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U.S. Geological Survey, Western Ecological Research Center

Data Summary Report Prepared for the U.S. Fish and Wildlife Service Region 8 Inventory and Monitoring Program and the California Landscape Conservation Cooperative

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Suggested Citation:

Takekawa, J.Y., Thorne, K.M., Buffington, K.J., Freeman, C.M., and Block G. 2013. Downscaling climate change models to local site conditions: San Diego National Wildlife Refuge Complex. Unpubl. Data Summary Report. U.S. Geological Survey, Western Ecological Research Center, Vallejo, CA. 100pp.

Executive Summary

- Southern California tidal marshes have been affected by coastal development and urbanization. Over the past 150 years, dredging and filling operations have resulted in the loss of 42% of San Diego Bay's historic shallow subtidal habitat, 84% of its intertidal mudflat habitat, and 70% of its salt marsh habitat (San Diego Bay NWR CCP 2006). The San Diego National Wildlife Refuge Complex, administered by the U.S. Fish & Wildlife Service, was established in 1972 with the goal of protecting rare birds, migratory species and marsh dependent species of southern California.

- Our study follows a bottom-up approach to evaluating local sea-level rise effects on tidal marshes. The study was conducted at the parcel scale while being relevant for landscape scale management. The objectives of this study were to: (1) develop high resolution digital elevation models (DEMs) for the salt marshes of the San Diego Refuge Complex, (2) monitor water levels and tidal cycles to assess parcel level inundation patterns and capture extreme water events, (3) inventory vegetation species composition and relationship to elevation and tidal ranges, and (4) develop sea-level rise marsh response models for Tijuana Slough marsh.

- This report contains baseline elevation, tidal range, and plant community results for the San Diego Bay National Wildlife Refuge Complex: Tijuana Slough National Wildlife Refuge (Tijuana), Sweetwater marsh unit (Sweetwater), South San Diego Bay unit (South Bay), and Seal Beach National Wildlife Refuge (Seal Beach).

- A total of 12,013 elevation points were measured across all sites between September and December 2011 with a Real Time Kinematic (RTK) GPS (± 2.5 cm vertical accuracy). 11,470 elevation data points were used to create digital elevation models (DEMs) for the marsh platforms. Elevation for all sites fell within a large range of 1.4 m (NAVD88) with 84% between 1.2 and 2.6 m. Across all sites mean elevation was 0.46 m (SD = 0.65) above mean high water (MHW).

- Vegetation was sampled in 0.25-m^2 quadrats at 2,855 locations across all sites. Distinct zonation in plant communities was observed in relation to elevation and tidal datum (MHW), because plants are typically restricted by their inundation tolerance and soil salinities. *Batis maritima* and *Sarcocornia pacifica* were the two most common species across all site; *B. maritima* occurred at 65% of the sampled quadrats, and *S. pacifica* occurred at 63% of all surveyed quadrats.

- Water level loggers were deployed at all sites (n=8) starting in September 2011. Water level data from September 2011 to January 2013 are presented in this report. Peak tide levels for this time period were averaged for each site to produce site-specific tidal datums for mean tide level (MTL), mean high water (MHW), and mean higher high water (MHHW).

- We used the Marsh Equilibrium Model (MEM) to project initial estimates of marsh elevation change under sea-level rise (SLR) scenarios to 2100 for Tijuana marsh. Results from the SLR response modeling for the north arm of the Tijuana marsh indicated that relative elevation will decrease through 2100 under mid (+93 cm) and high (+166 cm) SLR scenarios, but it will maintain elevation under the low (+44 cm) SLR scenario.

- MEM results were categorized by low, mid, and high marsh habitat types. Results showed that low marsh will decrease dramatically after 2030 under low SLR rates, whereas under mid SLR, low marsh will increase through 2090 before beginning to decrease. Under high SLR rates, low marsh increases to 2060 and then decreases until it disappears in 2090. Mid and high marsh will remain constant under low SLR rates. However, mid marsh decreases after 2060 and disappears after 2100 under mid SLR rates. Under high SLR rates, mid marsh decreases after 2030 and disappears after 2080. High marsh disappears after 2070 under mid SLR, and disappears after 2050 with high SLR.

- Ongoing work is underway to improve SLR marsh response modeling at Tijuana, Seal Beach and Sweetwater. This work includes the collection of soil cores at Tijuana (2012), Sweetwater (2013) and Seal Beach (2014) to assess long-term accretion rates. Installation of surface elevation tables (SETs) was completed at Tijuana (2012) and Seal Beach (2013) to assess accretion. Suspended sediment studies are being completed in the winter of 2013-2014 to determine sediment flux budgets at the subsided area of Seal Beach.

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1. INTRODUCTION

Climate change effects for coastal ecosystems include projected changes in mean and extreme ambient temperatures, precipitation patterns, ocean temperature and acidity, extreme storm events, and sea-level rise (Cayan and others, 2005; Hansen and others, 2006; IPCC 2007, NRC 2012). Projections of mean sea-level rise (SLR) to the year 2100 are characterized by high uncertainty because of the difficulty in modeling melting ice-sheet dynamics and other ocean processes. Global sea level has risen 1.8 millimeters per year (mm/year) between 1961 and 1993, and 3.1 mm/year since 1993 (IPCC 2007). Recent southern California SLR projections range from 44 - 166 cm by 2100, with a mean increase of 93 cm (NRC 2012).

Although global in distribution, the extent of tidal marshes is limited to the low-energy intertidal zones of temperate estuaries, with 16,000 square kilometers (km^2) found in North America (Greenberg and others, 2006). Tidal salt marshes are highly productive ecosystems found in the terrestrial-marine ecotones of mid to high-latitudes (Archibold 1995; Mitsch and Gosselink 2000). Marshes are dominated by plant communities that have varying tolerance to tidal inundation and salinity, resulting in zonation along the elevation gradient (Mancera and others, 2005). These low-lying areas are particularly vulnerable where variation in tidal depth and duration plays a major role in structuring these plant communities (Brittain and Craft, 2012).

In salt marshes, wildlife habitat diversity can be low because of the physiological conditions created by high salinity levels, tidal flooding, and low plant diversity. Fish, birds, marine mammals, several terrestrial mammals, and even a few reptiles are found living in or near salt marshes either as full-time residents or seasonal inhabitants and are adapted to survive in a dynamic tidal environment (Barbara W . Massey, 1984; Desmond, Zedler, & Williams, 2000; Rush et al., 2009; Thorne, Takekawa, & Elliott-Fisk, 2012; Tsao, Takekawa, Woo, Yee, & Evens, 2009). Studies have shown that wildlife populations in many ecosystems around the world are already responding to climate change effects (Parmesan 1996, 2006; Parmesan et al. 1999; Previtali et al. 2009; Solonen 2008; Thomas and Lennon 1999). Wildlife sensitivity and adaptability to climate change will depend on local rates of change and the ability of ecosystems to respond. Currently, many salt marsh vertebrates are listed as species of special concern or endangered species (Barbara W . Massey, 1984; Powell, 1993; Tsao et al., 2009; Zedler, 1996) whose ecology is often little-studied and poorly understood. Climate change will be one of the most significant factors threatening the longevity of salt marsh biodiversity (IPCC 2007; Cayan et al 2008a; Craft et al. 2009; FitzGerald et al. 2008; Kirwan et al. 2010; Menon et al. 2010).

Marshes will be affected by climate change through accelerating SLR (Holgate and Woodworth, 2004; Kemp and others, 2011), shifting precipitation patterns (Hamlet and Lettenmaier, 2007; Bengtsson and others, 2009), erosion (Leatherman and others, 2000), and changing frequency and intensity of storms (Emanuel, 2005; Webster and others, 2005; IPCC 2007). Marshes can keep pace with changes in local sea level through accretion processes that include sediment deposition and organic matter accumulation (Morris and others, 2002; Geden and others, 2011) if local suspended-sediment concentrations and organic production are high enough (Kirwan et al., 2010). However, marshes can be lost if SLR outpaces vertical accretion processes and upslope transgression is limited (Callaway, Parker, Vasey, & Shile, 2007; Morris, Sundareshwar, Nietch, Kjerfve, & Cahoon, 2002b).

Ecosystem effects from climate change typically address top-down global to continental scale changes; thus, few are easily interpretable to resource managers or contain vertical resolution that is precise enough to be useful at the local level for wetland adaptation planning. Our studies are directed at a bottom-up approach to evaluate SLR and storm effects for individual parcels providing information and databases at higher resolution useful in assessing local SLR responses that can be extended to a regional scale. Thus, the objectives of this study were to: (1) develop high resolution digital elevation models (DEMs), (2) monitor water levels and tidal cycles to assess parcel level inundation patterns and extreme water events, (3) inventory plant species composition and relationship to elevation and tidal ranges, and (4) develop SLR marsh response models for Tijuana Estuary.

2. STUDY AREA

Southern California tidal marshes have been heavily modified and affected by coastal development and urbanization with as much as 75% of historic tidal marshes lost region wide and 90% lost in San Diego Bay (Larson 2001). Over the past 150 years, dredging and filling operations have resulted in the loss of 42% of San Diego Bay's historic shallow subtidal habitat, 84% of its intertidal mudflat habitat, and 70% of its salt marsh habitat (San Diego Bay NWR CCP, 2006). The remaining marshes provide crucial habitat for Pacific Flyway wintering shorebirds and waterfowl, as well as for numerous threatened and endangered resident species. In particular, the federally endangered Light-footed Clapper Rail (*Rallus longirostris levipes*), California Least Tern (*Sternula antillarum browni*), Belding's Savannah Sparrow (*Passerculus sandwichensis beldingi*), green sea turtles (*Chelonia mydas*), and the Salt Marsh Bird's-Beak (*Cordylanthus maritimus*) plant are important marsh species in our study areas.

The San Diego Bay National Wildlife Refuge complex was established in 1972 and is administered by the U.S. Fish & Wildlife Service with the goal of protecting rare and endangered bird species of southern California's coastal marshes. In 1998, it was expanded to include the South San Diego Bay unit. The complex encompasses 1,885 hectares of diverse habitats that include coastal marshes and uplands, coastal sage scrub, and breeding and nesting grounds for a suite of migratory and resident bird species. The study sites encompass most of the tidal salt marsh of the San Diego Bay National Wildlife Refuge Complex: Tijuana Slough National Wildlife Refuge (Tijuana), Sweetwater marsh unit (Sweetwater), South San Diego Bay unit (South Bay), and Seal Beach National Wildlife Refuge (Seal Beach) (Fig. 1).

Tijuana NWR is located on the southern side of Imperial Beach, CA, along the Pacific Ocean just north of the U.S. Mexico border. It comprises 425 ha of beaches, open water, tidal marsh, and upland habitats. Our study area is composed of 376 ha of tidal marsh and upland. The South San Diego Bay unit is located on the northern side of Imperial Beach and encompasses 1594 ha; our study site was a 15 ha mudflat and proposed salt marsh restoration area. Sweetwater Marsh unit is located west of Chula Vista, on the eastern shore of the San Diego Bay, and is comprised of several marsh parcels totaling 128 ha, of which 63 ha made up our study site. Seal Beach NWR is located in Orange County, just south of Long Beach, CA. Seal Beach NWR is a 390 ha salt marsh, 266 ha of which made up our study area, and it is completely enclosed within Naval Weapons Station Seal Beach.

The San Diego NWR Complex protects a rich diversity of endangered marsh species. With low dispersal ability and specialized habitat requirements, these species are especially vulnerable to sea-level rise scenarios. Three species were identified as management concerns: salt marsh bird's beak (*Chloropyron maritimum* subspp. *maritimum*), light-footed clapper rail (*Rallus longirostris levipes*), and the Belding's savannah sparrow (*Passerculus sandwichensis beldingi*). Vegetation habitat requirements for these species were used to categorize future impacts from sea-level rise.

Salt Marsh Bird's Beak (*Chloropyron maritimum* ssp. *maritimum)*

Salt marsh bird's beak was listed as endangered under the Endangered Species Act in 1978. It is currently known to persist in seven coastal salt marshes: San Diego County at Tijuana Estuary (separated into Border Field State Park and Tijuana Slough NWR); Naval Radar Receiving Facility (NRRF) and Sweetwater Marsh Unit of San Diego Bay NWR; Orange County at Upper Newport Bay (State) Ecological Reserve; Ventura County at Naval Base Ventura County, Point Mugu; Santa Barbara County at Carpinteria Salt Marsh; San Luis Obispo County at Morro Bay.

Salt marsh bird's beak is an annual hemiparasitic and halophytic plant that has a naturally patchy distribution in sites subject to higher tidal influxes in coastal salt marshes. Salt marsh bird's beak was reported from the higher areas, identified as the middle littoral zone by Purer (1942, p. 84) growing with species of *Sarcocornia, Distichlis, Frankenia, Suaeda*, and *Atriplex*. The middle littoral zone is distinguished as the interface between the lower littoral zone that is inundated twice daily with tidal flows and the upper littoral zone that is partially inundated only during high tides (Purer 1942, p. 93).

The number of individuals at eight colonies in the northern portion of the Tijuana Estuary in 1981 ranged from 0 to 1,000 plants (Dunn and Zedler 1981, p. 4). After restoration plantings at Sweetwater between 1990 and 1992, individual plants numbered 14,000 in 1995. The size, position, and configuration of local occurrences may also change over time (MEC Analytical Systems, Inc. 2003, p. 4). If suitable host plants or native pollinators are not present, it is unlikely that any *C. maritimum* ssp. *maritimum* plants would persist to reproductive maturity (Noe and Zedler, 2000; Parsons and Zedler, 1997).

Salt marsh bird's beak, like many marsh endemics, is vulnerable to SLR for three main reasons: 1) the plants are restricted to mid tidal marsh zones; 2) the habitat is subject to hydrological fluctuations, where small changes in inundation could impact the plants; and 3) plants are hemiparasitic on associated salt marsh taxa. This species is categorized within the mid-marsh vegetation community based on Purer (1942, p. 84) classification and the location of its host plants.

Light-Footed Clapper Rail (*Rallus longirostris levipes*)

The Light-footed Clapper Rail was federally listed as an endangered species in 1970. They are a medium sized, tawny and gray-brown marsh bird that inhabits coastal marshes, lagoons, and maritime environments in southern California of the U. S., and northern Baja California of Mexico. Light-footed

Clapper Rails are omnivorous and opportunistic foragers, relying mostly on salt marsh invertebrates. They require shallow water and mudflats for foraging with adjacent higher vegetation for cover during high tide (Zeiner et al. 1990, p. 174). They forage in all parts of the salt marsh, concentrating their efforts in the lower marsh when the tide is out, and moving into the higher marsh as the tide advances. Nesting habitat includes tall, dense cordgrass (*Spartina foliosa*) and occasionally pickleweed (*Sarcocornia* spp.) in the low littoral zone, wrack deposits in the low marsh zone, and hummocks of high marsh within the low marsh zone (Massey et al. 1984, p. 78).

In a census of 19 marshes during 2007, eight marshes contained 92% of the light footed clapper rails counted; two of those marshes were the Seal Beach NWR (ranked second) and Tijuana NWR (ranked third). Loss and degradation of habitat threaten the continued existence of this bird, in spite of ongoing management efforts. Since Light-Footed Clapper Rails use low marsh for foraging and nesting, they were categorized within the low marsh vegetation community for the SLR scenarios.

Belding's Savannah Sparrow (*Passerculus sandwichensis belding*i)

The Belding's Savannah Sparrow resides year-round in the coastal salt marshes of southern California. This subspecies of Savannah Sparrow is a salt marsh endemic ranging historically from Santa Barbara County, California in the north, south to Baja California, Mexico (American Ornithologists Union 1983, Grinnell and Miller 1944, and Van Rossen 1947). Belding's are ecologically associated with dense pickleweed (*Sarcocornia* spp.), and most nests are found within this species. At Tijuana Estuary, Belding's more often nest in *Lycium californicum* (California boxthorn) and *Anthrocnemum subterminale* (Parish's glasswort, formerly *Salicornia subterminalis*) which are not inundated by higher tides. Breeding territories can be very small, and birds nest semi-colonially or locally concentrated within a larger block of habitat, all of which may appear generally suitable, although pairs are territorial and will deter conspecifics from their nesting territories. On the basis of the 2010 surveys, Belding's are doing well within their range in California but especially at Point Mugu Naval Weapons Station, Seal Beach NWR, Bolsa Chica Ecological Reserve, Upper Newport Bay Ecological Reserve, Sweetwater Marsh NWR, and Tijuana Slough NWR.

The Seal Beach subpopulation increased 11% from 2001 to 2010, comprising the second largest population in California. Many of the Belding's were concentrated in pickleweed in the muted tidal regime area north of Bolsa Avenue (130 pairs), including 12 pairs on the edge of the 3 islands in the north restoration area. The Tijuana Slough NWR subpopulation ranked third largest in California in 2010. The

Sweetwater NWR had the sixth largest subpopulation in California in 2010 after a 75% increase from 2006. The Belding's Savannah Sparrow was categorized within the mid and high marsh vegetation communities on the basis of its nesting habitat requirements of dense pickleweed and higher elevations that are less frequently inundated.

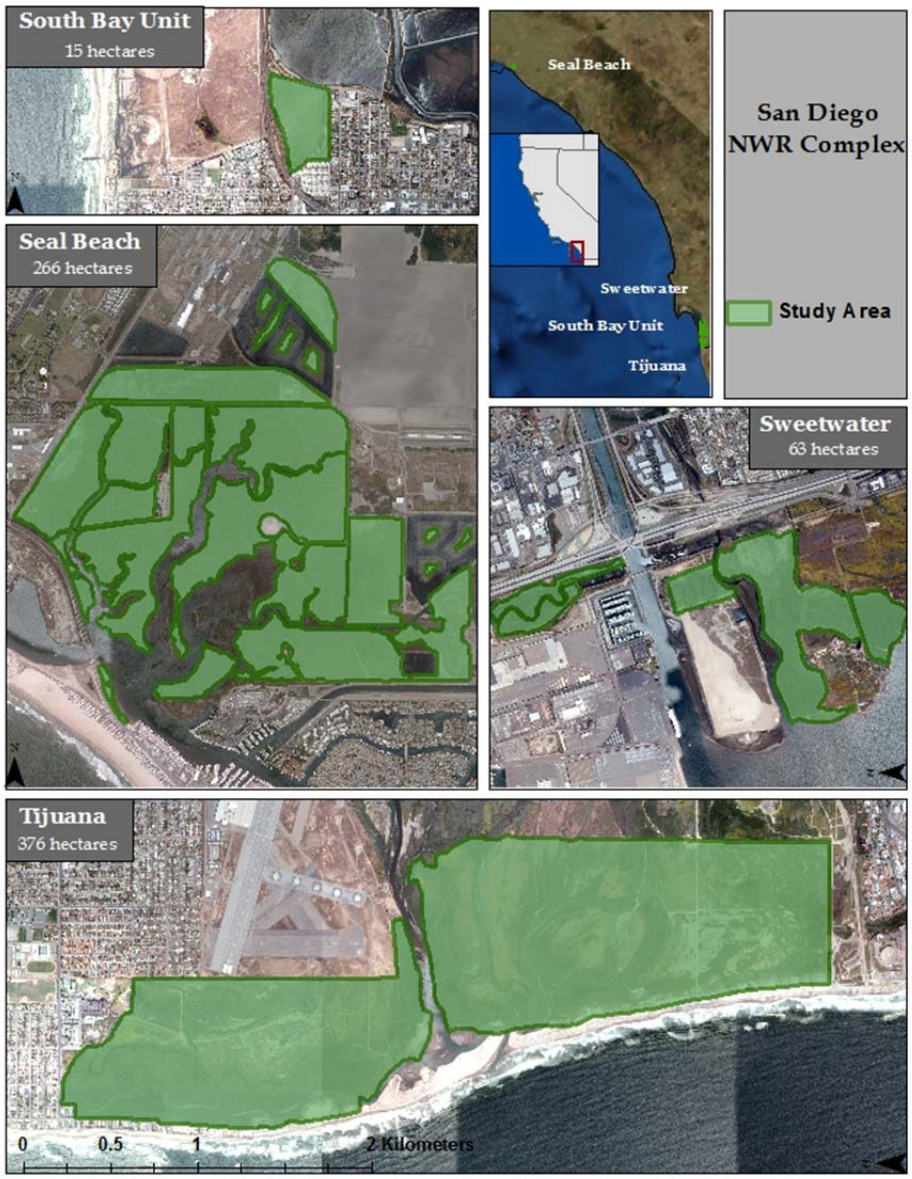

Figure 1. San Diego National Wildlife Refuge complex study areas

3. METHODS

3.1 Elevation surveys

Survey-grade elevation surveys were done at San Diego NWR Complex marshes between September and December 2011 with a Leica Viva Real Time Kinematic (RTK) Global Positioning System (GPS) rover (accuracy: ±1 cm x, y; ±2 cm z; Leica Geosystems Inc., Norcross, GA, Fig. 2). The rover positions were received in real time from the Leica GS10 antenna base station at the refuge headquarters via radio link. We used the WGS84 ellipsoid model for vertical and horizontal positioning. Positions were referenced to nearby benchmarks with known elevation heights (Table 1). The average measured vertical error for the benchmarks throughout the study was less then ±3 cm, near the stated error of the RTK GPS. Survey transects were oriented perpendicular to the water, with a survey point taken every 12.5 m; 50 m separated transect lines. The Geoid09 model was used in calculating elevations from ellipsoid to orthometric heights (NAVD88; North American Vertical Datum of 1988) and all points were projected to NAD83 UTM zone 11 using Leica GeoOffice (Leica Geosystems Inc., Norcross, GA, v 7.0.1).

Figure 2. Elevation survey conducted with RTK GPS at Tijuana Slough NWR

Table 1. NGS reference benchmarks used to assess error in elevation surveys

Site	Benchmark	Latitude (N)	Longitude (W)	Error Range
South Bay	B 899	32° 35’ 38’’	117° 07’ 21’’	NA
Sweetwater	S 57 RESET	32° 38’ 10.5’’	117° 05’ 53.7’’	0.023
Tijuana Slough	B 899	32° 35’ 38’’	117° 07’ 21’’	0.041
Seal Beach	BM # 5206	33° 44’ 41.76’’	118° 5’ 7.14’’	0.052

3.2 ArcGIS modeling

We synthesized the elevation survey data to create an elevation raster or digital elevation model (DEM) in ArcGIS 10.0 Spatial Analyst (ERSI 2009, Redlands, CA) with Kriging methods (5 x 5 m cell size). The exponential model for Ordinary Kriging was used and model parameters were adjusted to minimize the root-mean-square error (RMS), an internal measure of model performance. The elevation models were then used as the baseline conditions for subsequent analyses including tidal inundation patterns, SLR response modeling, and plant community relationships.

3.3 Vegetation surveys

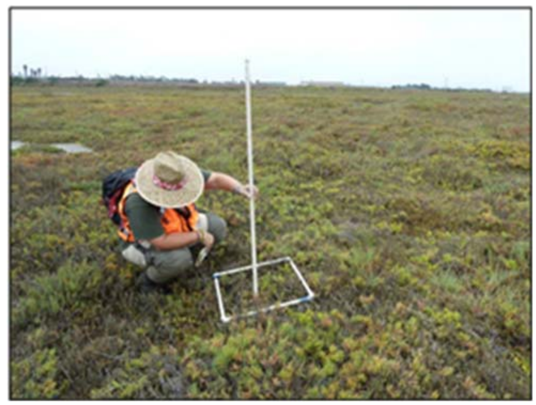

Figure 3. Vegetation surveys were conducted concurrently with elevation.

Vegetation surveys were done concurrently with elevation surveys at 25% of the elevation points for each site. For all plant species within a 0.25 m^2 quadrat, average and maximum height (within 0.05 cm) were measured along with estimated percent cover (Fig. 3). Vegetation was then related to elevation and tidal datum (m, NAVD88). For Tijuana NWR, plant species were categorized into low, mid, high marsh, and upland transition by measuring elevation relative to mean sea level (MSL, m), which was used to relate to changing elevations with SLR.

3.4 Water level monitoring

Figure 4. Water level loggers collected tidal data

We deployed a total of eight water level data loggers (Model 3001 LT, 0.01% FS resolution, Solinst Canada Ltd., Georgetown, Ontario) with four at Tijuana, two at

Sweetwater, and two at Seal Beach (Fig. 4). Loggers were placed at the mouth and upper reaches of second-order channels (tidal creeks) to capture the local tidal cycle and inundation patterns of the marsh. Water level data were collected continuously every six minutes from the fall of 2011 to the summer of 2013 to develop local hydrographs by season and month. Loggers were surveyed with the RTK GPS at the time of deployment. Water levels were corrected for local barometric pressure with data from independent barometric loggers (Model 3001, 0.05% FS accuracy, Solinst Canada Ltd., Georgetown, Ontario).

The local water level data were used to develop elevation and tidal datum relationships for all sites. Water level data throughout 2011 and 2012 were averaged to create mean tide level (MTL), mean high water (MHW), and mean higher high water (MHHW) datums relative to NAVD88 for each site. All results are reported relative to local MHW, calculated from local water data. MHW and MHHW are important metrics for understanding plant marsh communities and wildlife habitats.

3.5 Tijuana sea-level rise response modeling

We used the Marsh Equilibrium Model (MEM) to project estimates of marsh elevation under SLR scenarios (v. 3.4, Morris 2010; http://jellyfish.geol.sc.edu/model/marsh/mem.asp). MEM is a 1-D model of SLR response for tidal marshes. The basis of MEM is the productivity curve of biomass against elevation developed for tidal marshes (Morris, Sundareshwar, Nietch, Kjerfve, & Cahoon, 2002a). MEM uses estimates of mean annual suspended sediment concentration (SSC), organic matter decay rate, root to shoot ratio of dominant vegetation, refractory fraction of carbon, root depth, trapping efficiency, and sediment settling velocity as inputs. We used data from the literature to parameterize MEM for a pickleweed dominated marsh along with site-specific measurements of elevation and tidal datum (Table 2). For parameters with no pickleweed-specific data, we used the default value given in the MEM online tool. SSC at Tijuana is episodically driven by rain events, which occur primarily during the winter. We ran MEM with a range of SSC values to illustrate the sensitivity of the model to this important variable. In addition, we ran MEM for three SLR scenarios representing the lower, mean, and upper range of sea-level projections through 2110 at Los Angeles, CA (NRC 2012).

We ran MEM at three elevations for the North Arm marsh area of Tijuana NWR (Fig 17-22), representing the mean ±2 SD of elevations as determined from the DEM developed from the RTK GPS surveys. To project results spatially, we used a distance-weighted algorithm for elevation such that for a given initial elevation, $E(t_0)$, within the appropriate projected elevation (120-150, 150-180 cm) was used to calculate $E(t_x)$. Projections for initial elevations outside the range were calculated using the nearest projected elevation without the distance weighted function.

Plant communities were correlated with current elevation and projected with changing elevation to interpret results to 2110. We defined communities based on elevation by first including only species found in at least 5% of the survey plots across the entire marsh, reducing the number of species to eight. A one-way ANOVA was run for species and elevation. We then calculated pair-wise comparisons of elevation by species and determined significant differences using Tukey HSD tests. The elevation mean and SD for statistically similar species were again averaged and plotted as a normal distribution. The range of each community was determined by the intersections of the normal distribution curves among communities. The upper and lower ranges were determined by the mean ±2 SD of the upper and lower community (Table 8) and applied to provide the MEM model inputs (Table 2).

Table 2. Input parameters for the Marsh Equilibrium Model v. 3.4. Three sea-level rise scenarios were considered with four mean annual suspended sediment concentrations for a total of 12 model runs.

Parameters	Input	Units	Source
Start	2011	Year	-
Century Sea Level Rise	44, 93,166	Cm	NRC 2012
Mean High Water	141	cm NAVD	This study
Mean Sea Level	83.3	cm NAVD	This study
Lunar Nodal Amp	3.1	Cm	Default
Initial Rate sea-level rise	0.207	cm/yr	www.tidesandcurrents.noaa.gov
Suspended Sed. Conc.	20, 50, 100, 300	mg/liter	-
Marsh Elevation	120, 150, 180	cm NAVD	mean ± 2 SD

Biological Inputs			
Max Veg Elevation	239	Cm	This study
Min Veg Elevation	95	Cm	This study
Max Peak Biomass	700	g/m^2	Boyer *et al.* 2001
OM Decay rate	-0.8	1/time	Default
Root & Rhizome:Shoot Ratio	2.41	g/g	Woo & Takekawa 2012
BG turnover rate	3	$year^{-1}$	Default
Refractory Fraction (kr)	0.12	g/g	Callaway *et al.* 2012
Max (95%) Root Depth	10	cm	Default

Trapping Coefficient & Settling Velocity			
Ks	0.0322	$cm^{-1}\ yr^{-1}$	Default
Q	0.0015	$g\ cm^{-2}\ yr^{-1}$	Default

4. RESULTS

4.1 Elevation

A total of 12,013 elevation points were measured from September to December 2011, and 11,470 were used to create digital elevation models (DEMs) for the marsh platforms (Fig. 5, Fig 10, Table 3). Elevation fell within a range of 1.4 m with 84% of the surveyed points between 1.2 and 2.6 m (NAVD 88; Fig. 6). Across all sites, the mean elevation was 0.46 m (SD = 0.65) above MHW (Fig. 7, 8). The interpolated elevation models for all sites had a RMS error of 0.105 m (Table 4). Tijuana Marsh had the highest elevation, whereas South Bay was the lowest marsh surveyed relative to MHW (Fig 9).

Table 3. Number of elevation and vegetation data samples collected for each site.

Study Site	Area (ha)	Elevation points (n)	Mean Elevation (m)	Elevation Range (m)	Vegetation quadrats (n)
San Diego Bay	15	140	1.53	2.01	15
Seal Beach	266	4,297	1.38	2.92	1,083
Sweetwater Marsh	63	1,200	1.64	2.02	274
Tijuana Slough	376	5,830	2.22	4.33	1,483
Total	720	11,470	1.70	*2.82	2,855

*Average elevation range (m) for all study sites

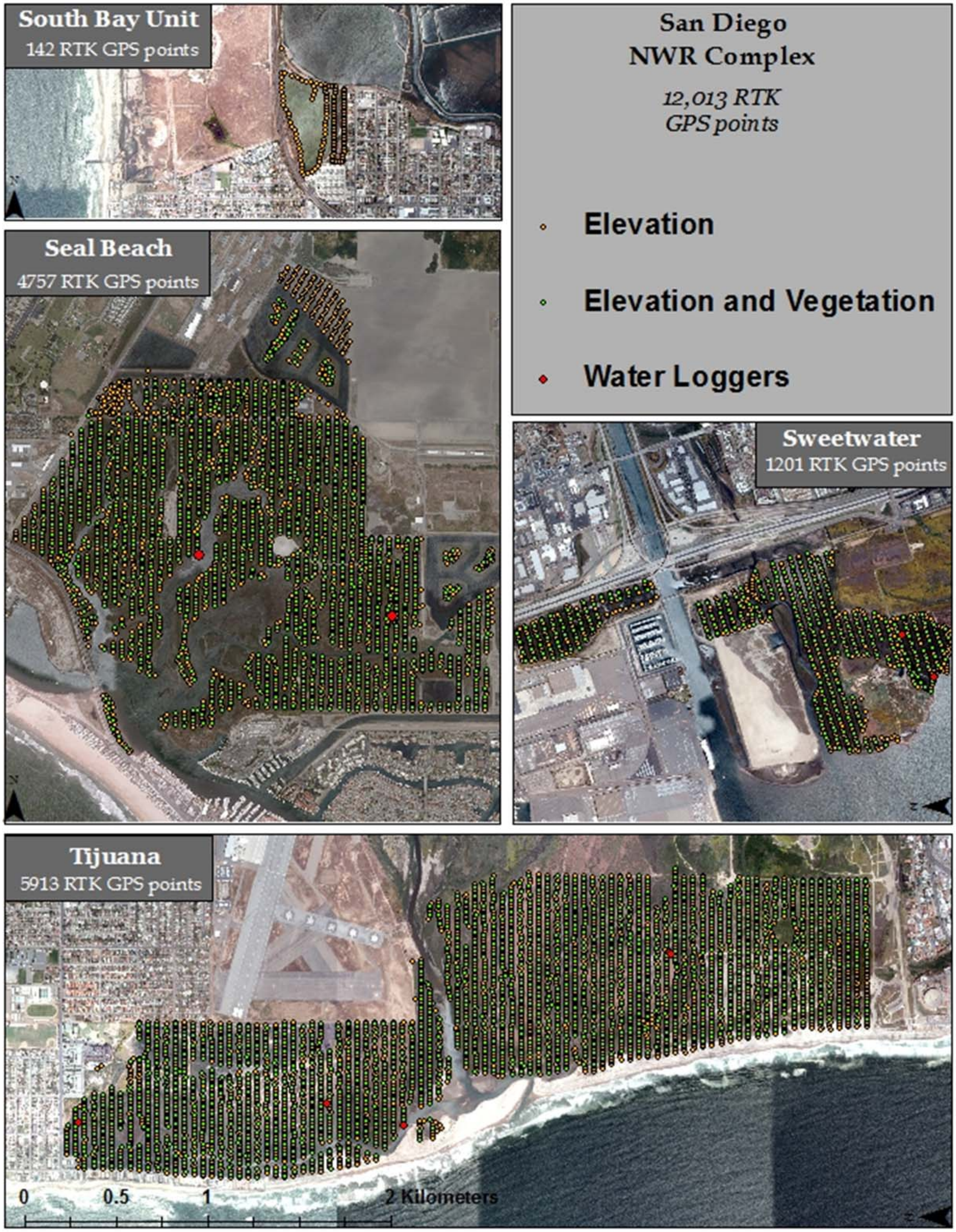

Figure 5. Elevation (yellow circles) and vegetation (green circles) sample points. Red circles indicate water level logger locations.

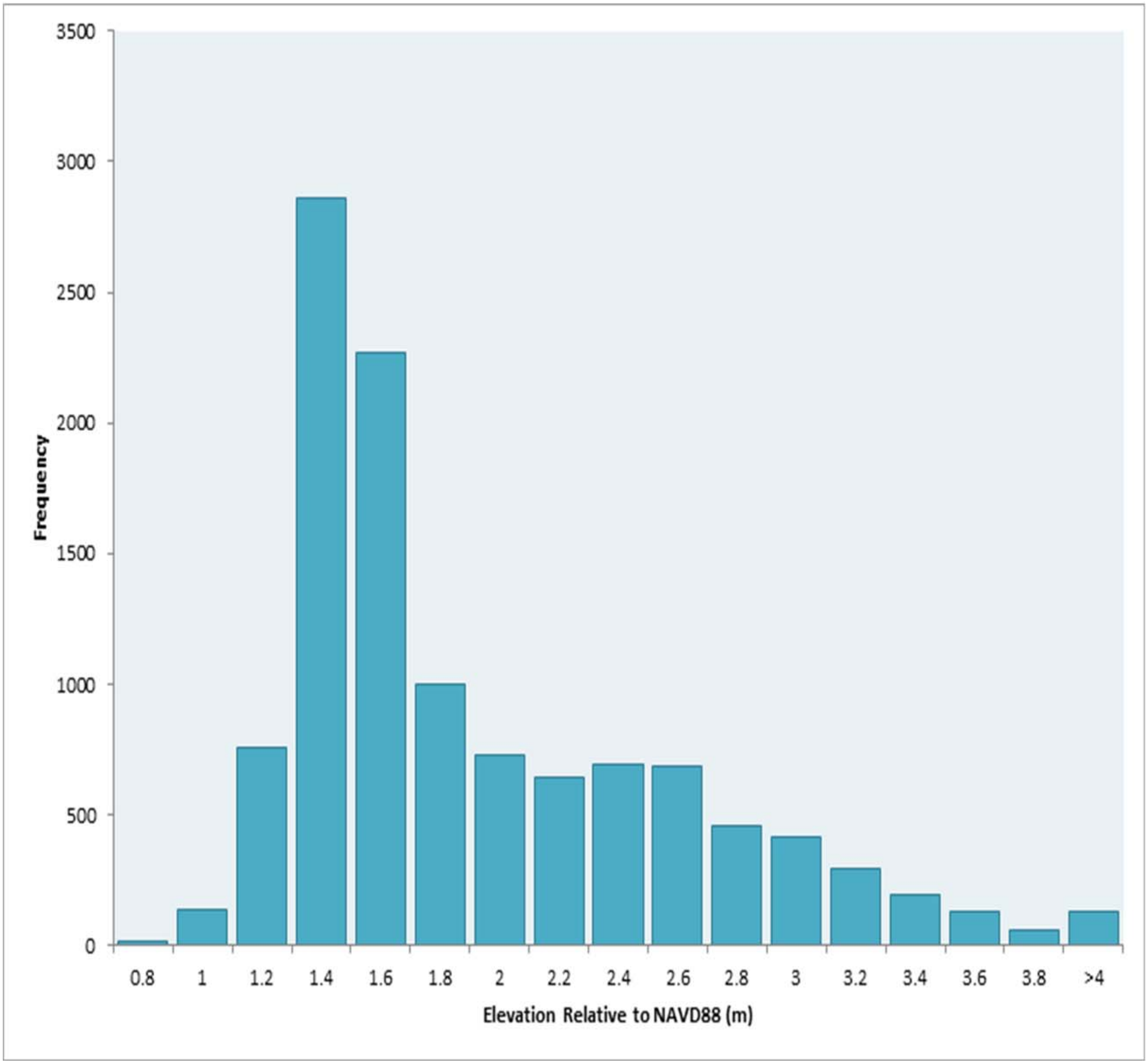

Figure 6. Distribution of marsh elevations relative to NAVD88 in meters (m) for all study sites in the San Diego NWR Complex (Tijuana River, South San Diego Bay, Sweetwater, Seal Beach).

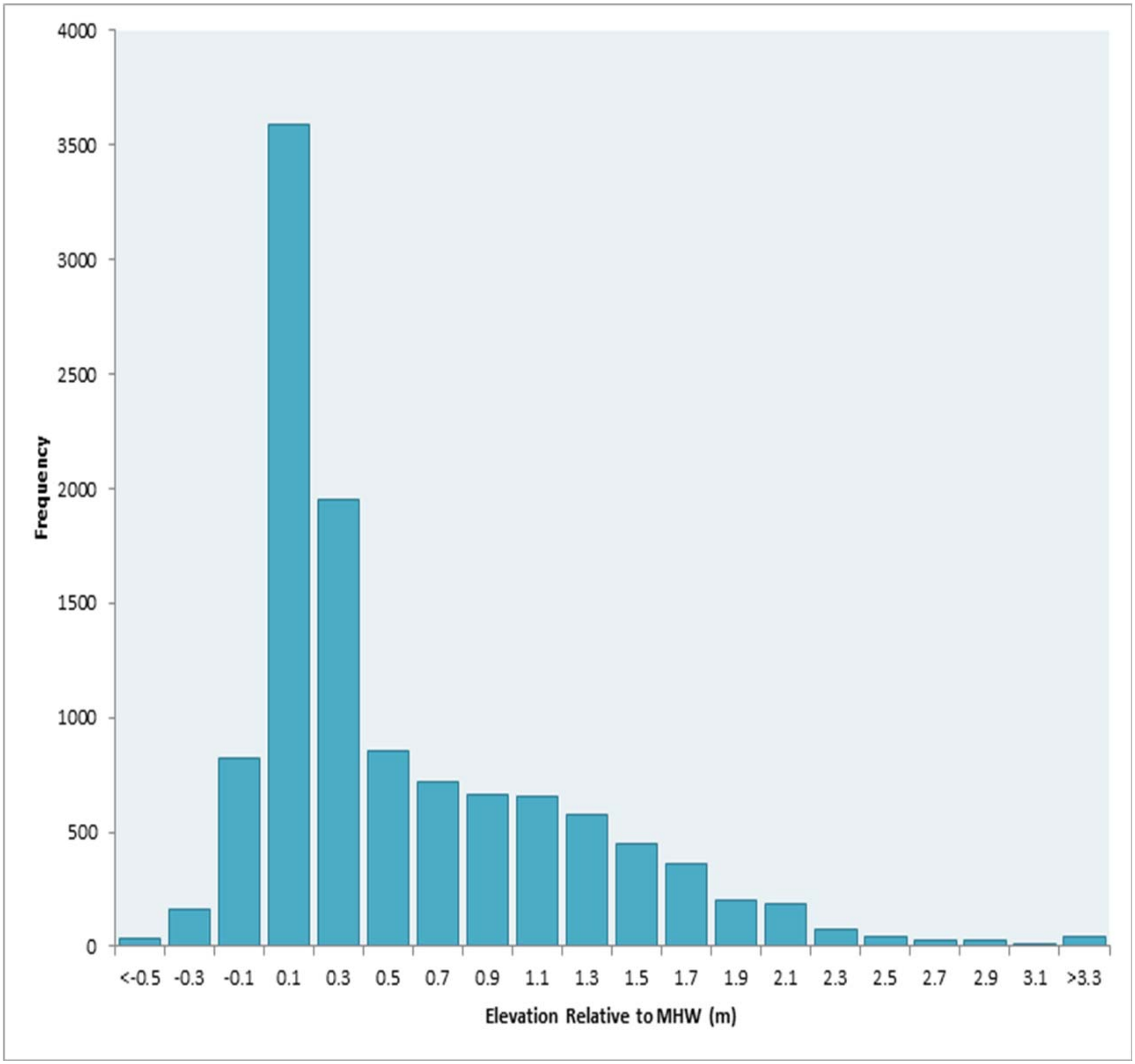

Figure 7. Distribution of marsh elevations relative to mean high water (MHW) in meters (m) for all study sites in the San Diego NWR Complex (Tijuana River, South San Diego Bay, Sweetwater, Seal Beach).

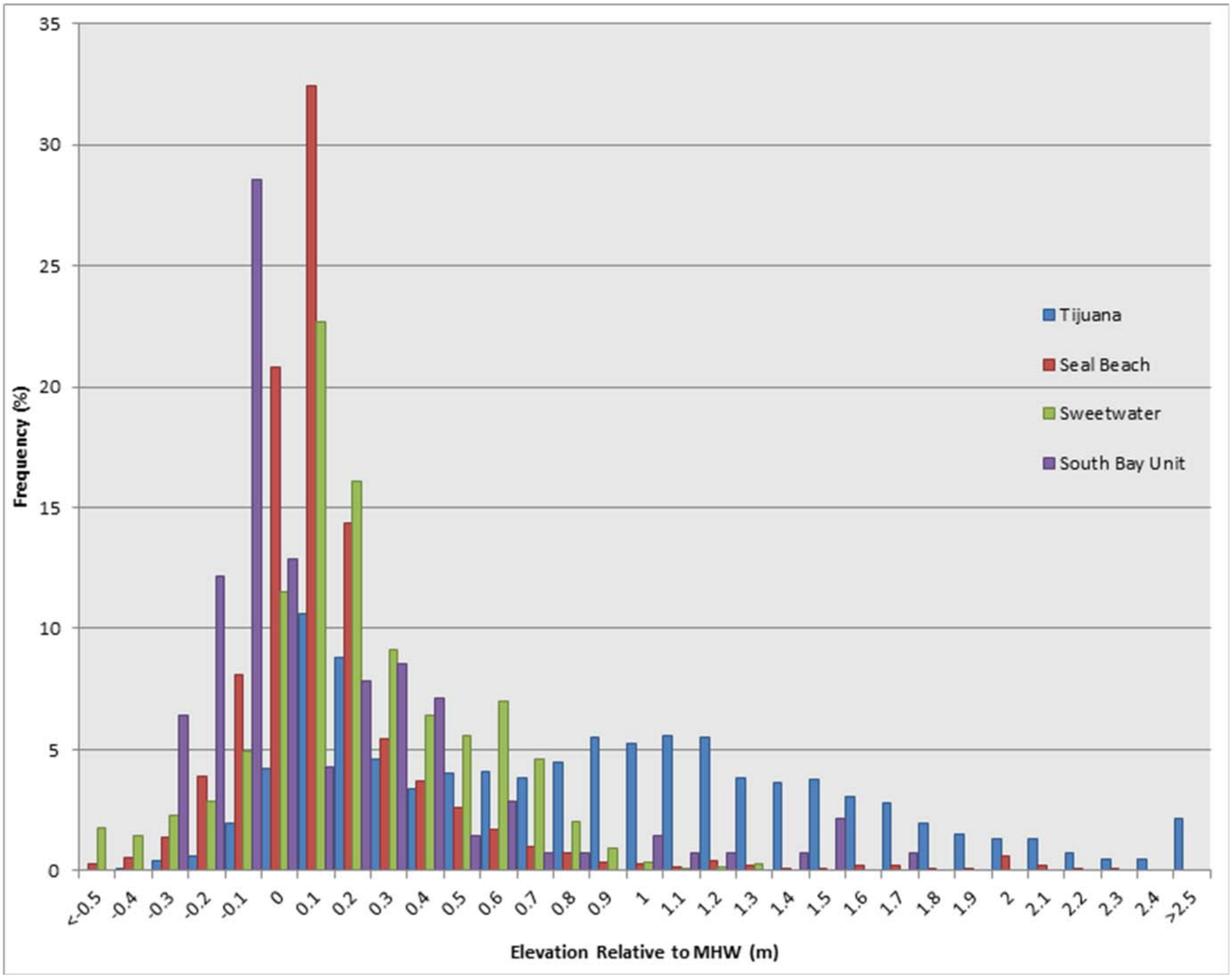

Figure 8. Elevation relative to mean high water (MHW) compared by study site for the San Diego NWR Complex. Elevation surveys were done in the upland area of Tijuana which is represented here by the data points above MHW.

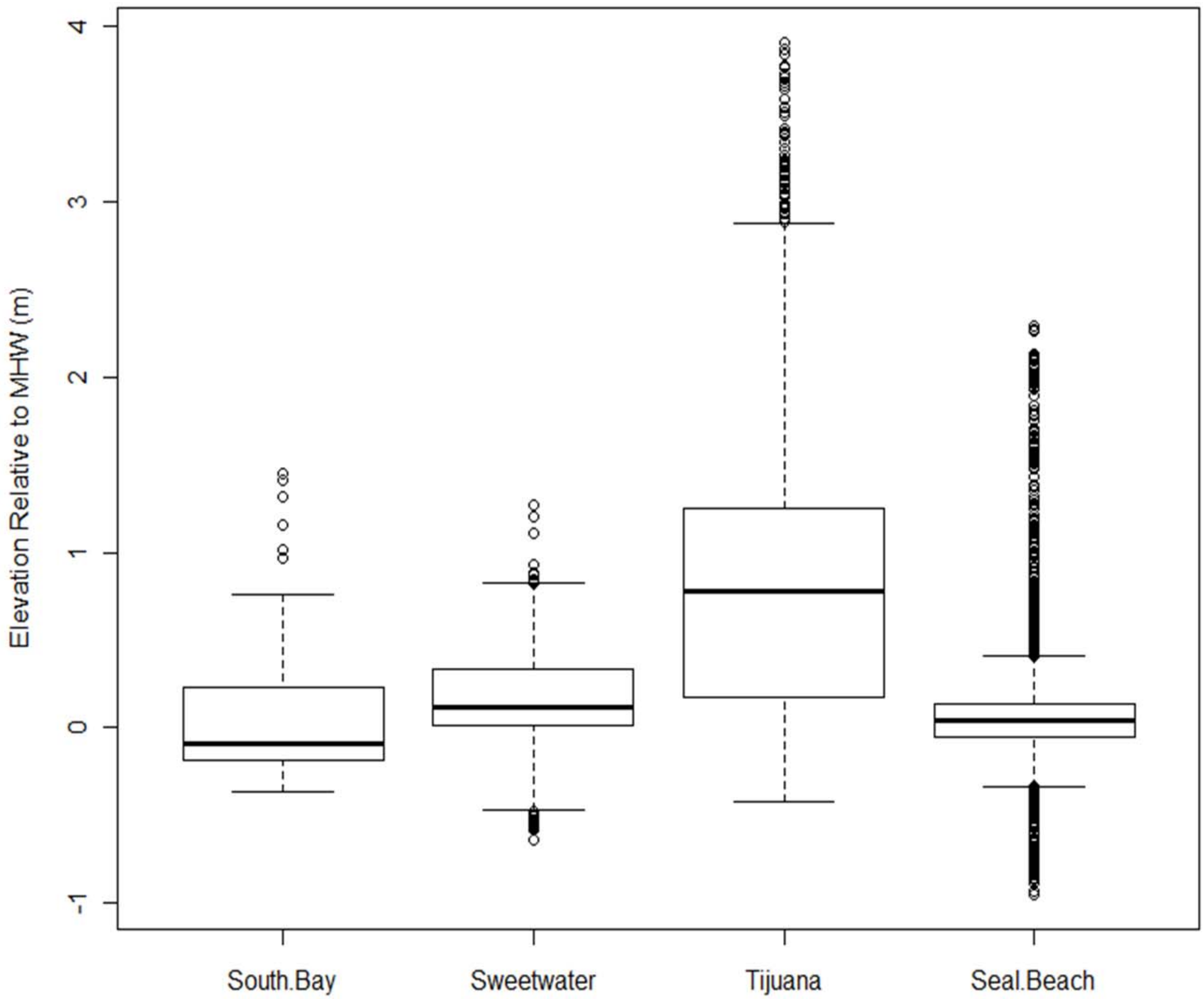

Figure 9. . Elevation relative to mean high water (MHW) in meters (m) by site for the San Diego NWR Complex. Median (solid line), 25 to 75 percentiles (box), and 1.5 interquartile range (whiskers) are shown.

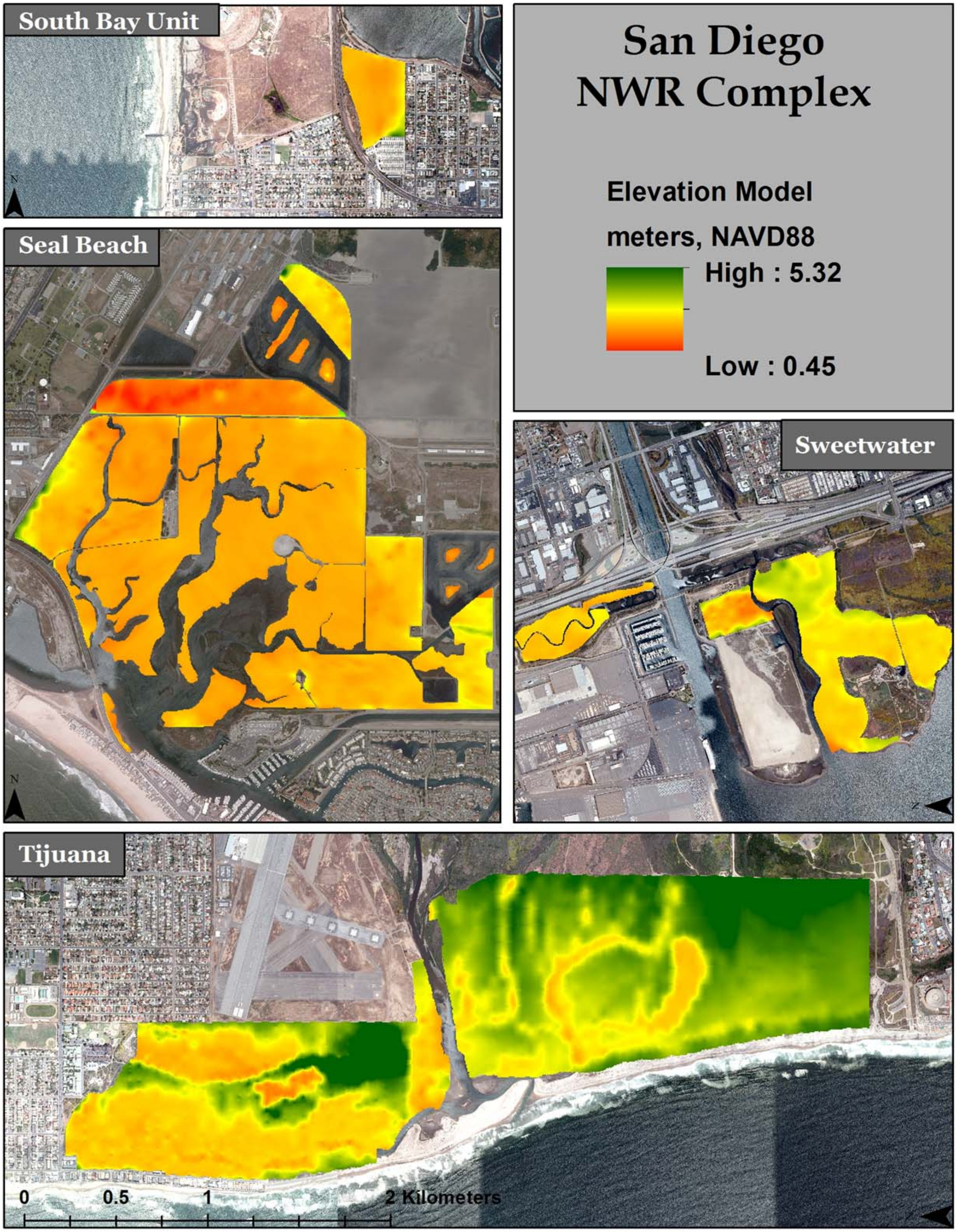

Figure 10. Digital elevation models (m, NAVD88) for the San Diego NWR Complex.

Table 4. ArcGIS elevation model root-mean-square error (RMS) and standard error (SE) by site.

Study Site	Model RMS	Model Mean SE
San Diego	0.07	0.18
Sweetwater	0.11	0.12
Tijuana	0.12	0.18
Seal Beach	0.12	0.12
Mean	0.11	0.15

4.2 Vegetation

Vegetation was sampled at 2,855 locations across all marsh sites (Table 3). Twenty-two different plant species were recorded throughout the San Diego NWR Complex study sites (Table 5), and species richness and diversity varied between sites. Distinct zonation in plant communities was observed in relation to MHW, because plants were restricted by their inundation and salinity tolerance (Fig 11-13). S*arcocornia pacifica* was the most common species surveyed across sites, occurring at 58 percent of 2,855 vegetation plots. *Spartina foliosa* was the second most common species (37 percent), followed by *Batis maritima* (33 percent), *Jaumea carnosa* (27 percent), *Frankenia salina* (24 percent), *Arthrocnemum subterminale* (14 percent), *Sarcocornia bigelovii (*13 percent), and *Distichlis spicata* (11 percent, Table 6). *S. pacifica*, a foundation species of tidal marshes in southern California*,* was dominant in the marshes. However, several species differed by site (Table B-1, C-1, D-1). Salt marsh bird's beak was observed at both the Tijuana and Sweetwater study sites; however, it was only recorded in one plot.

Table 5. Vegetation species recorded during vegetation surveys of study sites of the San Diego NWR Complex.

Species Code	Scientific name
ATSE	*Atriplex semibaccata*
ATSP	*Atriplex spinifera*
ATWA	*Atriplex watsonii*
BAMA	*Batis maritima*
COMA	*Chloropyron maritimum*
CRTR	*Cressa truxillensis*
DILI	*Distichlis littoralis*
DISP	*Distichlis spicata*
FRPA	*Frankenia palmeri*
FRSA	*Frankenia salina*
ISME	*Isocoma menziesii*
JACA	*Juamea carnosa*
JUAC	*Juncus acutus*
JUME	*Juncus mexicanus*
LICA	*Limonium californicum*
MECR	*Mesembranthemum crystallinum*
SABI	*Sarcocornia bigelovii*
SAPA	*Sarcocornia pacifica*
SASU	*Arthrocnemum subterminale*
SPFO	*Spartina foliosa*
SUES	*Sueda esteroa*
TRMA	*Triglochin maritima*

Table 6. Sample number, mean marsh elevation (m) relative to mean high water (MHW), average and max height (cm), percentage cover with standard deviations (SD), and presence by species at San Diego NWR Complex. See Table 5 for species code and scientific names of plants.

Species code	n	Mean Elevation Relative to MHW (m)	SD Elevation Relative to MHW	Mean Avg. Height (cm)	Mean Avg. Height SD	Mean Max Height (cm)	Mean Max Height SD	Mean Cover %	Mean Cover % SD	Presence (%)
ARSU	398	0.89	0.33	30	11	37	13	76	28	14.01
ATSE	2	1.16	1.08	8	4	10	1	13	11	0.07
ATSP	3	0.65	0.20	18	8	22	13	25	--	0.11
ATWA	6	0.56	0.13	14	6	17	7	21	18	0.21
BAMA	949	0.04	0.15	16	6	20	7	24	19	33.4
COMA	1	0.53	----	15	--	18	--	30	--	0.04
CRTR	34	0.60	0.27	22	8	26	9	21	21	1.2
DILI	224	0.43	0.24	17	7	22	9	56	37	7.88
DISP	309	0.44	0.51	24	8	29	10	31	29	10.88
FRPA	2	0.09	0.04	15	6	20	8	20	14	0.07
FRSA	672	0.27	0.34	20	8	25	10	36	31	23.65
ISME	41	1.52	0.46	57	23	81	33	60	34	1.44
JACA	776	0.06	0.12	13	5	18	6	54	32	27.31
JUAC	13	0.46	0.38	62	23	83	33	50	29	0.46
JUME	1	0.35	---	75	--	195	--	100	--	0.04
LICA	225	0.18	0.18	22	12	28	15	18	14	7.92
MECR	25	1.37	0.43	9	6	12	7	41	21	0.88
SABI	376	0.01	0.14	20	8	26	10	29	24	13.23
SAPA	1638	0.10	0.28	30	10	40	13	63	31	57.66
SPFO	1041	-0.02	0.12	55	16	67	20	44	27	36.64
SUES	99	0.12	0.14	22	8	27	11	25	23	3.48
TRMA	11	0.08	0.10	11	2	12	3	13	11	0.39

High Occurrence Species

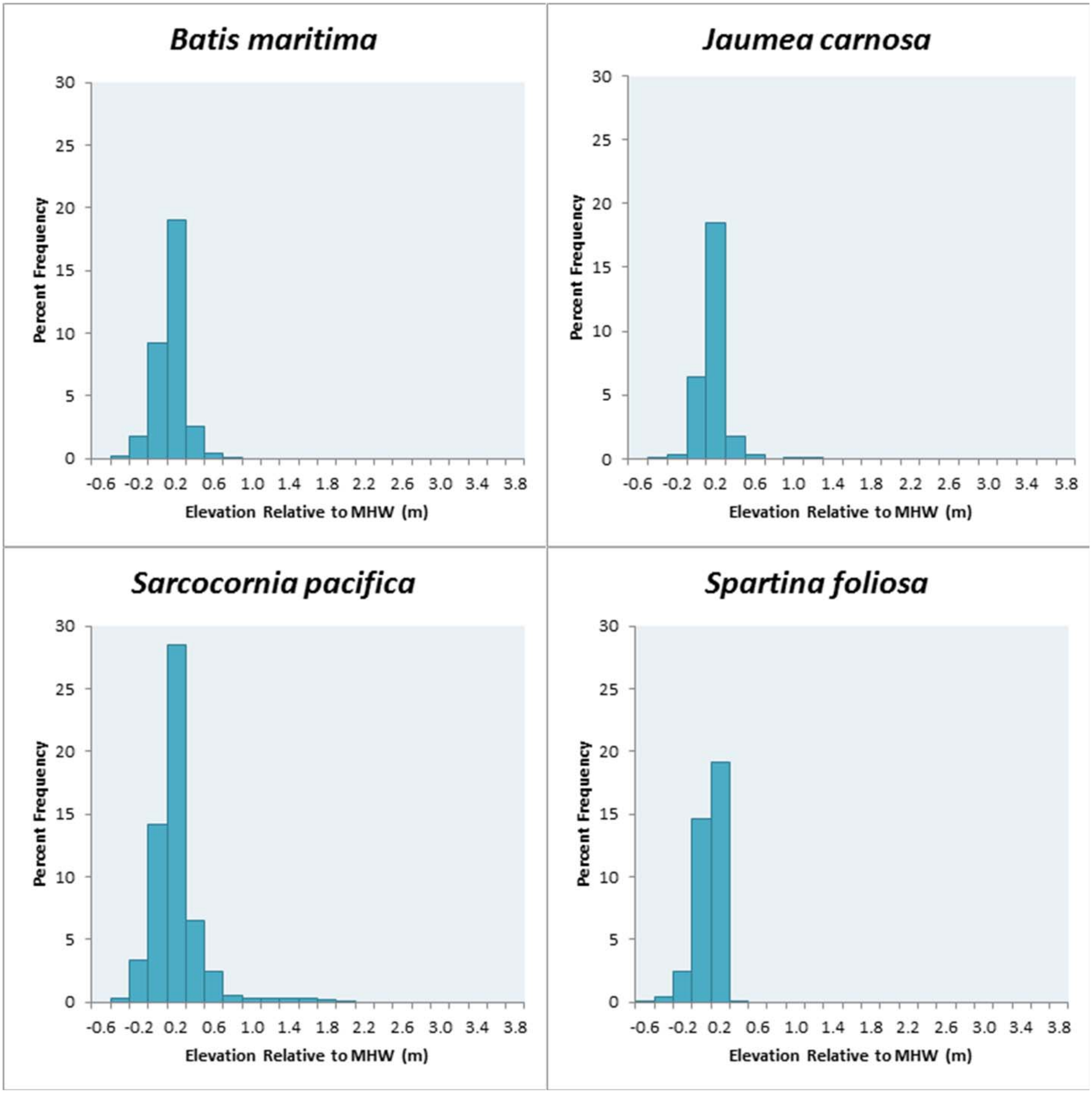

Figure 11. Distribution of high occurrence species (scaled to thirty percent frequency) observed relative to MHW across the San Diego NWR complex.

Medium Occurrence Species

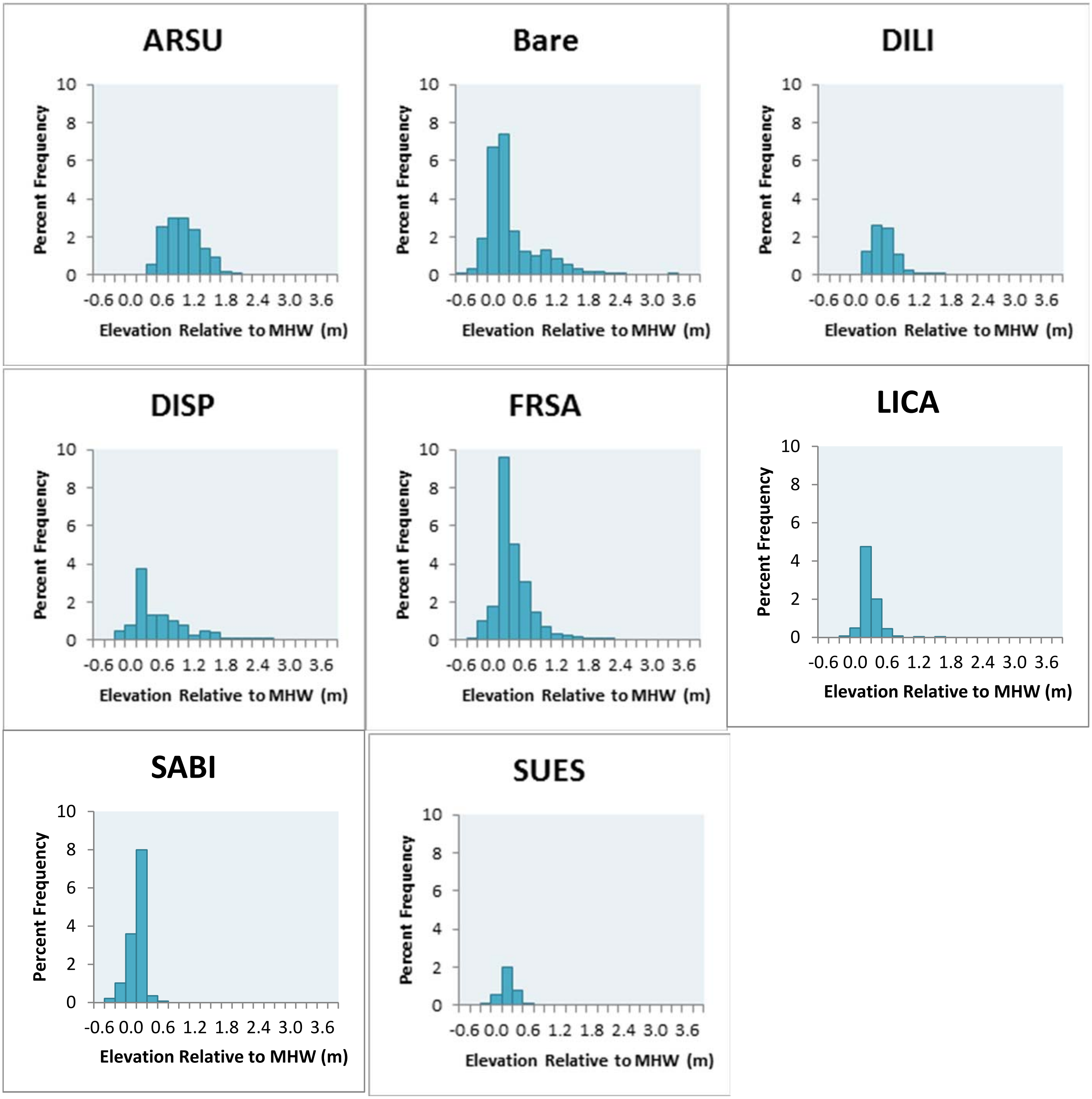

Figure 12. Distribution of medium occurrence plant species or categories (scaled to ten percent frequency) observed relative to MHW across the San Diego NWR complex. Species or categories included: ARSU = *Arthrocnemum subterminale*; Bare = bare ground; DILI = *Distichlis littoralis*; DISP = *Distichlis spicata*; FRSA = *Frankenia salina*; LICA = *Limonium californicum*; SABI = *Sarcocornia bigelovii*; SUES = *Sueda esteroa*.

Low Occurrence Species

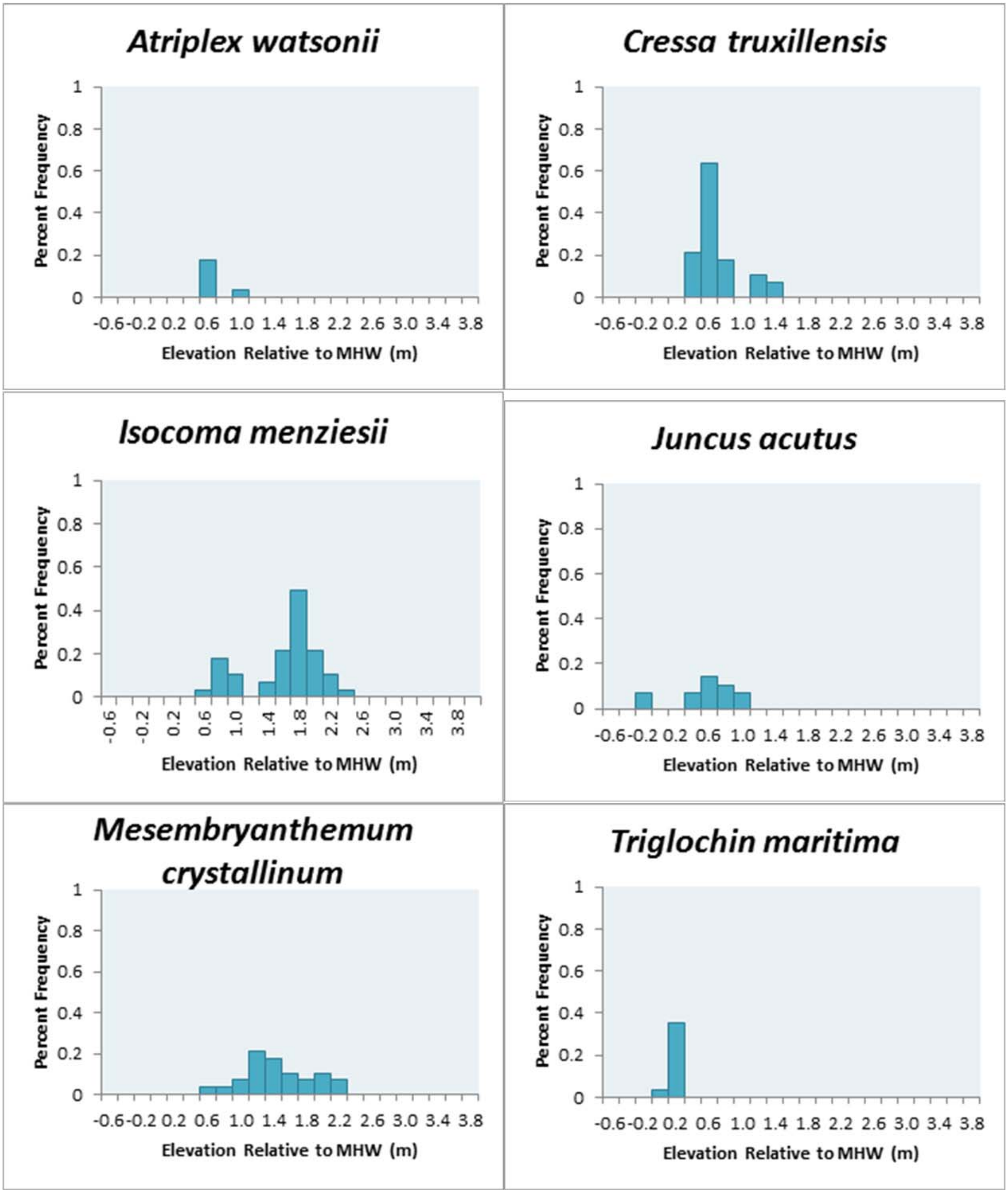

Figure 13. Distribution of low occurrence plants (scaled to one percent frequency) observed relative to MHW across the San Diego NWR complex. Species recorded in less than five sample plots were not presented here but are summarized elsewhere (Table 6).

4.3 Water level monitoring

We used water level loggers to record tide levels from September 2011 to January 2013. Some loggers did not capture the bottom portion of the tidal curve, because they were located above the thalweg in the marsh channels, so MLW and MLLW were not calculated at those loggers. Peak tide levels were averaged for each site to produce site-specific tidal datums for MTL, MHW, and MHHW (Table 7, Fig. 12). Our results indicated that marsh elevations were relatively high, as 91% of the marsh surface area was above MHW (Fig. 7, 14). For the four sites, MHW ranged from 1.27 to 1.48 m (NAVD88), and Seal Beach had the lowest MHW level. Inundation of all the marshes varied throughout the year with longest inundation periods during late summer months.

Table 7. Water elevations (NAVD88) in meters (m) for each marsh site in 2012. Mean tide-level (MTL), mean high water (MHW) and mean higher high water (MHHW) were calculated from *in situ* data loggers.

Site	MTL	MHW	MHHW
San Diego	0.95	1.48	1.72
Sweetwater	0.95	1.48	1.72
Tijuana	1.02	1.41	1.65
Seal Beach	0.88	1.27	1.55

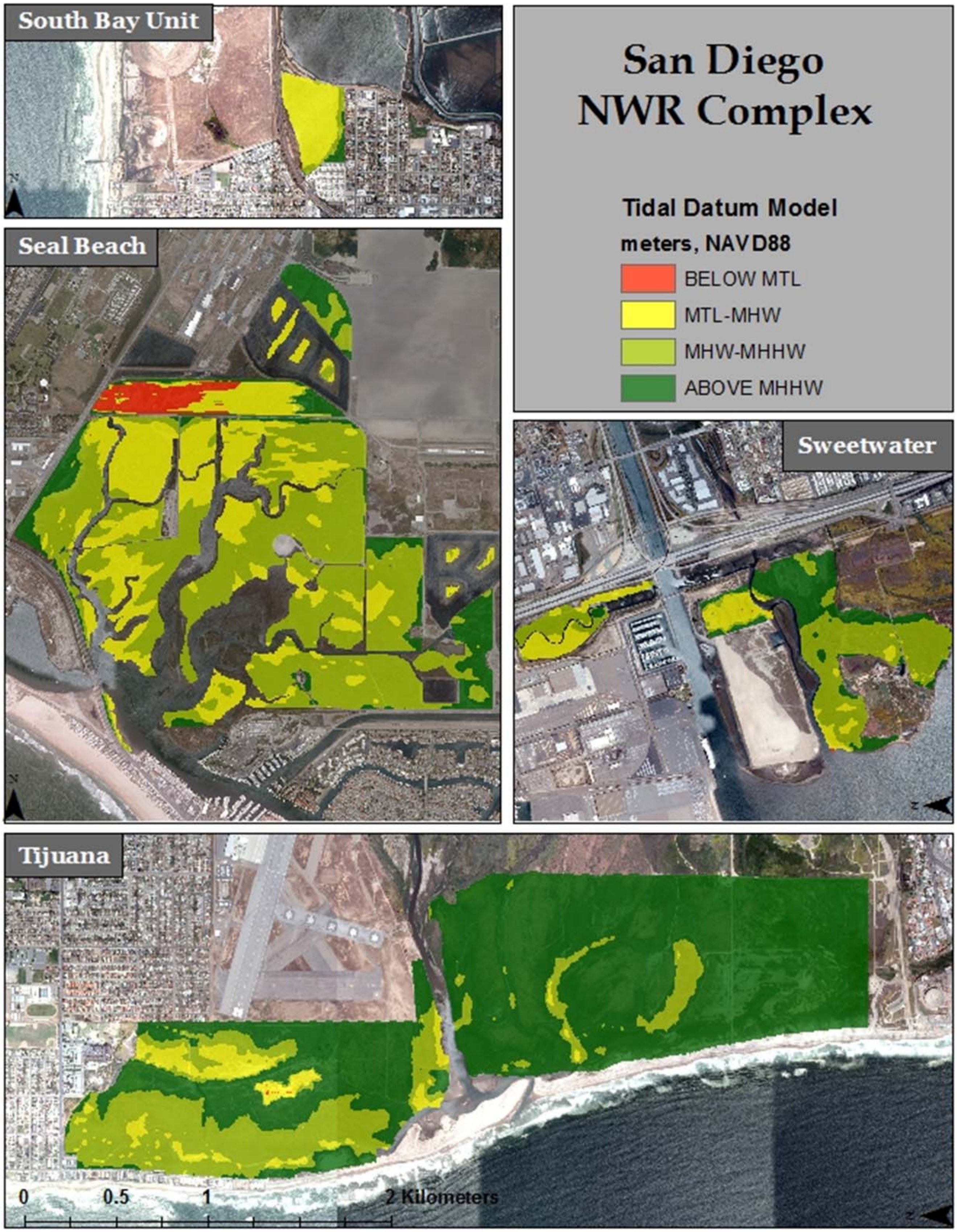

Figure 14. Tidal datum models in meters NAVD88 for the San Diego Complex

4.4 Tijuana Marsh elevation sea-level rise modeling

Results from the SLR response modeling for the north arm of Tijuana Estuary indicates that relative elevation will decrease through 2110 under the mid (+93 cm) and high (+166 cm) SLR scenarios but will maintain elevation under the low (+44 cm) scenario (Fig. 15). The four different suspended sediment concentrations (20, 50, 100, and 300 mg/l) had generally little effect on elevation change under the low and mid SLR scenarios. However, under the high SLR scenario, mean elevation diverged in ~2070 across the four SSC scenarios, and at the 300 mg/l scenario, a mean elevation of about 40 cm above MSL was maintained (Table 8). In the other three SSC scenarios, mean elevation continued to decrease, although that decrease varied by site (Fig 15).

Vegetation community change was determined by correlating current plant communities with their elevation and predicting community occurrence from projected future elevations. Normal plant community distributions are shown (Fig. 16, Table 9). Three community types were represented: low, mid and high marsh (Fig. 17-22). In the low SLR scenario, the low marsh extent was reduced but the mid and high marsh communities remained consistent in their extent through 2110 (Figs. 17, 20). In the mid SLR scenario, low marsh habitats expanded dramatically by 2030, replacing the mid marsh, while the mid marsh replaced the high marsh. By 2090, much of the low marsh community was predicted to transition to non-vegetated mudflat (Figs. C-18, 21). In the high SLR and 100 mg/l SSC scenario, the mid marsh was replaced by the low marsh by 2050, and by 2100, the low marsh transitioned to non-vegetated mudflat (Fig. 19). In the 20 mg/l SSC scenario, the largest difference was from the high SLR scenario where the low marsh transitions to non-vegetated mudflat by 2070 and most of the area is under MSL by 2090 (Fig. 22)

Table 8. Mean elevation (cm, MSL) of the marsh platform for three SLR (sea-level rise) scenarios and four mean annual suspended sediment concentrations (SSC), 2011-2110.

SLR (cm)	SSC (mg/l)	2011	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110
44	20	71	74	78	82	84	86	86	86	85	83	80
	50	71	74	79	82	85	86	87	87	86	84	81
	100	71	75	79	82	85	86	87	87	86	84	81
	300	72	75	80	83	86	87	88	88	87	85	82
93	20	71	74	77	78	76	73	69	62	52	41	28
	50	71	74	77	78	77	74	69	63	54	44	34
	100	71	72	71	69	66	60	55	50	46	42	38
	300	72	75	78	79	78	75	70	63	56	50	47
166	20	71	74	74	71	65	55	40	24	3	-16	-36
	50	71	74	75	72	65	55	42	29	13	-2	-14
	100	71	75	75	72	66	56	45	35	25	15	4
	300	72	75	76	72	66	56	49	43	40	36	36

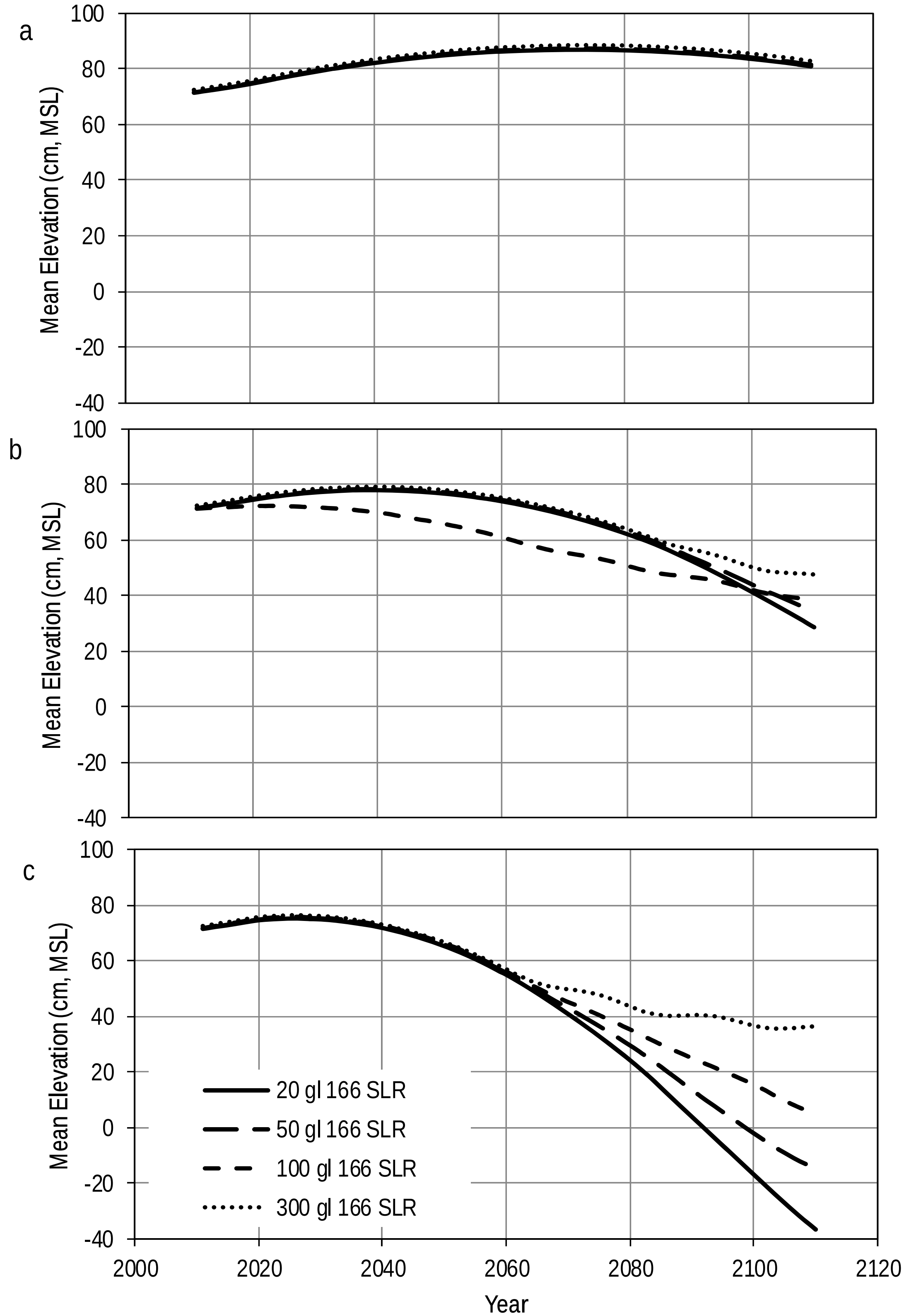

Figure 15. Results of modeling Tijuana Estuary (MEM 3.4) for four different suspended sediment concentrations and SLR rates of (a) 44 cm, (b) 93 cm, and (c) 166 cm by 2110.

Table 9. Community composition and elevation (cm, MSL) at Tijuana Estuary, based on the most commonly observed species (>5% of the survey plots). Values are in cm relative to mean sea level. Communities were separated by Tukey's HSD test. Indicator species included: Belding's Savannah sparrow = *Passerculus sandwichensis beldingi;* Bird's Beak = *Chloropyron maritimum* subsp*. maritimum;* and Light-footed Clapper Rail = *Rallus longirostris levipes*

Community	Vegetation Species	Indicator Species	Elevation Mean	SD	Community Mean	Community SD
Supra Marsh (d)	*Arthrocnemum subterminale*	Belding's Song sparrow	135.1	28.1	135.1	28.1
Generalist (a)	*Distichlis spicata*	Belding's/Bird's Beak	114.5	60.2	---	---
Generalist (a)	*Distichlis littoralis*	Belding's/Bird's Beak	107.7	21.8	111.5	43.4
High Marsh (b)	*Frankenia salina*	Belding's/Rail/Bird's Beak	91.9	30.7	91.9	30.7
Mid Marsh (c)	*Jaumea carnosa*	Belding's/Rail	71.5	10.0	---	---
Mid Marsh (c)	*Sarcocornia pacifica*	Belding's/Rail	69.0	14.6	---	---
Mid Marsh (c)	*Batis maritima*	Belding's/Rail	68.7	11.4	69.7	12.7
Low Marsh (e)	*Spartina foliosa*	Rail	58.7	9.2	58.7	9.2

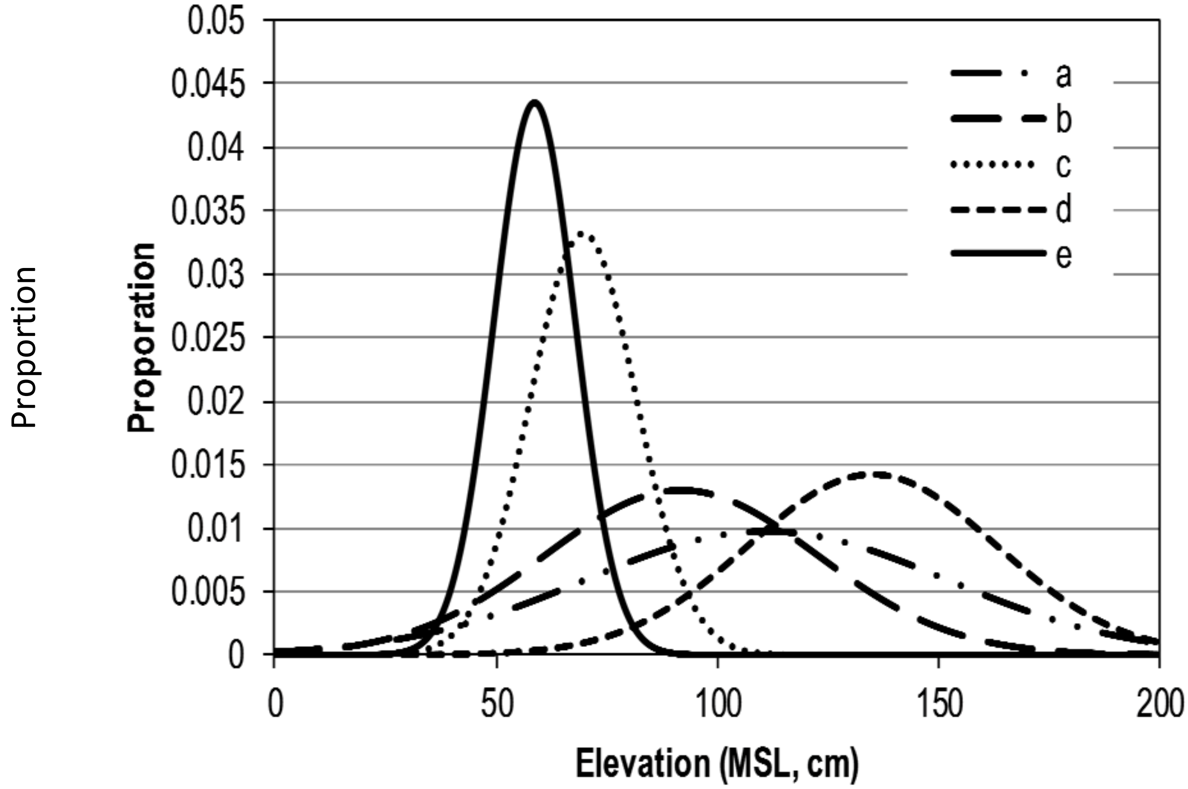

Figure 16. Distribution of plant communities by elevation: a= generalist, b = high marsh, c = mid marsh , d = supra marsh, e = low marsh. Community plant composition is defined in Table 9.

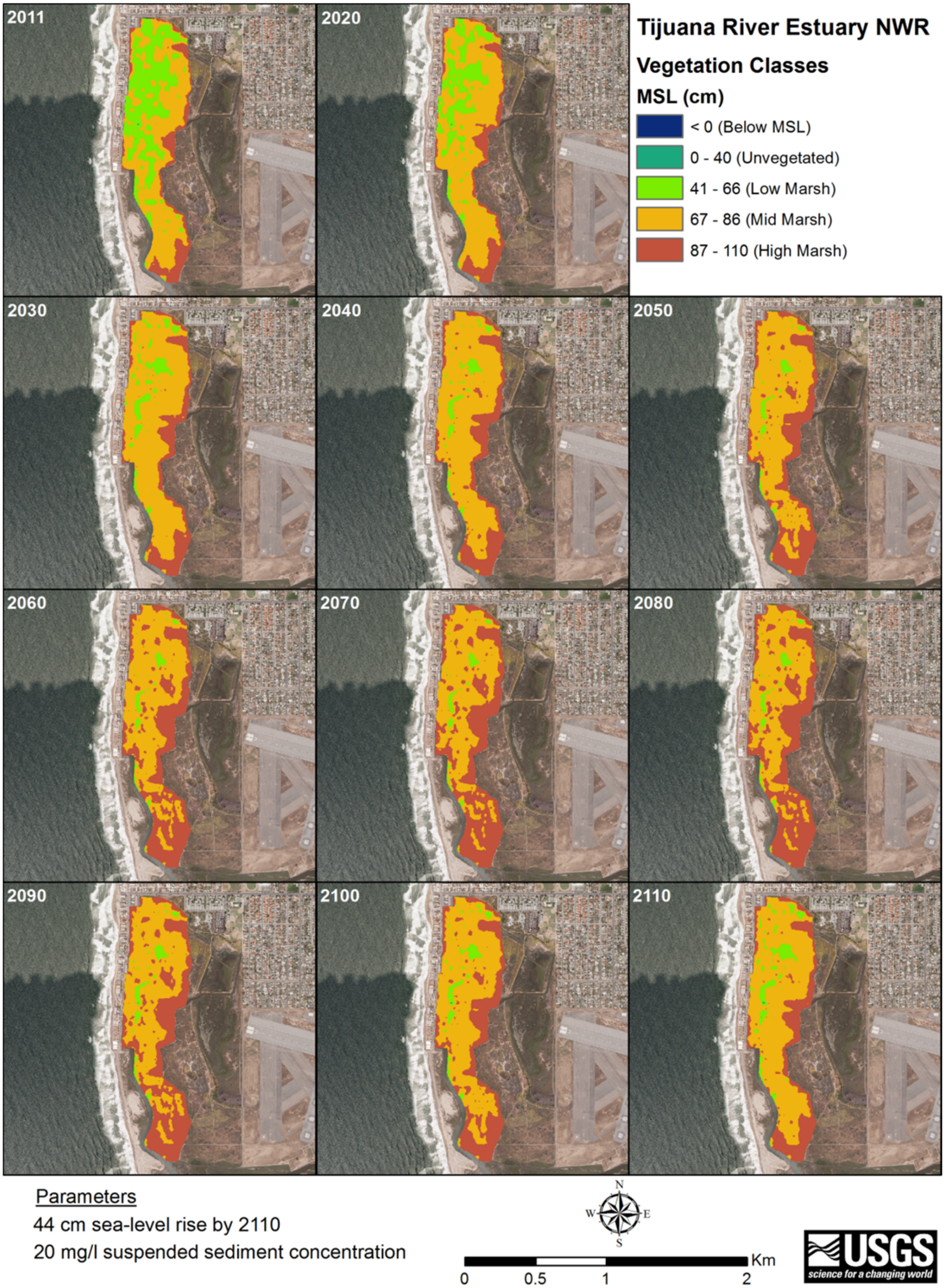

Figure 17. Results from MEM sea level response model for the north arm marsh at Tijuana National Wildlife Refuge under the low (+44 cm by 2110) sea-level rise scenario with 20 mg/l mean annual suspended sediment concentration.

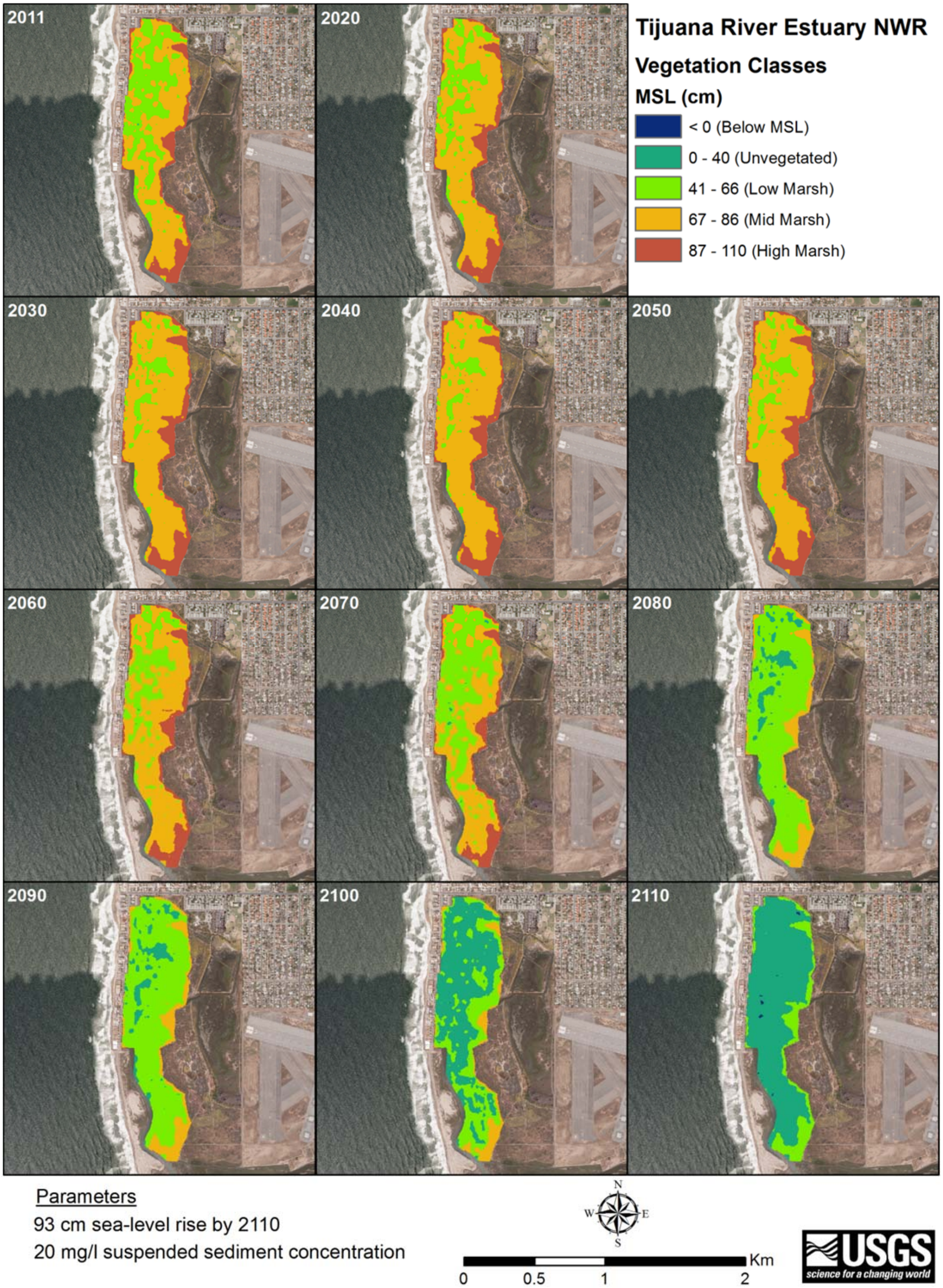

Figure 18. Results from MEM sea level response model for the north arm marsh at Tijuana National Wildlife Refuge under the mid (+93 cm by 2110) sea-level rise scenario with 20 mg/l mean annual suspended sediment concentration.

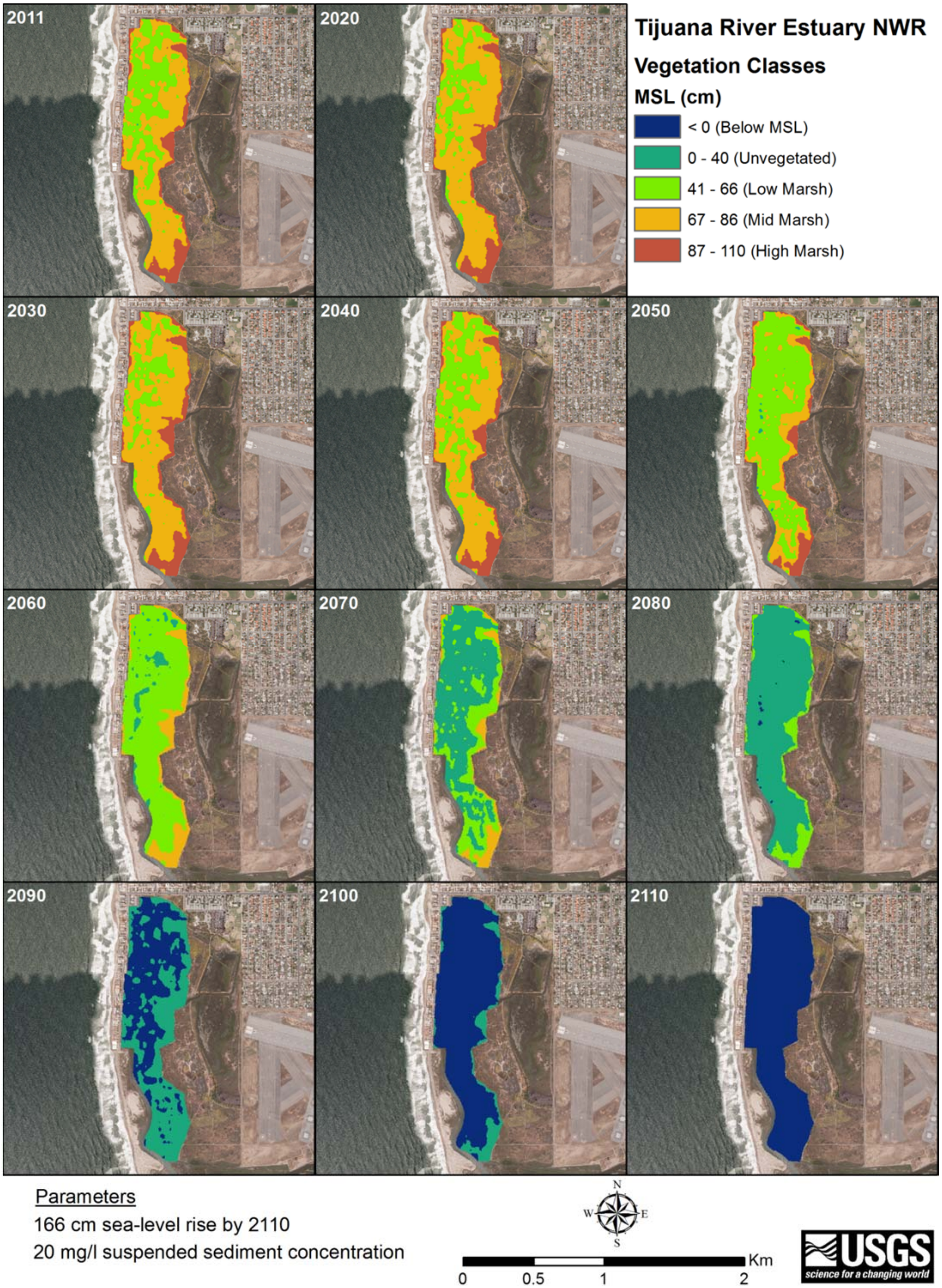

Figure 19. Results from MEM sea level response model for the north arm marsh at Tijuana National Wildlife Refuge under the high (+166 cm by 2110) sea-level rise scenario with 20 mg/l mean annual suspended sediment concentration.

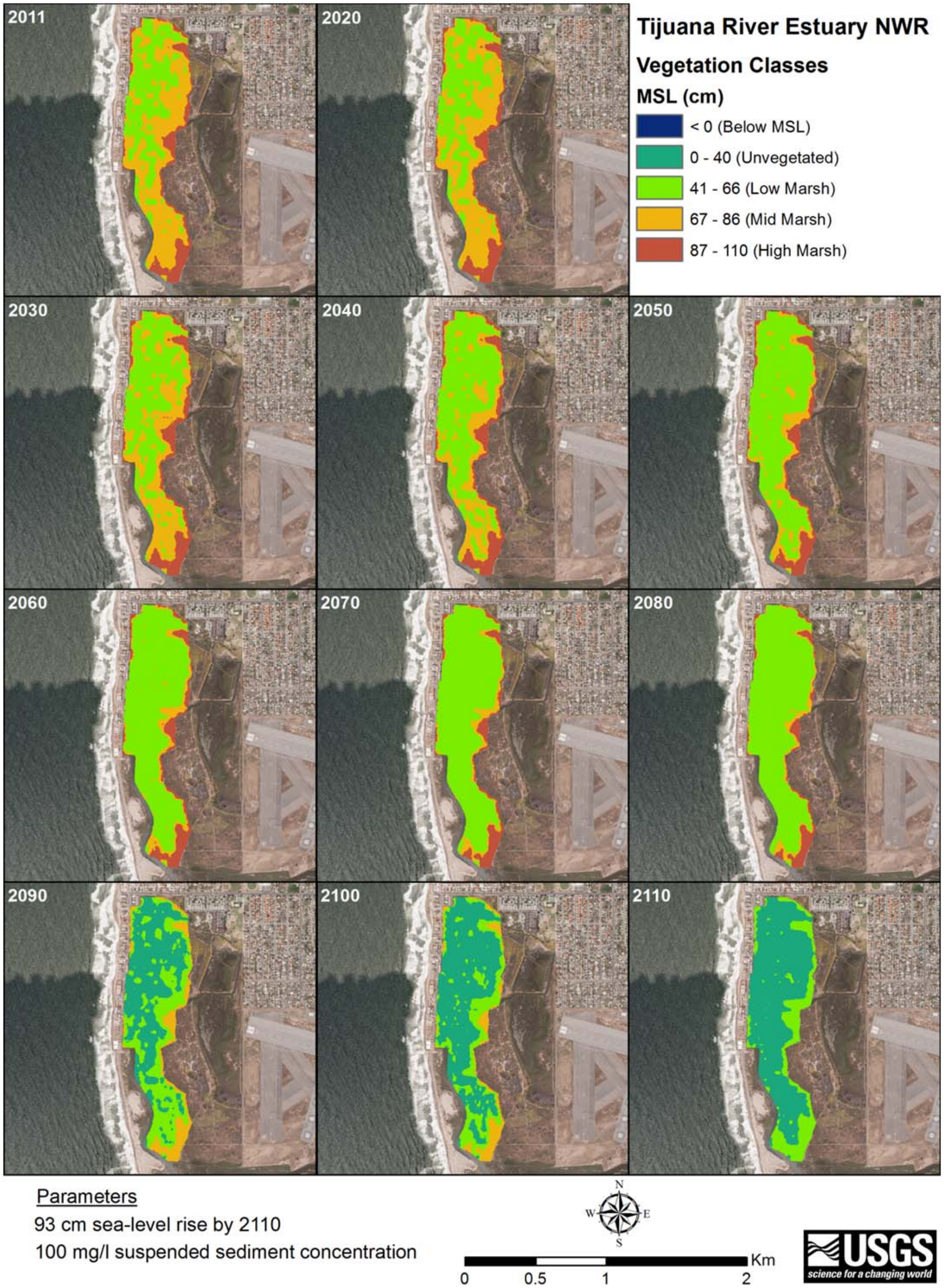

Figure 21. Results from the MEM sea level response model for the north arm marsh at Tijuana National Wildlife Refuge under the mid (+93 cm by 2110) sea-level rise scenario with 100 mg/l mean annual suspended sediment concentration.

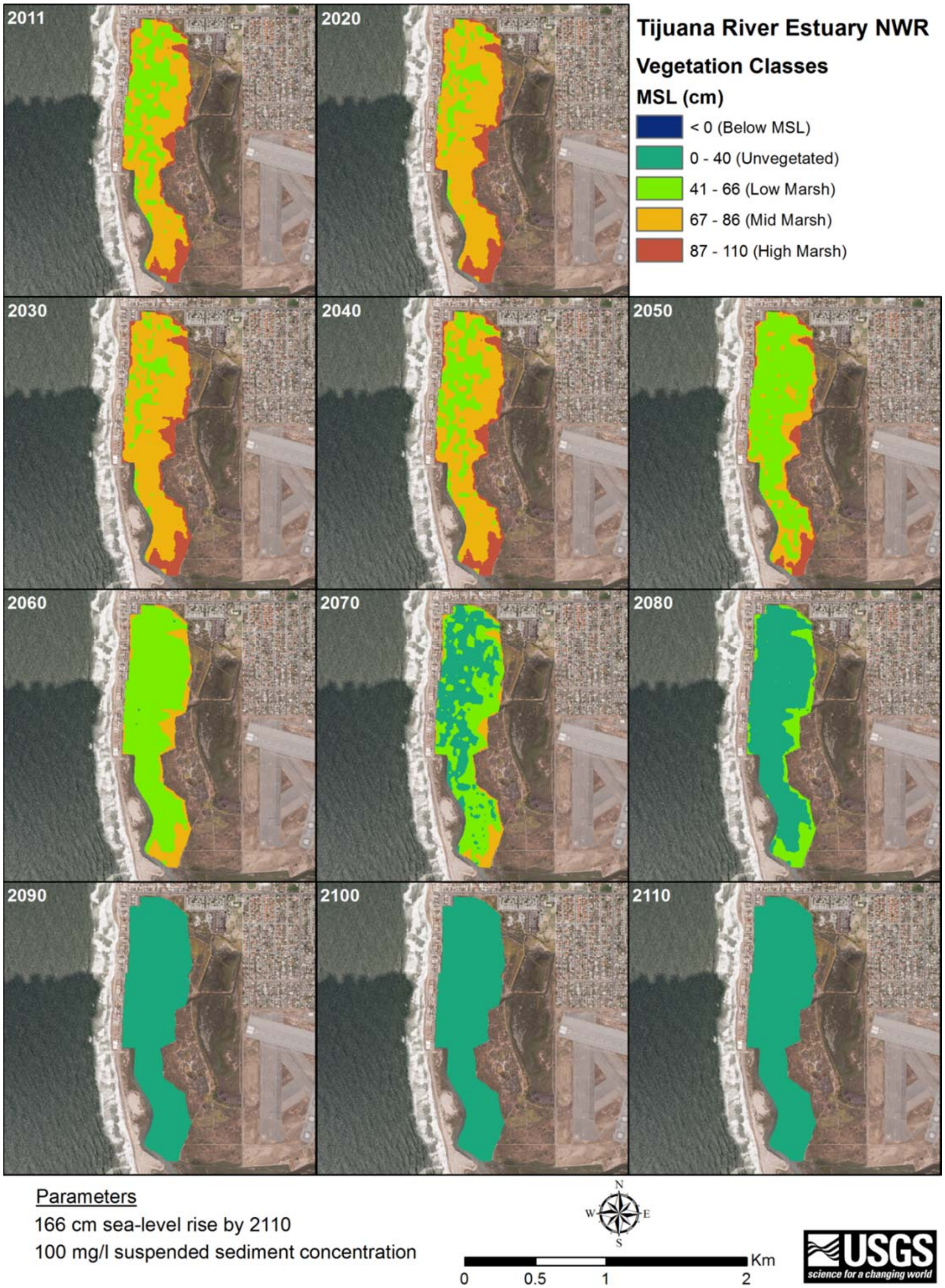

Figure 22. Results from the MEM sea level response model for the north arm marsh at Tijuana National Wildlife Refuge under the high (+166 cm by 2110) sea-level rise scenario with 100 mg/l mean annual suspended sediment concentration.

Tijuana modeling results and species of interest

Salt Marsh Bird's Beak (*Chloropyron maritimum* subsp. *maritimum)*

We assumed that the presence of mid marsh vegetation could represent salt marsh bird's beak habitat. Based on our MEM results, mid marsh vegetation communities will persist to 2110 under the low (+44 cm) SLR scenario at both levels of SSC. However, under the mid SLR scenario (+93 cm) mid marsh drastically decreases after 2060 and disappears by 2110 with 20 mg/l (SSC), and at 100 mg/l SSC, mid marsh was drastically reduced by 2030 and absent by 2110. The high (+166 cm) SLR scenario showed mid marsh will be lost by 2080.

Light-Footed Clapper Rail (*Rallus longirostris levipes*)

The Light-footed Clapper Rail primary habitat was assumed to be low marsh vegetation communities dominated by *Spartina*. Low (+44 cm) SLR scenarios indicated that low marsh will be drastically reduced by 2030 at both sedimentation concentrations. However, at mid (+93 cm) SLR scenarios low marsh communities actually increase until 2080 and then begin to decrease. High (+166 cm) SLR scenarios showed an increase of low marsh until 2060 and then a decrease, until it disappeared at 2090.

Belding's Savannah sparrow (*Passerculus sandwichensis beldingi*)

The primary habitat for Belding's Savannah Sparrow was mid and high marsh vegetation. Under low (+44 cm) SLR scenarios, mid and high marsh communities will persist through 2110. However, under the mid (+93 cm) SLR scenario at 20 mg/l SSC, mid and high marsh drastically decreased after 2060, with high marsh disappearing after 2070 and mid marsh disappearing after 2110. At 100 mg/l mean annual SSC, mid marsh was drastically reduced by 2030 with high marsh disappearing in 2080 and mid marsh disappearing after 2100. Under high (+166 cm) SLR scenarios, high marsh disappeared after 2050, while mid marsh disappeared after 2070.

DISCUSSION

Land managers responsible for the conservation and protection of wildlife species and their habitats need site-specific SLR information and projections to make decisions. By identifying the response of the plant community to SLR, our project provides science support to make informed decisions and develop climate change adaptation strategies. Our models identified differences in SLR risks for individual marshes in the San Diego NWR Complex. They also indicated that management actions would be needed to preserve low, mid, and high marsh vegetation communities for the persistence of endangered species that rely on these habitats.

Marsh elevation transects, plant community surveys, and tidal regime measurements provided site-specific, baseline conditions needed to develop SLR models. We found it was essential to collect ground elevation with an RTK GPS instead of modeling with aerial LiDAR (Light Detection And Ranging). LiDAR is generally unable to penetrate dense marsh vegetation cover and produces elevation errors 10–40 cm greater than ground-based measurements (Foxgrover and others, 2011; Schmid and others, 2011). The error in LiDAR may represent nearly half of the total marsh slope and may skew SLR response modeling results, especially from the present to the year 2050. Our results showed that initial elevation, along with tidal range and suspended-sediment availability, were key inputs for effectively modeling marsh response to SLR in the San Diego NWR Complex.

Urbanization makes the San Diego NWR Complex especially susceptible to SLR effects because there are limited opportunities for upslope transition. The marsh at Seal Beach is surrounded by the Naval Weapons Station and has the least opportunity to migrate upslope. Both Sweetwater and Tijuana have upslope areas adjacent to marsh areas where migration could occur. However, the processes by which marshes migrate are poorly understood; thus, the precise conditions needed for marsh sustainability with SLR are difficult to identify. Recognizing the disproportionate destruction of high marsh habitat, the infrequently inundated upper zone should be a focus for planning in marsh restoration. Upland restoration could compensate for some historic losses of Belding's Savannah Sparrow habitat and provide areas for marsh vegetation to migrate with SLR. Adjacent uplands and viable connections with larger open spaces are important components for ecologically functional wetlands and will become increasingly important with SLR. Additional studies of marsh restoration sites may lead to greater insight into the mechanisms of marsh migration.

The added effects of climate change on marsh ecosystems could greatly increase threats to already vulnerable wildlife populations and species (Ohlemuller and others, 2008). Increased rates of inundation will be ecologically significant for obligate marsh species, especially those that are already limited in number (for example, the Light-Footed Clapper Rail) and those species with low dispersal ability.

Species that rely on marsh habitat for feeding, reproduction, or cover from predators likely will be negatively affected by SLR changes.

Under mean SLR scenarios and low SSC, our projections show losses of high and mid-marsh vegetation by 2080 at Tijuana Estuary. These areas are dominated by *Sarcocornia pacifica,* a plant that is critical for providing habitat structure for nesting song birds. Low-marsh vegetation will persist in most areas until 2100 and is dominated by *Spartina* spp*.,* which provides habitat used by the Light-Footed Clapper Rail. However, low marsh is projected to be lost by 2100, and could result in the loss of a majority of habitats for the Light-Footed Clapper Rail population.

NEXT STEPS

Our program recognizes the importance of extensive and improved integration of physical and biological monitoring to facilitate the discovery of important trends and signals of SLR. Results from our MEM model indicate that accretion may partially offset SLR through 2110. The accuracy of marsh accretion models is largely dependent on accurate sediment accumulation functions and calibration data. The range of input values for suspended sediment presented in this report represents a cross section of possible scenarios for the San Diego NWR Complex. A better understanding of the spatial variability of available SSC and deposition rates for both organic matter and sediment would greatly improve these site-specific results. Sediment cores and surface elevation tables (SETs) installations were done in fall of 2012 to better model SLR response for Tijuana Estuary. In addition, soil cores were collected at Sweetwater marsh in the fall of 2013, and ongoing SSC studies are being conducted at Seal Beach NWR to inform SLR response models.

We believe that baseline data collection is critical for identifying and prioritizing restoration sites and land acquisitions that are the best candidates for marsh management in light of SLR. In addition, the continued risk to threatened and endangered species needs to be assessed by evaluating movements, nesting requirements, and food availability for these species now before their populations decrease. A better understanding of how wildlife responds to increased inundation of their habitats is especially needed. Consistent with the goal of the USGS Science Strategy, the Coastal Ecosystem Response to Climate Change (CERCC) program will support the creation of models that predict ecosystem change and assess consequences of climate change and its effects on coastal ecosystems.

Tijuana estuary

Additional research is being conducted at Tijuana NWR as part of our ongoing SWCSC project. Under that effort, the USGS WERC will improve SLR response models by calibrating them with local sediment cores to obtain historic accretion rates based on isotope dating and sediment composition data, including percent organic matter, pore space and bulk density. These data will allow for important marsh processes such as decomposition and compaction to be modeled explicitly. The models presented here represent the first attempt to model SLR response at Tijuana using local data, although several parameters were sourced from the literature to fill in knowledge gaps. While we are confident in the overall trends presented in this report, the specific details are subject to change as more site-specific data are included into response models.

Seal Beach NWR

We recently completed a study of local subsidence at Seal Beach NWR (Takekawa et al. 2013), and the results indicate that the marsh is experiencing relative SLR rates of over 6 mm/yr, an accelerated rate projected to occur only after 2036 in areas that are not experiencing similar subsidence. The implications of this result are important considering the extensive efforts to maintain breeding populations of the Light-Footed Clapper Rail. In addition to high relative SLR rates, the marsh at Seal Beach lacks any significant freshwater flow as a source of suspended sediment that can be trapped on the marsh platform and increase elevation. The USGS WERC, in collaboration with the USGS Woods Hole Science Center, is examining suspended sediment concentrations on ebb and flood tides at major inlets and channels of Seal Beach to determine the potential rates of erosion. Further study of sediment dynamics in marshes will be helpful not just at Seal Beach, but across the Pacific coast, to determine the long-term sustainability of marshes facing increasing SLR effects.

ACKNOWLEDGMENTS

The authors would like to thank the USGS Western Ecological Research Center, the California Landscape Conservation Cooperative (CA LCC) and U.S. Fish and Wildlife Service Region 8 Inventory and Monitoring and Science Applications Program for funding support. We would like to thank the San Diego Complex refuge staff and NOAA NERR for providing assistance and access support (A. Yuen, B. Collins, K. Gilligan, S. Buck, M. Cordrey, and J. Crooks). The authors would like to thank K. Powelson, K. Lovett, V. Bui, and H. Robinson for data collection. Helpful review comments were provided by B. Collins.

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Appendices:

Results by site

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Appendix A

South Bay

Introduction

The South Bay site is currently being restored from commercial salt pond production to tidal marsh. Starting in the fall of 2010, the salt ponds were dredged to create tidal channels, and the dredged material was moved to another restoration area to provide nesting habitat for threatened and endangered ground-nesting birds, including the California Least Tern and Western Snowy Plover. Two levee breaches now allow tidal inundation and natural recruitment of native marsh species. Native plants have also been planted at this site. This is an important restoration of historic tidal wetlands in an area where urbanization and development have drastically decreased the expanse of this important habitat. This study focused on 15 hectares (ha) of salt marsh and mudflat where elevation and vegetation surveys were conducted in September of 2011 with an RTK GPS. Tidal data from two water loggers deployed in September of 2011 at Sweetwater refuge were used for the analyses at South Bay.

Results

Elevation surveys

A total of 142 elevation measurements were taken at South Bay (Fig. A-1). The elevation range was 1.11-2.92 meters (m), with a mean of 1.53 m (NAVD88). South Bay is a low- to mid-elevation marsh, with 60 percent of the elevation points located between -0.3 and 0.1 m relative to mean high water (MHW; Fig A-2). South Bay is the lowest study site within the San Diego NWR Complex relative to MHW. A 5-m resolution elevation model was developed in ArcGIS 10 (ESRI, Redlands, Calif.) Spatial Analyst using the kriging method (Fig. A-3). This baseline elevation model was used as the initial state for tidal inundation models.

Figure A-1. South Bay with elevation survey points. Due to the expansive mudflat, elevation points were only collected on the marsh fringe to the pond.

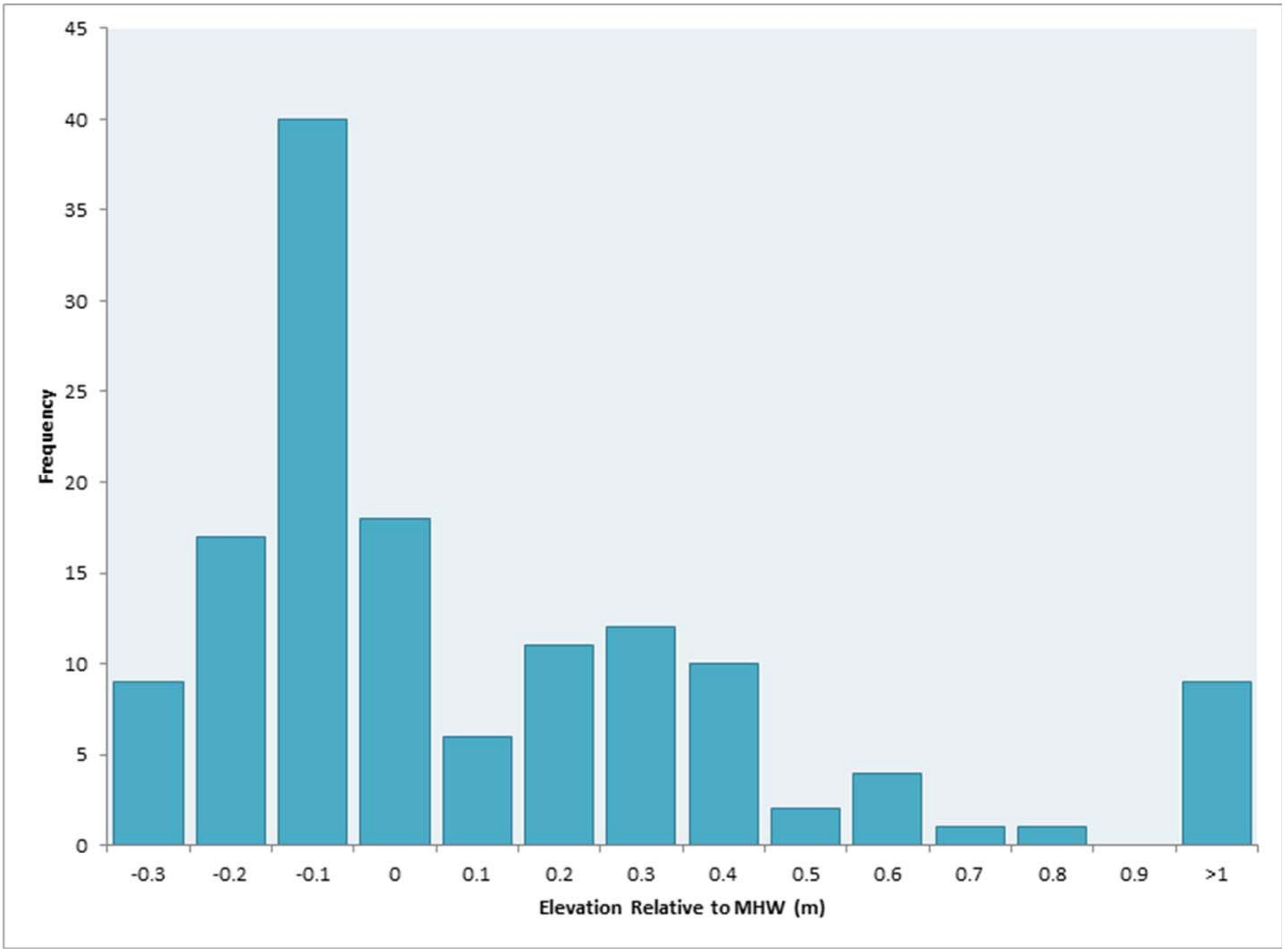

Figure A-2. Distribution of elevation samples relative to local mean high water (MHW), in meters (m), at the South Bay. N=140.

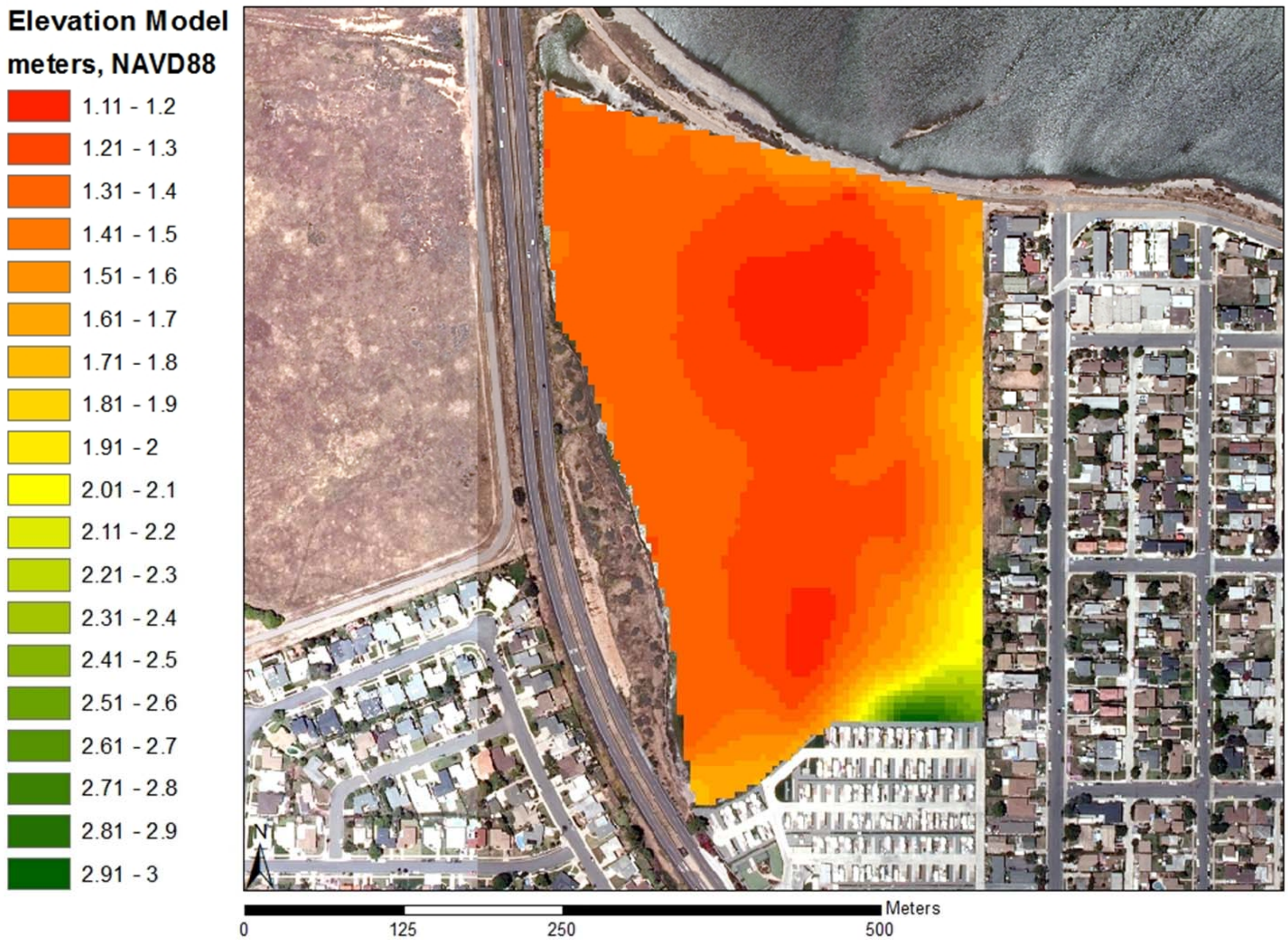

Figure A-3. Elevation model (5-meter resolution) for South Bay developed from ground RTK GPS elevation data. Parameters were optimized to produce minimal root-mean-square error.

Water-level monitoring

Water level logger data from Sweetwater, which is 5 kilometers away, was used for the analysis of the South Bay inundation patterns. Water level was measured using two data logger deployed at Sweetwater; one at the mouth of a second order channel and one in the marsh interior. Water levels were recorded throughout the year to evaluate seasonal patterns in tides. The period when the marsh platform was most inundated was between May and September (Fig. A-4). Based on the tidal data a tidal datum model was produced (Fig A-6). This model gives insight into what portions of the marsh are covered by water during different tidal periods. During 2011 and 2012, mean tide level (MTL) was 0.95 m, mean high water (MHW) was 1.48 m and mean higher high water (MHHW) was 1.72 m (NAVD88).

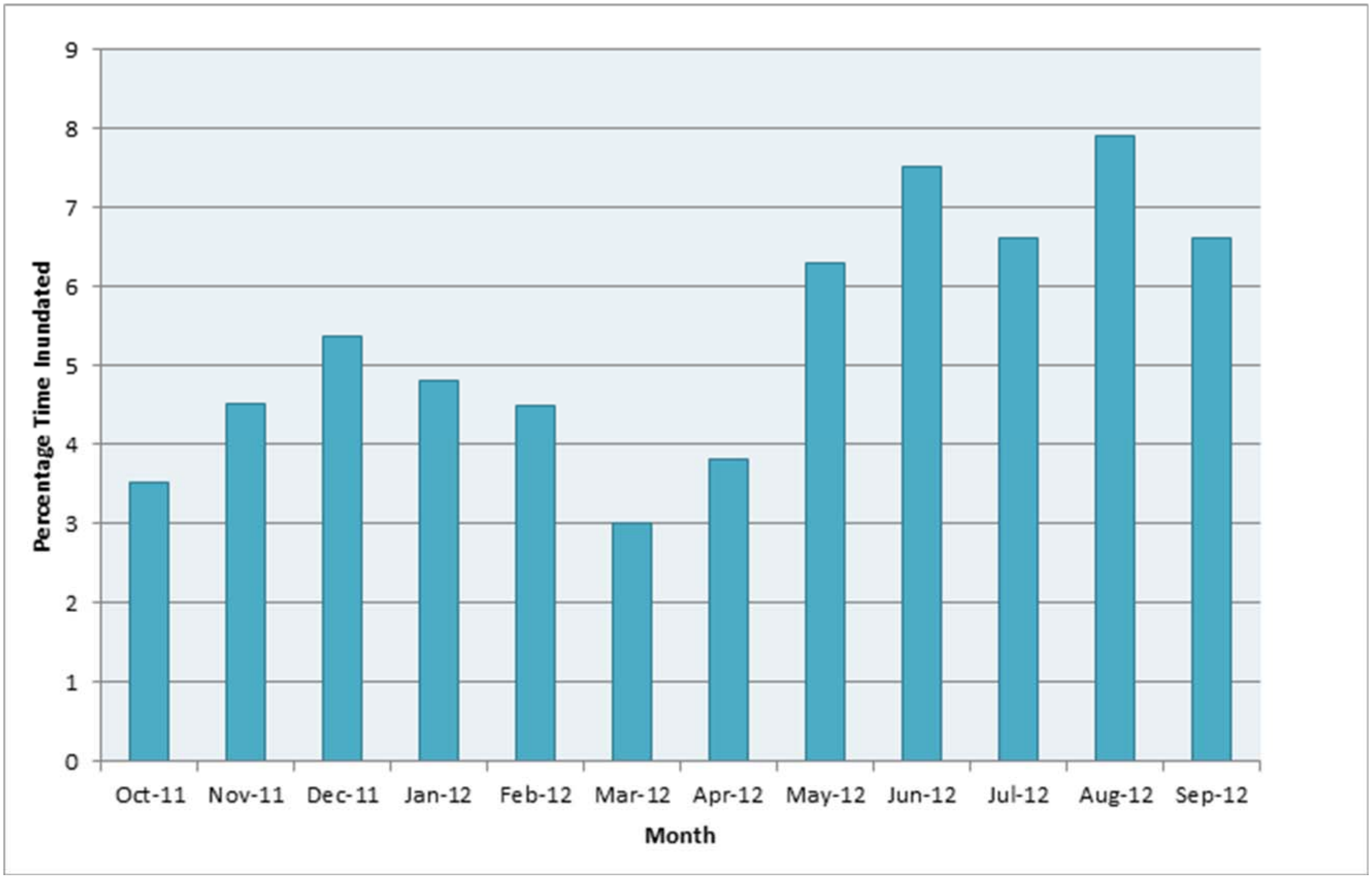

Figure A-4. Percentage of time the South Bay was inundated monthly based on the mean elevation of the marsh platform and water logger data.

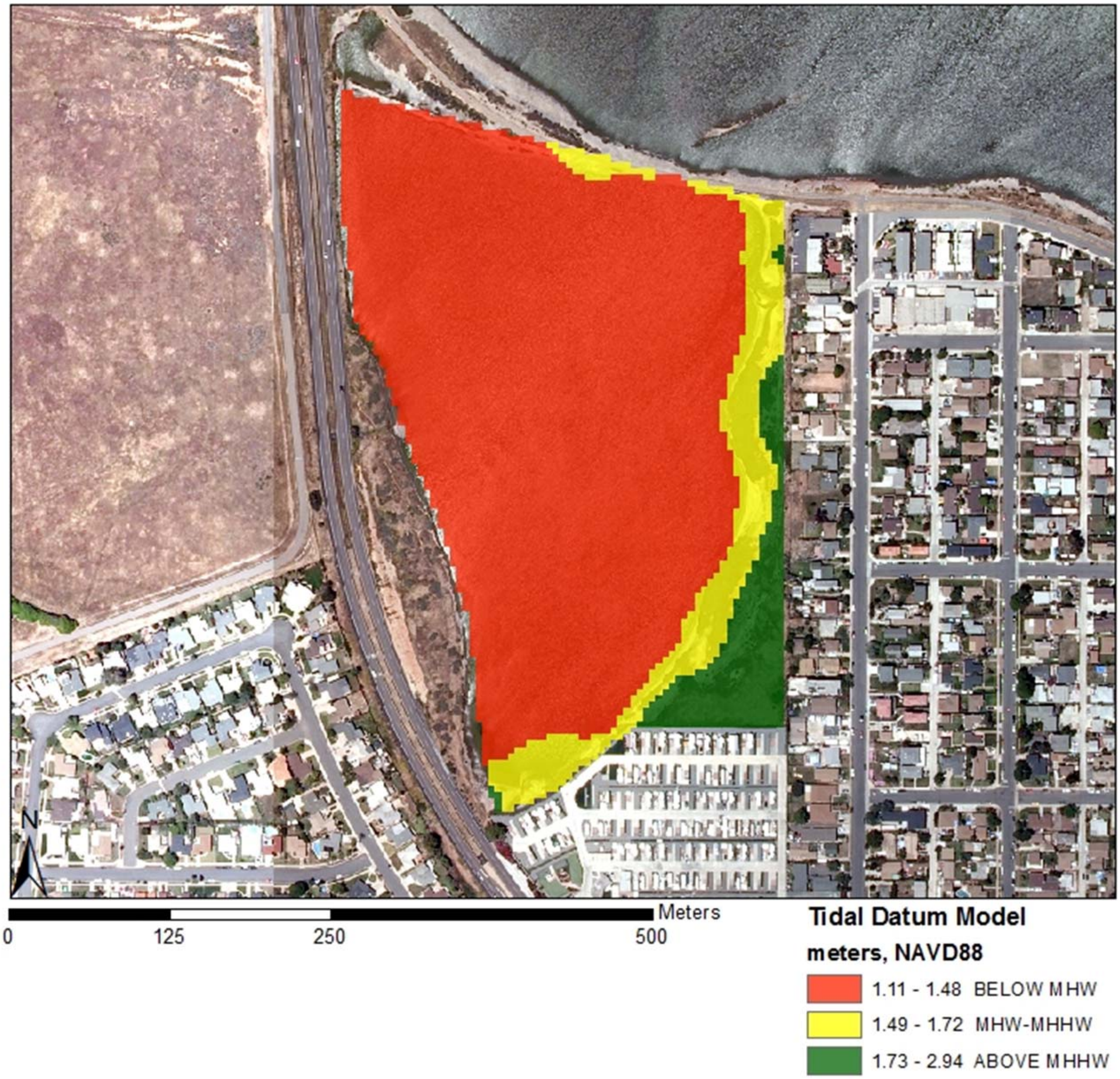

Figure A-6. Tidal inundation model for the South Bay using tidal data from a local water logger at Sweetwater.

Appendix B

Sweetwater

Introduction

Sweetwater marsh is 128 hectares and is located in Chula Vista, California, at the mouth of the Sweetwater River. As the largest remaining salt marsh on San Diego Bay, it provides important habitat for wintering waterfowl and shorebirds, as well as nesting habitat for several endangered bird species, including the California Least Tern (*Sternula antillarum browni*), Belding's Savannah Sparrow (*Passerculus sandwichensis beldingi)*, and the Light-footed Clapper Rail (*Rallus longirostris levipes*). In addition, it fosters the only known native population of the endangered plant, Palmer's Frankenia (*Frankenia palmeri*). This study focused on 63 hectares (ha) of salt marsh that was surveyed in September of 2011 using an RTK GPS. To monitor tidal inundation, two water loggers were deployed in September of 2011 at the site; one at the mouth of a primary channel and one in a secondary channel.

Results

Elevation surveys

A total of 1,201 elevation measurements were taken at Sweetwater, 1,156 of which were used in the interpolation process (Fig. B-1). The elevation range was between 0.83 m and 2.74 m, with a mean of 1.63 m (NAVD88). Over half (86 percent) of the survey points were located at elevations above mean high water (MHW; Fig B-2). A 5-m resolution elevation model was developed in ArcGIS 10 (ESRI, Redlands, Calif.), using the kriging method (Fig. B-3). This baseline elevation model was used as the initial state in tidal datum models.

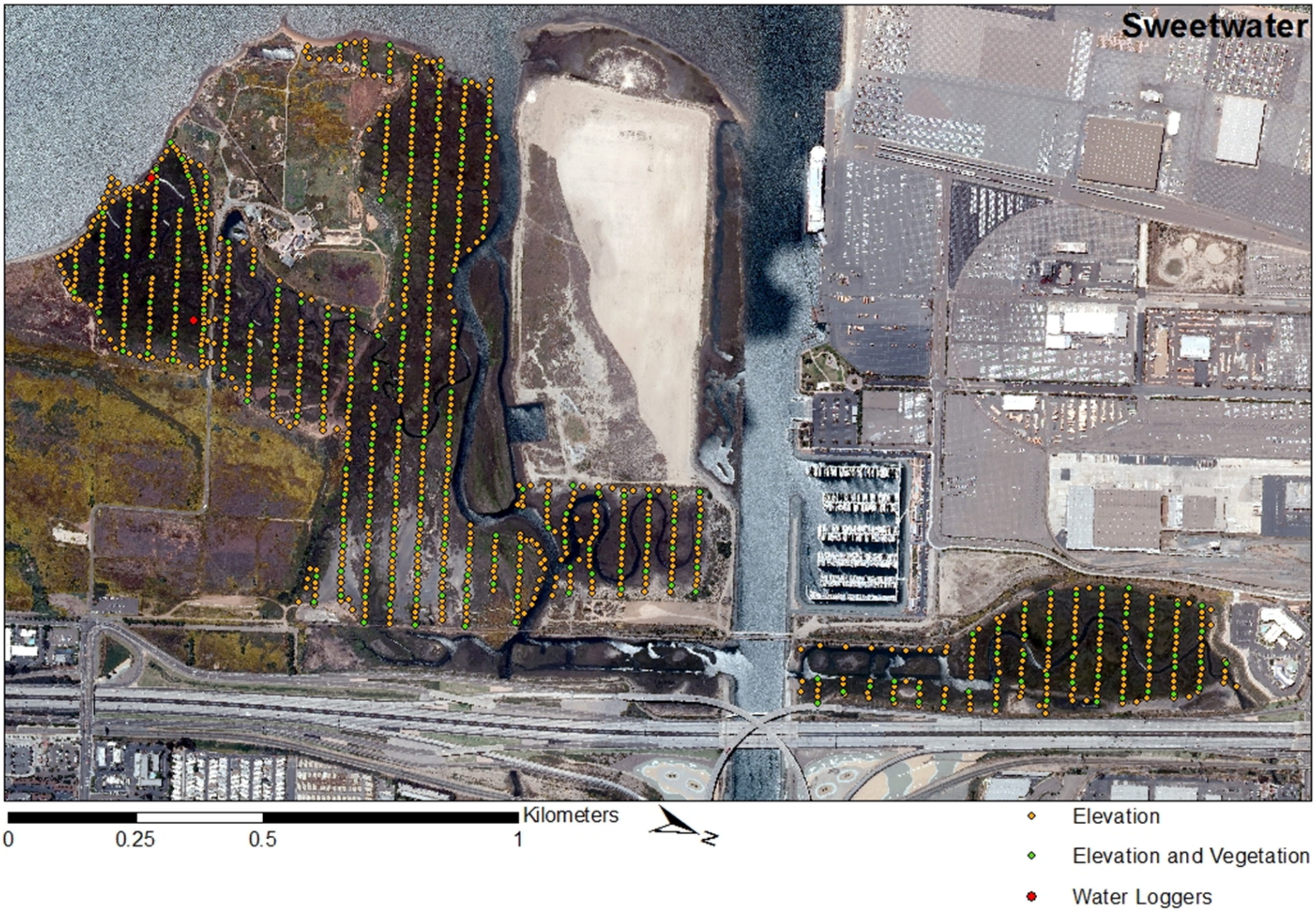

Figure B-1. Elevation and vegetation survey points and water logger locations at Sweetwater in 2011.

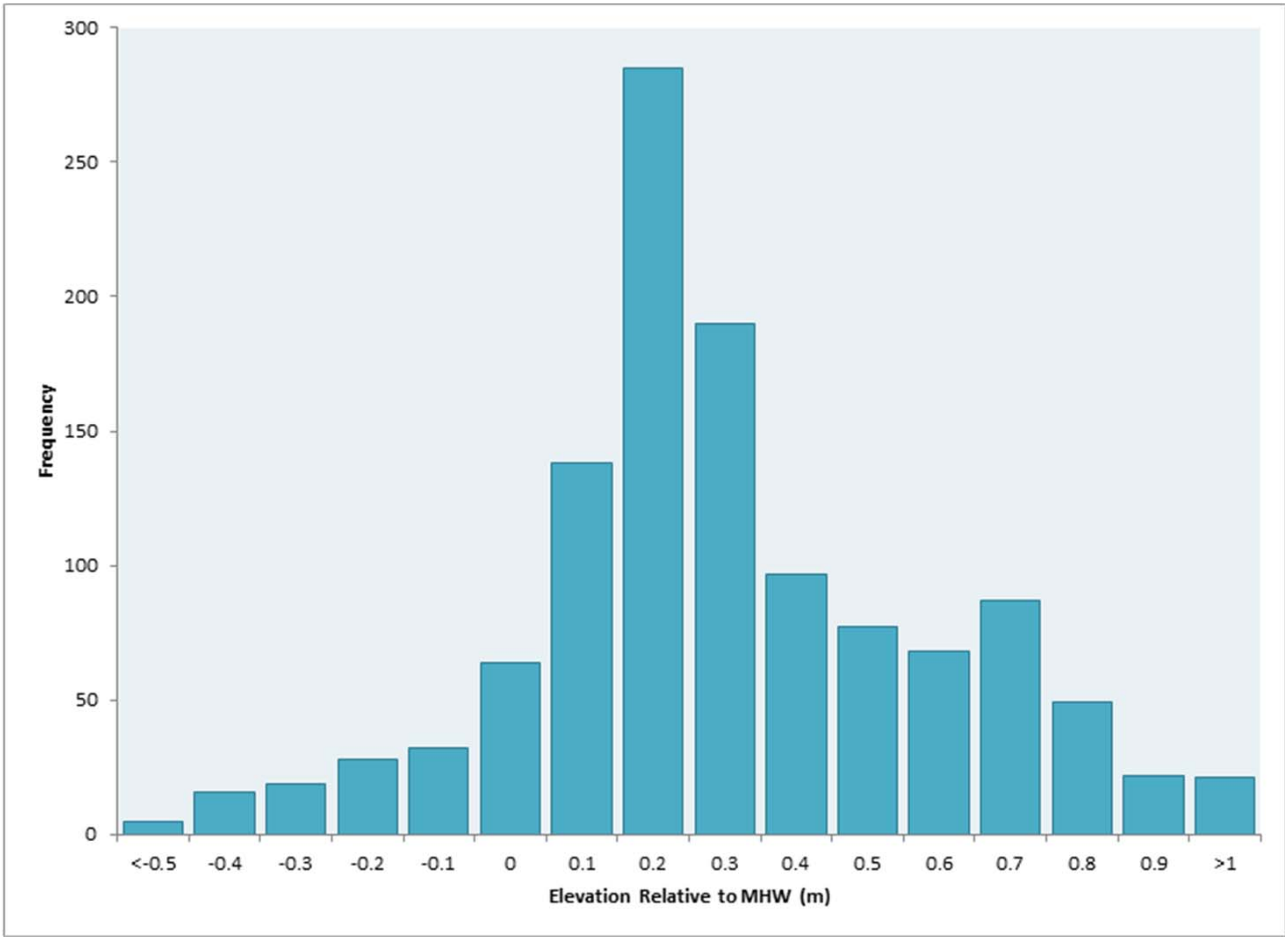

Figure B-2. Distribution of elevation samples relative to local mean high water (MHW), in meters (m), at Sweetwater.

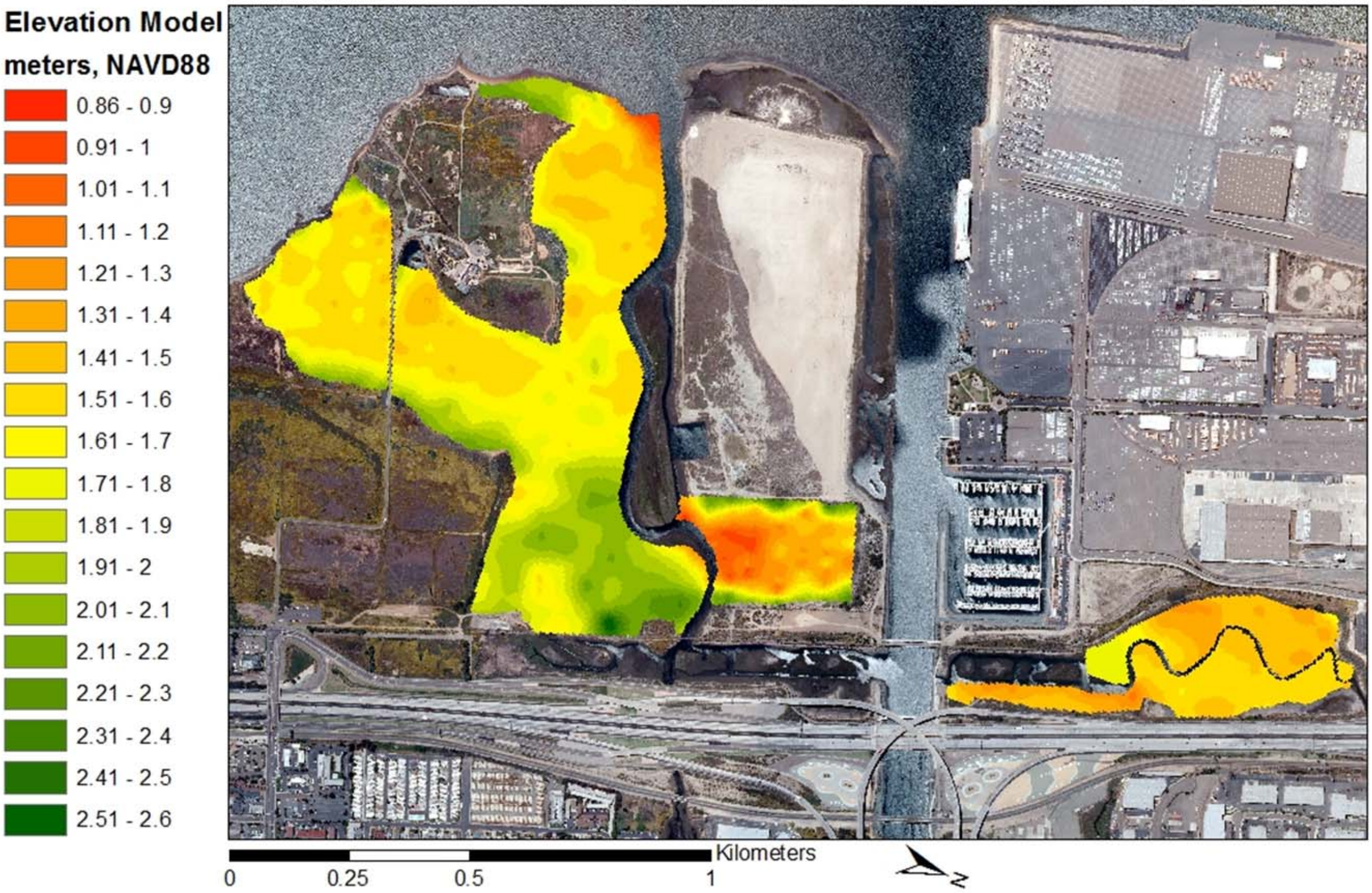

Figure B-3. Elevation model (5-meter resolution), for Sweetwater developed from ground RTK GPS elevation data. Parameters were optimized to produce minimal root-mean-square error.

Vegetation surveys

Vegetation was sampled at 274 locations, and 15 species where detected in the marsh (Table B-1, Fig. B-1). Distinct zonation in plant communities was observed in relation to MHW because plants are typically restricted by their inundation tolerance (Fig. B-4-6). Only 9 species occurred at more than 10 percent of the vegetation plots (Figs. B-4-6). Sarcocornia pacifica was the most common species surveyed across sites, occurring at 64 percent of vegetation plots. Batis maritima was the second most common species (63.5 percent), followed by *Jaumea carnosa* (36 percent), *Frankenia* *salina* (33 percent), *Sarcocornia bigelovii* (32 percent), *Spartina foliosa* (27 percent), *Limonium californicum* (21 percent), *Distichlis littoralis* (21 percent), and *Distichlis spicata* (14 percent).

The native population of salt marsh bird's beak at Sweetwater marsh was last seen in 1987. The California Department of Transportation (Caltrans) was required to establish a self-sustaining population of *Chloropyron maritimum* subsp*. maritimum* at Sweetwater Marsh as part of mitigation for a freeway expansion project (Parsons and Zedler 1997, p. 254). Seeds for this project were collected annually from Tijuana Estuary and sown at Sweetwater marsh each winter from 1990 to 1992 (Parsons and Zedler 1997, p. 254). Seeds were sown to create five clusters of small patches similar in elevation, canopy cover, and host plant species. *Monanthochloe littoralis*, *Anthrocnemum subterminale*, *Frankenia salina*, *Cressa truxillensis*, *Atriplex watsonii*, and *Limonium californicum* were prevalent at the reintroduction site. The estimated number of resultant individuals of *Chloropyron maritimum* subsp. *maritimum* was 5,000 in 1992, 5,700 in 1993, 14,300 in 1994, and 14,000 in 1995 (Parsons and Zedler 1997, p. 257). We have no updated information on the condition of this reestablishment effort.

During our study salt marsh bird's beak was only recorded in one vegetation plot at Sweetwater marsh and was not recorded at any other study site locations. Although it was not found in other vegetation plots field crews collecting the data did observe salt marsh bird's beak in more locations at Sweetwater marsh and at Tijuana marsh. Its lack of presence in our vegetation survey is most likely due to its patchy distribution and lower abundance than other species.

Table B-1. Sample number, mean marsh elevation relative to mean high water (MHW), average, and max height, percentage cover with standard deviations (SD), and presence by species at Sweetwater. See Table 5 for species code and scientific name. [cm, centimeter; m, meter; n, sample number]

Species code	n	Mean Elevation Relative to MHW (m)	SD Elevation Relative to MHW	Mean Avg. Height (cm)	Mean Avg. Height SD	Mean Max Height (cm)	Mean Max Height SD	Mean Cover %	Mean Cover % SD	Presence (%)
ARSU	25	0.60	0.16	28	12	33	11	68	29	9.12
ATWA	4	0.50	0.05	13	5	15	6	18	22	1.46
BAMA	180	0.02	0.16	13	7	17	8	17	14	65.69
COMA	1	0.53	-	15	-	18	-	30	-	0.36
CRTR	14	0.48	0.11	24	9	27	10	7	8	5.11
DILI	57	0.31	0.21	17	7	23	9	43	40	20.80
DISP	39	0.10	0.15	23	7	29	8	19	20	14.23
FRSA	90	0.22	0.20	18	8	22	9	23	28	32.85
JACA	98	-0.02	0.14	13	6	17	8	37	32	35.77
LICA	58	0.12	0.16	19	9	28	15	18	15	21.17
SABI	87	-0.02	0.16	17	7	23	10	20	18	31.75
SAPA	174	0.05	0.20	25	11	35	14	45	32	63.50
SPFO	75	-0.12	0.16	46	15	62	23	22	17	27.37
SUES	25	0.07	0.12	23	9	30	12	27	23	9.12
TRMA	3	0.03	0.20	11	4	15	5	16	21	1.09

High Occurrence Species

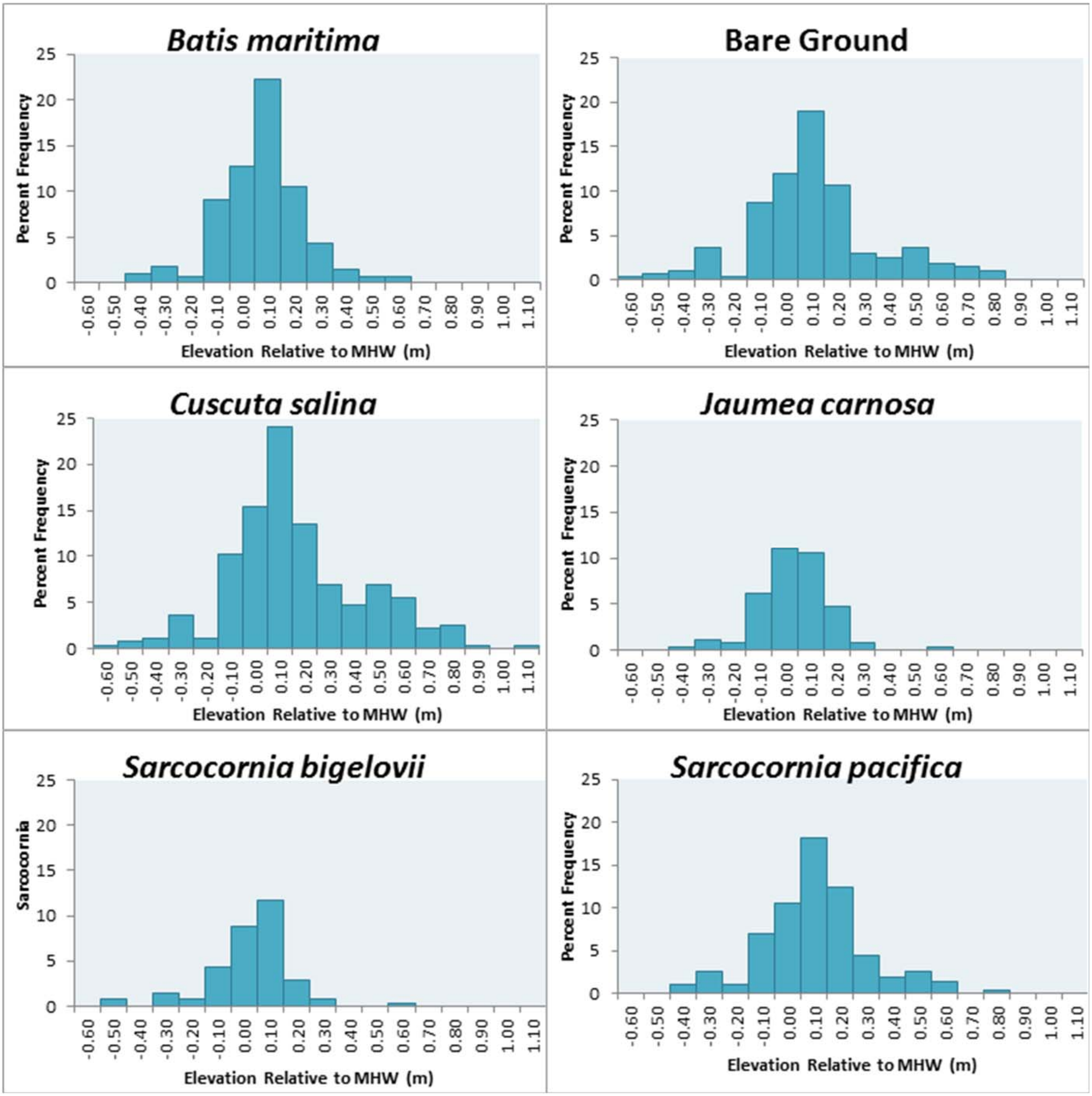

Figure B-4. Distribution of high occurrence (scaled at twenty-five percent frequency) plant species was observed relative to MHW across Sweetwater.

Medium Occurrence Species

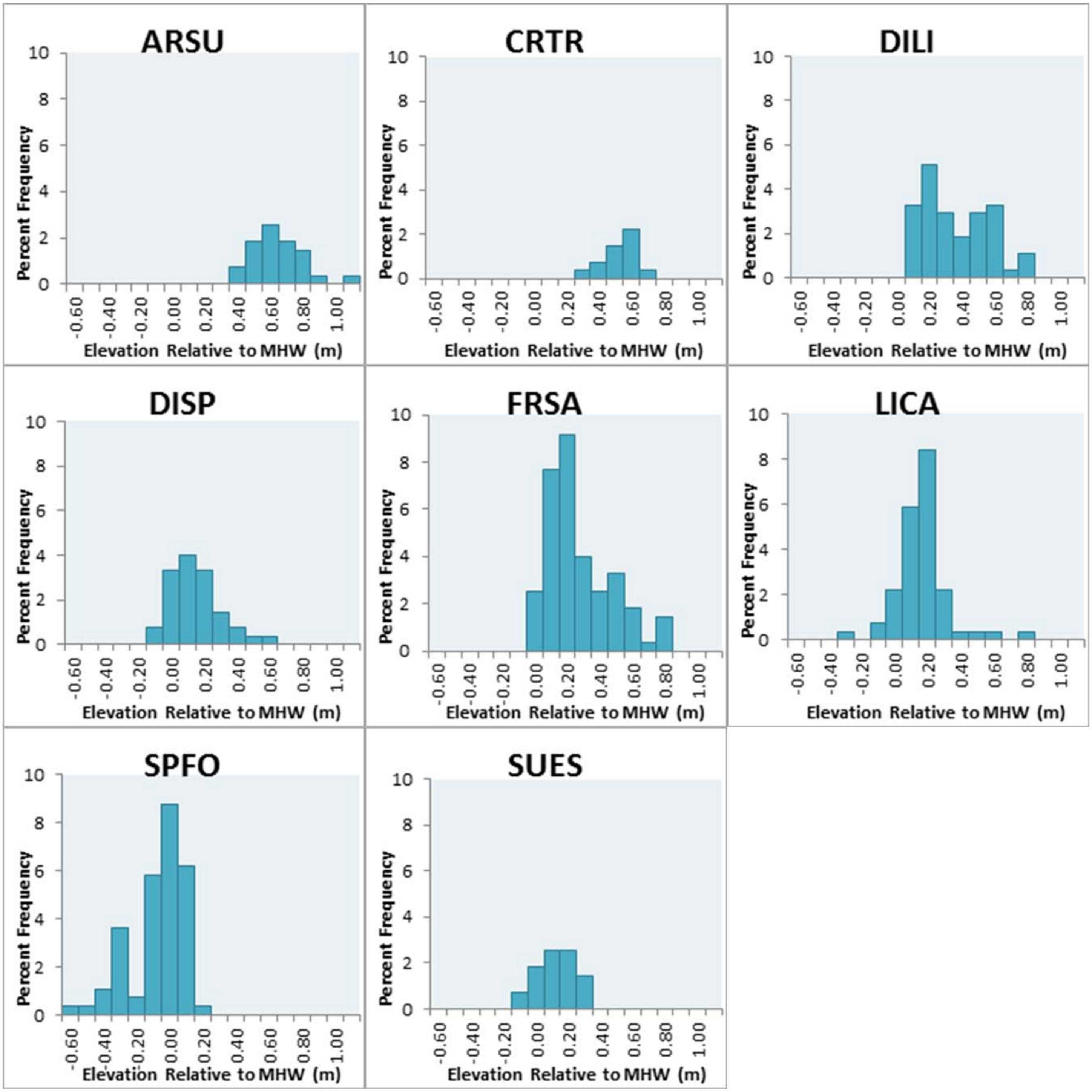

Figure B-5. Distribution of medium occurrence (scaled at ten percent frequency) plant species was observed relative to MHW across Sweetwater. Species codes are: CRTR = *Cressa truxillensis*; DILI = *Distichlis littoralis*; DISP = *Distichlis spicata*; FRSA = *Frankenia salina*; LICA = *Limonium californicum*; ARSU = *Arthrocnmum subterminale*; SPFO = *Spartina foliosa*; SUES = *Sueda esteroa*; See Table 5 for species code and scientific name.

Low Occurrence Species

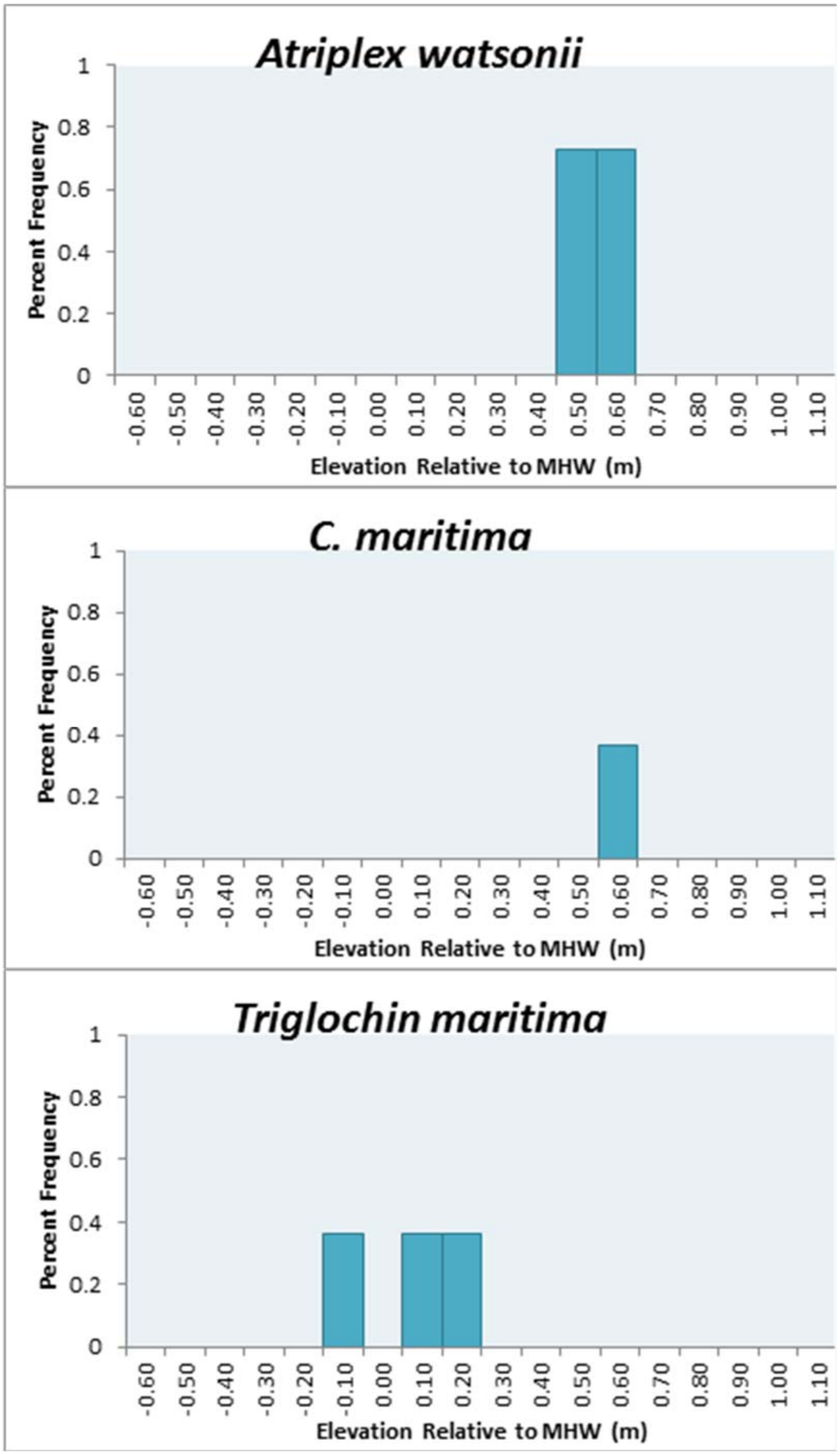

Figure B-6. Distribution of low occurrence (scaled at one percent frequency) plant species was observed relative to MHW across Sweetwater.

Water-level monitoring

Site-specific water level was analyzed from October 2011 to September 2012. Water level was measured using two data loggers: one deployed at the mouth of a second order channel and one in the marsh interior; water level monitoring is ongoing. Mean tide level (MTL) was 0.85 m, mean high water (MHW) was 1.38 m, and mean higher high water (MHHW) was 1.62 m for the site during this time (in NAVD88). The period when the salt marsh platform (defined as mean marsh elevation) was inundated most often was during August and September of 2012 (Fig. B-7). Based on the tidal data, a tidal datum model was produced (Fig B-8). This model gives insight into portions of the marsh covered by water during different tidal periods.

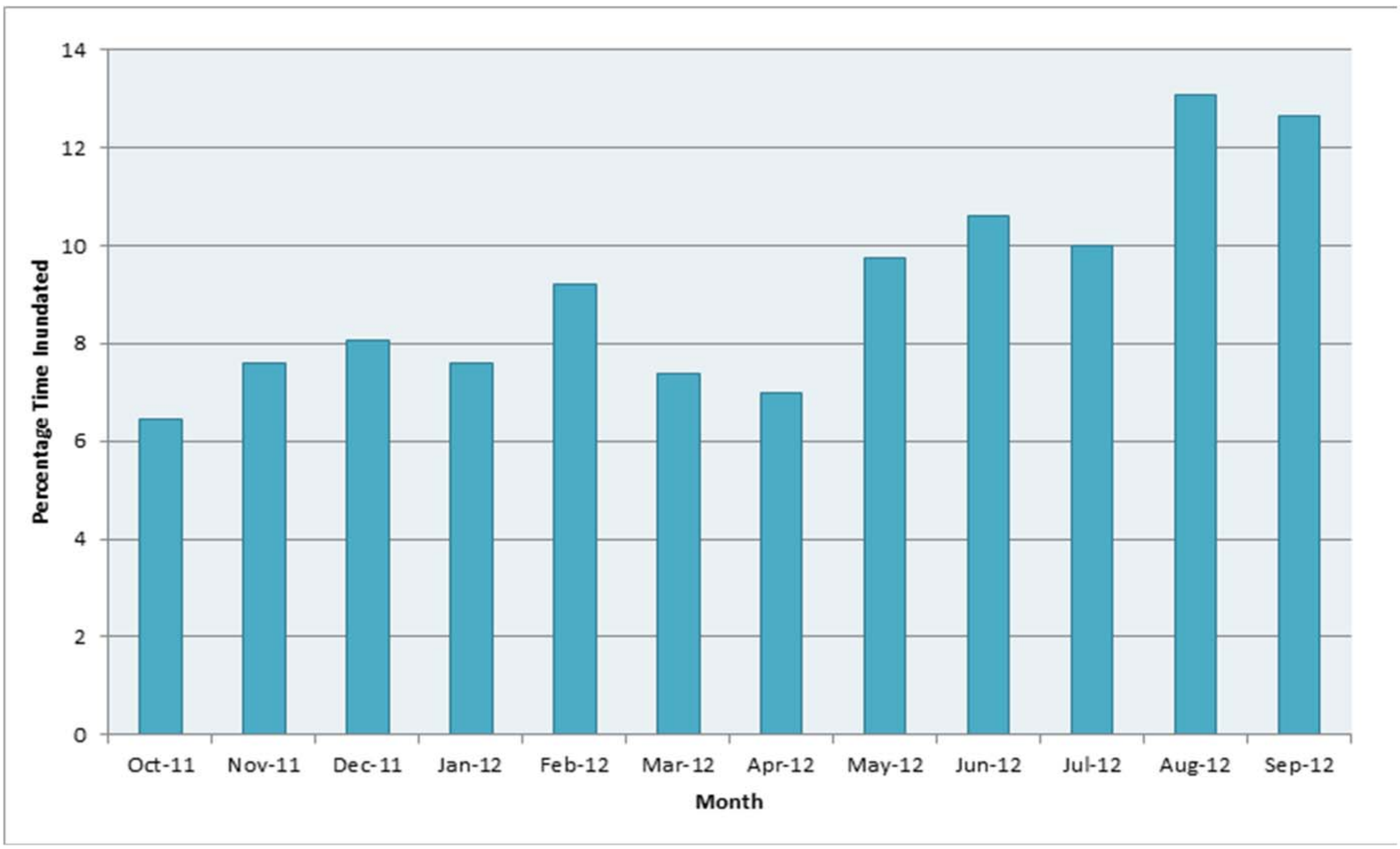

Figure B-7. Percentage of time Sweetwater was inundated monthly, based on the mean elevation of the marsh platform.

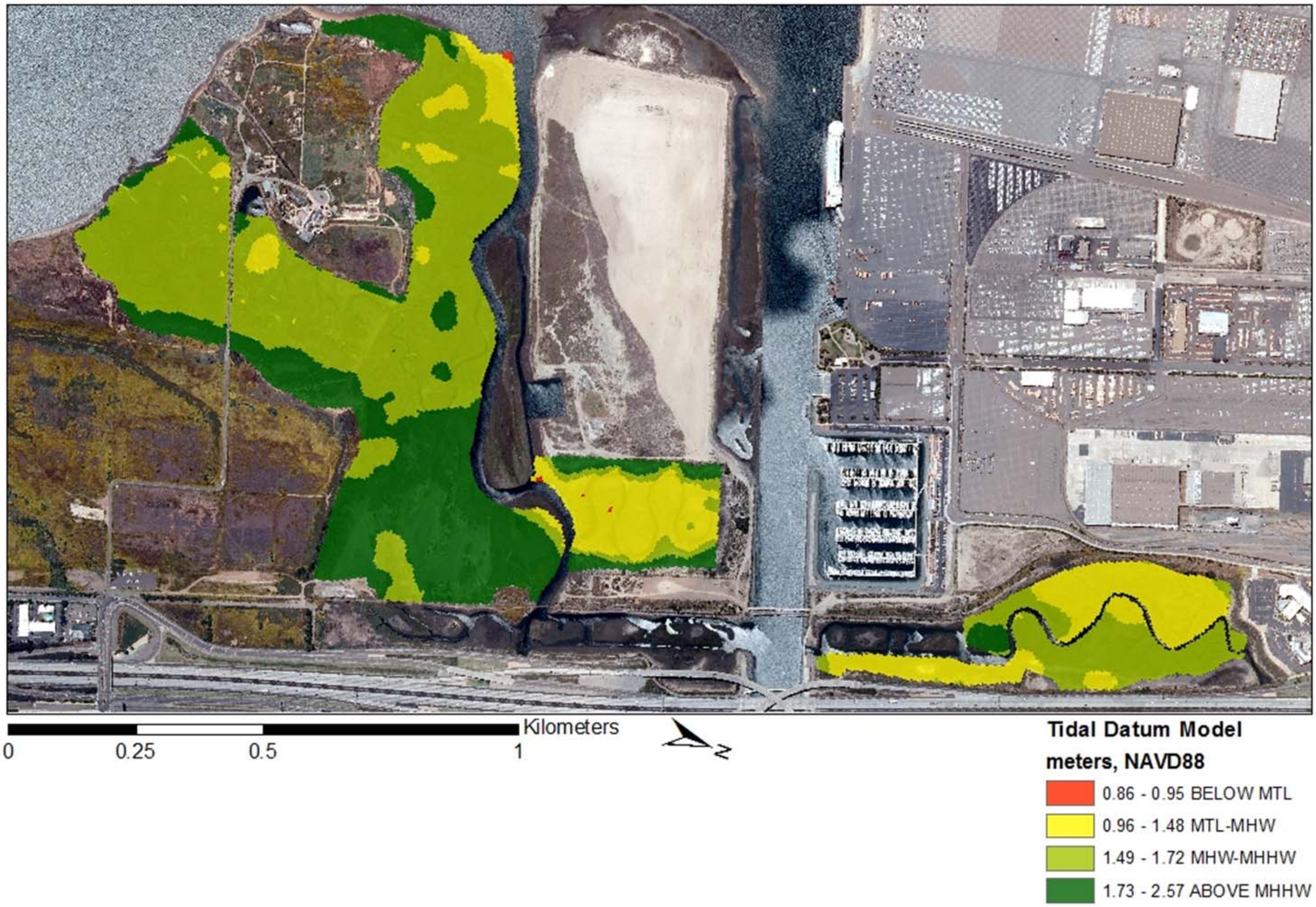

Figure B-8. Tidal Inundation model for Sweetwater based on local tidal data from a local water logger.

Appendix C

Tijuana

Introduction

Tijuana Slough National Wildlife Refuge is located in Imperial Beach, California. Due to its ecological importance, it is a NOAA National Estuarine Research Reserve (NERR). The marsh comprises 425 ha of wetland and is part of a 927 ha reserve that encompasses the Tijuana River watershed. Episodic winter storms cause the Tijuana River to flow high, bringing substantial amounts of sediment to the marsh system. It is the only Southern California coastal lagoon that is not bisected by a road or rail line and with 75% of the watershed located in Mexico and much of the refuge bordered by residential developments, the Tijuana Slough NWR represents an important local and international effort to maintain and restore natural wetlands. The study focused on 376 hectares (ha) of salt marsh that was surveyed during November and December of 2011. To monitor tidal inundation, four water loggers were deployed in September of 2011 at the site.

Results

Elevation surveys

A total of 5,913 elevation measurements were taken at Tijuana marsh, 5,832 of which were used in the interpolation process (Fig. C-1). Upland fringe areas of Tijuana marsh were mapped and therefore Tijuana had the largest elevation range of all five sites. The elevation ranged from 0.99–5.32 meters, (m) with a mean of 2.22 m (NAVD88). Tijuana marsh had low tidal areas, but was predominantly high marsh with the majority (97 percent) of survey points at elevations above mean high water (MHW). A 5-m resolution elevation model was developed in ArcGIS 10 (ESRI, Redlands, Calif.), Spatial Analyst applying the kriging method (Fig. C-3). This baseline elevation model was used as the initial state for tidal inundation modelling

Figure C-1. Tijuana marsh with elevation and vegetation survey points and water logger locations from 2010.

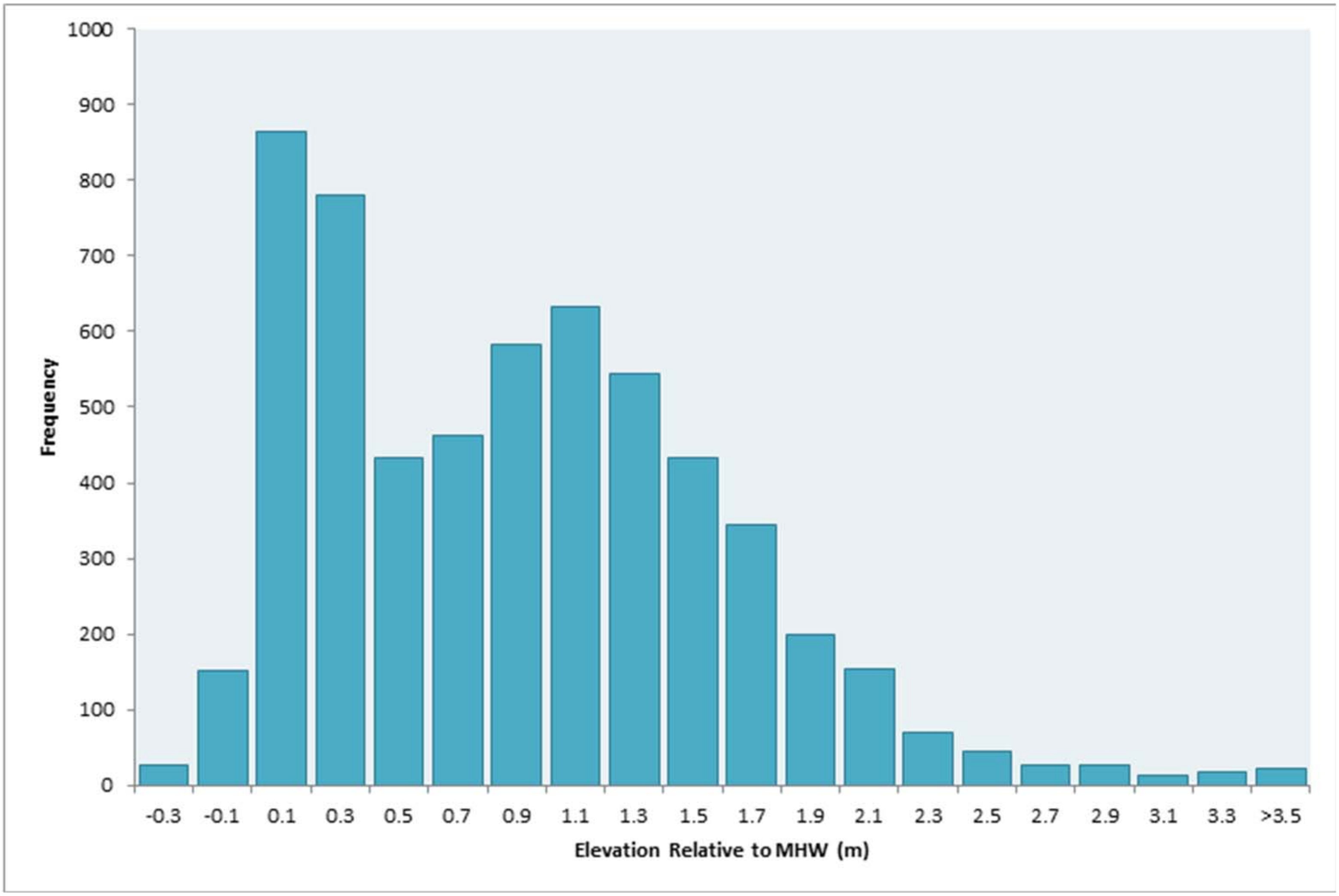

Figure C-2. Distribution of elevation samples relative to local mean high water (MHW), in meters (m), at Tijuana.

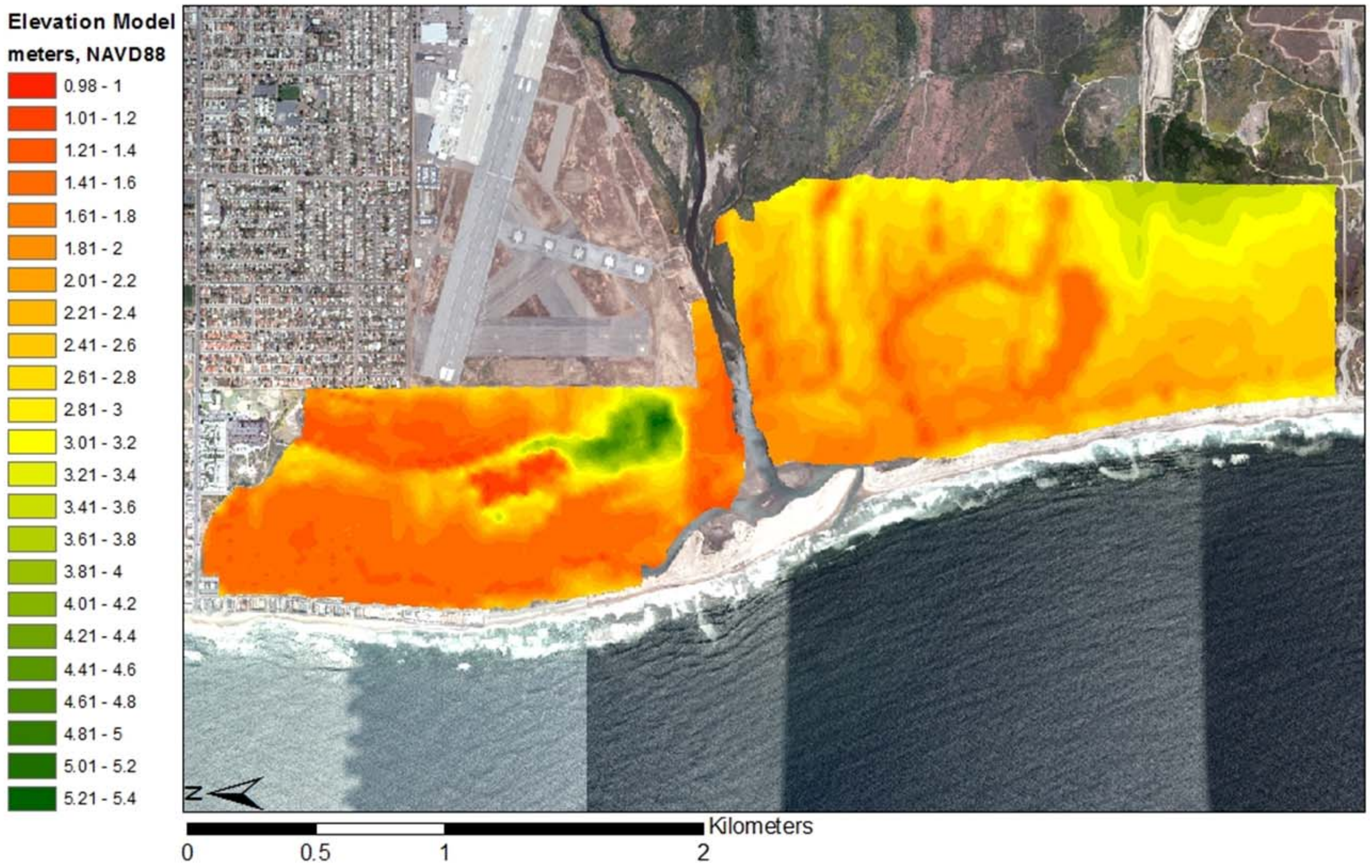

Figure C-3. ArcGIS elevation model (5-meter resolution) for Tijuana developed from ground RTK GPS elevation data. Parameters were optimized to produce minimal root-mean-square error (RMSE).

Vegetation surveys

Vegetation was sampled at 1,483 locations, and 18 species where detected in the marsh (Table B-1,Fig. C-4). Distinct zonation in plant communities was observed in relation to MHW because plants are typically restricted by their inundation tolerance (Figs. C-4-6). Only 6 species occurred at more than 10 percent of the vegetation plots (Fig. C-4-6). *Sarcocornia pacifica* was the most common species surveyed across sites, occurring at 39 percent of vegetation plots. *Arthrocnemum subterminale* was the second most common species (25 percent), followed by *Frankenia salina* (24 percent), *Jaumea carnosa* (13 percent), *Distichlis spicata* (12 percent), and *Spartina foliosa* (11 percent).

Table C-1. Mean marsh elevation relative to mean high water (MHW), average, and max height, percentage cover with standard deviations (SD), and presence by species at Tijuana. See table 5 for species code and scientific name. [cm, centimeter; m, meter; n, sample number]

Species code	n	Mean Elevation Relative to MHW (m)	SD Elevation Relative to MHW	Mean Avg. Height (cm)	Mean Avg. Height SD	Mean Max Height (cm)	Mean Max Height SD	Mean Cover %	Mean Cover % SD	Presence (%)
ARSU	364	0.92	0.32	30	11	38	13	76	28	24.54
ATSE	1	0.39	-	10	-	10	-	5	-	0.07
ATWA	2	0.68	0.17	17	10	21	8	28	4	0.13
BAMA	118	0.10	0.10	19	5	23	7	23	18	7.96
CRTR	19	0.69	0.32	22	7	26	8	30	23	1.28
DILI	108	0.54	0.24	18	7	24	9	59	34	7.28
DISP	185	0.68	0.53	26	9	32	11	37	32	12.47
FRSA	357	0.43	0.35	23	8	29	9	43	32	24.07
ISME	41	1.52	0.46	57	23	81	33	60	34	2.76
JACA	190	0.15	0.13	14	4	19	6	63	30	12.81
JUAC	13	0.46	0.38	62	23	83	33	50	29	0.88
LICA	39	0.34	0.27	22	13	26	15	16	12	2.63
MECR	25	1.37	0.43	9	6	12	7	41	21	1.69
SABI	4	0.08	0.02	29	5	37	5	43	12	0.27
SAPA	582	0.24	0.37	35	10	48	13	78	26	39.24
SPFO	167	0.00	0.09	66	18	85	21	51	30	11.26
SUES	16	0.23	0.16	24	7	30	9	20	12	1.08
TRMA	6	0.09	0.04	11	2	11	2	9	7	0.40

High Occurrence Species

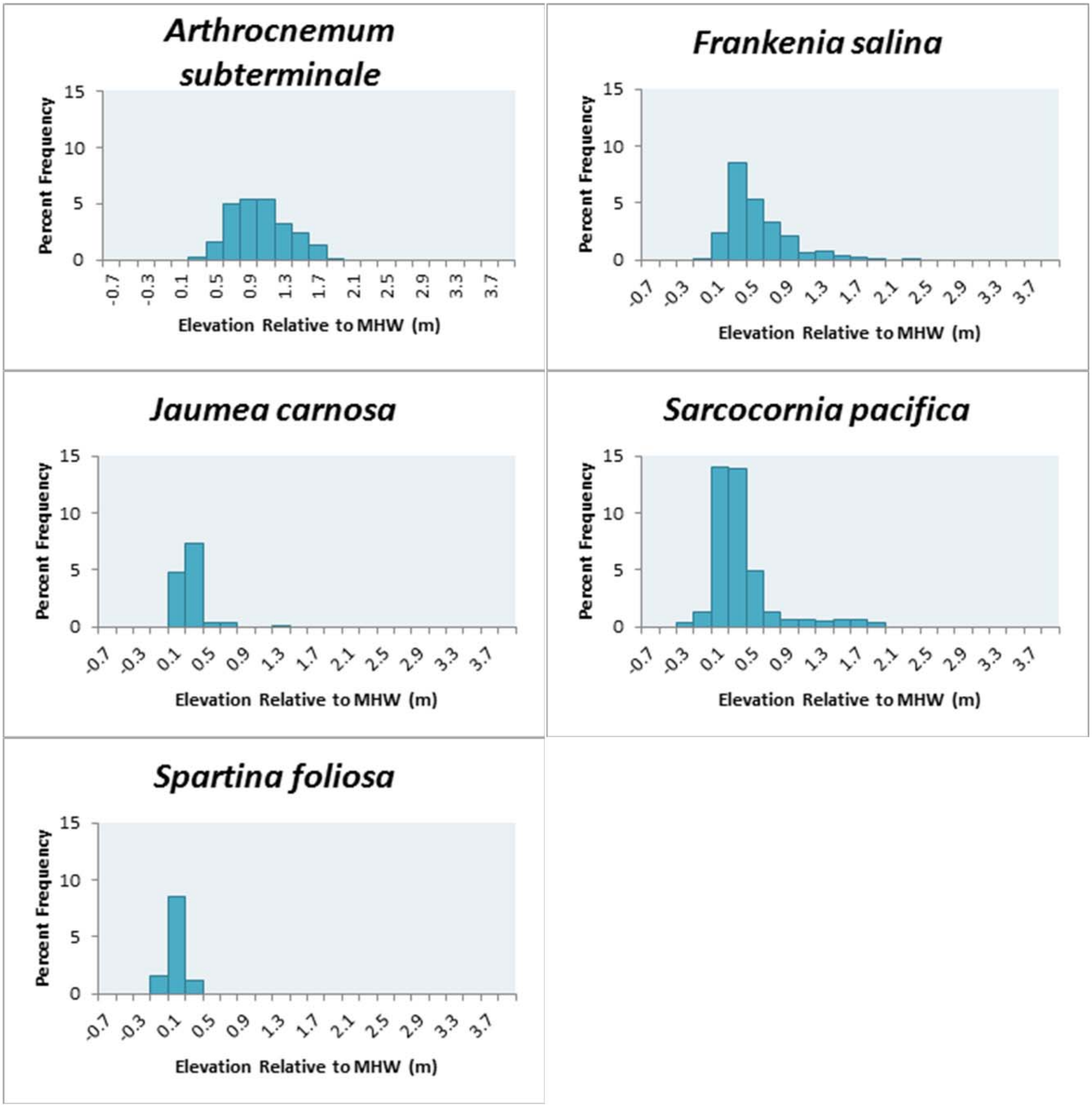

Figure C-4. Distribution of high occurrence (scaled at fifteen percent frequency) plant species observed relative to MHW across Tijuana.

Medium Occurrence Species

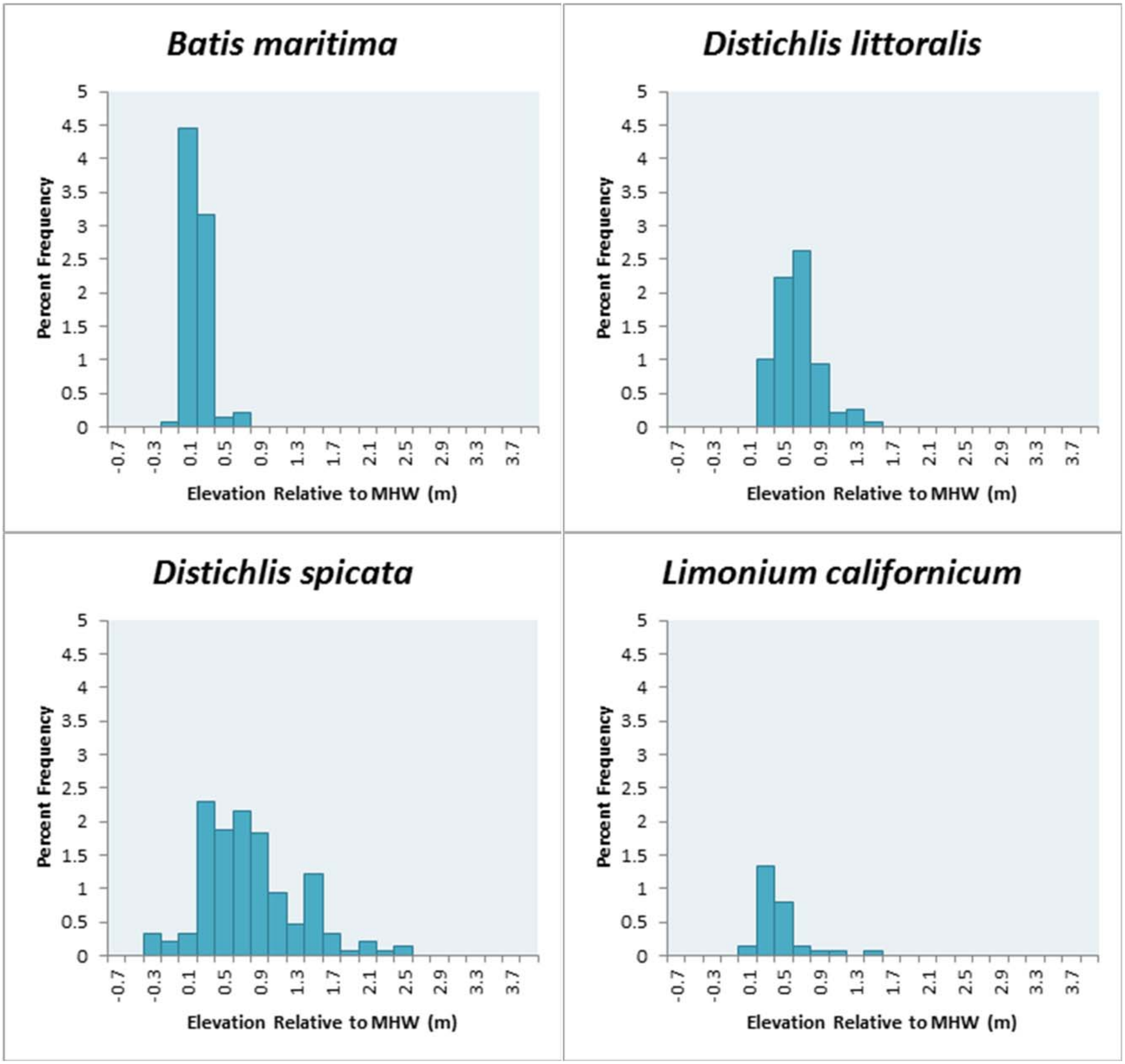

Figure C-5. Distribution of medium occurrence (scaled at five percent frequency) plant species observed relative to MHW across Tijuana.

Low Occurrence Species

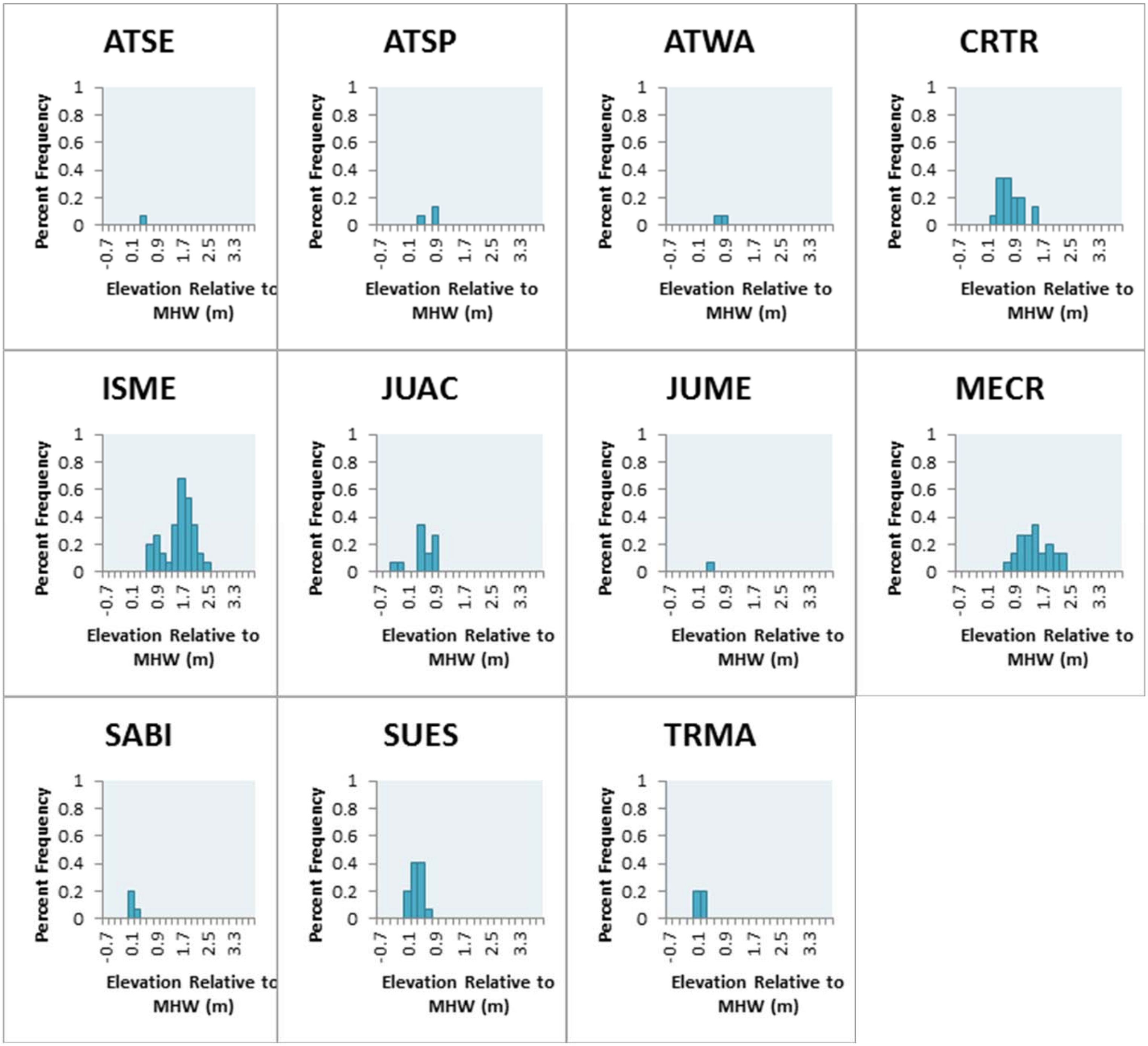

Figure C-6. Distribution of low occurrence (scaled at one percent frequency) plant species was observed relative to MHW across Tijuana. Species codes are: ATSE = *Atriplex semibaccata*; ATWA = *Atriplex watsonii*; BAMA = *Batis maritima*; CRTR = *Cressa truxillensis*; DILI = *Distichlis littoralis*; DISP = *Distichlis spicata*; FRSA = *Frankenia salina*; ISME = *Isocoma menziesii*; JACA = *Jaumea carnosa;* JUAC = *Juncus acutus*; JUME = *Juncus mexicanus*; LICA = *Limonium californicum*; MECR = *Mesembryanthemum crystallinum*; SABI = *Sarcocornia bigelovii*; SAPA = *Sarcocornia pacifica*; ARSU = *Arthrocnemum subterminale*; SPFO = *Spartina foliosa*; SUES = *Sueda esteroa*; TRMA = *Triglochin maritima*; See Table 5 for species code and scientific name.

Water-level monitoring

Site specific water level was analyzed at Tijuana from November 2011 to June 2012. Water level was measured using four data loggers deployed in channels in the marsh platform; water level monitoring is ongoing. MTL was 1.02 m, MHW was 1.41 m, and mean higher high water (MHHW) was 1.65 m for the site (NAVD88). The period when the marsh platform (defined as mean marsh elevation of the north arm, 1.55 m) was inundated most often was during June of 2012 (Fig. C-7). Based on the tidal data a tidal datum model was produced (Fig C-8). This model gives insight into what portions of the marsh are covered by water during different tidal periods.

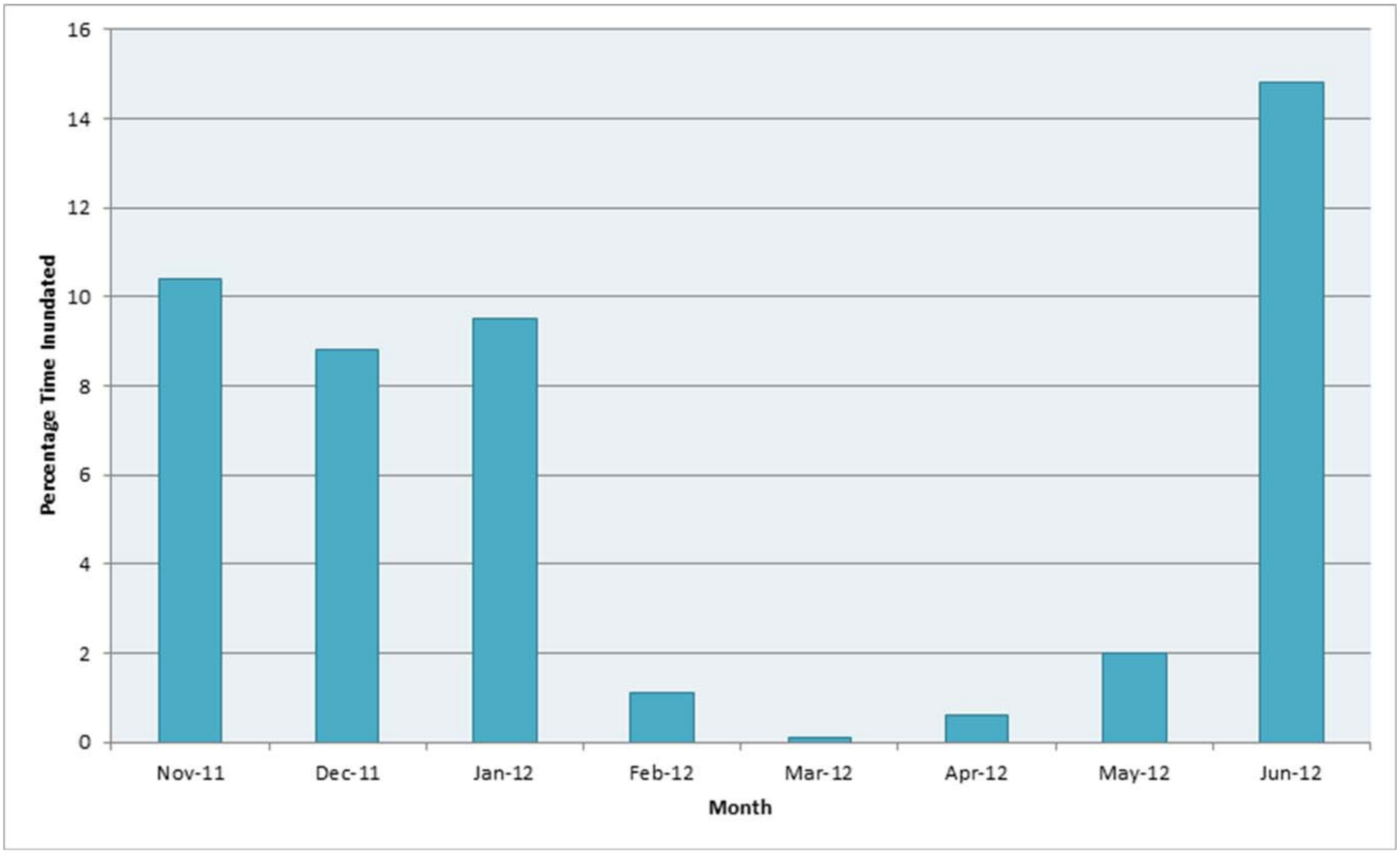

Figure C-7. Percentage of time Tijuana was inundated monthly, based on the mean elevation of the marsh platform.

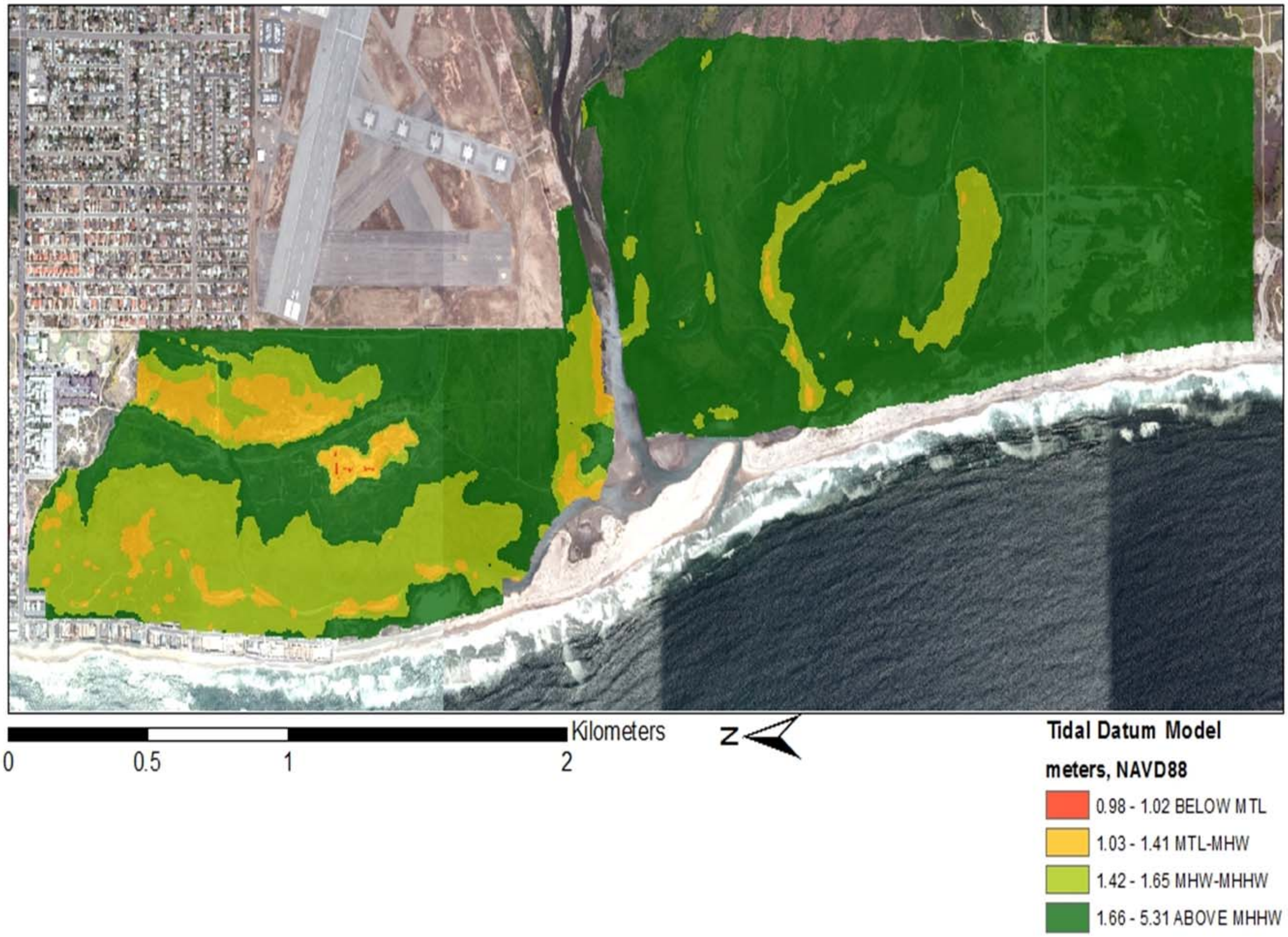

Figure C-8. Tidal inundation model for Tijuana based on local tidal data from a local water logger

Appendix D

Seal Beach

Introduction

The Seal Beach NWR marsh is located in Seal Beach, California and encompassed by the Seal Beach Naval Weapons Station. It is the only remaining salt marsh in the Anaheim Bay estuary. Originally set up as a Navy Preserve in the 1960s, it came under U.S. Fish and Wildlife jurisdiction in 1972 for endangered species management. At 390 ha, Seal Beach NWR provides important habitat for the federally threatened green sea turtle and critical nesting habitat for the California least tern and Light-Footed Clapper Rail, among other threatened and endangered species. The study focused on 266 ha of salt marsh that was surveyed between September and December of 2011. To monitor tidal inundation, four water loggers were deployed in December of 2011 at the site.

Results

Elevation surveys

A total of 4,757 elevation measurements were collected at Seal Beach marsh, 4,617 of which were used in the interpolation process to create the DEM (Fig. D-1). The elevation range was 0.31–3.56 meters (m), with a mean of 1.34 m (NAVD88). This was a relatively low marsh and showed a small range in elevation, with 81 percent of all points surveyed being between -0.1 m and 0.3 m relative to MHW. A 5-m resolution elevation model was developed in ArcGIS 10 (ESRI, Redlands, Calif.) Spatial Analyst using the kriging method (Fig. D-3). This baseline elevation model was used as the initial state for the tidal inundation model.

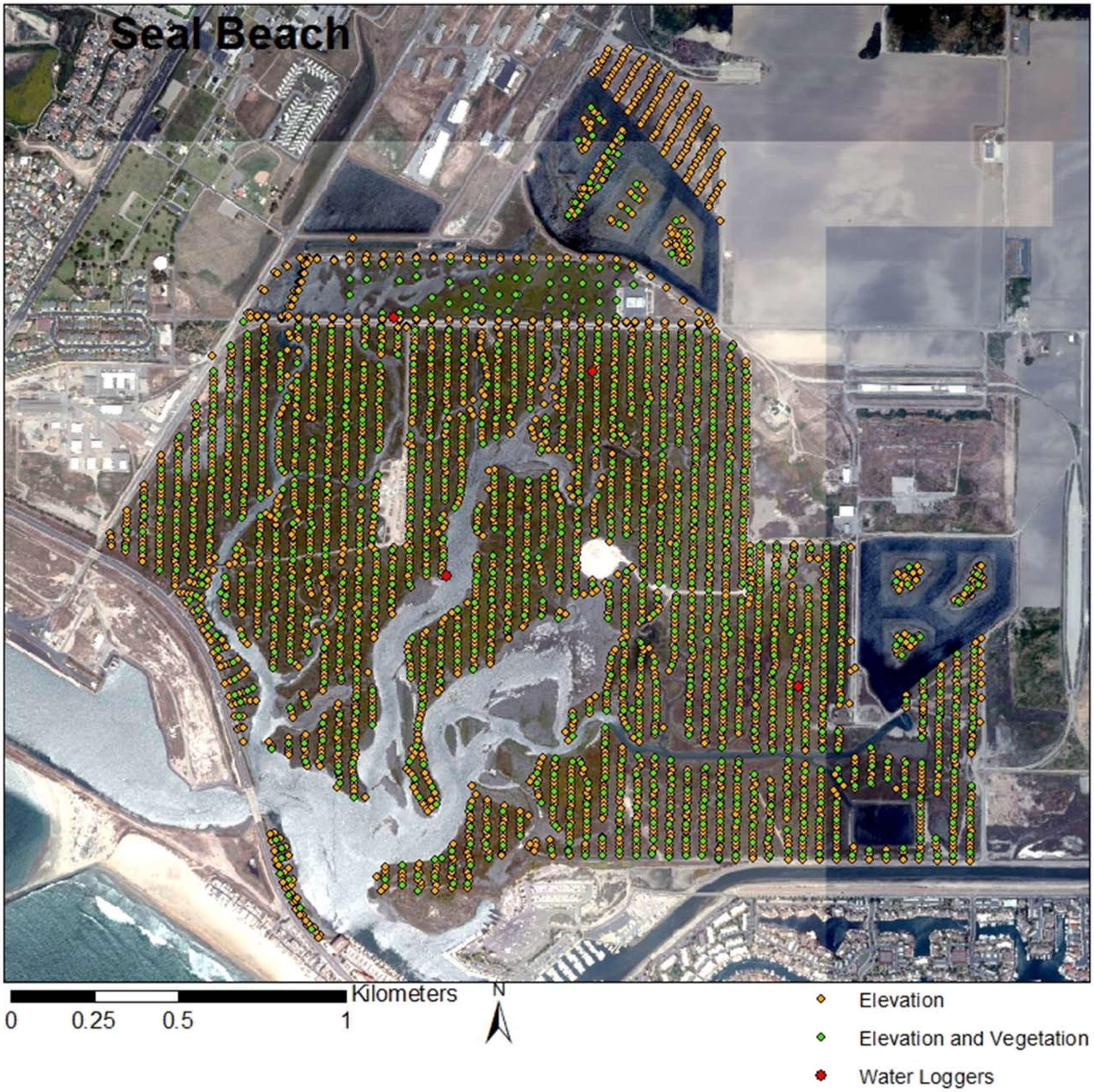

Figure D-1. Seal Beach, with elevation and vegetation survey points and water logger locations from 2011.

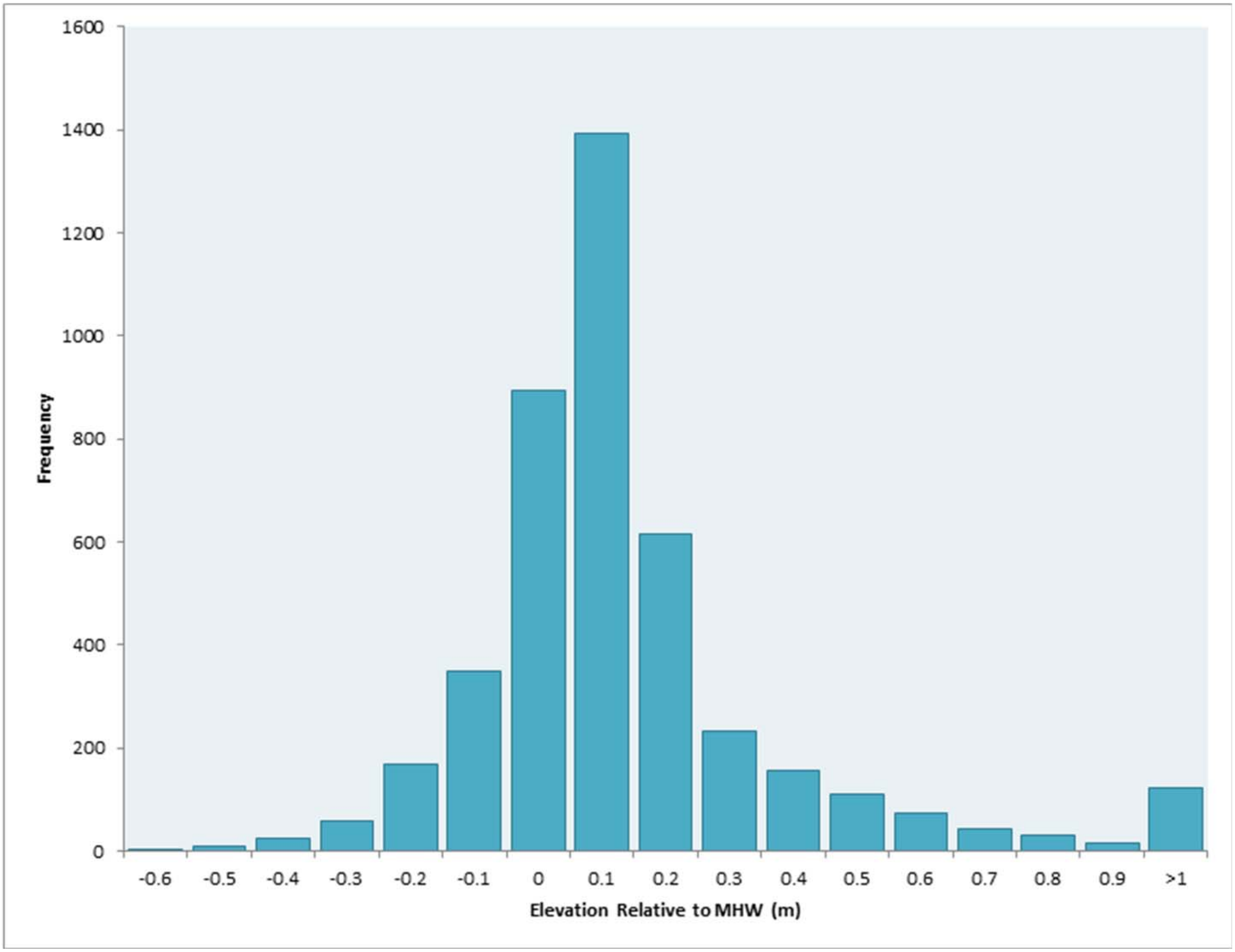

Figure D-2. Distribution of elevation samples relative to local mean high water (MHW, in meters) at Seal Beach.

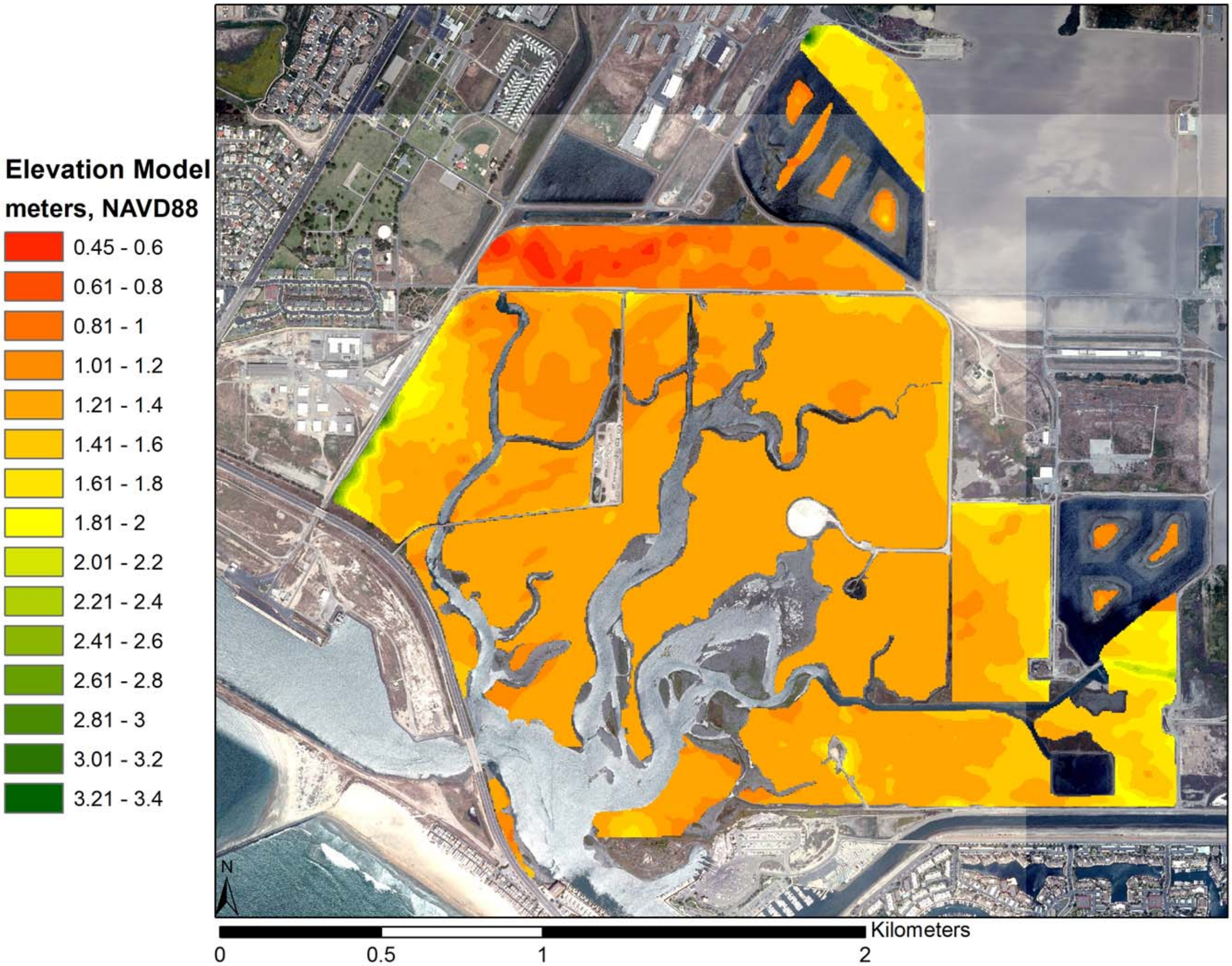

Figure D-3. Elevation model (5-meter resolution) for Seal Beach developed from ground RTK GPS elevation data. Parameters were optimized to produce minimal root-mean-square error (RMSE).

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Vegetation surveys

Vegetation was sampled at 1,083 locations, and 13 species where detected in the marsh (Table B-1,Fig D-4). Distinct zonation in plant communities was observed in relation to MHW because plants are typically restricted by their inundation tolerance (Fig D-4-6). Only 7 species occurred at more than 10 percent of the vegetation plots (Fig. D-4-7). *Sarcocornia pacifica* was the most common species surveyed across sites, occurring at 81.3 percent of vegetation plots. *Spartina foliosa* was the second most common species (74 percent), followed by *Batis maritima* (60 percent), *Jaumea carnosa* (45 percent), *Sarcocornia bigelovii* (26 percent), *Frankenia salina* (21 percent), and *Limonium californicum* (12 percent).

Table D-1. Mean marsh elevation relative to mean high water (MHW), average, and max height, percentage cover with standard deviations (SD), and presence by species at Seal Beach. See Table 5 for species code and scientific name. [cm, centimeter; m, meter; n, sample number]

Species code	n	Mean Elevation Relative to MHW (m)	SD Elevation Relative to MHW	Mean Avg. Height (cm)	Mean Avg. Height SD	Mean Max Height (cm)	Mean Max Height SD	Mean Cover %	Mean Cover % SD	Presence (%)
ARSU	9	0.51	0.20	20	8	28	13	61	20	0.83
ATSE	1	1.92	-	5	-	9	-	20	-	0.09
BAMA	651	0.03	0.15	16	6	20	7	26	20	60.06
DILI	59	0.34	0.15	13	4	17	5	65	36	5.44
DISP	85	0.07	0.16	21	5	25	6	23	23	7.84
FRSA	225	0.05	0.19	16	6	19	7	29	28	20.76
JACA	488	0.05	0.10	13	5	17	6	54	32	45.02
LICA	128	0.15	0.12	24	13	29	15	19	14	11.81
SABI	285	0.02	0.13	21	8	27	9	32	25	26.29
SAPA	882	0.02	0.16	28	9	36	11	57	29	81.37
SPFO	799	-0.01	0.12	53	14	64	17	44	26	73.71
SUES	58	0.11	0.13	20	8	25	11	26	25	5.35
TRMA	2	0.13	0.09	12	2	14	0	18	4	0.18

High Occurrence Species

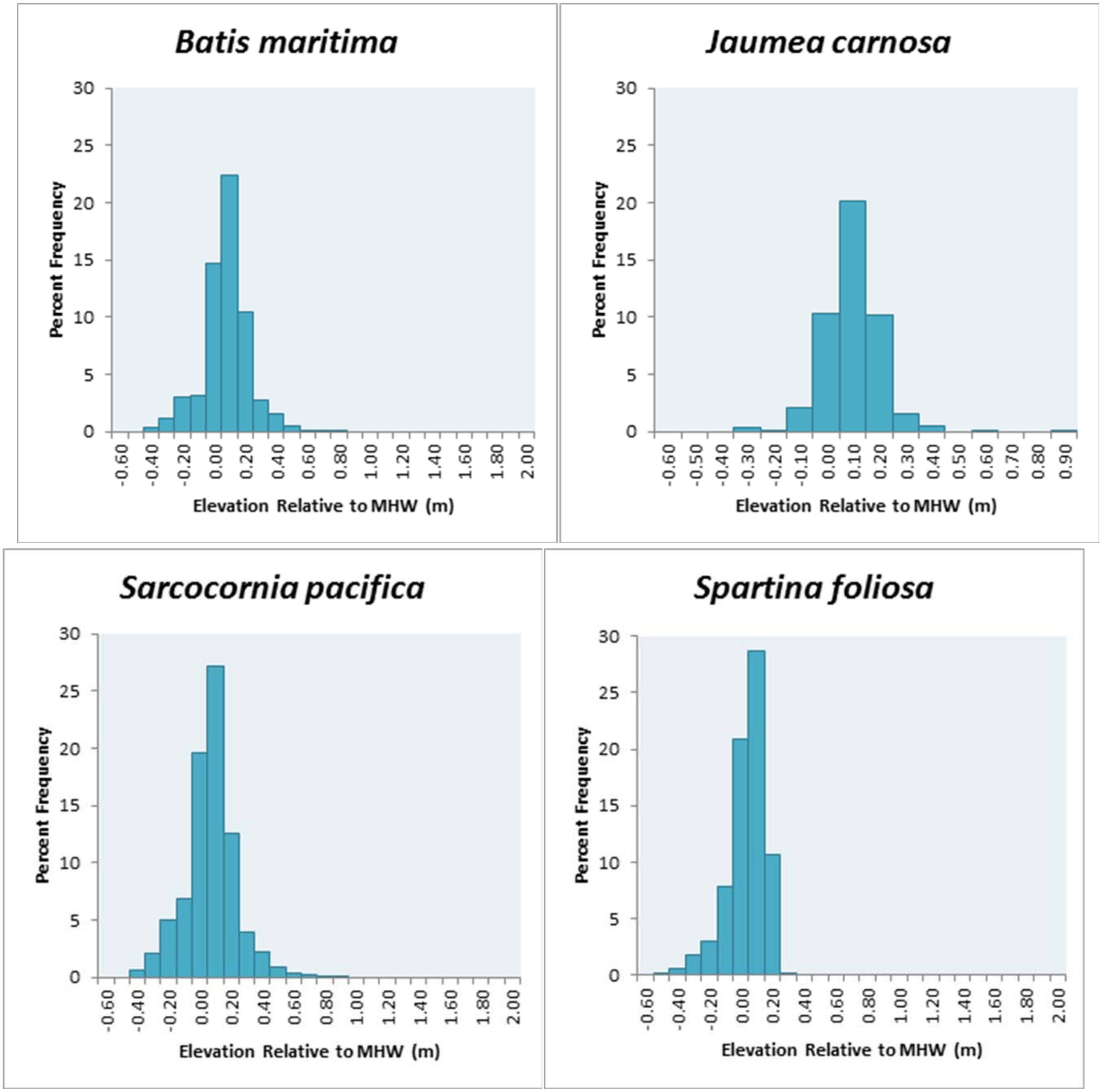

Figure D-4. Distribution of high occurrence (scaled at 30 percent frequency) plant species observed relative to MHW across Seal Beach

Medium Occurrence Species

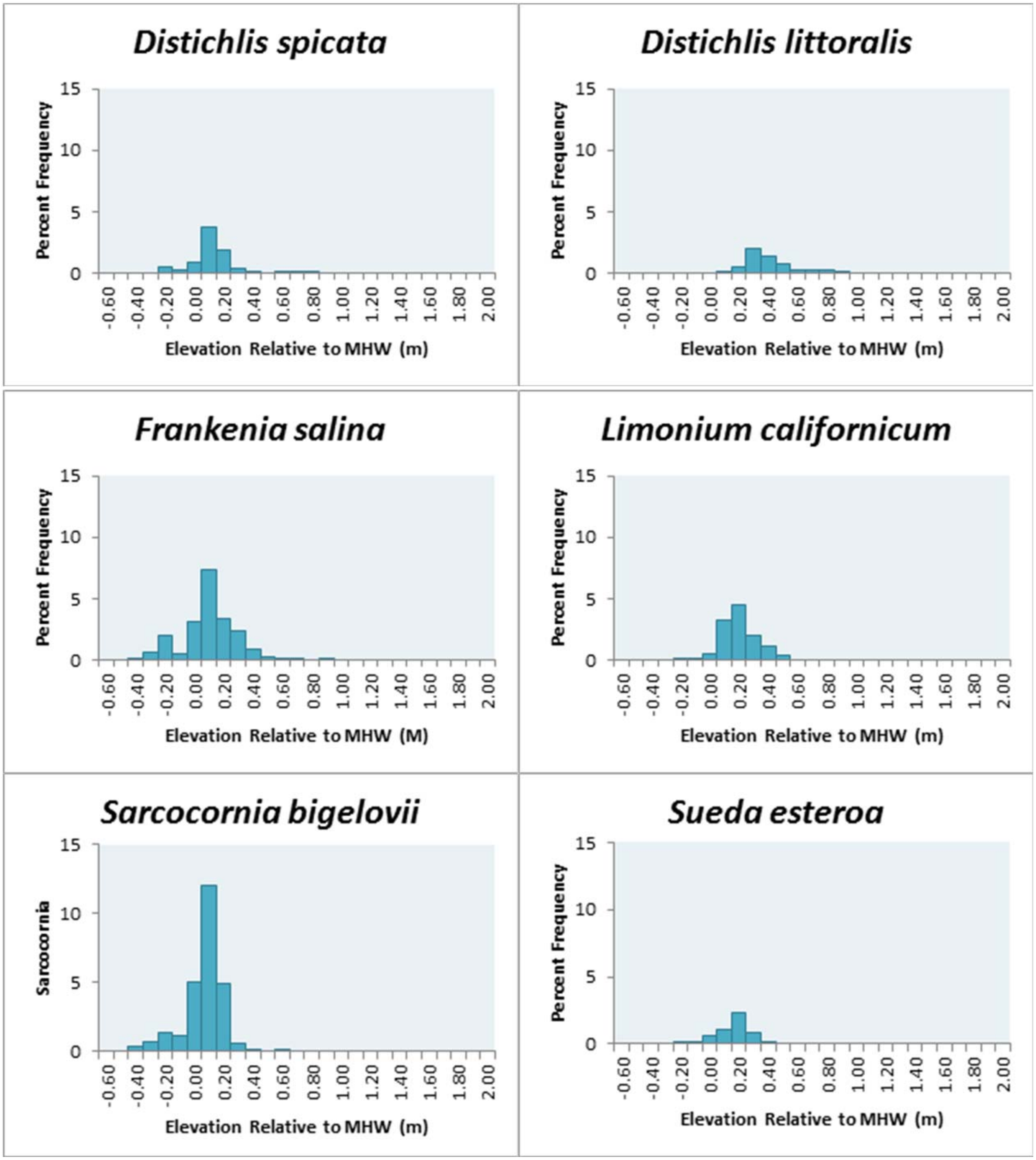

Figure D-5. Distribution of medium occurrence (scaled at 15 percent frequency) plant species observed relative to MHW across Seal Beach.

Low Occurrence Species

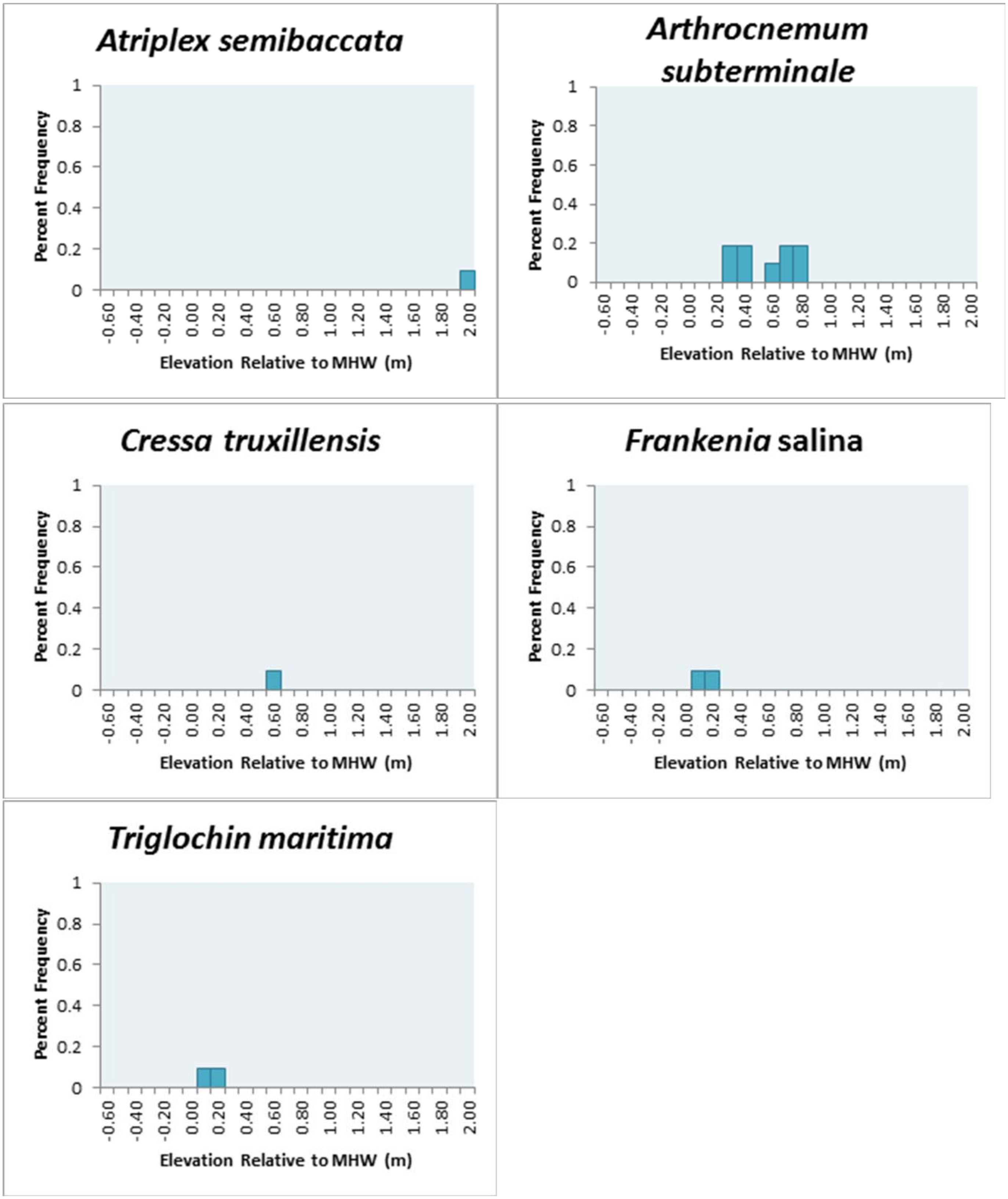

Figure D-6. Distribution of low occurrence (scaled at one percent frequency) plant species observed relative to MHW across Seal Beach.

Water-level monitoring

Site-specific water level was analyzed at Seal Beach for December 2011 through August 2012. Water level was measured using one data logger deployed at the mouth of a channel and one in a second order channel; water level monitoring is ongoing. MTL was 0.88 m, MHW was 1.27 m, and mean higher high water (MHHW) was 1.55 m for the site (NAVD88). The period when the marsh platform (defined as mean elevation) was inundated most often was in August 2012 (Figure D-7). Being the lowest elevation marsh in the study we found corresponding longer durations of time that the site was inundated (*see* Figure D-7) compared to other San Diego Refuge Complex marshes. Based on the tidal data a tidal datum model was produced (Fig D-8). This model gives insight into what portions of the marsh are covered by water during different tidal periods.

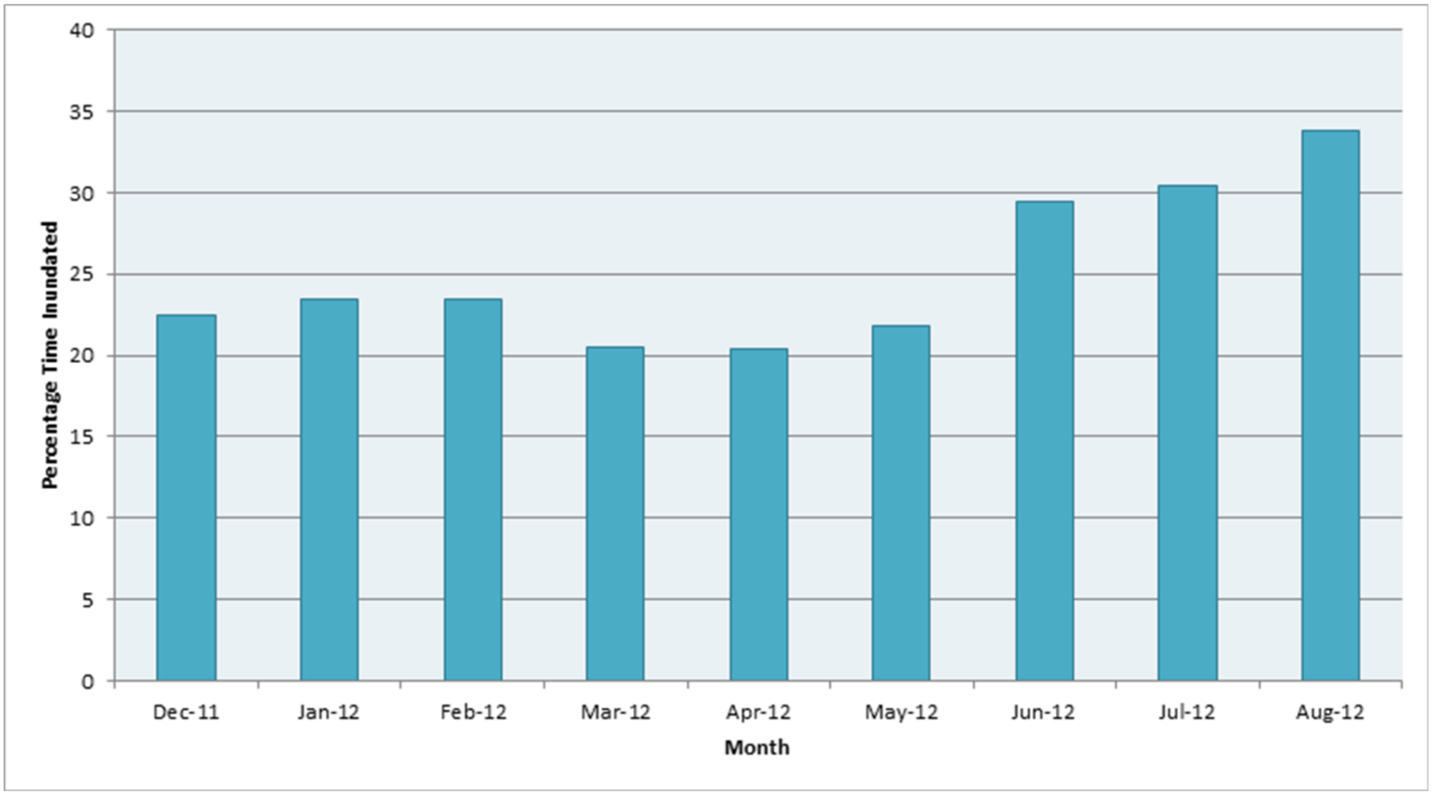

Figure D-7. Percentage of time Seal Beach was inundated monthly based on the mean elevation of the marsh platform.

Figure D-8. Tidal inundation model for Seal Beach based on local tidal data from local water loggers.