seawalls and revetments were built along the beach (Taraval Seawall, Great Highway Seawall, and southern revetments in 1997 and 2010) in order to protect stormwater infrastructure, parking lots, and the highway, fortifying an additional 1.45 km (0.9 mi) of coastline. From 1929 to 1995, the net volume of beach and dune accretion was approximately 0.9 million m^3 (1.3 million yd^3), which was largely due to beach nourishment (Moffat & Nichol 1995). Recent trends along Ocean Beach include accretion in the north (average beach width of 160 m [525 ft]) and erosion in the south (average beach width of 30 m [98 ft]); as a result, the beach widths along the two sections have an average difference of 130 m (427 ft) (Barnard et al. 2012). Below we review three different segments of the beach (North, Middle and South Ocean

Beach – see Figure 39) to highlight significant anthropogenic alterations and subsequent impacts to sediment transport processes.

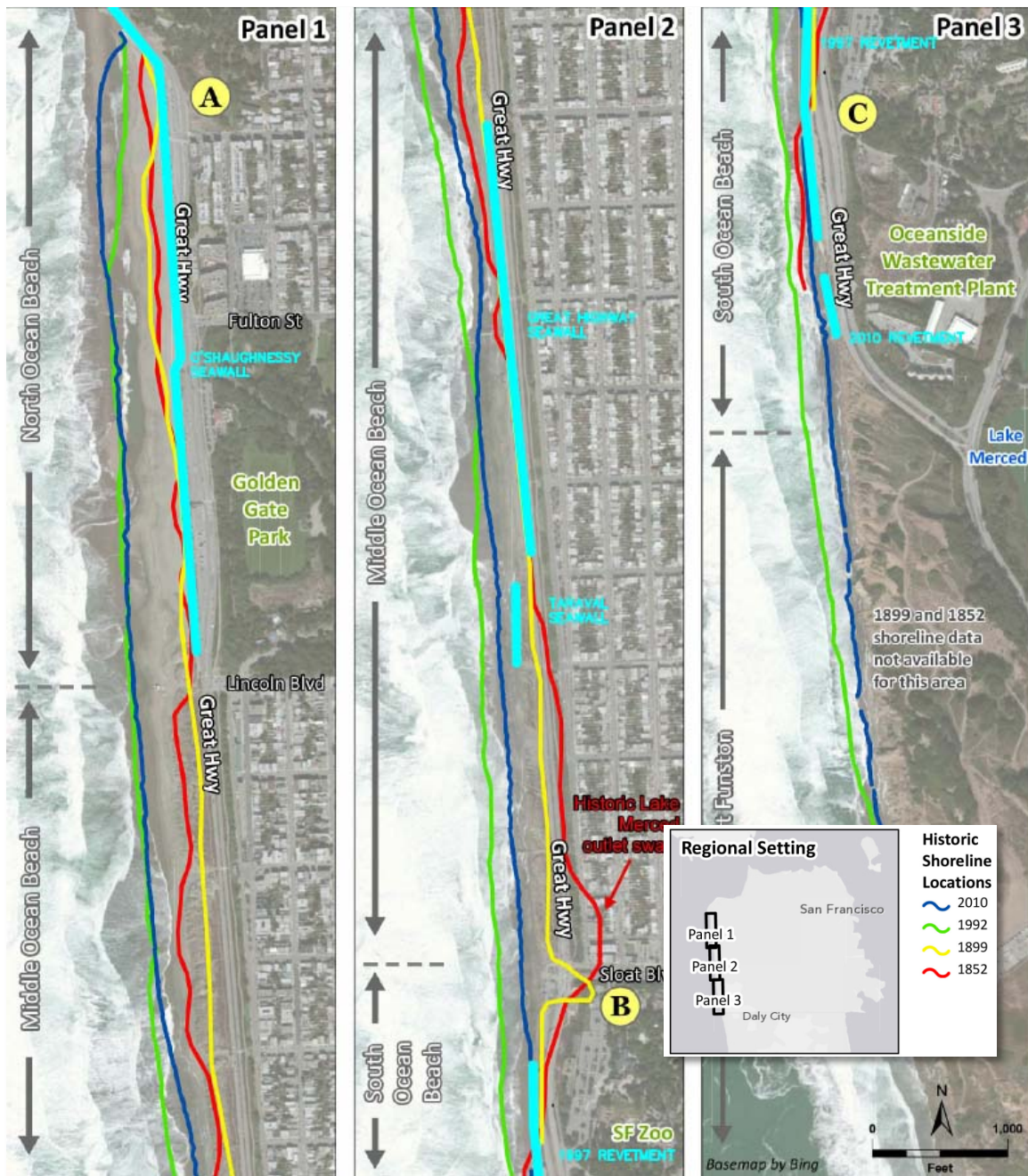


Figure 39. Historic shorelines at Ocean Beach (modified after image from Elena Vandebroek and Bob Battalio, ESA PWA).

Panel 1: North Ocean Beach/ O'Shaughnessy Seawall (Section A, Figure 39)

From the the early 20th century to the 1970s northern Ocean Beach experienced shoreline recession. Since the 1970s, however, this area has experienced pronounced progradation (Figure 39) (McLaughlin 2012). Northern Ocean Beach is in the shadow of the ETD, which has been

eroding in both the short-term (1960s–80s to 2002) and long-term (1850s–90s to 2002) (Barnard et al. 2012). Dredging within the main shipping channel across the delta has likely improved hydraulic efficiency, decreasing flow within the peripheral flood channels adjacent to Ocean Beach, which has led to infilling of the channels (Hanes and Barnard 2007). This offshore deposition has served to protect northern Ocean Beach as waves break farther offshore, dissipating their energy (Dallas 2009). Disposal of over 18 million m³ (23 million yd³) of dredged sediment since 1971 at SF-08 (Figure 29), an offshore disposal site, may also contribute to accretion at northern Ocean Beach (Battalio and Trivedio 1996).

The extent to which the O’Shaughnessey Seawall modified or changed sediment transport dynamics is not known, although the regional sediment trends have likely dwarfed its impact (Barnard et al. 2007). With a crest of 7.77 m (25.5 ft) above mean low tide, the seawall has historically provided protection against large storm events (Weggel 1988). The success of the seawall is likely attributed to the fact that it traps wind-blown sediment (Barnard et al. 2007). The local terrestrial geology also plays an important role as Point Lobos likely acts like a natural jetty trapping northern littoral transport (Figure 40). Point Lobos also creates a strong return flow originating from an eddy that forms in its vicinity (Barnard et al. 2007). Shoreline change trends, natural forcings and structural impacts at middle and south Ocean Beach, however, are dramatically different.



Figure 40. A 2002 oblique aerial image of Point Lobos and northern Ocean Beach shows how the headlands of Point Lobos act as a littoral barrier. View is to the southeast (from Adelman and Adelman 2012).

Panel B: Middle Ocean Beach and Taraval Seawall (Section B, Figure 39)

In this area of Ocean Beach, fill projects have altered the local landscape along the shoreline. Prior to filling, circa 1900, the shoreline was concave at the Lake Merced discharge outlet (Figure 39) (McLaughlin 2012). Just north of the former Lake Merced outlet lies the Taraval Seawall, which for the most part has been buried in the beach since its construction in 1941

(Figure 27), except after large storm events (such as the winters of 1977–1978 and 1982–1983) (Weggel 1988). Impacts to the fronting beach due to the seawall are thought to be negligible except during periods of high wave activity when it provides protection against erosion (Weggel 1988).

Shoreline change rates switch from accretional to erosional around Sloat Boulevard, with most of the coastline south of the ETD eroding in both the short-term (1960s–1980s to 2002) and long-term (1850s–1990s to 2002) (Figure 41) (Barnard et al. 2012). Barnard et al. (2012) documents a strong correlation between the accretion/erosion trends along the beach and the location where the crest of the ETD attaches to the shoreline. At this location there is thought to be a divergence in sediment transport direction, with northerly transport to the north of the crest, and southerly transport to the south (Battalio and Trivedi 1996). Contraction of the ETD has caused offshore shoal erosion and wave focusing, likely contributing to the erosional trend at southern Ocean Beach (Eshleman et al. 2007). Accelerated retreat in recent years has eroded the dunes and bluffs and now threatens the Great Highway and southern parking lots. This area is known to be key habitat for shorebirds (i.e. the threatened western snowy plover). As beach habitat is removed from the system due to erosion, so is this sensitive foraging area (NPS no date f).

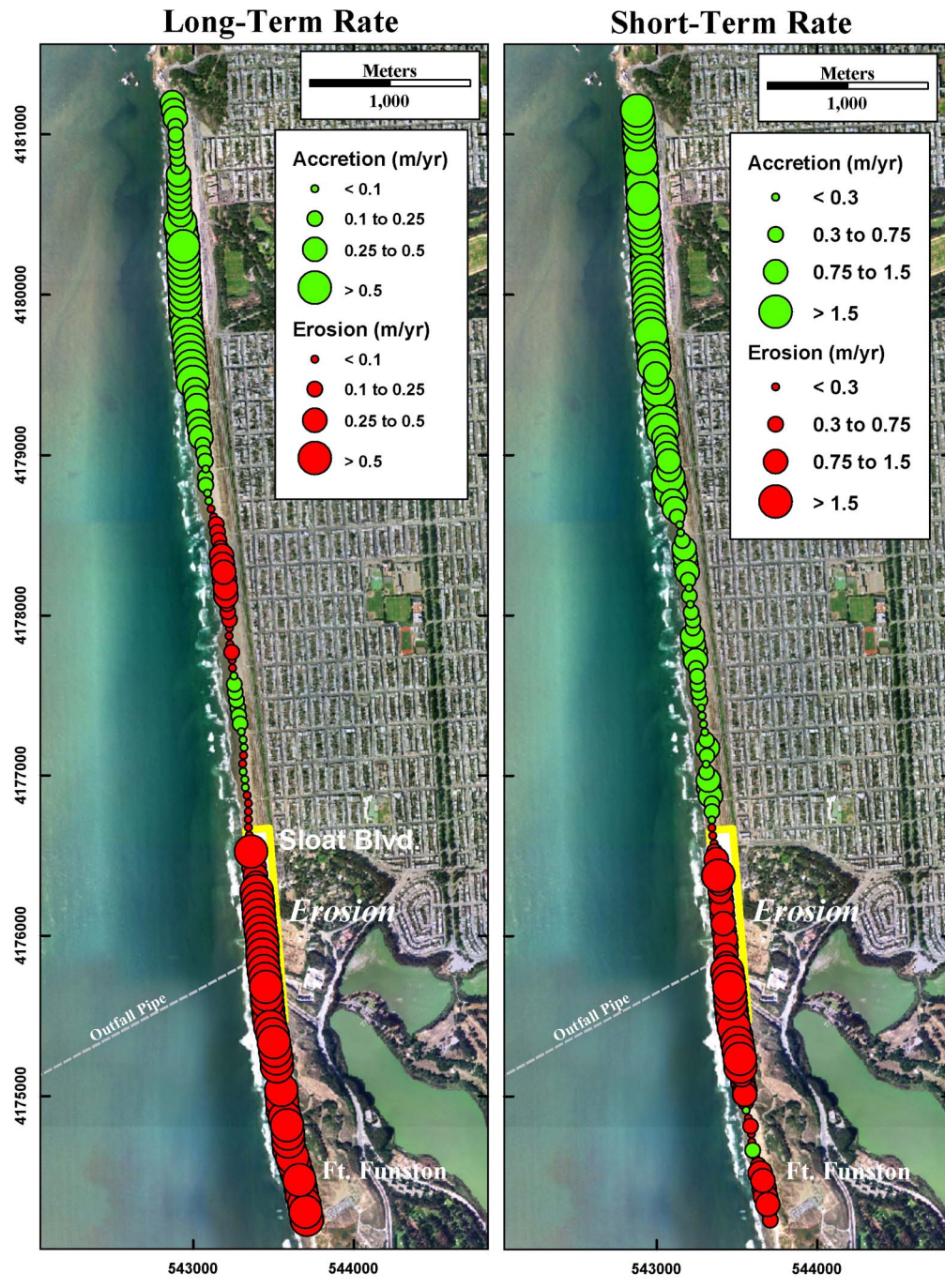


Figure 41. Historical shoreline changes at Ocean Beach in the long-term (1899–2002) (left) and short-term (1983–2002) (right) (from Barnard et al. 2012).

Panel 3: South Ocean Beach and 2010 Revetment (Section C, Figure 39)

South Ocean Beach has experienced significant erosion over the past two decades. Accelerated erosion has caused the shoreline to retreat to its pre-1900s position, eroding the bluffs and artificial dunes and threatening valuable wastewater infrastructure, parking lots, and the Great Highway. This region is beyond the influence of tidal current sediment transport; the reduced

sediment supply likely effects the significant control over the shoreline behavior, as is typical of the California coastline (Barnard et al. 2012, Hapke et al. 2006). As a consequence of continued erosion, the NPS and local stakeholders have constructed emergency revetments, beach nourishment projects, and a sandbag installation to protect infrastructure and thwart additional retreat.

One example of an emergency revetment is the 130 m (425 ft) long revetment placed in the winter of 2010 to provide bluff protection along an unarmored section of coastline immediately adjacent to the Great Highway (Panel 3, Figure 39). The hardening of bluff shorelines may have a negative impact on downdrift areas because it cuts off sediment supply, contributing to erosion. Additionally, hardening of the bluffs limits habitat for the Bank Swallow, a state listed threatened species that inhabits the bluffs (SPUR 2012).

Discussion and Recommendations for Further Study

Coastal engineering projects within Golden Gate National Recreation Area, coupled with innumerable projects within the greater San Francisco Bay region, have significantly altered sediment supply, habitat characteristics, and coastal shoreline change trends. Alterations to sediment supply have contributed to morphological changes of the ETD, which have in turn affected erosion and accretion rates along the outer coast. Historic fill and stabilization measures are increasingly under erosive pressure, stressing sensitive ecosystems and infrastructure.

The wide-ranging geomorphology of GOGA includes rocky cliffs, estuarine landscapes and sandy beaches, each of which vary in susceptibility to changes in sea level and wave energy. The National Academy of Sciences (NRC 2012) has predicted that by the year 2100, sea level will rise between 0.42 to 1.67 m (1.38 to 5.48 ft) in the region, with 0.92 m (3 ft) likely. This rise is higher than the Intergovernmental Panel on Climate Change projections that global sea level will rise 0.19 to 0.59 m (0.62 to 1.92 ft) by the year 2100. (IPCC 2007).

Higher sea levels will have a major impact within the San Francisco Bay system. The Goals Project (2012) calculated that a 1 m (3.3 ft) rise in sea level would threaten \$48 billion of commercial, residential and industrial structures and have the potential to flood nearly 388 km² (150 mi²) of land. If the deepening of the estuary outpaces sediment inflow, which is likely given existing deficiencies in sediment inflow, changes may include habitat redistribution and flooding of productive marshlands, although the extent of impacts are not fully known (Jaffe 2009). Marsh restoration efforts such as the Crissy Field project are important steps towards restoring and protecting ecosystem health, and should continue to be designed with climate change impacts in mind (Figure 42).



Figure 42. Map showing Crissy Field's increased vulnerability to flooding given a 1.4 m (4.6 ft) rise in sea level (from NPS 2013c).

The U.S. Geological Survey's coastal vulnerability assessment for GOGA (Pendleton et al. 2005) indicates that 50% of the park's shoreline is at high or very high risk to future sea level rise impacts, and only 24% of shoreline has low vulnerability. Sea level rise, coupled with the possibility of more frequent and intense winter storms, will likely exacerbate coastal erosion within the park and result in flooding of low-lying areas such as Crissy Field. The most vulnerable areas are gently sloping open coast beaches that have high wave energy, such as Ocean Beach (Pendleton et al. 2005).

Ocean Beach is thought to be particularly sensitive to changes in sea level rise and storm frequency given its extensive infrastructure along the coastal zone. King et al. (2011) estimates that a 1.4 m (4.6 ft) rise in sea level has the potential to cause \$540 million in damages at Ocean Beach from land, buildings and infrastructure being lost or damaged, in addition to \$16 million in habitat and recreation losses caused by a 92% reduction in beach area due to erosion. The Ocean Beach Master Plan (SPUR 2012) recommends a managed retreat strategy that incorporates elements of relocation and a wide range of soft and hard coastal engineering techniques in preparation of future threats.

Sediment transport processes and coastal change rates along the outer coast have been well documented through numerous studies (e.g. Battalio and Trivedi 1996, Hapke et al. 2006, Barnard et al. 2007, Barnard et al. 2012, Dallas and Barnard 2012 and others). Regional work should continue to focus on alternatives to restore wetlands in a manner consistent with anticipated sea level rise. Alternatives to erosion hazards should continue to be evaluated at Ocean Beach. Where possible, obsolete coastal structures within the park should be removed. Park managers should work with the San Francisco Bay Conservation and Development Commission, and other agencies involved with aggregate mining, to communicate about mining activities located adjacent to park property. In coordination with other partners, the National Park Service should continue to evaluate options to maintain and promote ecosystem health while providing recreational opportunities along the park's shoreline.

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Appendix A. Glossary

Accretion: The accumulation of sediment on a beach, deposited by natural fluid flow processes.

Beach Nourishment: The introduction of sediment along a shoreline to increase or protect the size of a beach (includes dune and berm construction and nearshore disposal of sediment for the purpose of shoreline stabilization).

Breakwater: Shore-parallel structures that reduce the amount of wave energy reaching a harbor or stretch of shoreline located behind the structure. Breakwaters are similar to natural bars, reefs or nearshore islands and are designed to dissipate wave energy. The reduction in wave energy results in gradients in littoral drift, causing sediment deposition in the sheltered area behind the breakwater. Some longshore sediment transport may continue along the coast behind the breakwater. Structures can be detached, attached or utilized as a headland control feature depending on design and functionality characteristics.

Bulkhead: Vertical structures or partitions, usually running parallel to the shoreline, for the purpose of retaining upland soils while providing protection from wave action and erosion. Bulkheads are either cantilevered or anchored sheet piles or gravity structures such as rock-filled timber cribs and gabions, concrete blocks or armorstone units.

Dike: Earthen structures (dams) that keep elevated water levels from flooding interior lowlands. The protected area is often below sea level. In open coast areas, dikes that separate low-lying areas from open water are often constructed with a revetment or similar armor layer on the open waterside to protect the dike from wave action and erosion.

Dredging: The mechanical removal of sediment, often used to increase or maintain the depth of a navigable waterway.

Erosion: The wearing away of land and the removal of beach or dune sediments by wave action, tidal currents, wave currents, or drainage.

Groin: Structures that extend perpendicular or at nearly right angles from the shore and are relatively short when compared to navigation jetties at tidal inlets. Often constructed in groups called groin fields, their primary purpose is to trap and retain sand. Groins can be constructed from a wide range of materials including armorstone, pre-cast concrete units or blocks, rock-filled timber cribs and gabions, steel sheet pile, timber sheet pile, or grout filled bags and tubes.

Headland Control: The concept of systematically placing structures (typically breakwaters) to create artificial headlands in an effort to promote equilibrium beach formation. Bays are sculptured between these headlands, such that diffraction and refraction cause waves to develop perpendicular to the coast. This is intended to result in a stable shoreline even if sediment is still passing through a system of headlands. This concept is often employed as a regional approach to shore protection.

Jetty: Structures that extend perpendicular or at nearly right angles from the shore commonly used to limit the volume of sediment deposited in inlet channels and prevent inlet migration.

Levee: Flood protection structure that holds back water during flood stage, typically built along a river to protect against flooding.

Pier: A platform extending over water from a shore that is supported by piles or pillars, used to secure, protect, and provide access to ships or boats.

Revetment: A cover or facing of material placed directly on an existing slope, embankment or dike to protect the area from waves and strong currents. Revetments are designed to armor and protect the land behind them and are commonly constructed using armorstone (high wave energy environments) or riprap stone (lower wave energy environments) in combination with smaller stone and geotextile fabrics. Other construction materials include gabions, poured concrete (usually in stepped fashion), pre-cast concrete blocks, and grout filled bags. Structures can be partially detached from the shore (spur) depending on design considerations.

Seawall: Vertical structures used to protect backshore areas from heavy wave action, and in lower wave energy environments, to separate land from water. They can be constructed using a range of materials including poured concrete, steel sheet pile, concrete blocks, gabions, sandbags, or timber cribs.

Sill: Combination of elements from offshore breakwaters and rock revetments, typically built relatively close to shore, continuous and low-lying. Sills are generally built in lower wave energy regimes with the intent of reducing the wave climate and establishing marsh ecosystems or beaches.

Appendix B. Coastal Structure Data

ID	Location	Structure	Material	Year Built	Year Maint.	Length (m)	On NPS Prop.	¹ Source
1	Stinson Beach	Revetment	Rock	circa 1983		2,306	No	1
2	Fort Baker	Revetment	Rock			120	Yes	
3	Fort Baker	Revetment	Broken concrete			152	Yes	
4	Fort Baker	Revetment	Broken concrete			417	Yes	
5	Fort Baker	Bulkhead	Concrete	1929	1932	246	Yes	2
6	Fort Baker	Pier	Concrete	1937		142	Yes	3
7	Fort Baker	Breakwater	Rock	1937–1945	1990s	94	Yes	3
8	Fort Baker	Pier	Concrete	1988		84	Yes	2
9	Fort Baker	Pier	Concrete	1958		25	Yes	2
10	Fort Baker	Bulkhead	Wood	1942	1980s	239	Yes	4
11	Fort Baker	Revetment	Broken concrete	before 2000		227	Yes	
12	Fort Baker	Pier	Wood	1943–1946		20	Yes	2
13	Fort Baker	Pier	Wood	1937		88	Yes	2
14	Fort Baker	Revetment	Broken concrete	before 1987		170	Yes	4
15	Fort Baker	Pier	Wood	circa 1969		165	Yes	2
16	Fort Baker	Breakwater	Rock	1943	various 1951-1984	274	Yes	2
17	Fort Baker	Pier	Wood	circa 1969		96	Yes	2
18	Sausalito-Marin City Sanitary	Bulkhead	Concrete	pre 1987		115	Yes	
19	Alcatraz	Seawall	Concrete	1935		72	Yes	5
20	Alcatraz	Revetment	Rock	1935		72	Yes	5
21	Alcatraz	Seawall	Concrete	sometime 1907–1933	1937	88	Yes	3?, 5
22	Alcatraz	Revetment	Rock			65	Yes	
23	Alcatraz	Groin	Concrete			11	Yes	
24	Alcatraz	Pier	Concrete	1934	2000s	230	Yes	6
25	Alcatraz	Revetment	Rock			115	Yes	
26	Alcatraz	Seawall	Concrete	1920s		211	Yes	5
27	Fort Mason	Pier	Concrete	1931		130	Yes	7
28	Fort Mason	Seawall	Concrete	1931–1933		378	Yes	8
29	Fort Mason	Seawall	Concrete	circa 1910		429	Yes	9
30	Fort Mason	Pier	Concrete	1912	1933	203	Yes	7
31	Fort Mason	Pier	Concrete	1912	1933, 2002-2004	201	Yes	7
32	Fort Mason	Pier	Concrete	1912		154	Yes	7
33	San Francisco Marina	Revetment	Rock			1,385	Yes	
34	East Harbor	Pier		circa 1965		113	Yes	10
35	East Harbor	Pier		circa 1965		99	Yes	10
36	East Harbor	Pier		circa 1965		104	Yes	10
37	East Harbor	Pier		circa 1965		105	Yes	10
38	East Harbor	Pier		circa 1965		106	Yes	10
39	East Harbor	Pier		circa 1965		234	Yes	10
40	East Harbor	Pier		circa 1965		190	Yes	10
41	East Harbor	Breakwater	Concrete			305	Yes	

ID	Location	Structure	Material	Year Built	Year Maint.	Length (m)	On NPS Prop.	¹ Source
42	East Harbor	Pier		circa 1965		171	Yes	10
	San Francisco			finished				
43	Marina	Seawall	Rock	1938	1935, 1964-1966	1,291	Yes	10
44	West Harbor	Breakwater	Concrete	2011		56	Yes	4
45	West Harbor	Pier		1963		288	Yes	
			Broken					
46	West Harbor	Breakwater	concrete	circa 1940s		47	Yes	4
47	West Harbor	Breakwater	Rock	pre 1915		133	Yes	11
48	West Harbor	Pier		1963		209	Yes	10
49	West Harbor	Pier		1963		37	Yes	10
50	West Harbor	Pier		1963		283	Yes	10
51	West Harbor	Pier		1963		404	Yes	10
52	West Harbor	Pier		1963		129	Yes	10
53	West Harbor	Pier		1963		369	Yes	10
54	St. Francis Spit	Seawall	Rock	pre 1938		787	Yes	5
55	West Harbor	Revetment	Rock			210	Yes	
56	West Harbor	Pier		1963		137	Yes	10
57	West Harbor	Pier		1963		35	Yes	10
58	West Harbor	Pier		1963		35	Yes	10
59	West Harbor	Pier		1963		24	Yes	10
60	St. Francis Spit	Breakwater		1940s	1958	368	Yes	10
61	St. Francis Spit	Revetment	Rock	pre 2000		138	Yes	4
62	Crissy Field	Revetment	Rock	1990s		180	Yes	4
63	Crissy Field	Seawall	Concrete	2000		172	Yes	12
64	Crissy Field	Groin	Concrete	pre 1987		18	Yes	4
65	Crissy Field	Groin	Rock	1999		129	Yes	4
			Broken					
66	Crissy Field	Revetment	concrete			176	Yes	
67	Crissy Field	Pier	Wood	1915–1919	1928	134	Yes	13
68	Crissy Field	Seawall	Concrete	circa 1935		115	Yes	13
69	Crissy Field	Breakwater	Wood	1938		73	Yes	
70	Crissy Field	Groin	Concrete	1921		77	Yes	14
71	Fort Point	Revetment	Rock	1983		911	Yes	13
					1909, 1915, 1933, 1963			5, 13, 15,
72	Fort Point	Seawall	Rock	1861–1869	1980s	1,118	Partial	16
73	Fort Point	Seawall	Steel			12	Yes	
74	Fort Point	Pier	Concrete	1907–1910	1943	177	Yes	5, 17
75	Baker Beach	Seawall	Concrete			143	No	
76	China Beach	Seawall	Concrete	circa 1951		144	Yes	
77	Sutro Baths	Revetment	Rock	circa 1889		118	Yes	18
78	Sutro Baths	Seawall	Concrete	circa 1889		111	Yes	18
79	Ocean Beach	Seawall	Concrete	1915–1929		1,460	Yes	19
80	Ocean Beach	Groin	Concrete			20	Yes	
81	Ocean Beach	Seawall	Concrete	1986–1993		964	Yes	20
82	Ocean Beach	Seawall	Concrete	1940–1941		190	Yes	21
83	Ocean Beach	Groin	Concrete			28	Yes	
84	Ocean Beach	Revetment	Rock	1997	1998	452	Yes	21
85	Ocean Beach	Groin	Concrete	1984		104	Yes	22
86	Ocean Beach	Revetment	Rock	2010		138	Yes	23
87	Fort Funston	Seawall	Concrete	1955–1956		43	Yes	24
88	Fort Funston	Groin	Concrete	1950–1951		29	Yes	24

ID	Location	Structure	Material	Year Built	Year Maint.	Length (m)	On NPS Prop.	¹ Source
89	Pacifica - Sharp Park	Revetment	Rock	mid 1980s		1,101	Partial	
90	Pacifica - Sharp Park	Seawall	Concrete	mid 1980s		797	Partial	
91	Pacifica - Sharp Park	Pier		1973		382	Yes	25
92	Mori Point	Revetment	Rock			368	Yes	
93	Mori Point	Levee	Earth	1980s		974	Yes	26
94	Mori Point	Revetment	Rock			80	Yes	

¹Source: 1: Savoy et al. (2005), 2: NPS (2004), 3: NPS (2005a), 4: Google Earth, 5: Bishop (2012), 6: NPS (2001), 7: Hoke and Foulds (2004), 8: NPS (2010), 9: ARG (2009), 10: SFPD (2007), 11: NOAA (2012a), 12: Porter (2003), 13: NPS (2006a), 14: Haller (1994), 15: Martini (no date), 16: Bearss (1973), 17: Thompson (1997), 18: NPS (2005c), 19: Moffat & Nichol (1995), 20: USACE (1996), 21: USACE (not date), 22: Moffat & Nichol (2007), 23: SFDPAW (2012), 24: Patrick Sweetland (City of Daly City), 25: Pacifica Pier (2012), 26: ESA PWA (2011), 27: NPS (2006b).

Appendix C. Beach Nourishment and Dune Construction Data

Location	Type	Reason	First Year	Renourish Year	Total Volume (m ³)	¹ Length (m)	² Source
North Ocean Beach	Beach Nourishment	Stabilize dunes and develop highway	1872–1882		unknown	2,186	1
All Ocean Beach	Beach Nourishment	Seawall construction	1915–1927	1927–1929	1,713,400	4,590	1
North & Central Ocean Beach	Beach Nourishment	Develop highway	1931–1935		107,000	2,498	1
North & Central Ocean Beach	Dune Nourishment	Sand excavated for sewer transport box	1980–1981		458,730	2,833	1
Central Ocean Beach	Beach Nourishment	Sand excavated for seawall construction	1986–1992		267,590	923	1
South Ocean Beach	Beach Nourishment	Build sand barrier	2000	2001, 2003–2009	70,330	112	2
Crissy Field's East Beach	Beach Nourishment	Combat erosion	2000		1,910	149	3

¹Length is very approximate

²Source: 1: Moffat & Nichol (1995), 2: Moffat & Nichol (1997), 3: Porter (2003), 4: NPS no date e.

Appendix D. Dredge, Mining, and Fill Data

This table contains only those dredge and fill projects where a year and an approximate location could be determined, and therefore may omit other dredge, fill, and mining projects that have occurred in the area. Refer to the Ocean Beach section in the report for a discussion of additional sand mining.

Location	Type	Reason	First Year	Last Year	Episodes	Volume (m ³)	¹ Area (m ²)	² Source
Northern SF Waterfront	Fill	Development, Fair	1851	1917	unknown	unknown	776,000	1,2
Fort Baker	Fill	Build fort	1903			61,160	25,000	3,4
Main SF Ship Channel	Dredge	Navigation Channel	1921	2011	72	40,931,396	4,870,000	5,6, 10
Presidio, Alcatraz, Pt. Knox shoals	Mining	Aggregate mining	1978	2008	31	9,987,100	927,830	7
Pt. Knox	Mining	Aggregate mining	1980	2008	29	4,462,450	414,580	7
West Harbor	Dredge	Marina	1994	2011	15	393,889	39,100	8, 9
Alcatraz Shoal	Mining	Aggregate mining	1995	2008	14	586,166	54,460	7
Pt. Knox	Mining	Aggregate mining	1995	2004	14	3,616,806	336,010	7
Alcatraz Shoal	Mining	Aggregate mining	1999	2008	10	832,896	77,380	7

¹Area is very approximate

²Source: 1: Bonilla (1991), 2: Treadwell & Rollo (1997), 3: NPS (no date a), 4: NPS (2004), 5: Moffat & Nichol (1995), 6: USACE (2012), 7: Dallas (2009), 8: SFPD (2009), 9: Frank Filice (SFDPW), 10: Alyssa Moore (USACE).

³Markwart (1915) reports that 0.7 km² (184 ac) were filled in 1912 with 1.3 million m³ (1.7 million yd³) of sand dredged from Central Bay.

Appendix E. San Francisco Main Ship Channel Dredging Data

Bold volumes indicate deepening projects (1931–1993 data from Moffat & Nichol (1995), 1994–2012 data from USACE (2012)).

Year	Volume (m ³)	Year	Volume (m ³)
1921–1930	unknown	1983	485,875
1931	1,188,118	1984	59,612
1932	1,016,093	1985	680,874
1933	981,688	1986	690,546
1934	1,943,498	1987	524,606
1935	724,798	1988	510,455
1936	1,043,617	1989	151,497
1941	42,051	1990	400,741
1942	678,925	1991	208,178
1943	841,010	1992	337,834
1950	532,895	1993	319,333
1951	3,823	1994	677,845
1952	313,467	1995	224,833
1953	767,613	1996	771,433
1954	194,197	1997	367,579
1955	1,092,931	1998	304,872
1956	236,247	1999	204,959
1957	454,910	2000	509,700
1958	478,611	2001	59,645
1959	2,935,891	2002	100,989
1960	583,355	2003	289,119
1961	668,986	2004	178,059
1962	875,415	2005	313,970
1963	643,755	2006	291,915
1964	444,206	2007	248,541
1965	511,487	2008	153,150
1966	314,997	2009	220,424
1967	331,052	2010	344,519
1968	363,928	2011	259,592
1969	505,371	TOTAL	40,921,396
1970	155,969		
1971	801,253		
1972	1,035,972		
1972	461,027		
1973	1,029,855		
1973	565,771		
1974	1,247,754		
1974	488,551		
1975	1,094,017		
1976	678,354		
1977	237,012		
1978	581,826		
1979	644,902		
1980	595,309		
1982	700,192		

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