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Introduction

Tidal marshes are dynamic ecosystems that occur at the interface between land and sea which experience regular inundation from tides. Tidal inundation brings suspended sediment to the marsh surface for deposition which is an important contribution to accretion processes to maintain their elevation relative to local sea level. However, the threat of sea-level rise raises important questions regarding the long-term sustainability of marshes. Projections of sea-level rise for southern California range from 44 - 166 cm by 2100, with a mean increase of 93 cm (NRC 2012). Threats to marsh sustainability with sea-level rise include low rates of sediment accretion and subterranean subsidence. Tidal marshes lacking sediment accretion and experiencing subterranean subsidence are at a greater risk of submergence as sea levels rise.

Background

Seal Beach National Wildlife Refuge (SBNWR) is located within the greater Los Angeles area in the city of Seal Beach, Orange County, California and is encompassed within Naval Weapons Station Seal Beach (NWSSB, Fig. 1-2). SBNWR is administered by the U. S. Fish and Wildlife Service under the San Diego National Wildlife Refuge Complex and is comprised of 391 ha (965 ac) with 304 ha (750 ac) of tidal salt marsh and three intertidal and subtidal restored ponds (47 ha [116 ac] CCP 2011; Picture 1). The refuge is home to the federally endangered California least tern (*Sterna antillarum browni*) and one of the largest populations of the endangered light-footed clapper rail (*Rallus longirostris levipes*), making it an important site for conservation. The light-footed clapper rail is a tidal marsh dependent species.

Picture 1. High tide at Seal Beach National Wildlife Refuge

Subterranean subsidence in the greater Los Angeles area has been well documented since 1986 when survey-grade GPS measurements for crustal deformation were initiated (e.g. Bawden *et al*. 2001, Shen *et al*. 2011). Crustal deformation includes faulting, uplift, down drop, and warping of the earth's crust from tectonic plate movement. Subterranean subsidence has resulted from groundwater and oil extraction; however, it does not occur uniformly across the Los Angeles area (Bawden et al. 2001). Heterogeneity in the amount and direction of elevation change depends on several factors including distance from major extraction point (wells) and locations of geologic faults. Previous studies document (1960s, 1980s, and 1994) subsidence and rebound locations at NWSSB (Minor and Crider 1988, RBF Consulting 1994). Benchmarks on NWSSB were surveyed in 1988, and mean subsidence was estimated to be 6.9 mm/yr when compared with elevations from the 1960s (Minor and Crider 1988, Fig. 2). In addition, another study was conducted at NWSSB in 1994 where a total of 54 benchmarks were surveyed; 19 new benchmarks were established and 35 benchmarks were resurveyed -- 31 of those resurveyed benchmarks were originally established in 1968 (RBF Consulting 1994, Fig. 2). The RBF (1994) study reported that many areas at NWSSB rebounded in elevation since the previous survey was conducted in 1988. The mean change in elevation was +1.63 mm/yr.

The purpose of this study was to determine the amount of subsurface subsidence at NWSSB areas which include SBNWR since the last extensive survey in 1994. Since no benchmarks were established on the tidal marsh, data from the surrounding NWSSB was used for the SBNWR. Rates of subsidence could vary between terrestrial and tidal environments since benchmarks were only terrestrial, but if subsidence was occurring in terrestrial areas surrounding the SBNWR, we assumed the same surface subsidence in the tidal marsh. We sought to update established benchmarks and examine sub-surface elevation changes from Continuously Operating Reference Stations (CORS) established by the National Geodetic Survey (NGS). This information will be critical for modeling sea level rise at SBNWR. The sustainability of the marsh may have important implications for conservation strategies of habitat and endangered species.

Methods

An extensive survey of National Geodetic Survey (NGS) benchmarks at the NWSSB was completed in 1994 by the consulting firm RBF. Our goal was to resurvey these benchmarks (N=54) to determine current subsidence or rebound rates for NWSSB and augment that information with data from CORS. CORS was used to show elevation changes on a broad scale for the greater Los Angeles area and relate to our site specific data collected at NWSSB. The RBF Consulting report (1994) did not include GPS locations for the benchmarks measured; reporting only measured elevation and elevation change by benchmark name. In addition, the online database of NGS records for many of the original benchmarks did not have accurate GPS locations (accuracy ±180 m) making recovery difficult. Construction activities on NWSSB over the last 18 years resulted in the destruction or removal of several historic benchmarks (Picture 2). Between 29 November 2012 and 4 December 2012, we searched for NGS benchmarks on or near NWSSB (N=25) and measured their elevation (Picture 3, Fig 2, Table 1). Using NGS and RBF consulting descriptions of benchmark locations, we attempted to recover 25 benchmarks at NWSSB. We recovered 6 benchmarks near the harbor, but access restrictions when Navy ships were in port as well as poor weather conditions precluded surveying their elevations. Ultimately, we recovered and surveyed four benchmarks from the 1994 survey, each of which was established in 1968 and provided a long-term basis for comparison (Table 1).

Picture 2. Destroyed benchmark located on Naval Weapons Station Seal Beach

We surveyed each of the four benchmarks with a Leica GS-10 unit, antenna, and tripod (base station) which was left to run continuously for at least one hour to provide a horizontal accuracy of 10 mm ± 1 mm and vertical accuracy of 20 mm ± 1 mm (https://myworld.leica-geosystems.com). Once the base station was established, we surveyed two control benchmarks (NGS: HPGN CA 12 01, Seal Beach Survey Control 5206) that had known locations and were established less than a year before the survey, and therefore, it showed little to no change from subsidence. We used a Leica Real Time Kinematic (RTK) GPS GS-15 rover (accuracy; horizontal: 10mm ± 1 mm, vertical: 20mm ± 1 mm) from a 2 m rod to assess the error from OPUS

Picture 3. USGS surveyor at Seal Beach National Wildlife Refuge

corrections. OPUS is an automated data processing system operated by NGS. OPUS uses satellite observations from the base station and precise ephemeris vectors from the satellites to calculate an x, y position relative to the North American Datum 1983 (NAD83) using the 2010 epoch. The raw data (RINEX files) from the base station was submitted to the OPUS system for precise ephemeris processing (Table 2). North American Vertical Datum of 1988 (NAVD88) elevations were calculated using the 2012 geoid model of gravity. The OPUS corrected positions of the control points were compared to their NGS published positions to assess horizontal and vertical accuracy. The 1994 survey data were converted from feet relative to the NGVD 1929 datum, to meters relative to the NAVD 1988 datum using a conversion tool provided by the NGS (http://www.ngs.noaa.gov/cgi-bin/VERTCON/vert_con.prl). This allowed for a direct comparison between 1994 and current elevation data. NGS benchmark surveys were augmented with CORS data which operate in close proximity (10-20 km) to NWSSB. NOAA National Ocean Service (NOS) coordinates a network of geodetic-quality CORS stations that provide Global Positioning System (GPS) carrier phase and code range measurements in support of 3-dimensional positioning activities throughout the United States.

The positions of these CORS sites help define the National Spatial Reference System (NSRS). The NSRS provides a consistent national coordinate system to support mapping, charting, navigation, boundary determination, property delineation, infrastructure development, resource evaluation surveys, and scientific applications. The CORS system enables positional accuracies that approach a few centimeters relative to the NSRS, both horizontally and vertically (http://www.nsof.class.noaa.gov/). The NGS uses the CORS to define and manage the NSRS, which is the framework for latitude, longitude, height, scale, gravity, orientation and shoreline throughout California. The CORS network of GPS receivers are dense in Los Angeles and Orange County and provide a continuous record of elevation dynamics; the first stations were installed in the mid-1990s. For CORS stations near SBNWR, data collection started between 2002 and 2008 (http://sopac.ucsd.edu/sites/). Here, we report mean annual rates of elevation change for six nearby CORS stations by fitting least-squared regression lines through the data plotted as elevation against year.

Results

We observed continued subsidence relative to the 1968 and 1994 surveys among the four recovered and surveyed benchmarks (U1000, X1000, P371, X1001). Benchmark p371 had the smallest average amount of elevation change of -2.28 mm/yr from 1994 to 2012 and -3.57 mm/yr from 1968 to 2012. Benchmark U1000 had the largest elevation change of -7.61 mm/yr from 1994 and 2012 and -5.68 mm/yr from 1968 and 2012. Benchmark X1000 had an average elevation change of -3.83 mm/yr from 1994 and 2012 and -4.45 mm/yr from 1968 and 2012. Benchmark X1001 had an elevation change of -2.78 mm/yr from 1994 and 2012 and -3.84 mm/yr from 1968 to 2012. Across all four benchmarks elevation change was -4.13m/yr (SE ± 1.21 mm/yr) from 1994 to 2012 and -4.39 mm/yr (SE ± 0.47 mm/yr) from 1968 to 2012 (Table 3, Fig 4). Rover positions for the vertical control were within the horizontal error tolerance of the RTK GPS measurements (<2 cm).

Similar trends in subsidence were observed at four of the five local CORS stations near NWSSB (Fig. 3, 5-7, 9). CORS Station PVRS showed an average rate of elevation change of -2.14 mm/yr, while station LBCH showed an average change of -3.01 mm/yr. At Station LBC2, we measured average change of -2.98 mm/yr, and station HBCO had the greatest elevation change of -6.49 mm/yr. CORS station LBC1 showed a positive trend compared to the other CORS locations with an elevation change of +5.86 mm/yr. The mean elevation change was -3.71 mm/yr (SE ± 0.75 mm/y) at the four CORS stations. The differing elevation trend in CORS stations demonstrates regional spatial heterogeneity in elevation change across the area and illustrates the importance of having local measurements. The cyclic nature of groundwater drawdown and recharge is apparent in the CORS data (Figs. 5-9).

Discussion

Results from our NGS benchmark surveys showed that subsidence is still occurring at NWSSB at a rate of -4.13 mm/yr (SE ± 1.21 mm/yr) since the last survey in 1994. The nearby CORS elevation trends confirm local subterranean subsidence and were within the range of measured local subsidence on the refuge. However, the differing elevation trends in the CORS demonstrates the need for local measurements and site specific data. The mean rate of subsidence from the measured NGS benchmarks is in agreement with results from a broader study of elevation change done for the Los Angeles Basin (Fig. 10; Shen *et al*. 2011). Subterranean fluid extraction along with tectonic action is believed to be causing the regional patterns in subsidence and uplift (Bawden *et al*. 2001), and the cyclical patterns in the continuous CORS data are likely showing patterns of withdrawal and recharge from precipitation (Figs. 5-9).

The long-term sustainability of SBNWR tidal salt marsh ecosystem faces threats from regional and local subsidence, sediment availability and sea-level rise. The current rate of sea-level rise in southern California is 2.1 mm/yr (NRC 2012) and when combined with subsidence rates, SBNWR is experiencing a relative sea-level rise rate three times more (6.23 mm/yr) than that of similar southern California marshes not experiencing subsidence. Compared to the NRC (2012) sea-level rise projection curve, we found that the current rate of relative sea-level rise at SBNWR with subsidence is now similar to the rate expected in 2036 for areas of southern California without subsidence.

Next Steps

Our USGS program on Coastal Ecosystem Response to Climate Change (CERCC) program recognizes the importance of extensive and improved integration of both physical and biological monitoring to facilitate the understanding of important trends and ecosystem response from sea-level rise. A better understanding of the spatial variability of available suspended-sediment and deposition rates for mineral and organic matter will greatly improve site-specific sea-level rise modeling results to better understand marsh sustainability into the future. Beginning in the winter of 2012, we are using YSI turbidity sensors (Picture 4) within channels in and around SBNWR to monitor seasonal suspended sediment concentrations (SSCs). This will allow an improved understanding of temporal and spatial sediment delivery to the tidal marsh and will help develop a sediment flux model. This understanding can inform management decision concerning marsh stability and accretion processes, as suspended sediment is critical for marsh elevation building relative to local sea levels.

Picture 4. Deployment design for YSI at SBNWR

Combining the effects of sea-level rise coupled with subsidence, it is critical to determine the amount of accretion that is occurring at SBNWR and whether this accretion rate can offset sea level rise and subsidence rates. The YSI turbidity sensors were deployed between November 2012 and March 2013 to capture winter storm events, a key time for sediment delivery to the marsh surface. This data will be augmented with site-specific water level loggers to associate sediment delivery with water level and drainage. Finally, deposition data on the marsh platform may be collected with surface elevation tables (SET's) that measure both accretion and erosion. Overall, collecting these detailed baseline data may be used to identify accretion potential and prioritize restoration and management in light of projected future sea-level rise and extreme storm events.

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Table 1. Benchmarks identified and surveyed in the Seal Beach vicinity. Benchmarks categorized as Not Surveyed were found but were not surveyed because of access operational restrictions by the Navy.

Benchmark	Year surveyed	Latitude	Longitude	Status	Location Description
U1000(5206)*	1965, 1968	33 44 43	118 05 07	Recovered	0.2 miles SW along Kitts Hwy from entrance of U.S. Naval weapons Station, 21 ft. SE of Kitts Hwy, Base of power pole
X1000(5207)*	1965, 1968	33 44 41	118 03 39	Recovered	In cement at base of large white pumping station #3
P371	1949, 1968	33 45 21	118 04 37	Recovered	In drill hole on NE corner of loading dock on building 41
X1001	1965, 1968	33 45 08	118 04 34	Recovered	33 ft. SW of the SW corner of building GM-1, fourth lighting rod off of 3rd St to the south, cemented at base
Tidal 2	1958, 1964, 1965	33 44 15	118 05 27	Not Surveyed	264 ft. NE of building W1, in cement of first of two manholes after the 2nd paved road to the NW on the harbor side of the overpass under the 3rd lamppost
Tidal 1	1955, 1965, 1968, 2007	33 44 12	118 05 29	Not Surveyed	In blue ledge of the steps, 4 ft. SW of the entrance of building 302 on Kitts Hwy on the harbor side
Q280	1954, 1960, 1968, 2007	33 44 09	118 05 24	Not Surveyed	In blue ledge of the steps 11 ft. west of the south corner of building 305 (painted over blue)
Tidal 4	1959, 1964, 1968	33 44 10	118 05 27	Not Surveyed	In manhole by high voltage fence, 103 ft. west of building 305 and west of green fence in south corner of foundation
P280	1954, 1964, 1968	33 44 09	118 05 31	Not Surveyed	In the top of the cement wall of the wharf exactly at the end of Kilts Hwy (painted over yellow)
V1001	1965, 1968	33 44 13	118 05 36	Not Surveyed	In cement on top of wharf at the SW corner of the wharf, 4.5 ft. east of the west end
V1000	1965, 1968,	33 44 42	118 04 38	Missing	Set in the top of 12 inch concrete cylinder 26 feet west of power line pole # 1039842E, 47 ft. south of Bolsa avenue, 0.5 miles from Kitts Hwy
Y1001	1965,	33 45 08	118 04 05	Missing	81.5 feet south of a loading dock along building A0-1, 2.6 ft. SE of lighting pole and cemented in a drill hole at base

Benchmark	Year surveyed	Latitude	Longitude	Status	Location Description
C1001	1965, 1968	33 44 14	118 03 08	Missing	2 miles east along bolas avenue from Kitts Hwy, .5 miles south country to bunker 18, 119.5 ft. SW of the NE end of the bunker set in a drill hole in the NW side of the bunker
A1001	1965, 1968	33 44 14	118 02 33	Missing	2.5 miles east on Bolsa avenue from Kitts Hwy, .5 miles south on dirt road, 46 ft. east of dirt road, se in top of 12 in concrete cylinder 6 in below the surface of the ground
B1001	1965, 1968	33 43 53	118 02 34	Missing	2.5 miles east along Bolsa avenue from Kitts Hwy, 0.8 miles south along road, 10 feet east of road, and 1.3 ft. east of security fence, set in concrete cylinder 6 in below surface of the ground (New fence)
D1001	1965, 1968	33 43 51	118 03 06	Missing	2.5 miles East on Bolsa avenue from Kitts Hwy, 0.8 miles south along road, 0.5 miles west along road, 9 feet south of road, 1 ft. north of chain-link fence, set in 12 in concrete cylinder 6 in below surface of the ground (New fence)
E1001	1965, 1968	33 43 51	118 03 36	Missing	2.5 miles east on Bolsa avenue from Kitts Hwy, 0.8 miles south along road, 1 mile west along road, 40 ft. SW of the culvert headwall, 1 ft. north of a chain-link fence in concrete cylinder 6 in below surface of the ground (New fence)
Y1000	1965, 1968	33 44 42	118 03 06	Missing/Destroyed	2 miles east along Bolsa avenue from Kitts Hwy, 46 ft. north from Bolsa avenue, set in concrete cylinder 1.5 feet west of telephone pole (now tilled field)
Z1000	1965, 1968	33 44 40	118 02 33	Missing/Destroyed	new levee construction
W1001	1965, 1968	33 45 05	118 05 08	Missing/Destroyed	from building A-9, 95 ft. west of hussy road, cemented in drill hole north side of the steps at the east entrance and 2.8 feet above the surface of the ground (New Steps)
Tidal 3	1958, 1964, 1968	33 44 18	118 05 25	Missing/Destroyed	0.2 miles NE of building W1, 16 ft. NW of Kitts Hwy, in the top of the south concrete foundation of street light # 8 (New road)
U1001	1965, 1968	33 44 06	118 05 24	Missing/Destroyed	In SW corner of the U.S. Naval Weapons Station at seal beach, cemented in drill hole in the concrete wharf, 5.2 ft. north of the south edge of the concrete and 4 ft. west of the east end (New asphalt)

Benchmark	Year surveyed	Latitude	Longitude	Status	Location Description
T1001	1965, 1968	33 44 04	118 05 47	Missing/Destroyed	South corner of the west jetty on Anaheim Bay, 53 ft. north of a wooden dock (New construction on jetty)
G1001	1965, 1968	33 44 14	118 03 36	Destroyed	1.4 miles east on Bolsa avenue from Kitts Hwy, 0.1 mile south along paved road,0 .35 mile SE along track road, 66 ft. SW of an iron gate post, 39 ft. SE of track road set in top of 12 in concrete cylinder 5 in above surface of the ground

[Recovered= surveyed, Not Surveyed= found but not surveyed due to access and weather restraints, Missing= could not find (possible missing landmarks), Missing/Destroyed= could not find (likely destroyed during construction); Location Descriptions from NGS and RBF consulting. * Benchmarks 5206 & 5207 were survey control point identifiers from the 2010 RBF survey.]

Table 2. Data from National Geodetic Survey (NGS) OPUS corrections for benchmarks surveyed near Seal Beach National Wildlife Refuge

Benchmark	Duration (min.)	Number of Observations Used (%)	Normalized Root mean squared
p371	94	9522 (96)	0.254
U1000	78	4752 (72)	0.307
X1000	61	5319 (84)	0.318
X1001	64	6183 (84)	0.285

Table 3. Location and elevation change data for surveyed NGS benchmarks with ellipsoid height, standard deviation, and best estimates of total elevation change among surveys. Rates and total elevation change were calculated with NAVD88 elevations. (Table amended December 2013)

Benchmark	p371	U1000	*X1000*	X1001
SPSN	3371	1000	1200	2301
Latitude (N)	33° 45' 21.0405"	33 44' 41.52374"	33 44' 41.36912"	33 45' 4.49"
Longitude (W)	118 4' 37.07394"	118 5' 7.9"	118 3' 37.41366"	118 4' 41.2693"
Northing (m)	3735605.952	3734397.143	3734268.156	3735097.628
Easting (m)	400258.713	399452.625	401781.031	400145.451
NAVD88, 1968 (m)	4.764	3.537	3.122	3.566
NAVD88, 1994 (m)	4.648	3.424	2.995	3.447
NAVD88, 2012 (m)	4.607	3.287	2.926	3.397
Ellipsoid Height (m)	-31.015	-32.337	-32.661	-32.223
Ellipsoid StDev (m)	0.032	0.019	0.017	0.008
NADV88 StDev, 2012 (m)	0.039	0.029	0.028	0.024
Rate (mm/yr, 1968-1994)	-4.5	-4.3	-4.9	-4.6
Rate (mm/yr, 1968-2012)	-3.6	-5.7	-4.5	-3.8
Rate (mm/yr, 1994-2012)	-2.3	-7.6	-3.8	-2.8
Total Elevation Change (mm, 1968-1994)	-116	-113	-127	-119
Total Elevation Change (mm, 1994-2012)	-41	-137	-69	-50
Total Elevation Change (mm, 1968-2012)	-157	-250	-196	-169

Figure 1. Seal Beach National Wildlife Refuge location.

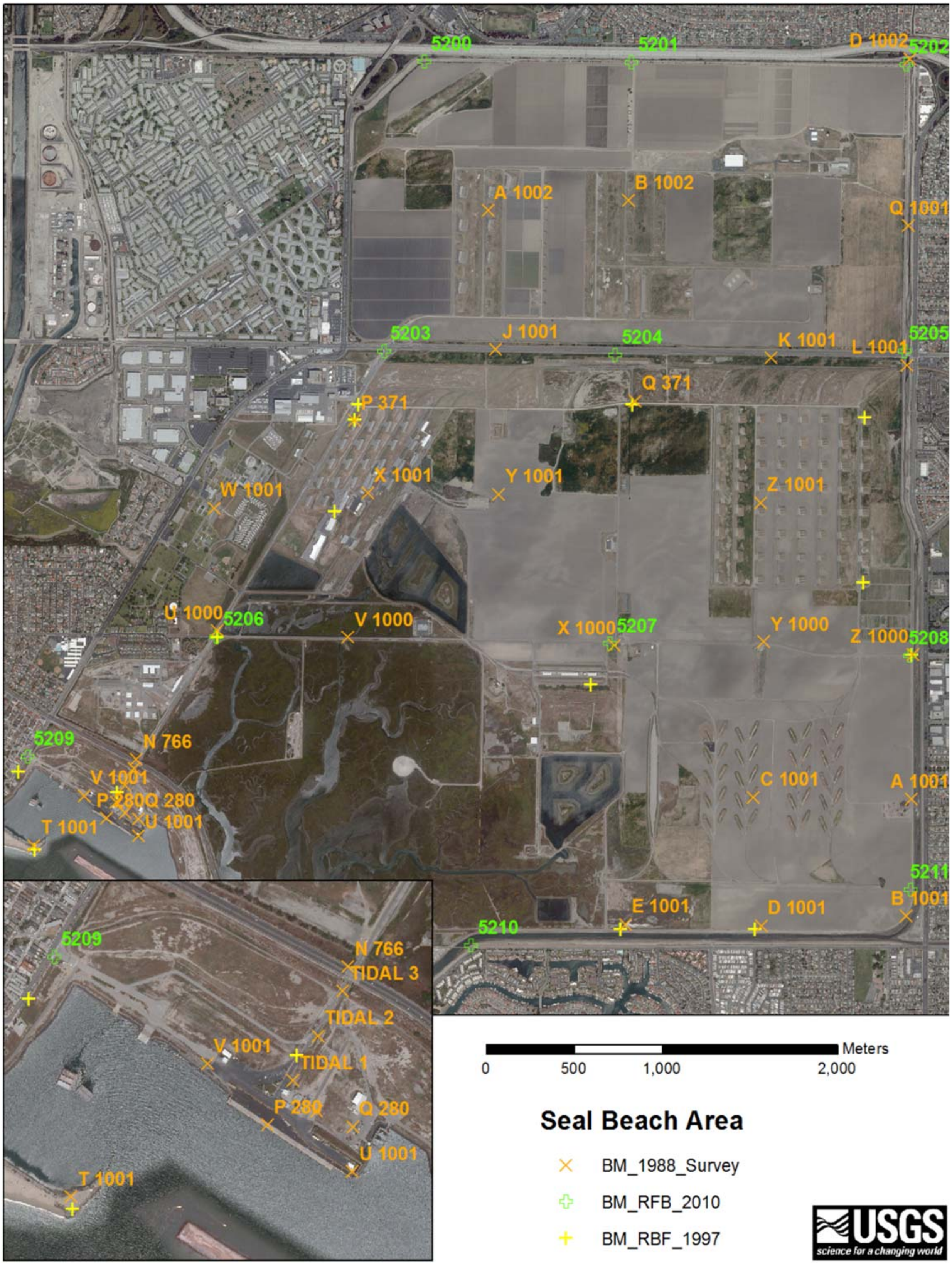

Figure 2. Naval Weapons Station Seal Beach. Locations of benchmarks and years surveyed.

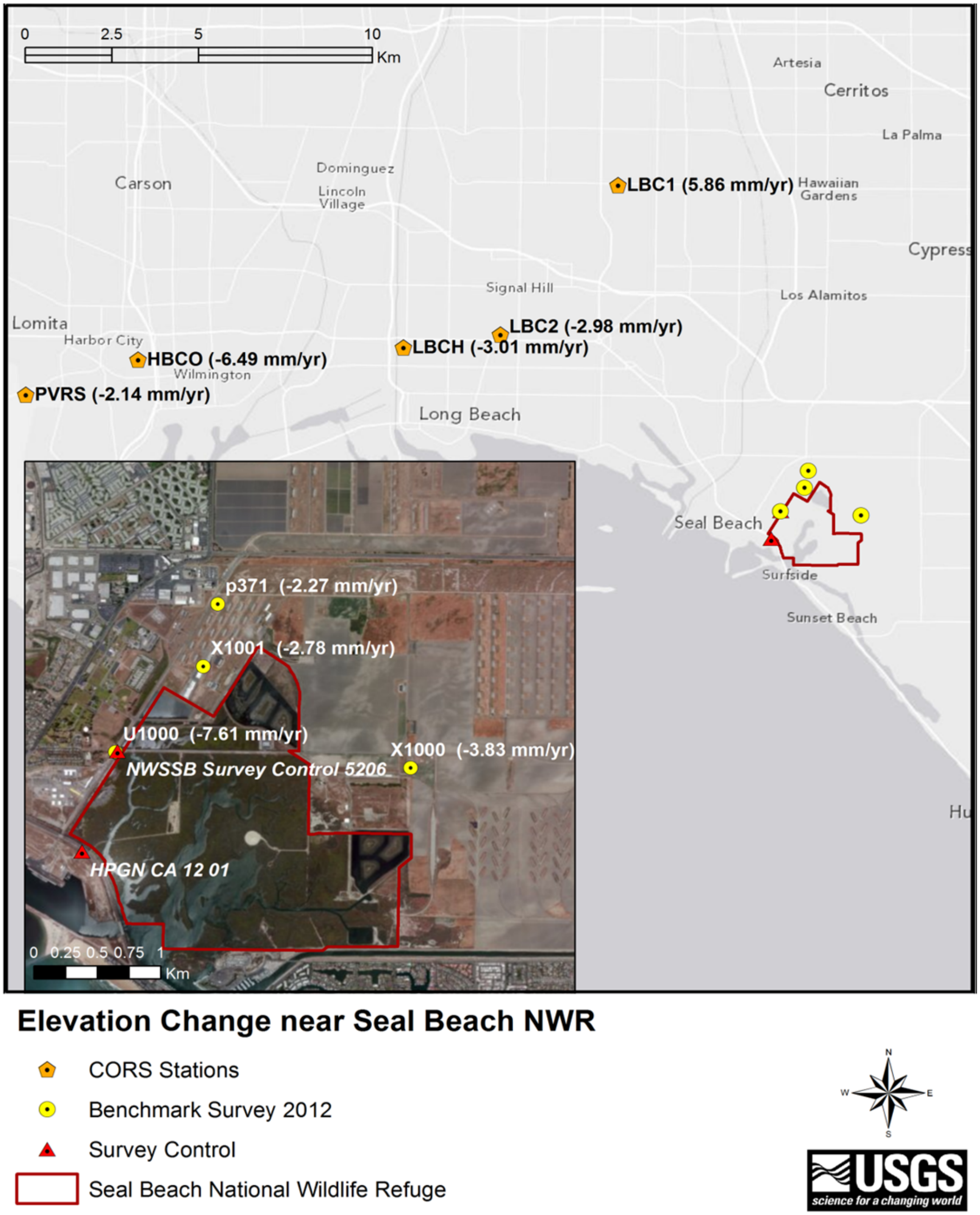

Figure 3. Locations of surveyed benchmarks at Seal Beach National Wildlife Refuge and nearby continuously operating CORS GPS stations.

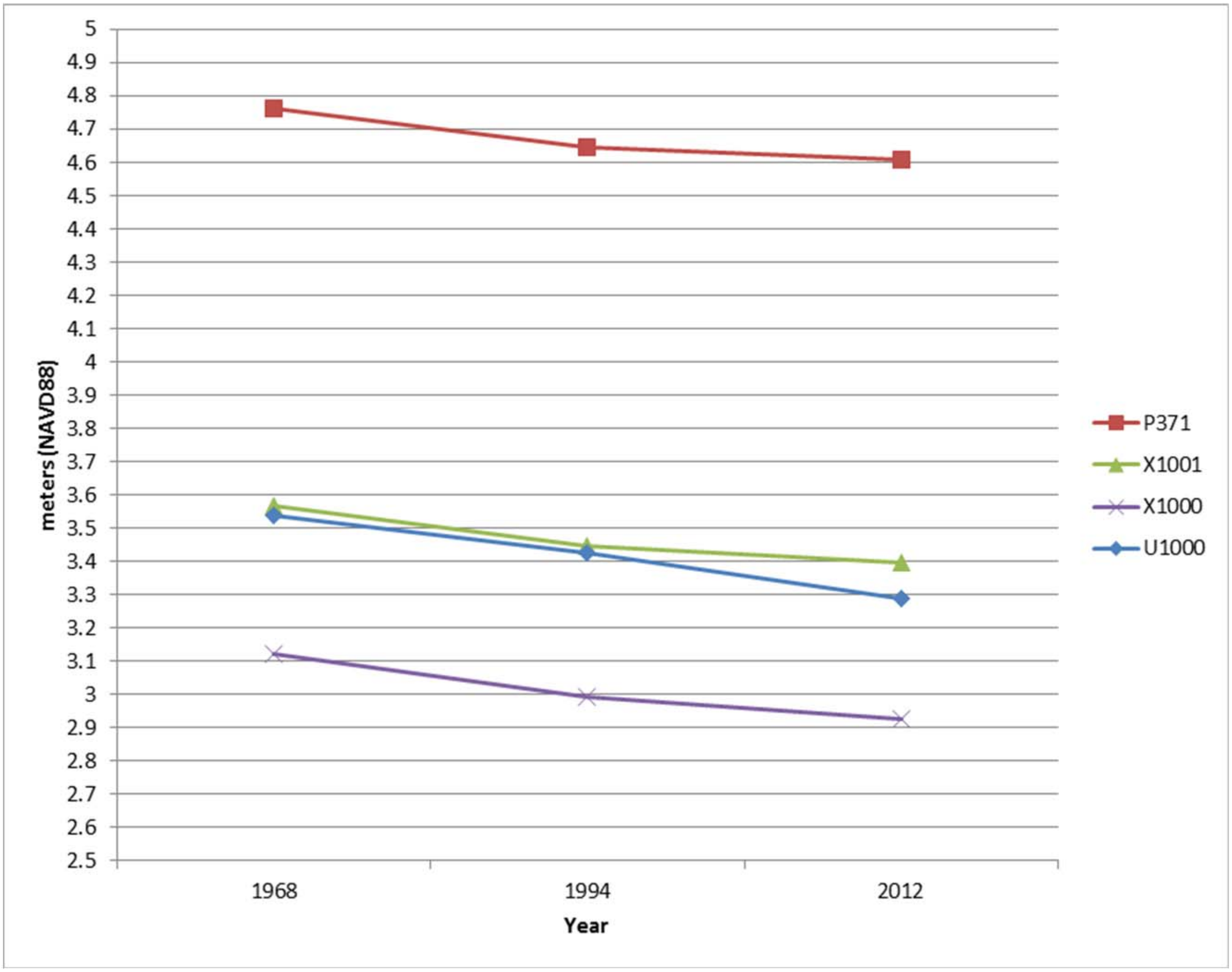

Figure 4. Elevation change of the four benchmarks resurveyed from 1968, 1994, and 2012.

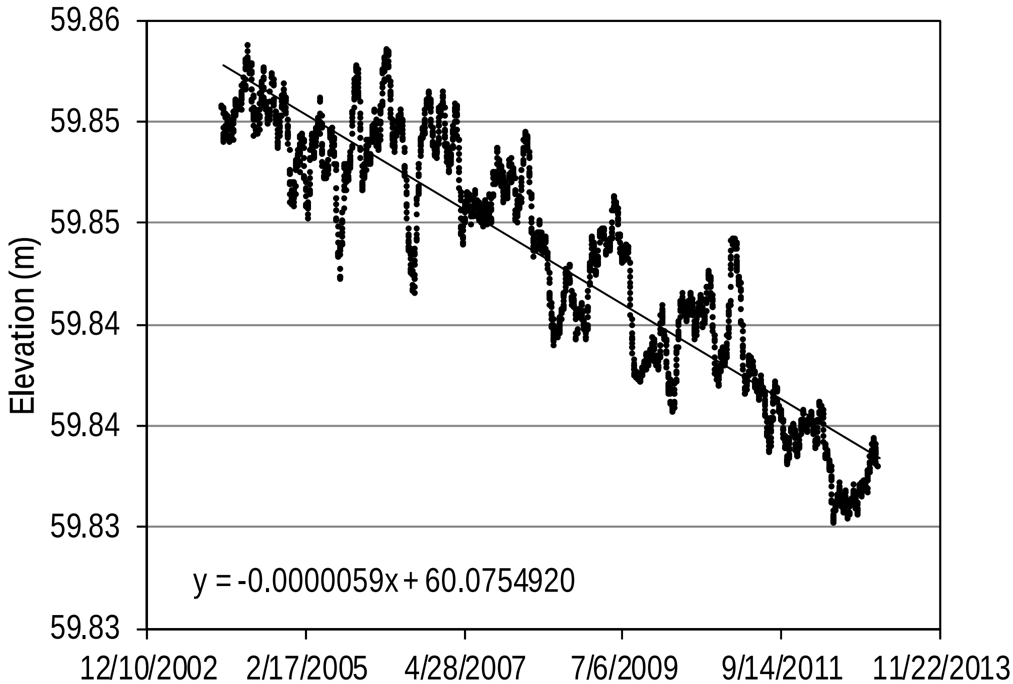

Figure 5. Elevation (m, ellipsoid height) of the PVRS CORS station. The rate of elevation change is - 2.14 mm/yr. Rates of elevation changes are yearly averages accounting for the time between measurements (for the benchmarks, 1994-2012) or the slope of a regression line fitted through elevation plotted against time.

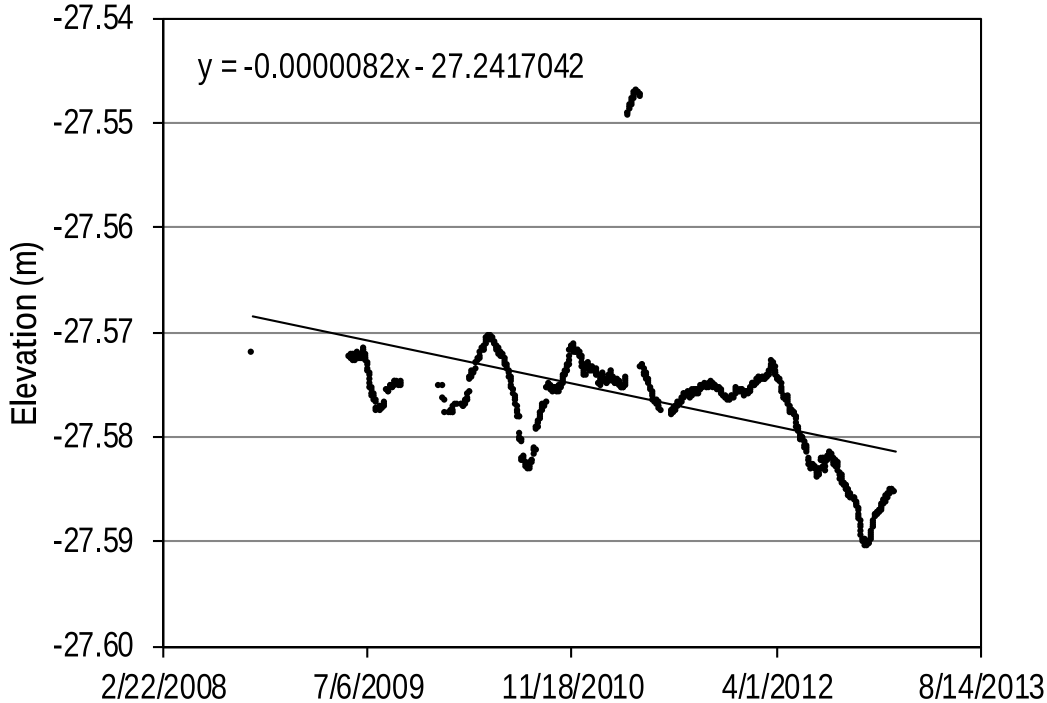

Figure 6. Elevation (m, ellipsoid height) of the LBCH CORS station. The rate of elevation change is - 3.01 mm/yr. Rates of elevation changes are yearly averages accounting for the time between measurements (for the benchmarks, 1994-2012) or the slope of a regression line fitted through elevation plotted against time.

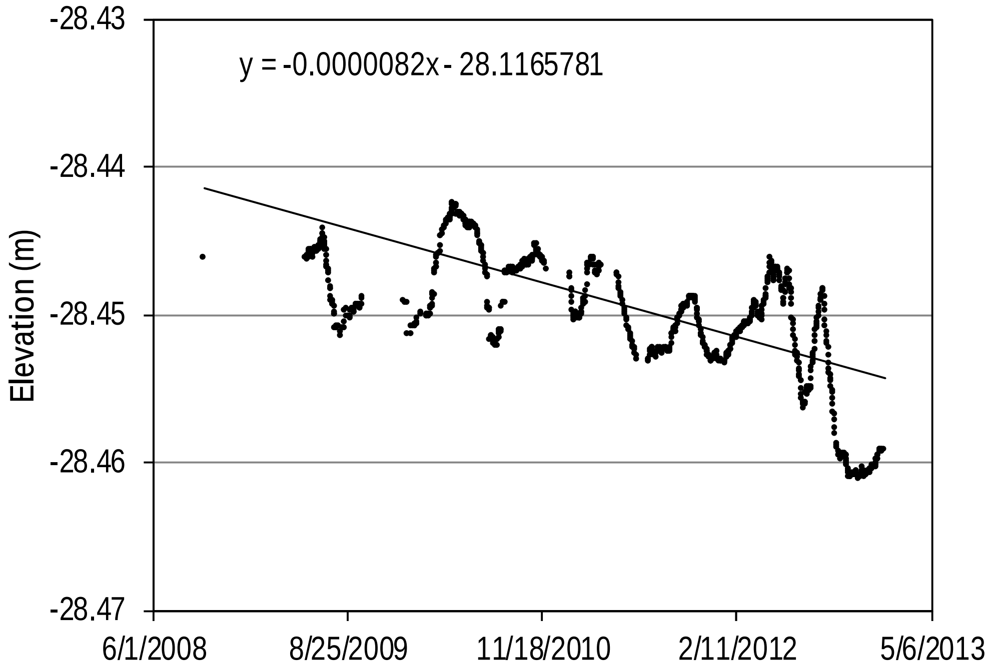

Figure 7. Elevation (m, ellipsoid height) of the LBC2 CORS station. The rate of elevation change is - 2.98 mm/yr. Rates of elevation changes are yearly averages accounting for the time between measurements (for the benchmarks, 1994-2012) or the slope of a regression line fitted through elevation plotted against time.

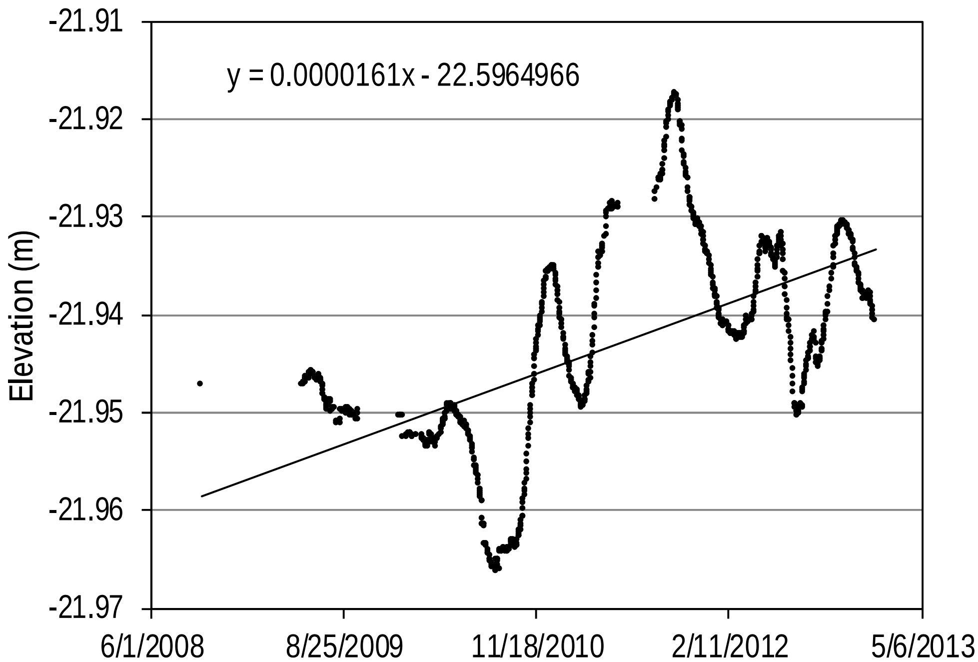

Figure 8. Elevation (m, ellipsoid height) of the LBC1 CORS station. The rate of elevation change is + 5.86 mm/yr. Rates of elevation changes are yearly averages accounting for the time between measurements (for the benchmarks, 1994-2012) or the slope of a regression line fitted through elevation plotted against time.

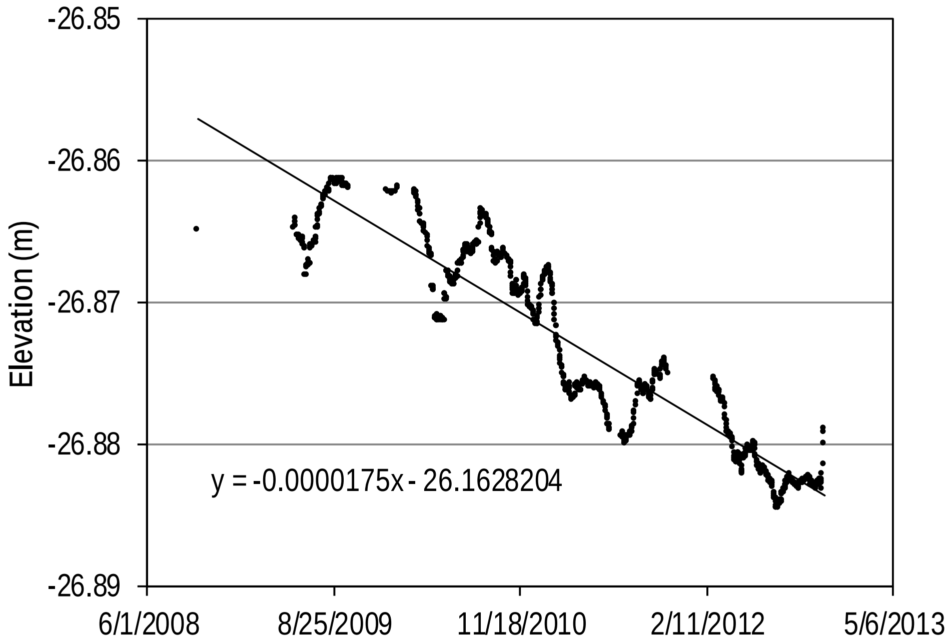

Figure 9. Elevation (m, ellipsoid height) of the HBCO CORS station. The rate of elevation change is - 6.49 mm/yr. Rates of elevation changes are yearly averages accounting for the time between measurements (for the benchmarks, 1994-2012) or the slope of a regression line fitted through elevation plotted against time.

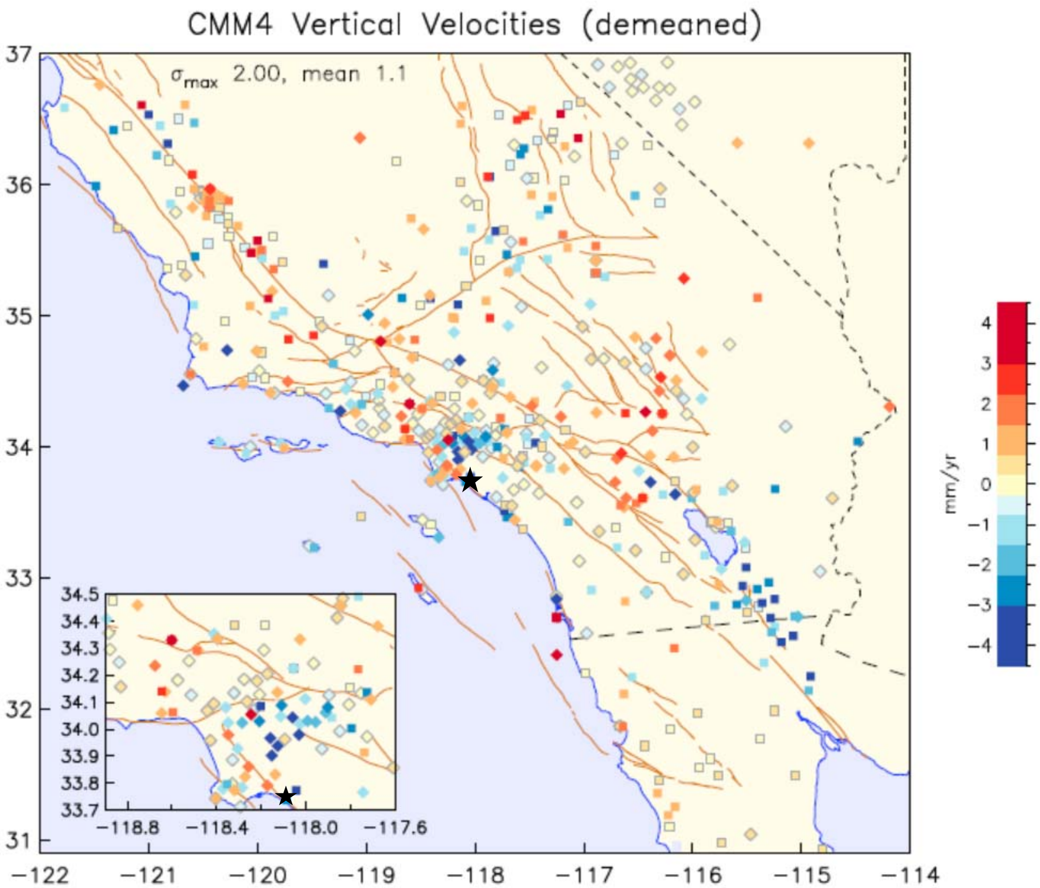

Figure 10. Vertical movement at crustal motion model stations, from Shen *et al.* 2011. Diamonds represent continuously operating GPS, while squares represent survey-mode GPS. The location of Seal Beach NWR is the represented by the black star.