2013

Assessing marsh response from sea-level rise applying local site conditions: Humboldt Bay National Wildlife Refuge

USGS

USGS
science for a changing world

Assessing marsh response from sea-level rise applying local site conditions: Humboldt Bay National Wildlife Refuge

U. S. Geological Survey, Western Ecological Research Center

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

John Y. Takekawa, Karen M. Thorne, Kevin J. Buffington, Chase M. Freeman, Katherine W. Powelson and Giselle Block

Assessing marsh response from sea-level rise applying local site conditions: Humboldt Bay National Wildlife Refuge

U. S. Geological Survey, Western Ecological Research Center

Data Summary Report

Prepared for the U. S. Fish and Wildlife Service, R8 Inventory and Monitoring Program and North Pacific Landscape Conservation Cooperative

By John Y. Takekawa[1], Karen M. Thorne[2], Kevin J. Buffington[1], Chase M. Freeman[1], Katherine W. Powelson[1], and Giselle Block[3]

[1] U.S. Geological Survey, Western Ecological Research Center, San Francisco Bay Estuary Field Station, 505 Azuar Drive Vallejo, CA 94592 USA

[2] U.S. Geological Survey, Western Ecological Research Center, 3020 State University Dr. East, Modoc Hall Suite 2007, Sacramento, CA 95819 USA

[3] U.S. Fish & Wildlife Service, Pacific Southwest Region, Inventory and Monitoring Program, 735B Center Blvd. Fairfax, CA 93930 USA

For more information contact:

John Y. Takekawa, PhD
U.S. Geological Survey
Western Ecological Research Center
505 Azuar Dr.
Vallejo, CA 94592
Phone: (707) 562-2000
john_takekawa@usgs.gov

Karen M. Thorne, PhD
U.S. Geological Survey
Western Ecological Research Center
3020 State University Dr. East
Modoc Hall, Suite 2007
Sacramento, CA 95819
phone: (916)-278-9417
kthorne@usgs.go

Suggested Citation:

Takekawa, J.Y., Thorne, K.M., Buffington, K.J., Freeman, C.M., Powelson, K.W., and Block G. 2013. Assessing marsh response from sea-level rise applying local site conditions: Humboldt Bay National Wildlife Refuge. Unpubl. Data Summary Report. USGS Western Ecological Research Center, Vallejo, CA. 44pp + Appendices.

Executive Summary

- Climate change scenarios typically address top-down global scale changes; thus, few are easily interpretable to local land managers or contain a vertical resolution that is useful at the local level for planning climate change adaptation strategies. Our studies are directed at a bottom-up local approach to evaluating sea-level rise (SLR) effects at the parcel scale (however relevant at a landscape scale), and provide information and data sets useful in assessing local responses.

- The Humboldt Bay National Wildlife Refuge (NWR) is located on Humboldt Bay in northern California. Humboldt Bay NWR was established in 1971 and consists of a mosaic of mudflats, estuarine eelgrass meadows, salt marshes, brackish marshes, seasonally flooded freshwater wetlands, riparian wetlands, streams, active coastal dunes, and stabilized dune forests that total nearly 1,618 hectares.

- Humboldt Bay NWR is part of a larger USGS climate change study of sixteen tidal marsh sites on the Pacific coast to examine the vulnerability of tidal marshes to sea-level rise and storms along a Pacific coast latitudinal gradient.

- Our study focused on seven marsh sites distributed throughout Humboldt Bay and largely within refuge boundaries; Hookton Slough Island, Salmon Creek marsh, White Slough marsh, Eureka Slough marsh, Jacoby Creek marsh, Mad River Slough marsh, and Manila marsh. These marshes provide important habitat for marsh-dependent species, such as Humboldt Bay Owl's Clover (*Castilleja ambigua)*, Western Snowy Plover (*Charadrius alexandrinus nivosus*), and Steelhead (*Oncorhynchus mykiss*).

- We collected detailed site-specific biotic and abiotic data that is used to model ecological response to SLR and storms. Our research effort to assess Humboldt Bay NWR response to SLR was conducted in two phases. The first phase was the collection of baseline data and elevation modeling presented in this report. The second phase which will be completed in 2014 will use baseline data to model marsh responses to SLR. In particular, the objectives for the first phase of the study were to (1) develop high resolution digital elevation models (DEMs) for the tidal marshes, (2) monitor water levels and tidal cycles to assess parcel level inundation patterns and extreme water events, and (3) inventory plant community composition and the relationship of individual plant species to elevation and tidal range.

- We collected 3,641 Real time Kinematic (RTK) GPS elevation points during May-June 2012 and January 2013 at Humboldt Bay NWR and an adjoining site. These tidal marshes showed low elevation gradients with 77% of surveyed points between 1.7 and 2.2 m (NAVD 88), excluding Salmon Creek marsh which was considerably lower (elevation) because of its land use and management history.

- We collected 740 vegetation plots during May 2012 and recorded 28 plant species across all marsh sites; however, only 9 species occurred in more than 10 percent of the vegetation plots. These species in order of greatest frequency were: *Sarcocornia pacifica, Distichlis spicata, Jaumea carnosa, Spartina densiflora, Castilleja ambigua* ssp. *humboldtiensis, Limonium californicum, Triglochin maritimum, Plantago maritima, and Triglochin concinna. Spartina densiflora* is an

invasive species at Humboldt Bay NWR and other marsh sites along the Pacific Coast, and efforts to eradicate this species are underway.

- We deployed 9 water level loggers beginning in May 2012 and analyzed data through January 2013, while continuing to monitor 7 water level loggers through May 2013. We found that 90% of the marsh areas surveyed were above MHW and ranged from 57 – 94% above mean high water (MHW) depending on the site.

- At the time of the survey, the majority of salt marshes on HBNWR were undergoing mechanical treatments for the control of invasive *Spartina densiflora*. These treatments involve subsoil tilling and brush cutting that resulted in elevation loss of up to 5 cm for up to 1.5 years. The individual sites surveyed were at different stages of restoration when the survey occurred, creating the potential for confounding of elevation and vegetation results.

- On the basis of our results, collection of sediment cores and installing surface elevation tables (SETs) was done in fall of 2013, to better understand sediment accretion rates in marshlands of Humboldt Bay. These data will improve our projections about SLR effect on these areas.

Table of Contents

1. Introduction

Projected effects of climate change on coastal ecosystems include changes in mean and extreme ambient temperatures, precipitation patterns, ocean temperature and acidity, extreme storm events, and sea-level rise (Cayan et al. 2005; Hansen et al. 2006; International Panel on Climate Change, 2007). Projections of mean sea-level rise (SLR) to the year 2100 are characterized by high uncertainty because of the difficulty in assessing 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 (International Panel on Climate Change, 2007). Due to climate change and tectonic plate movement, sea levels north of Cape Mendocino, which is 20 kilometers south of the Humboldt Bay spit, are projected to change between -4 cm (sea-level fall) and +23 cm (sea-level rise) by 2030, -3 cm and +48 cm by 2050, and +10 to +143 cm by 2100 (NRC 2012). However, a large earthquake (> 8 on the Richter scale) would cause some coastal areas including Humboldt Bay to immediately subside and relative sea level to rise. This may result in relative SLR of an additional meter or more over projected levels (NRC 2012).

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

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). Sensitivity and adaptability of wildlife to climate change effects will depend on local rates of change and the spatial habitat patterns, therefore it is important to understand how salt marshes will responds to SLR at the local scale. Currently, many salt marsh vertebrates are listed as species of special concern or endangered species (USFWS 1991, USFWS 2009, IUCN 2011) whose ecology is often not fully understood. A main area of concern for vertebrates in Humboldt Bay are the

federally endangered fisheries of Coho Salmon (*Oncorhynchus kisutch)*, Steelhead (*Oncorhynchus mykiss)*, and Chinook Salmon (*Oncorhynchus tshawytscha),* all of which are federally endangered species. The main threats to these species are human activities that destroy or alter their habitat including logging, farming, and development that alters water temperatures, pH, and suspended sediment concentrations. Although 90% of Humboldt Bay marshes were diked and converted to agriculture, its estuary and marshes are important habitat for these salmonids as they transition from fresh water to salt water conditions.

Climate change factors will be the most significant threat to these ecosystems and their dependent biodiversity in the future (Thorne et al. 2012). In particular, salt marshes will be affected by climate change through accelerating SLR (Holgate and Woodworth, 2004; Kemp et al. 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 et al. 2005; International Panel on Climate Change, 2007). Salt marshes can keep pace with changes in local sea level through marsh accretion processes that include sediment deposition and organic matter accumulation (Morris and others, 2002; Geden et al. 2011), if suspended-sediment concentrations and organic production can keep pace with SLR (Kirwan and Gutenspergen, 2010). However, salt marshes can be lost if SLR outpaces vertical accretion processes (Morris and others, 2002; Callaway, 2007; Takekawa et al. 2012).

Purpose and Scope

Climate change scenarios typically address top-down global to continental scale changes; thus, few are easily interpretable to local land managers or contain vertical resolution that is useful at the local level for developing climate change adaptation strategies. Our studies support a bottom-up local approach to evaluating SLR effects at the parcel scale providing information and data sets useful in assessing responses. We collect comprehensive, detailed site-specific data that are used to model marsh ecological response from SLR and storms. By implementing this approach across sites in Humboldt Bay and along the Pacific coast our results are also relevant at a landscape scale.

Our research effort to assess Humboldt Bay NWR marsh response from SLR was divided into two phases. The first phase of the project was to collect baseline data, while the second phase was to model projected marsh ecosystem response to SLR that will be completed in 2014. For the first phase of the study

presented in this report, the objectives of the study were to: (1) develop high resolution digital elevation models (DEMs) for the salt marshes, (2) monitor water levels and tidal cycles to assess parcel level inundation patterns and extreme water events, and (3) document the distribution of plants species along the tidal elevation gradient with recognition that recent restoration activities have likely altered distributions of some species.

Study Area

Humboldt Bay National Wildlife Refuge (NWR) is located on Humboldt Bay in northern California (Fig. 1, 1-1). The refuge was established in 1971 with two main purposes: to protect and enhance wetlands and bay habitats for migratory birds, especially black brant (*Branta bernicla nigricans*), and to protect endangered species and their habitats, including the peregrine falcon (*Falco peregrinus*), bald eagle (*Haliaeetus leucocephalus*), brown pelican (*Pelecanus occidentalis*), Humboldt Bay wallflower (*Erysimum menziesii*), and beach layia (*Layia carnosa*) (U.S. Fish and Wildlife Service, 2009). The refuge consists of a mosaic of mudflats, estuarine eelgrass meadows, salt and brackish marsh, seasonally flooded freshwater wetlands, riparian wetlands, streams, active coastal dunes, and stabilized dune forests that total nearly 1,620 ha. Over the last 120 years, the Humboldt Bay estuary has been changed dramatically through diking, dredging, sedimentation, and conversion to farmland and development. Humboldt Bay historically sustained over 3,640 ha of salt marsh, whereas now only 360 ha remain, leading to efforts to restore and enhance areas to recover historic ecological function (Pickart 2001, USCGS).

Humboldt Bay is the largest estuary between San Francisco and Coos Bay, Oregon and is an important stopover for the millions of migratory birds that move along the Pacific Flyway each year. Eighty species of waterbirds use the high quality food and habitat resources provided by the refuge (U.S. Fish and Wildlife Service, 2009). The three species of salmonids present in the Humboldt Bay watershed, Coho salmon (*Oncorhynchus kisutch*), Chinook salmon (*O. tshawytscha*), and steelhead trout (*O. mykiss*), are considered to be at high risk of extinction and are listed as threatened under the Federal Endangered Species Act. These remaining salmonid populations in northern California are critical to conservation and restoration of salmonids because they represent the region's last significant gene resources (*Humboldt Bay Watershed Salmon and Steelhead Conservation Plan*, 2005). In order for Pacific salmonid populations to be conserved and restored, a well dispersed network of habitats that retain a high degree of ecological

integrity (i.e. salt marshes) must be recovered and preserved to serve as centers for population expansion (Spence et al. 1996).

Our study included seven sites distributed throughout the bay: Salmon Creek Marsh (21 ha), Hookton Slough Marsh (3 ha), White Slough marsh (4 ha), Eureka Slough marsh (33 ha), Jacoby Creek marsh (31

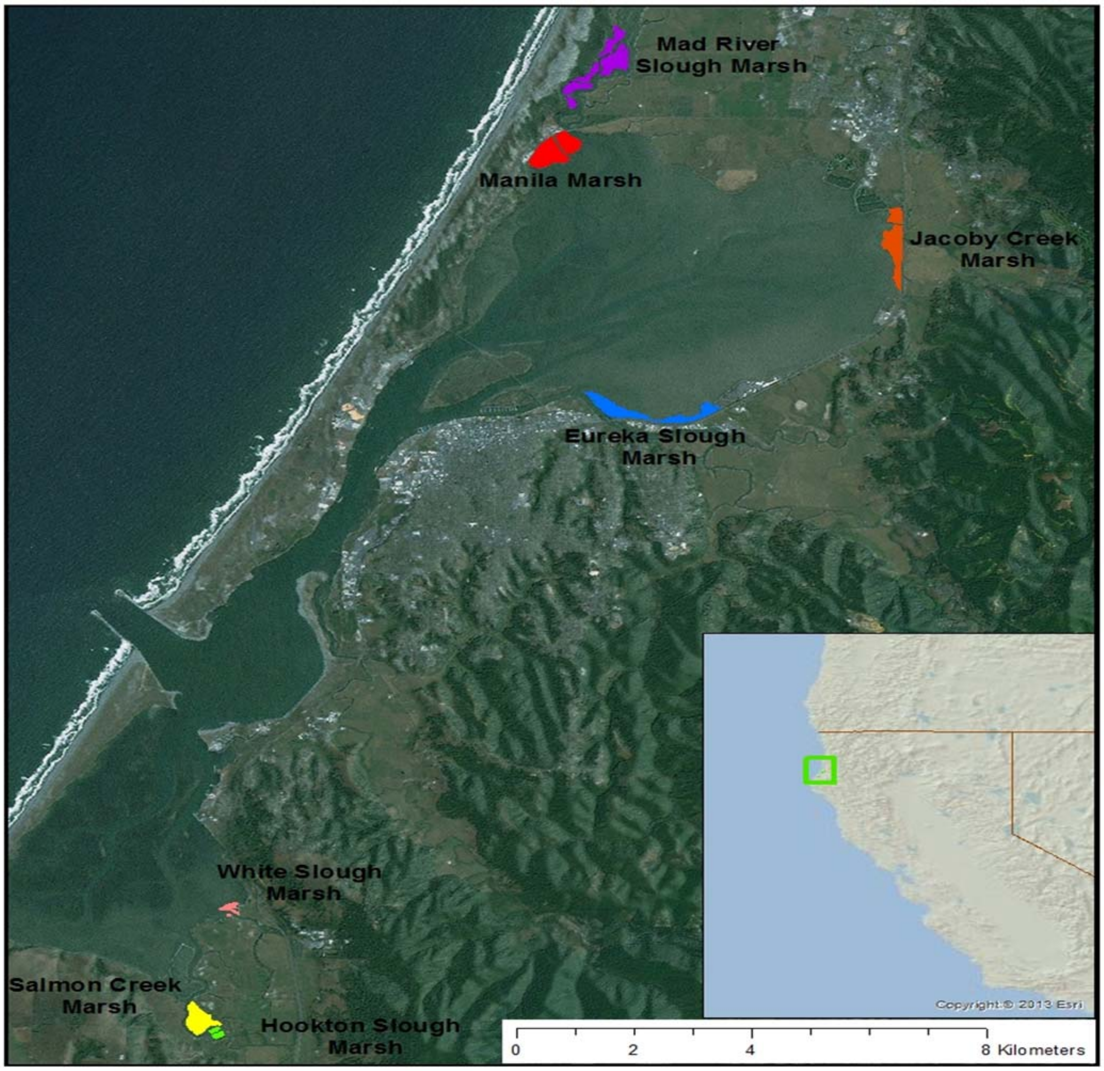

Figure 1. Study sites on the Humboldt Bay NWR and adjacent areas. Salmon Creek Marsh, Hookton Slough Marsh, White Slough Marsh, Eureka Marsh, Jacoby Marsh, Mad River Slough Marsh, and Manila Marsh.

ha), Mad River Slough marsh (38 ha) and Manila marsh (38 ha) (Fig. 1, 2). These sites account for 48 percent of all salt marsh in Humboldt Bay, are representative of the salt marsh ecosystems in the Humboldt Bay estuary, and provide valuable information on determining its vulnerability to sea-level rise.

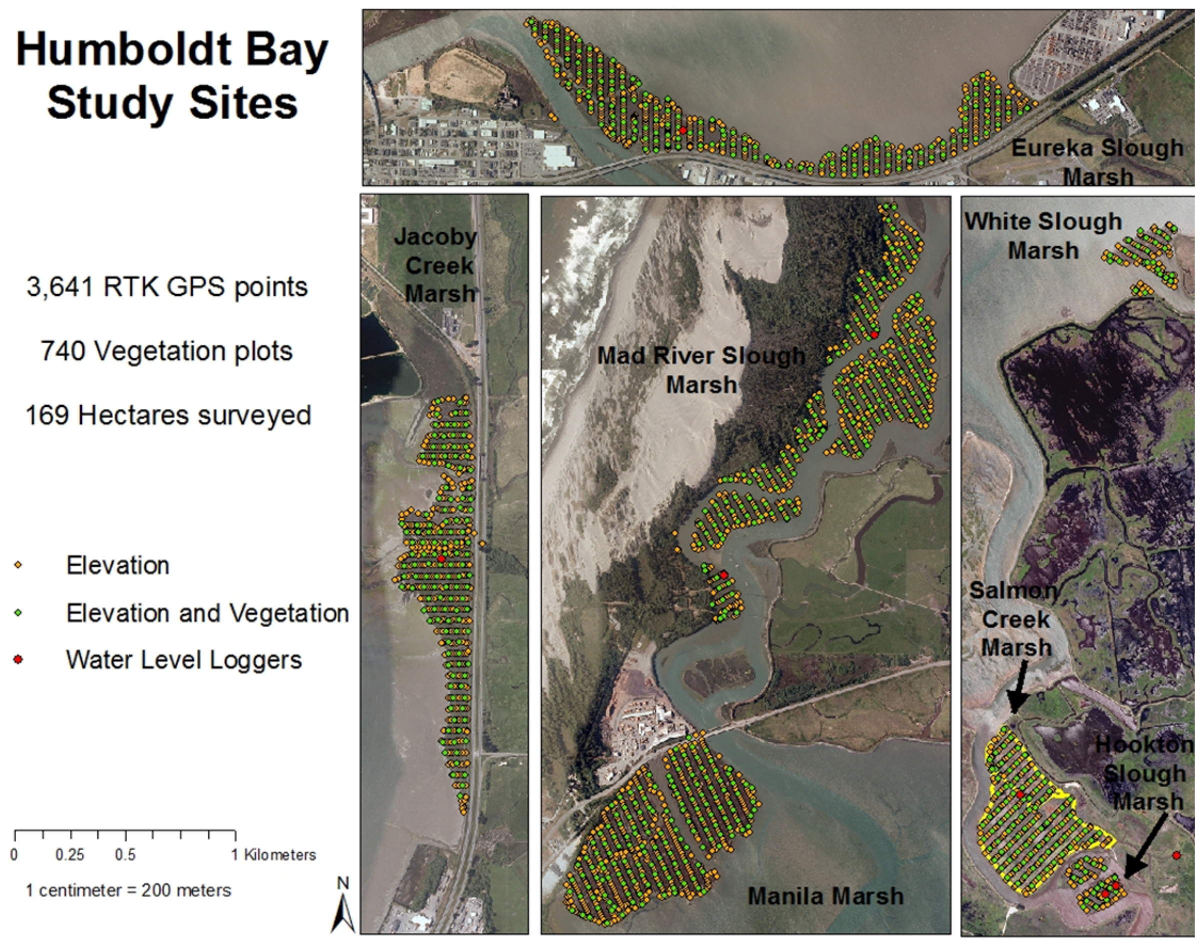

Figure 2. Study sites on the Humboldt Bay NWR and adjacent areas where elevation, vegetation, and water levels were measured.

2. Methods

2.1 Elevation surveys

We conducted survey-grade elevation transects at Humboldt Bay NWR and adjoining salt marshes in May-June 2012 and January 2013 with a Leica Viva Real Time Kinematic (RTK) Global Positioning System (GPS) rover (± 1 cm x, y, ± 2 cm z accuracy; Leica Geosystems Inc., Norcross, GA; Fig.1-3). The rover positions were received in real time from the Leica GS10 antenna base station via radio link. We used the WGS84 ellipsoid model for vertical and horizontal positioning. Positions were referenced to a nearby National Geodetic Survey (NGS) benchmark and assessed for error using an OPUS correction (see Table 1). OPUS is an automated data processing system operated by NGS which 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) datum using the 2010 epoch.

Figure 3. Elevation survey with RTK GPS.

The raw data (RINEX files) from the base station were submitted to the OPUS system for precise ephemeris processing. North American Vertical Datum of 1988 (NAVD88) elevations were calculated using the 2012a geoid model of gravity. The OPUS corrected positions of the NGS benchmarks taken by the rover were compared to their published positions. The average measured vertical error for the benchmark throughout the study was similar to the stated error of the RTK GPS (see Table 1). Elevation was surveyed along transects that ran perpendicular to the water with a survey point taken every 12.5 m; 50 m separated transect lines. The NGS 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 10 with Leica GeoOffice (Leica Geosystems Inc., Norcross, GA, v 7.0.1).

Table 1. National Geodetic Survey Benchmarks used as references in elevation survey with associated measured error [UTM zone 10 NAVD88].

Site	Benchmark	Northing	Easting	Height	Measured Error range
Hookton Slough and Salmon Creek Marshes	K 1087	40 40 48	124 12 03	1.695	0.0021
White Slough Marsh	K 1087	41 40 48	125 12 03	1.695	0.0021
Eureka Slough Marsh	W 1087 RESET	40 48 15	124 07 34	1.81	0.0095
Jacoby Creek Marsh	G 75 RESET	40 50 36	124 04 53	3.736	0.0080
Mad River Slough Marsh and Manila Marsh	J 735 RESET	40 51 54	124 09 00	4.542	0.0131

We synthesized the elevation data in ArcGIS 10.0 Spatial Analyst (ERSI 2009, Redlands, CA) with Kriging methods (5 x 5 m cell size) to create an elevation raster or digital elevation model (DEM). We used the exponential model for Ordinary Kriging and adjusted model parameters to minimize the root-mean-square (RMS) error, an internal measure of model performance. Lag size and number of lags were selected for the site using the optimize parameters feature in the Geostatistical Wizard. We then used the DEMs as the basis for subsequent analysis, such as tidal inundation patterns and vegetation relationships.

2.2 Vegetation surveys

Figure 4. Vegetation survey

We recorded vegetation data within a 0.25 m^2 quadrat concurrently with elevation surveys. Data were taken at every fourth (25%) elevation point (n=740 quadrats; Fig. 4). We measured height (mean and maximum, measured within 0.05 m) and visually estimated percent cover for each species within each quadrat. This allowed us to develop a relationship between plant species, elevation and tidal datum across all sites. We also characterized the most common species, which were defined as those found at

>10 % of the plots. Plant species frequency was plotted relative to MHW. This comprehensive vegetation dataset allows the baseline characterization of the salt marshes and allows for modeling of SLR in relation to plant communities. Taxonomic nomenclature for plants follows USDA Plants (http://plants.usda.gov).

2.3 Water monitoring

We deployed water level data loggers (Model 3001, 0.01% FS resolution, Solinst Canada Ltd., Georgetown, Ontario) at all sites for continuous monitoring. Each site had one to five loggers (n=10) depending on its size and monitoring requirements such as evaluating the restoration change at Salmon Creek. Loggers were placed at the mouth and upper reaches of second-order channels (tidal creeks) to capture the local tidal cycle, inundation patterns and salinity at three logger locations.

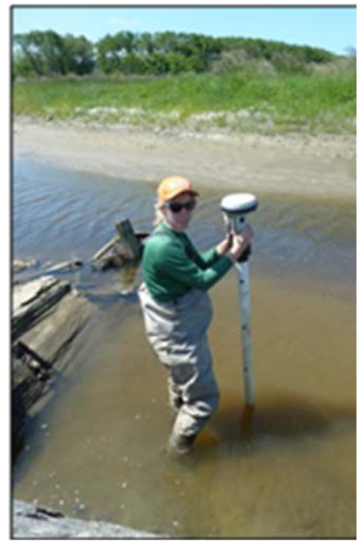

Figure 5. Water level logger monitoring.

We collected continuous data every six minutes for water level loggers (pressures sensors), and twelve minutes for combined water level (pressure) and salinity loggers. All water level and salinity loggers were deployed from May 2012 to May 2013 to determine local hydrographs, inundation rates, and variation in salinity. Seven loggers were currently still deployed in Humboldt Bay when this report was finalized; two were located at the Mad River Slough site and five spread throughout the Salmon Creek restoration project encompassing the Salmon Creek marsh site. Loggers were surveyed with an RTK GPS at the time of deployment and at each data download to correct for any movement (Fig. 5). Water levels were corrected for local barometric pressure with data from independent barometric loggers using Solinst Levelogger 4.0.3 Software (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 levels from May 2012 to Jan 2013 were used to create mean tide level (MTL), mean high water (MHW), and mean higher high water (MHHW) datum's relative to NAVD88 for each site. The development of a local mean low water (MLW) tidal datum was not possible because of the need for within marsh tide data and the fact that these locations are at relatively high elevations are not inundated at low tide. All results are reported relative to local MHW calculated from local water data. For our study in Humboldt Bay NWR,

we assumed elevation (particularly MHW and MHHW) and salinity were the most important water metrics for understanding marsh-associated plant communities.

3. Results

Our results were first summarized across sites here, while site-specific characterizations were included in appendices following the report text.

3.1 Elevation

Low elevation gradients were characteristic of all salt marshes surveyed at Humboldt Bay (Fig. 6, 7). A total of 3,641 elevation points were measured during the spring of 2012 (Table 2, Fig. 2). Overall, elevation fell within a small range, where 77% of surveyed points fell between 1.7 and 2.2 m excluding Salmon Creek marsh which was considerably lower in elevation and had muted or restricted tidal flow because of its location behind a levee (NAVD 88; Fig. 7, 8). Mean elevation was 0.04 m (SD = 0.10) above MHW across all sites excluding Salmon Creek marsh -- mean elevation of Salmon Creek was 0.1 m (SD= 0.25) below MHW. Elevation models for all sites had a RMS error of 0.12 m (Table 3). When comparing different sites, Salmon Creek slough was the lowest with White Slough, Hookton Slough and Manila marsh considered low to medium elevation marshes. Jacoby Creek and Eureka Slough marshes had higher elevation marsh platforms with a shallow slope to lower elevations, while Mad River Slough marsh had a consistently higher elevation platform than the other sites.

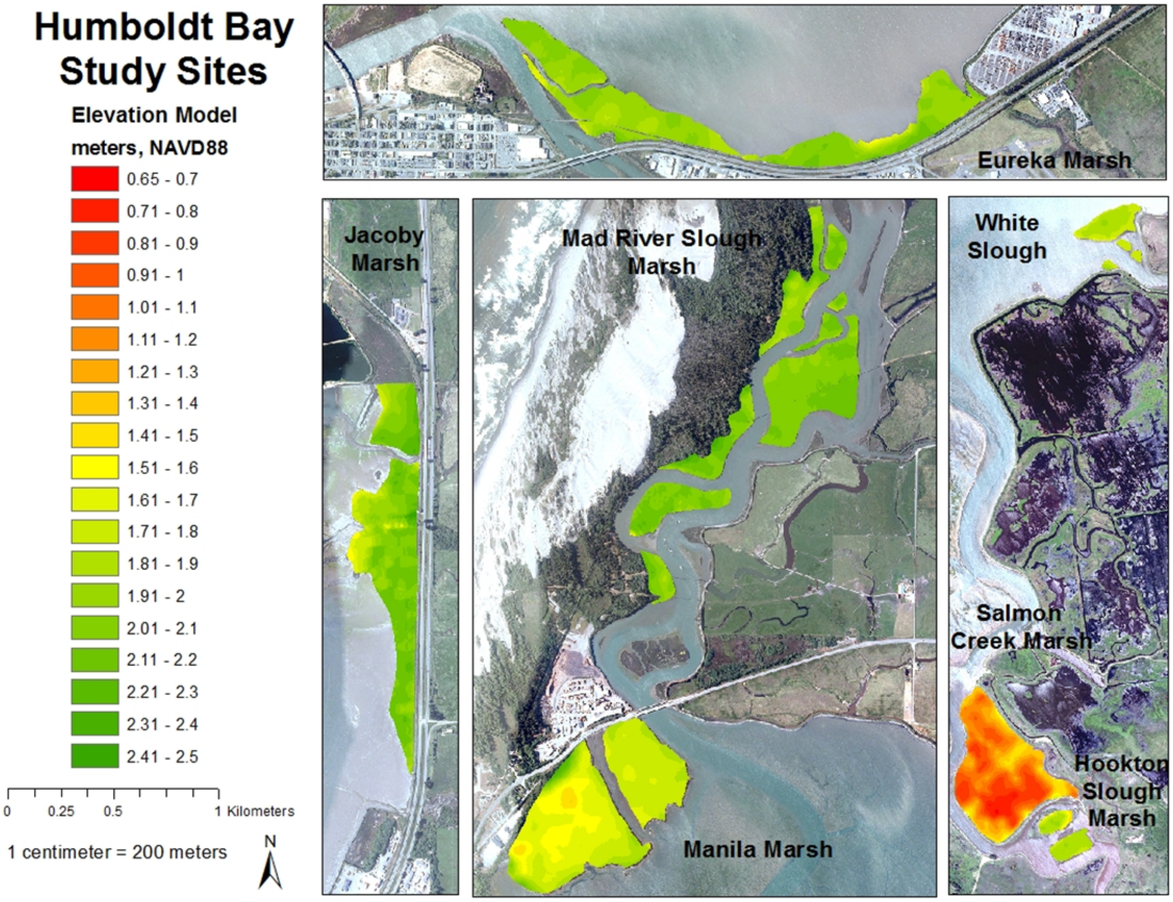

Figure 6. Digital elevation models (DEMs) for all marsh sites at Humboldt Bay NWR and vicinity (NAVD88). Model parameters were optimized to reduce root-mean-square error. Scale bar = 1 Kilometer (km).

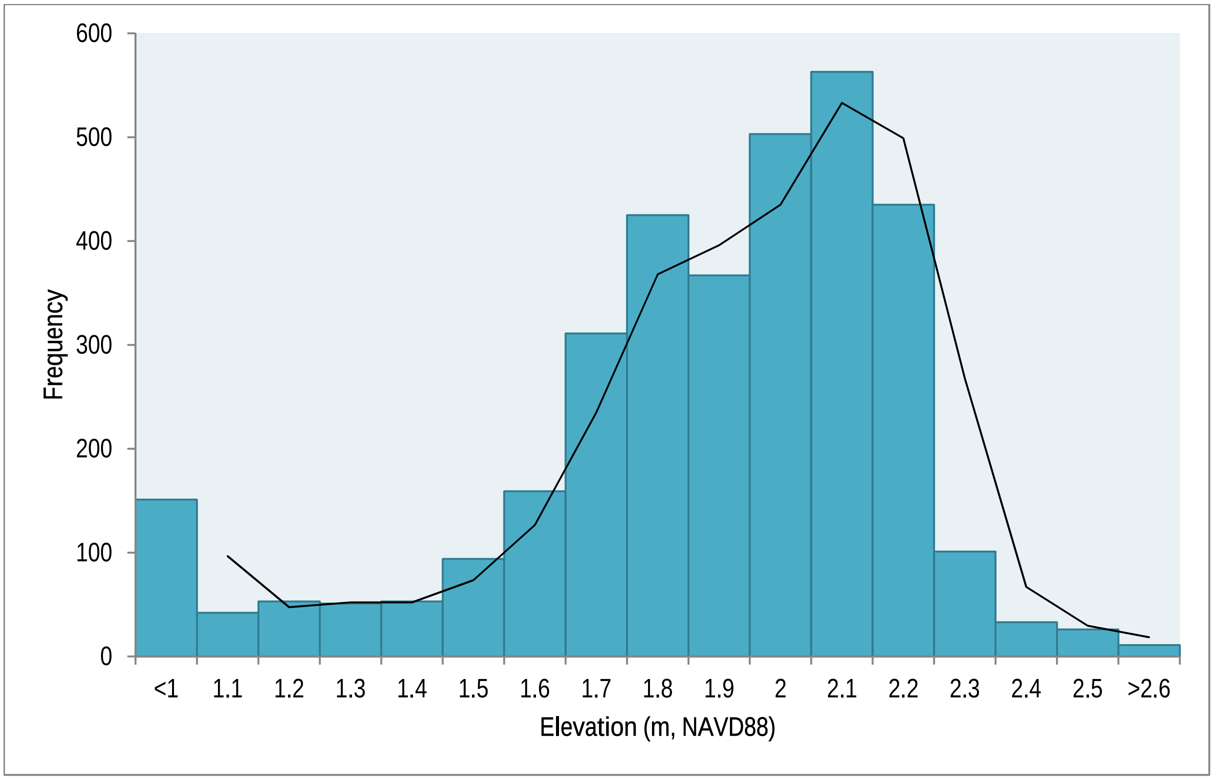

Figure 7. Distribution of marsh elevations relative to NAVD88 in meters (m) for all study sites at Humboldt Bay NWR except Salmon Creek marsh.

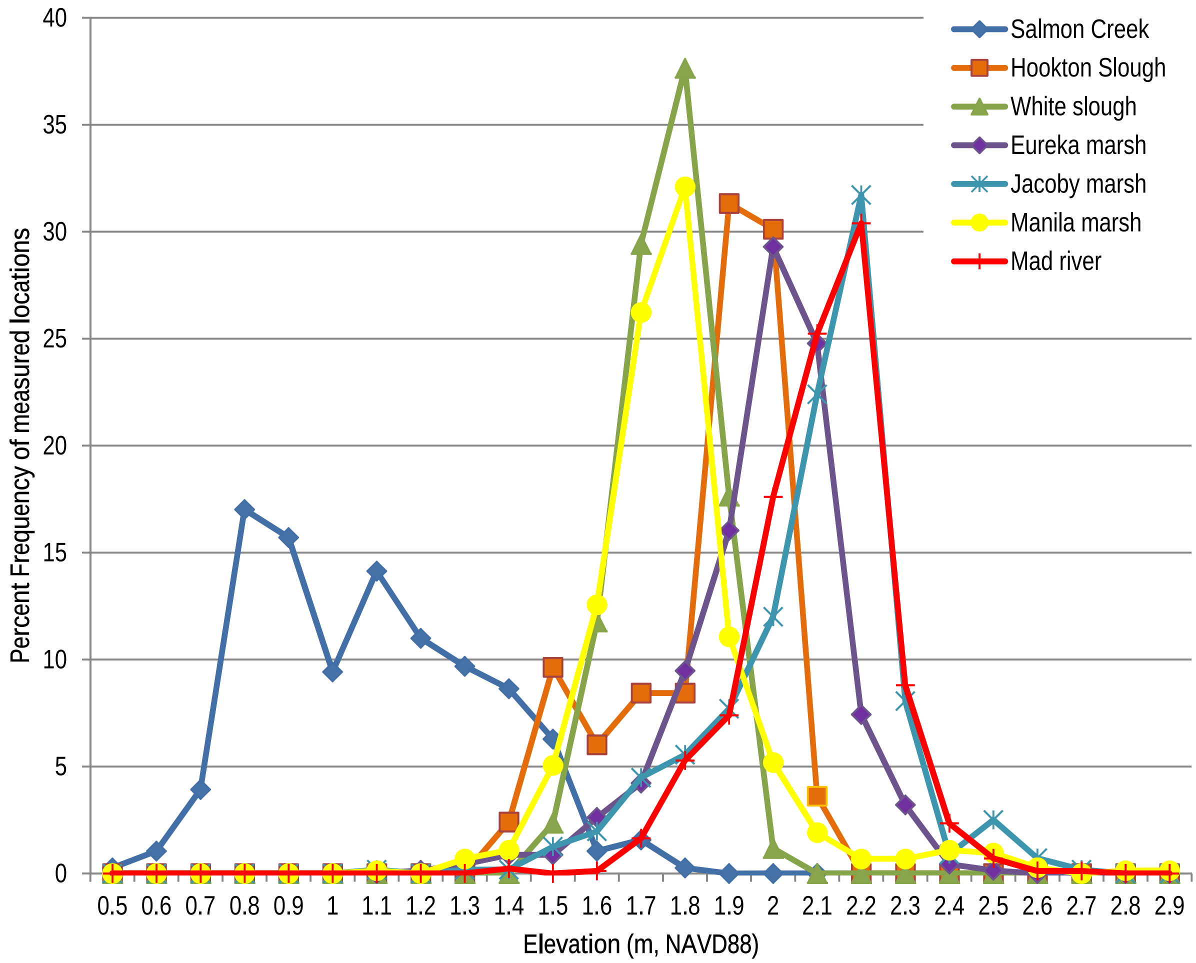

Figure 8. Percent frequency distribution of marsh elevations relative to NAVD88 in meters (m) by site at Humboldt Bay NWR.

Table 2. Summary of elevation and vegetation data collected (N=7), 2012. [ha=hectares, m=meters, n=sample size]

Site	Area (ha)	Elevation Points (n)	Mean Elevation (m)	Elevation Range (m)	Vegetation Quadrats (n)
Hookton Slough	3.2	83	1.79	0.70	17
Salmon Creek Marsh	21.4	382	1.11	1.22	89
White Slough	3.9	109	1.78	0.47	25
Eureka Marsh	33.2	686	1.96	1.28	145
Jacoby Marsh	30.5	558	2.03	1.57	125
Mad River Slough	38.3	852	2.05	1.26	184
Manila Marsh	38.1	732	1.73	1.72	155
Total	168.7	3020	1.77	2.24	740

Table 3. ArcGIS elevation model root-mean-square error (RMS) and standard error (SE) by site.

Study Site	Model RMSE	Model Mean SE
Hookton Slough	0.13	0.14
Salmon Creek Marsh	0.14	0.14
White Slough	0.07	0.07
Eureka Marsh	0.14	0.13
Jacoby Marsh	0.13	0.13
Mad River Slough	0.15	0.15
Manila Marsh	0.14	0.14
Mean	0.12	0.12

3.2 Vegetation

Vegetation was sampled at 740 points concurrently with elevation surveys (Table 2). Vegetation plots collected at the Manila marsh south of State Highway 255 (n=157) were not analyzed, because the survey was conducted during January which was a period of vegetation senescence and may bias results. This part of the survey was conducted opportunistically to connect marsh survey to bathymetric surveys completed on the shoals adjacent to this marsh, as well as having a low elevation site that had not been subjected to Spartina treatment.

A total of 28 species were recorded across all marsh sites (Table 4). All of the surveyed marshes had extensive cover of *S. pacifica* which was the characteristic marsh species of our study sites since it occurred across a wide elevation range. However, species richness and cover varied widely by sites. Plant species were organized along an elevation gradient related to their inundation and salinity tolerance (Table 6, Fig. 10-12). Vegetation results were presented by site to illustrate differences in species composition and occurrence relative to mean high water across the different sites (Fig. 13-19). Nine species were the most common and occurred at a minimum of 10% of the vegetation plots (Table 5). *Sarcocornia pacifica* was the most common species surveyed across sites, occurring at 463 of the 583 (79.4%) vegetation plots. *Distichlis*

Figure 9. Jacoby Marsh Platform recently after *S. densiflora* removal

spicata was the second most common species (55.8%), followed by *Jaumea carnosa* (50.8%), *Spartina densiflora* (37.9%), *Castilleja ambigua* ssp. humboldtiensis (25.7%), *Limonium californicum* (20.9%), *Triglochin maritima* (17.7%), *Plantago maritima* (15.6%) and *Triglochin concinna* (15.4%).

Spartina densiflora, a non-native invasive plant species, was found at all sites. Removal efforts have been underway at Humboldt Bay NWR since 2004, with the earliest restoration carried out in the Mad River Slough site (Pickart 2012, available on website) which was evident from the vegetation survey results (Fig. 9). Areas in which dense stands of *S. densiflora* had recently been removed were dominated by bare ground and contained early successional species (e.g. *Sarcocornia pacifica)*. We observed that if S*.* *densiflora* had been removed in the recent past, there seemed to be higher diversity of plant species, although this could be due to areas being in the early stages of succession. Vegetation results were framed within the context of ongoing S. *densiflora* removal efforts at individual study sites.

Table 4. Scientific and common names of all vegetation species detected

Scientific Name	Common Name	hereafter as
Alopecurus sp.	foxtail grass	*Alopecurus sp.*
Atriplex patula	fat hen	*A. patula*
**Atriplex prostrata*	triangle orache	*A. prostrata*
Carex lyngbei	Lyngbye's sedge	*C. lyngbei*
**Cotula coronopifolia*	brass buttons	*C. coronopifolia*
Deschampsia cespitosa	tufted hairgrass	*D. cespitosa*
Distichlis spicata	salt grass	*D. spicata*
Festuca rubra	red fescue	*F. rubra*
Glaux maritima	sea milkwort	*G. maritima*
Grindelia stricta	gumweed	*G. stricta*
Hordeum brachyantherum	meadow barley	*H. brachyantherum*
Jaumea carnosa	fleshy jaumea	*J. carnosa*
Juncus lesueurii	Lesueur's rush	*J. lesueurii*
Limonium californicum	California sea lavender	*L. californicum*
Oroboanchaceae sp.		*Oroboanchaceae sp.*
**Parapholis incurva*	curved sicklegrass	*P. incurva*
Plantago maritima	sea plantain	*P. maritima*
Potentilla anserina	silverweed	*P. anserina*
Salicornia bigelovii	dwarf saltwort	*S. bigelovii*
Sarcocornia pacifica	pickleweed	*S. pacifica*
Schoenoplectus acutus	hardstem bulrush	*S. acutus*
Scirpus cernuus	low bullrush	*S. cernuus*
Schoenoplectus maritimus	saltmarsh bullrush	*S. maritimus*
Spergularia canadensis	Canadian sand spurry	*S. canadensis*
**Spartina densiflora*	dense-flowered cord grass	*S. densiflora*
Spergularia macrotheca	sticky sandspurry	*S. macrotheca*
Triglochin concinna	sea arrowgrass	*T. concinna*
Triglochin maritimum	arrowgrass	*T. maritimum*

*non-native species

Table 5. Marsh plant community characteristics over all sites in 2012, arranged from highest to lowest abundance [cm=centimeter; n=number of quadrats where species was observed]

Species	Presence (%)	Mean Avg. Height (cm)	Mean Avg. Height SD	Mean Max Height (cm)	Mean Max Height SD	Mean Cover %	Mean Cover % SD	n
S. pacifica	79.42	19	9	24	10	39	30	463
D. spicata	55.75	20	8	24	8	48	30	325
J. carnosa	50.77	9	4	12	5	30	27	296
**S.densiflora*	37.91	36	18	45	22	38	35	221
C. ambigua humboldtiensis	25.73	12	4	15	5	18	21	150
L. californicum	20.93	9	3	12	4	10	7	122
T. maritimum	17.67	30	11	39	16	23	17	103
P. maritima	15.61	15	5	20	6	17	15	91
T. concinna	15.44	16	7	20	8	31	23	90
S. canadensis	8.75	7	4	8	4	7	8	51
G. stricta	6.52	25	10	29	13	11	9	38
D. cespitosa	3.6	40	16	49	20	43	34	21
P. anserina	3.6	23	12	28	16	14	12	21
S. cernuus	3.26	6	2	9	3	14	12	19
S. bigelovii	2.06	4	1	6	2	13	21	12
A. prostrata	1.72	15	5	17	6	6	6	10
J. lesueurii	1.72	55	15	70	18	61	39	10
**C. coronopifolia*	1.37	4	3	6	5	11	14	8
S. macrotheca	1.03	15	3	17	4	10	8	6
H. brachyantherum	0.86	31	5	36	8	9	12	5
S. acutus	0.51	109	93	140	120	67	53	3
Alopecurus	0.34	2	1	15	6	28	4	2
C. lyngbei	0.34	50	6	63	17	20	7	2
G. maritima	0.34	28	18	31	13	4	1	2
**P. incurva*	0.34	2	0	4	1	18	11	2
A. patula	0.17	13	-	19	-	5	-	1
F. rubra	0.17	51	-	51	-	1	-	1
S. maritimus	0.17	27	-	29	-	5	-	1

Table 6. Sample size, mean elevation, minimum elevation, maximum elevation, and elevation range for all plant species sampled at all Humboldt Bay National Wildlife Refuge marsh sites relative to MHW (m), arranged from highest to lowest mean elevation.

Species	n	Mean Elevation Relative to MHW (m)	SD Elevation Relative to MHW	Minimum Elevation Relative to MHW (m)	Maximum Elevation Relative to MHW (m)	Elevation Range (m)
Alopecurus	2	0.33	0.09	0.27	0.39	0.13
A. *patula*	1	0.50	-	-1.22	-1.22	0.00
A. *prostrata*	10	0.45	0.25	-0.97	0.71	1.68
C. *ambigua humboldtiensis*	150	0.33	0.12	-0.19	1.00	1.19
C. *lyngbei*	2	0.51	0.18	0.39	0.64	0.25
*C. *coronopifolia*	8	0.11	0.19	-0.17	0.39	0.56
D. *cespitosa*	21	0.31	0.17	0.15	0.67	0.53
D. *spicata*	325	0.30	0.17	-1.22	1.00	2.22
F. *rubra*	1	0.83	-	0.83	0.83	0.00
G. *maritima*	2	0.60	0.01	0.59	0.61	0.02
G. *stricta*	38	0.35	0.14	0.24	0.64	0.40
H. *brachyantherum*	5	0.16	0.33	-0.18	0.64	0.81
J. *carnosa*	296	0.32	0.16	-1.22	1.00	2.22
J. *lesueurii*	10	0.58	0.20	0.09	0.83	0.75
L. *californicum*	122	0.35	0.11	-0.97	0.68	1.66
*P. *incurva*	2	0.18	0.04	0.16	0.21	0.05
P. *maritima*	91	0.36	0.14	-0.19	1.00	1.19
P. *anserina*	21	0.36	0.25	-0.13	0.83	0.96
S. *bigelovii*	12	0.37	0.06	0.22	0.48	0.26
S. *pacifica*	463	0.25	0.22	-1.22	1.00	2.22
S. *acutus*	3	0.21	0.34	-0.17	0.48	0.64
S. *maritimus*	1	-0.16	-	-0.16	-0.16	0.00
S. *cernuus*	19	0.30	0.11	0.13	0.50	0.38
S. *canadensis*	51	0.33	0.11	0.02	0.54	0.52
*S. *densiflora*	221	0.29	0.14	-1.22	1.00	2.22
S. *macrotheca*	6	0.36	0.18	0.01	0.48	0.47
T. *concinna*	90	0.36	0.14	-0.15	1.00	1.15
T. *maritimum*	103	0.31	0.16	-0.24	0.70	0.94

High Occurrence Plant Species

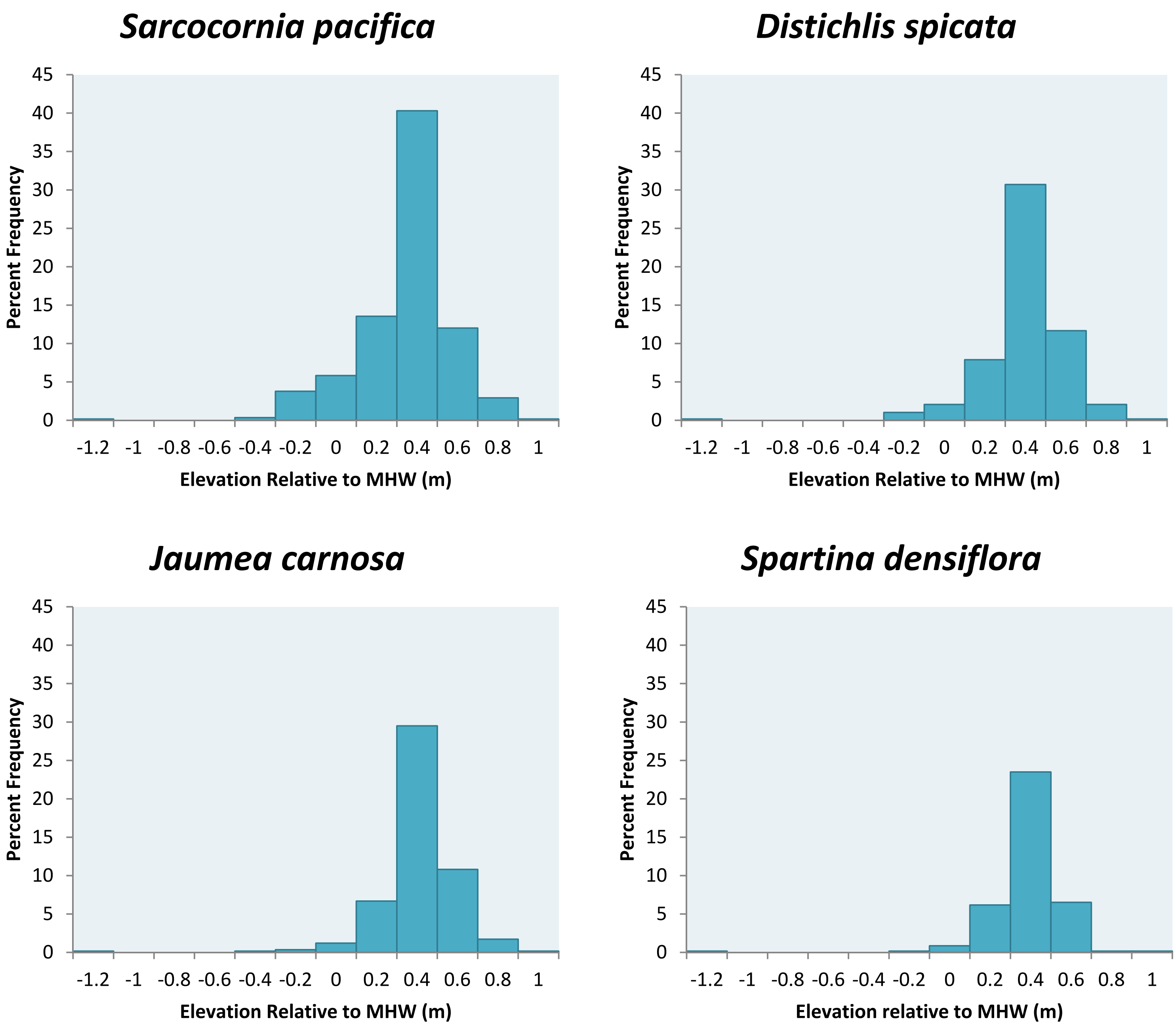

Figure 10. Frequency distribution of high occurrence (scaled at forty-five percent frequency) plant species relative to MHW across all sites.

Medium Occurrence Species

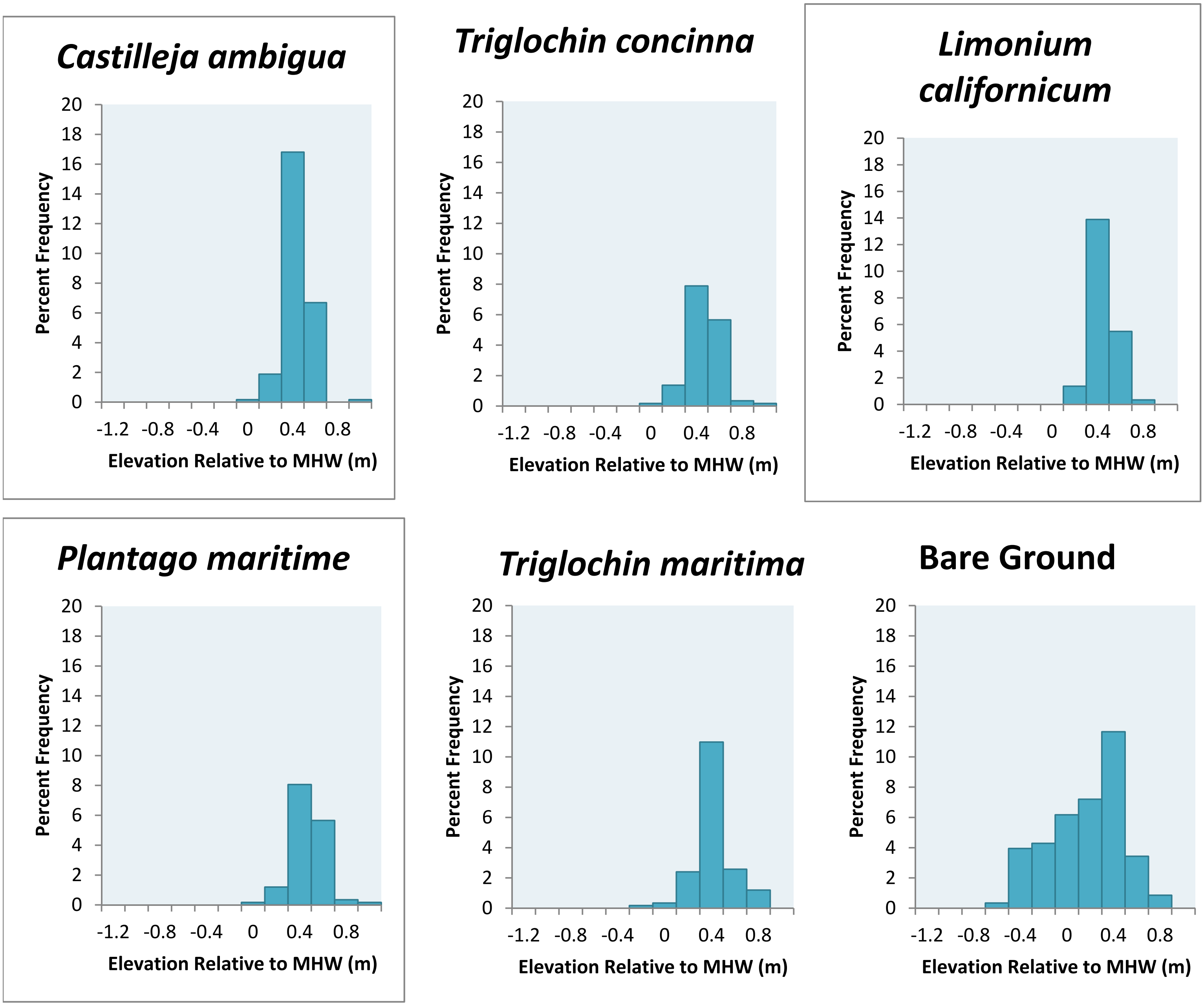

Figure 11. Frequency distribution of medium occurrence (scaled at twenty percent frequency) plant species relative to MHW across all sites.

Low Occurrence Species

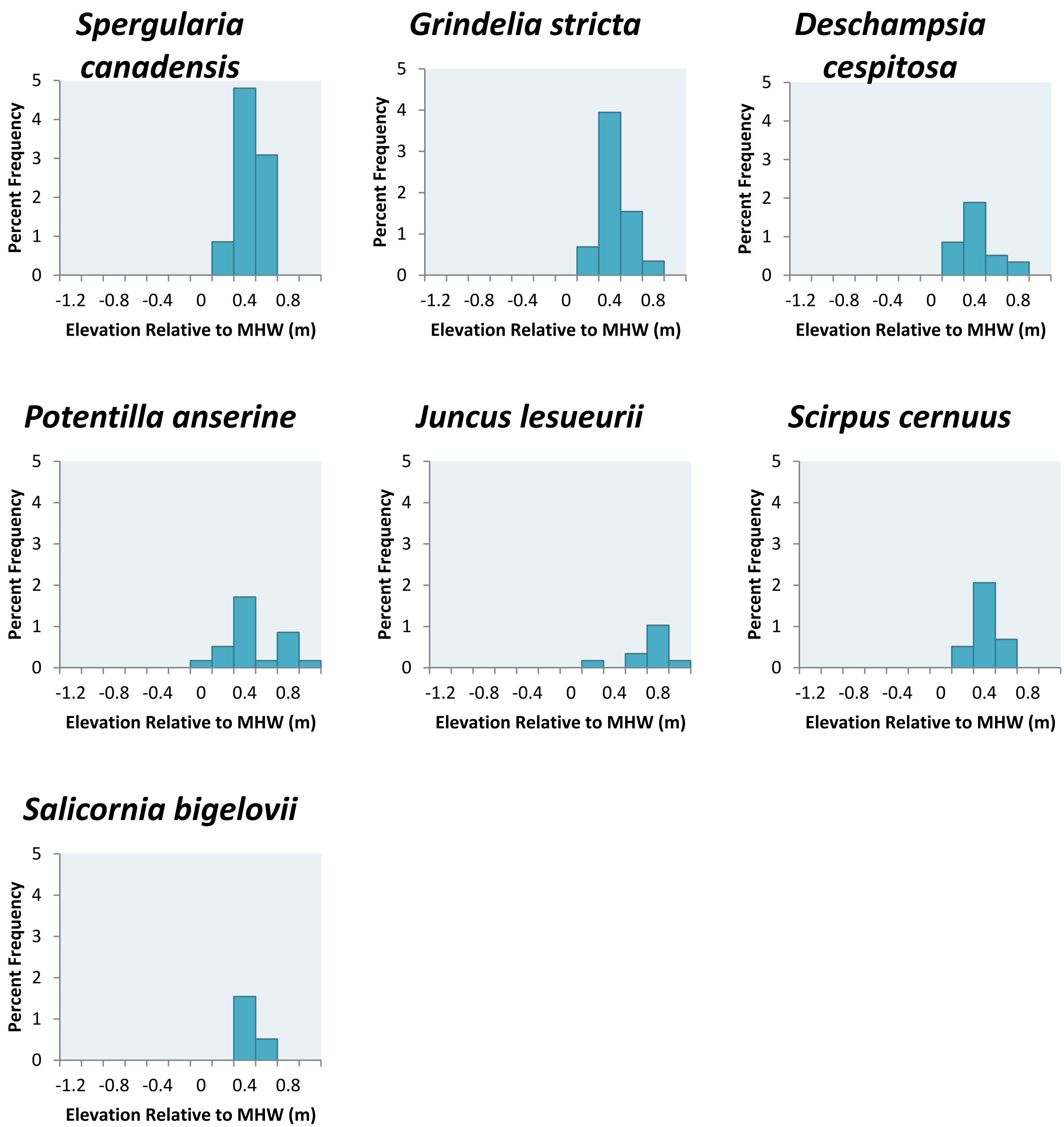

Figure 12. Frequency distribution of low occurrence (scaled at five percent frequency) plant species relative to MHW across all sites. Species recorded in less than ten sample plots where not displayed graphically, however, Tables 5-6 provide results.

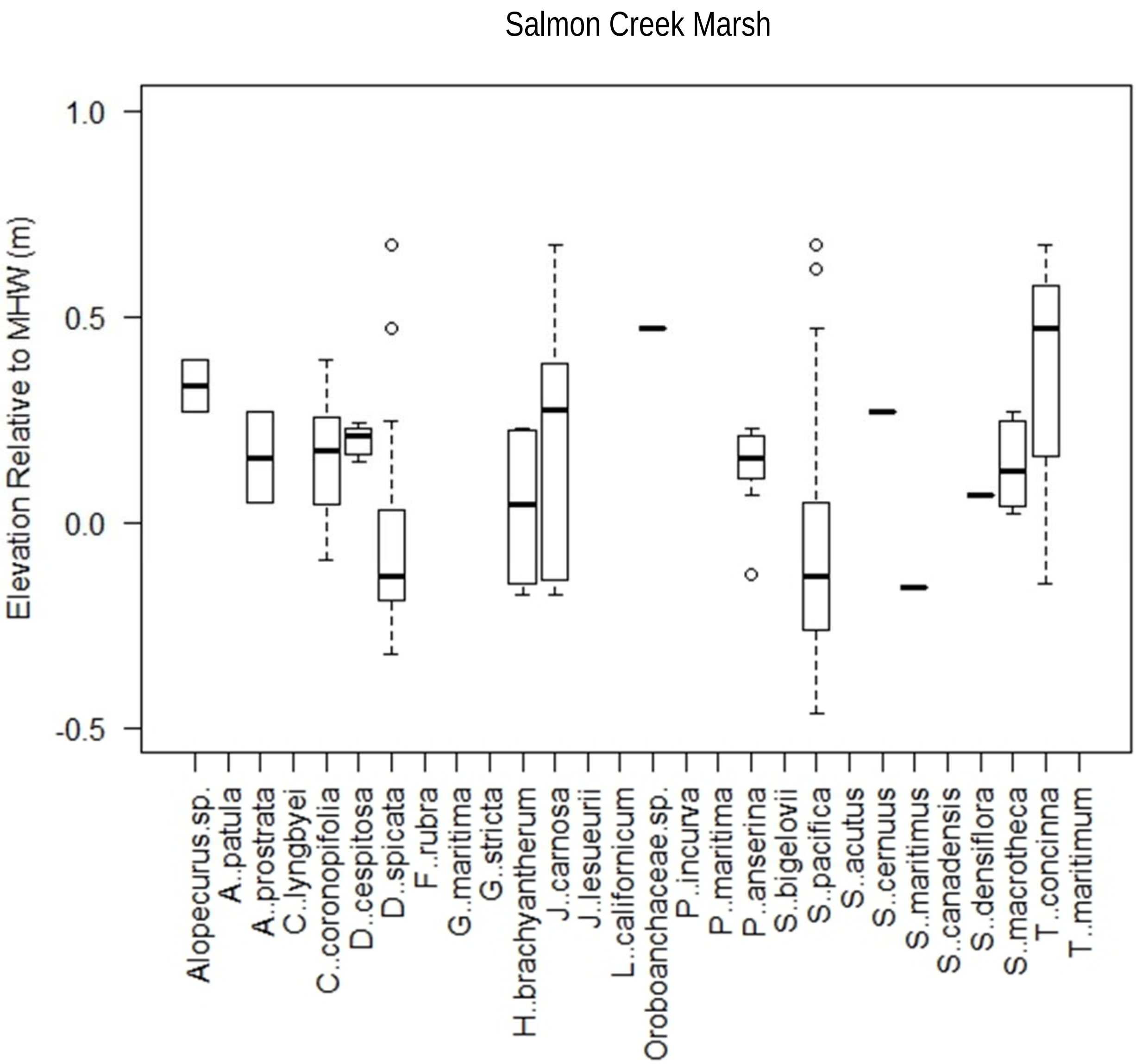

Figure 13. Elevation of plant species relative to mean high water (MHW), in meters (m), at Salmon Creek Marsh. Median (solid line), 25 and 75 percentiles (box), and 1.5 interquartile range (whiskers).

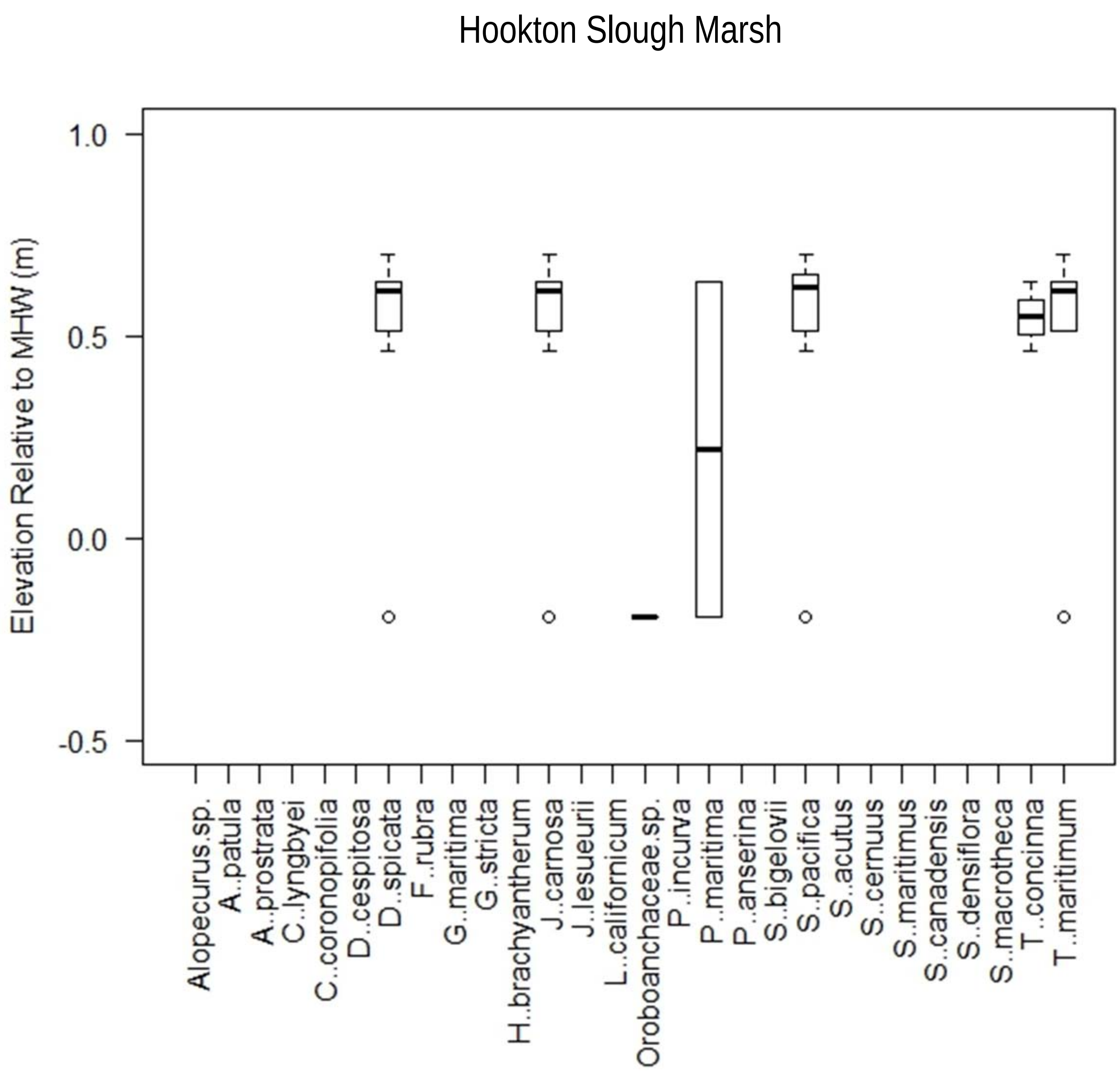

Figure 14. Elevation of plant species relative to mean high water (MHW), in meters (m), at Hookton Slough Marsh. Median (solid line), 25 and 75 percentiles (box), and 1.5 interquartile range (whiskers).

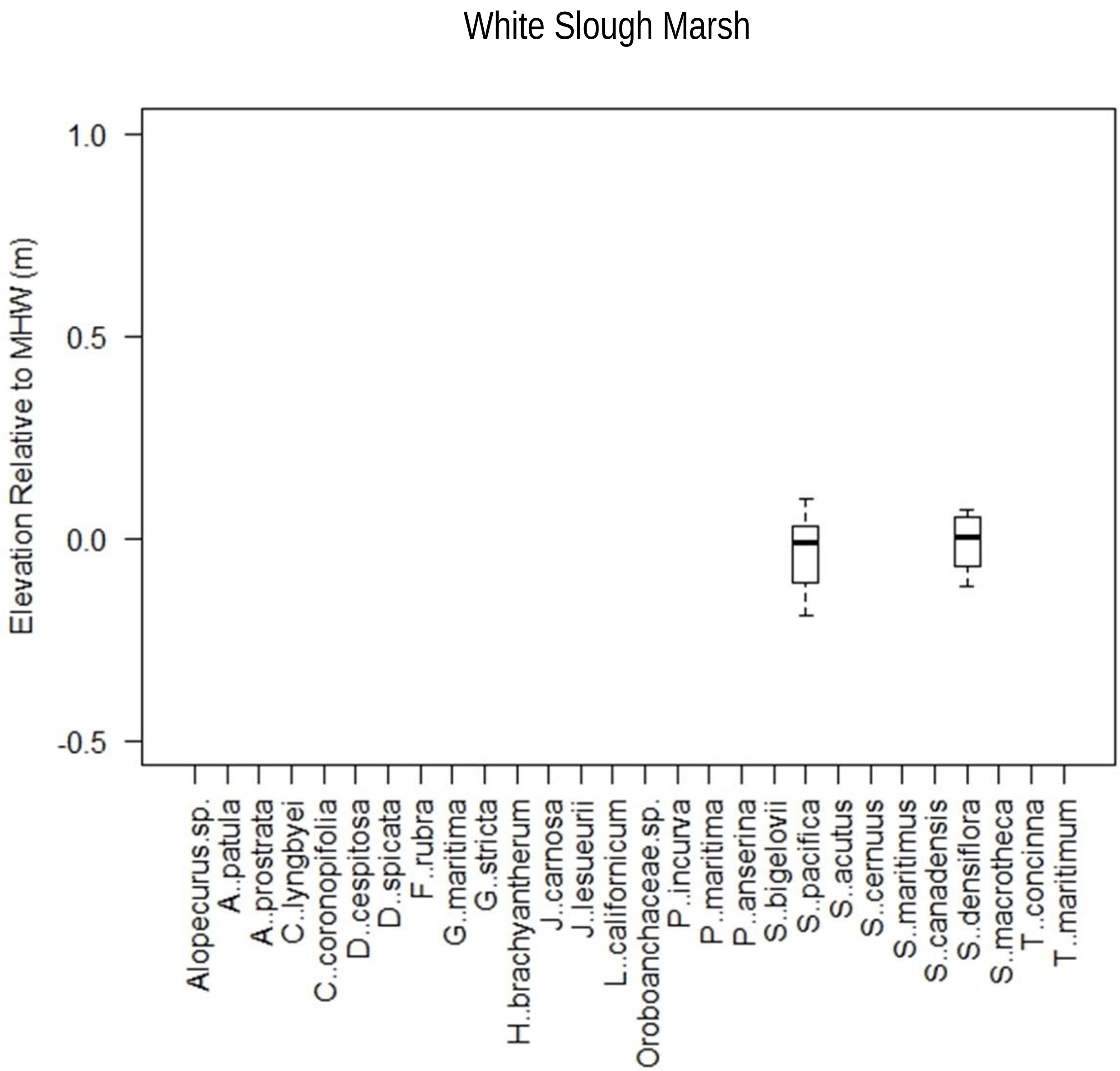

Figure 15. Elevation of plant species relative to mean high water (MHW), in meters (m), at White Slough Marsh. Median (solid line), 25 and 75 percentiles (box), and 1.5 interquartile range (whiskers).

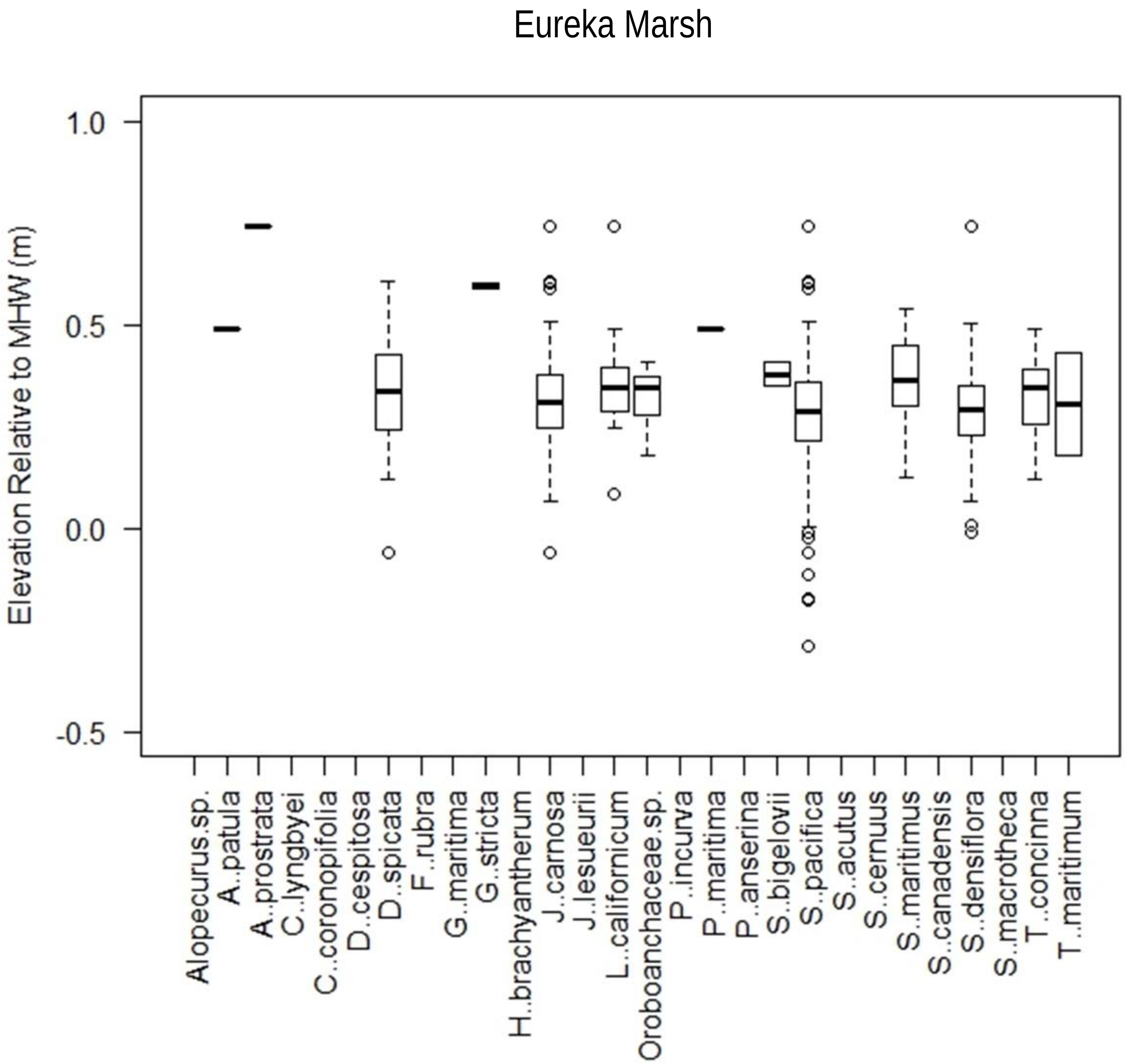

Figure 16. Elevation of plant species relative to mean high water (MHW), in meters (m), at Eureka Marsh. Median (solid line), 25 and 75 percentiles (box), and 1.5 interquartile range (whiskers).

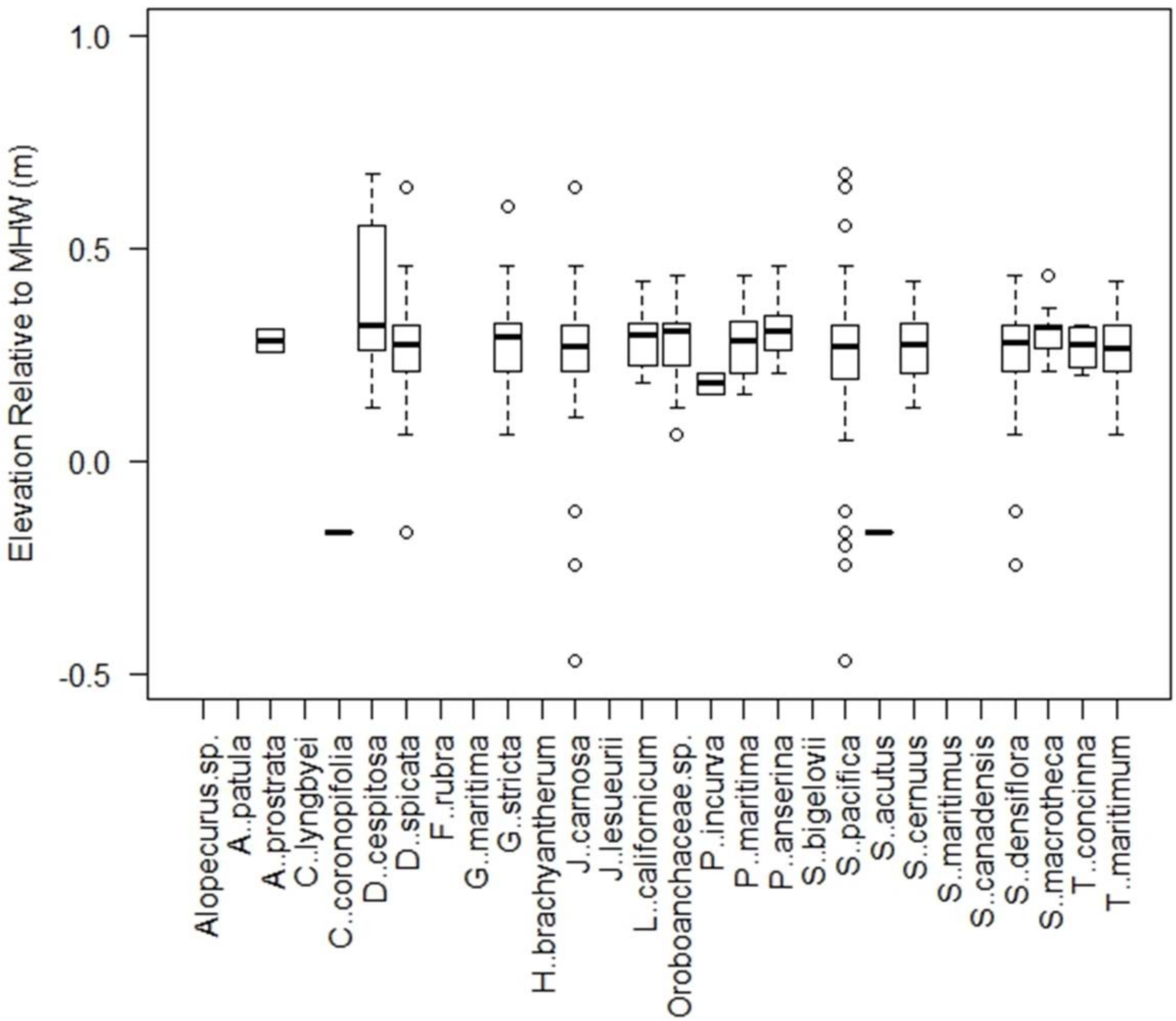

Figure 17. Elevation of plant species relative to mean high water (MHW), in meters (m), at Jacoby Marsh. Median (solid line), 25 and 75 percentiles (box), and 1.5 interquartile range (whiskers).

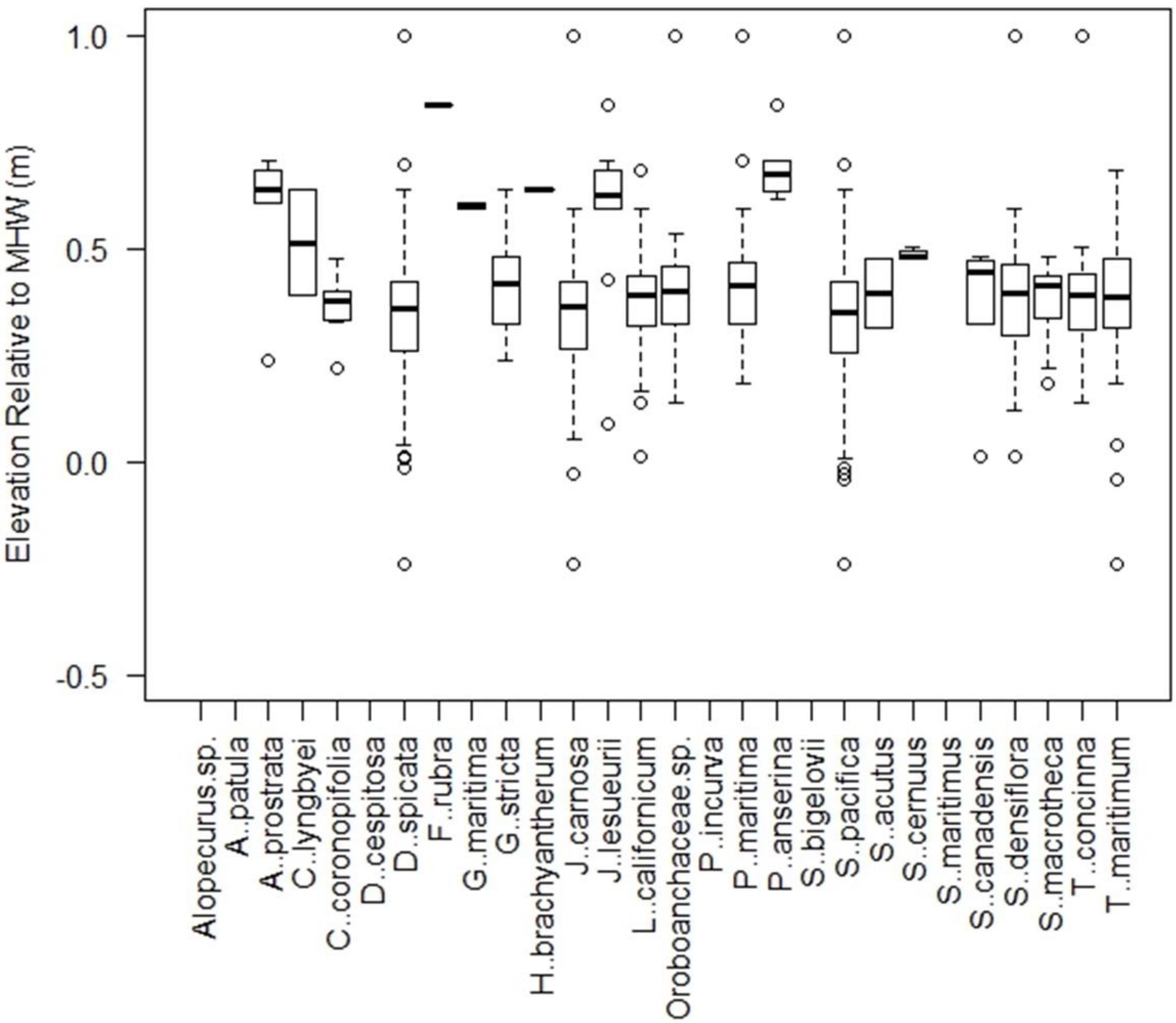

Figure 18. Elevation of plant species relative to mean high water (MHW), in meters (m), at Mad River Slough Marsh. Median (solid line), 25 and 75 percentiles (box), and 1.5 interquartile range (whiskers).

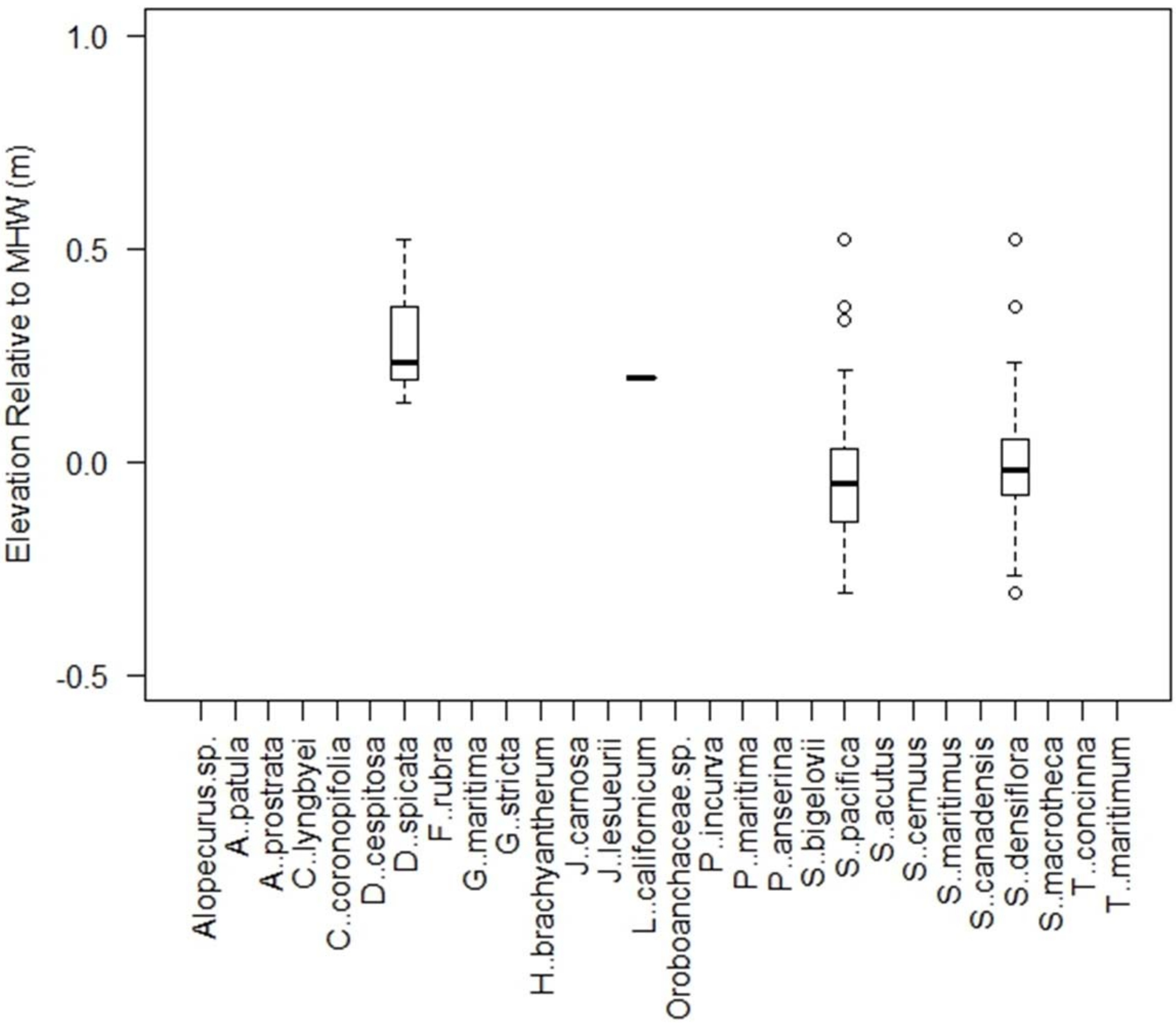

Figure 19. Elevation of plant species relative to mean high water (MHW), in meters (m), at Manila Marsh. Median (solid line), 25 and 75 percentiles (box), and 1.5 interquartile range (whiskers).

3.3 Water level and salinity monitoring

We deployed water level loggers to record tide levels from May 2012 to January 2013 at study sites. We used these data to develop local tidal datums relative to marsh elevations (Fig. 20) with continued monitoring at Mad River Slough and Salmon Creek marsh sites. If loggers were placed in high marsh channels, they did not capture the bottom portion of the hydrograph; therefore the mean low water (MLW) datum was not estimated. During periods of high water levels, we calculated site-specific tidal datum for mean tide level (MTL), mean high water (MHW), and mean higher high water (MHHW) (Table 7, Fig 25).

Our results indicate marsh elevations lie relatively high in the tidal frame (Fig. 21-23) with 90% of the marsh surface area above MHW (Fig.25). Mean high water ranged from 1.22 to 1.85 m (NAVD88) across four of our study sites (excludes Salmon Creek Marsh). Marsh elevations were also relatively high in the tidal frame when compared to mean higher high water (MHHW) (Fig. 24) with 59% of the marsh surface area above MHHW. The sites with greatest elevation measurements above MHHW were Eureka (91%), Mad River (83%), and Jacoby (81%), while the other sites are considerably lower with Salmon Creek (26%), Manila (10%), Hookton (8%) and White only having 1% of its area above MHHW. Inundation of all marshes varied throughout the year with the longest inundation periods occurring during peak rainfall in December. Water level and salinity monitoring results for the Salmon Creek Restoration project at the Salmon Creek Marsh are presented in Appendix A.

Precipitation in the winter (November – January) led to a large influx of freshwater which resulted in a decrease in measured salinity at sites (see appendices for site results). High precipitation levels during these winter months increased freshwater amounts into Humboldt Bay and through drainage of Jacoby Creek, Elk River, Freshwater Creek, Janes Creek, and numerous other small creeks and sloughs (Fig. 26).

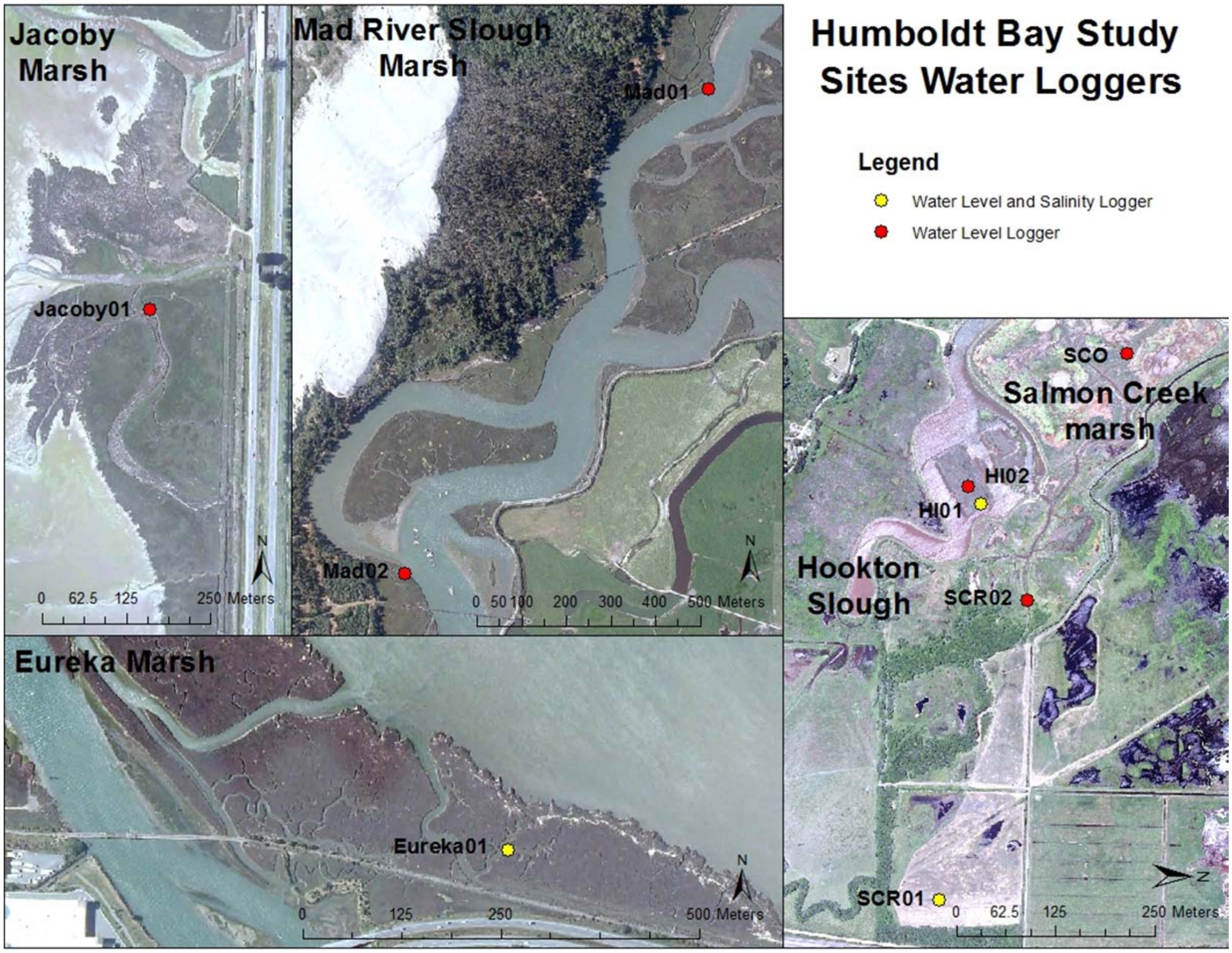

Figure 20. Map of water level and salinity logger locations.

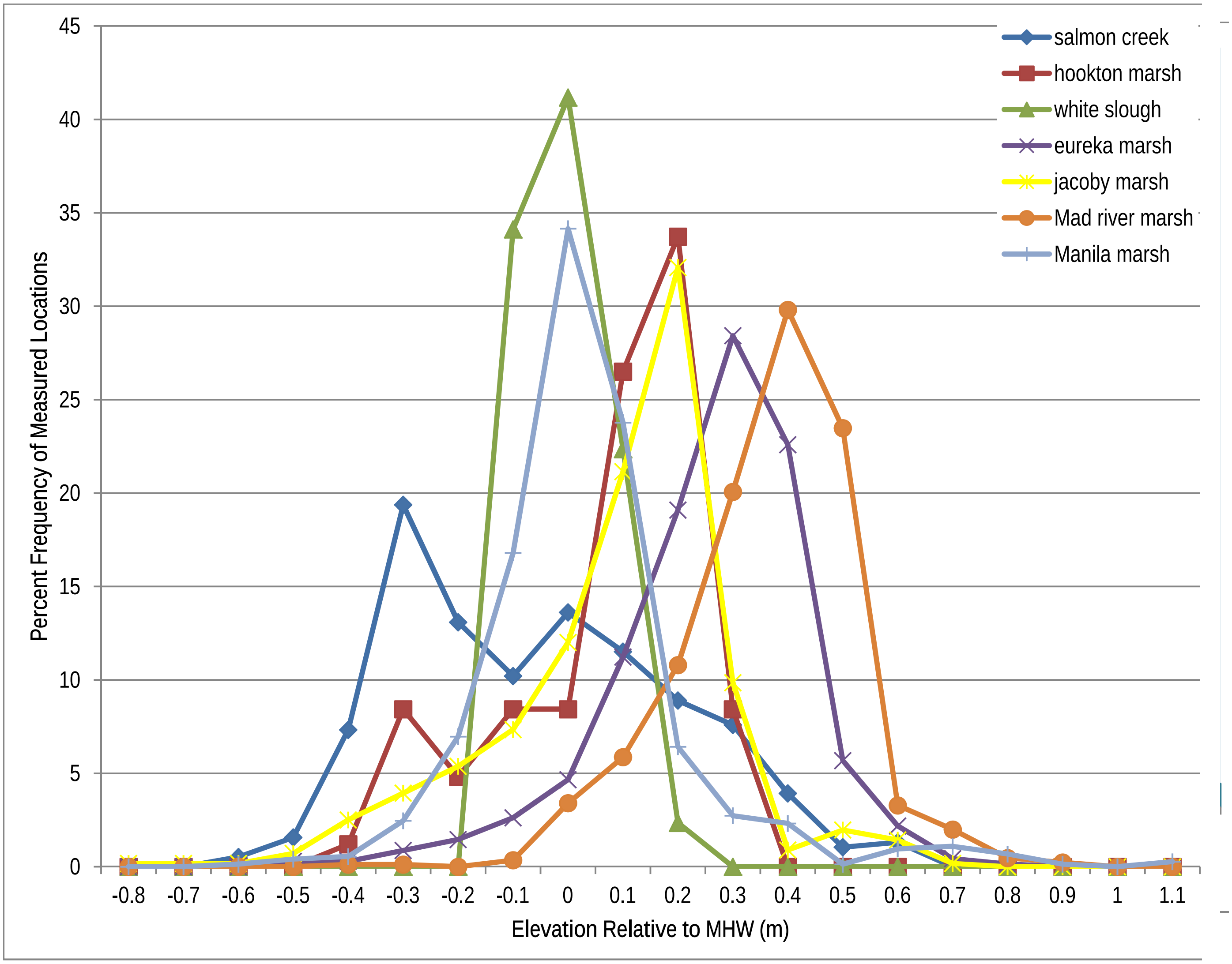

Figure 22. Elevation comparison relative to mean high water (MHW) between all study sites

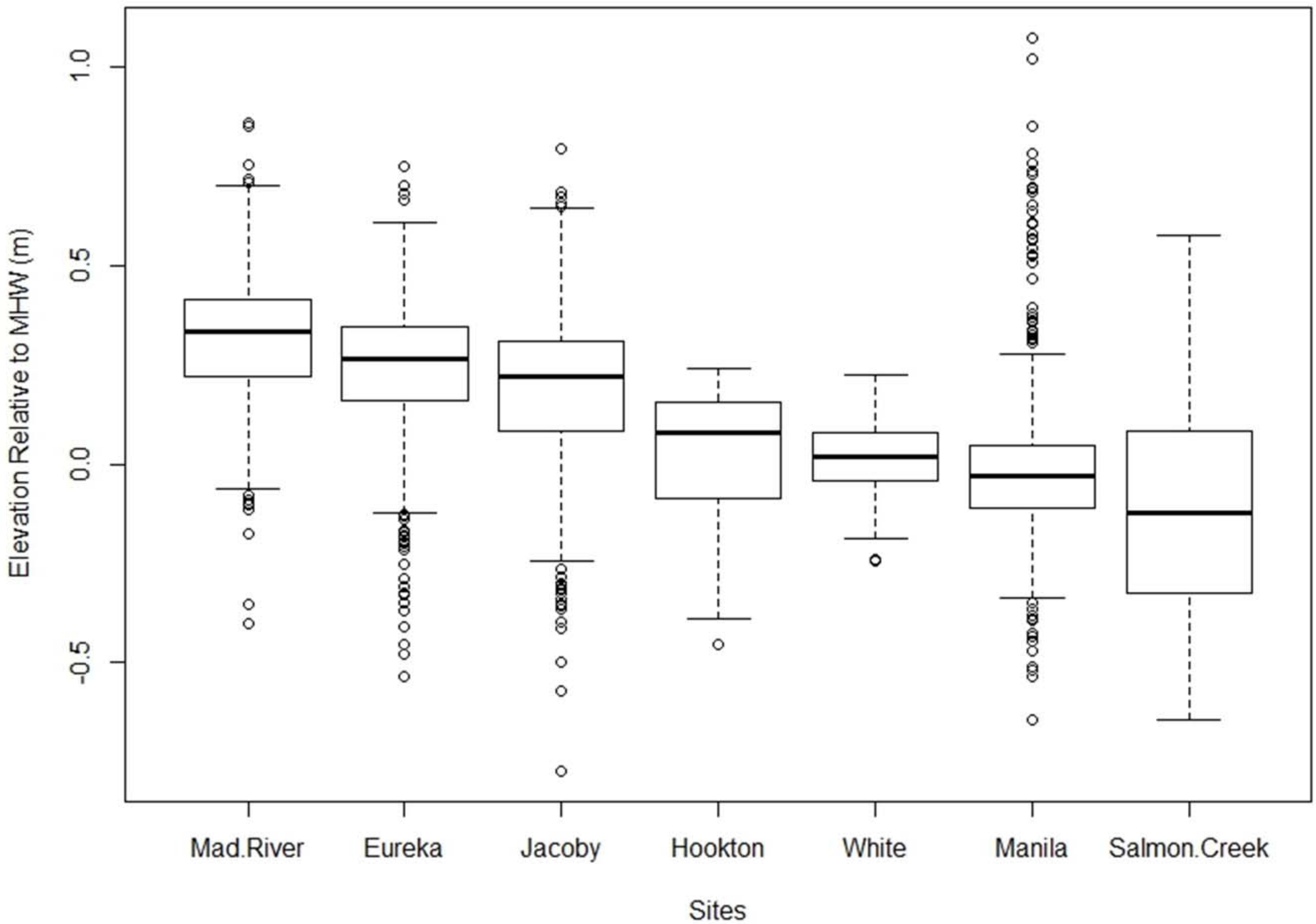

Figure 23. Elevation relative to mean high water (MHW), in meters (m), by site. Median (solid line), 25 and 75 percentiles (box), and 1.5 interquartile range (whiskers).

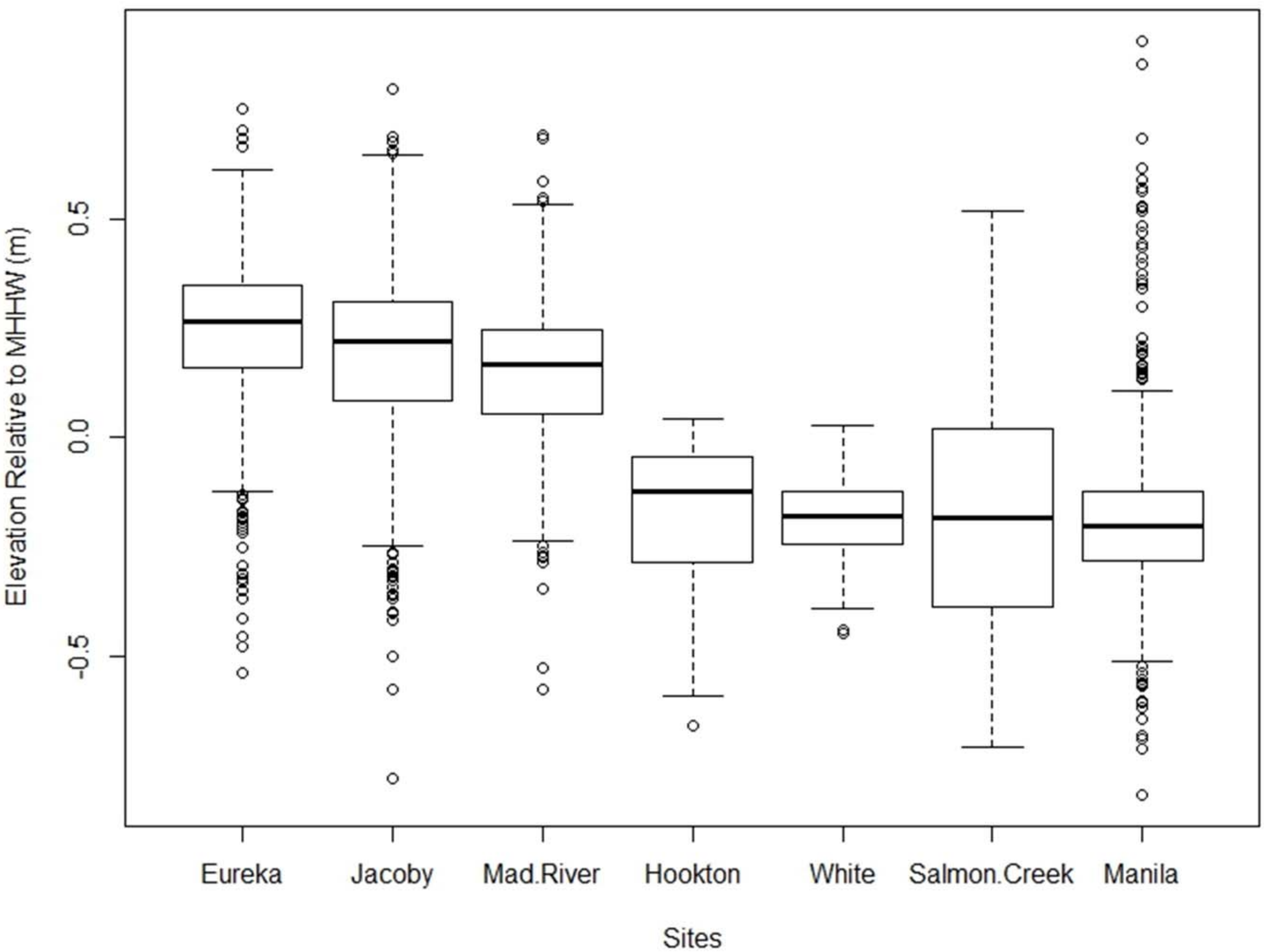

Figure 24. Elevation relative to mean higher high water (MHHW), in meters (m), by site. Median (solid line), 25 and 75 percentiles (box), and 1.5 interquartile range (whiskers).

Table 7. Tidal datum conversion calculated from water level loggers deployed at each site. Water elevations (NAVD88) were recorded 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
Salmon Creek Marsh	0.68	1.22	1.28
Hookton and White Slough Marshes	1.14	1.77	1.97
Eureka Marsh	0.99	1.72	1.92
Jacoby Creek Marsh	1.33	1.85	1.97
Mad River Slough and Manila Marsh	1.16	1.74	1.91

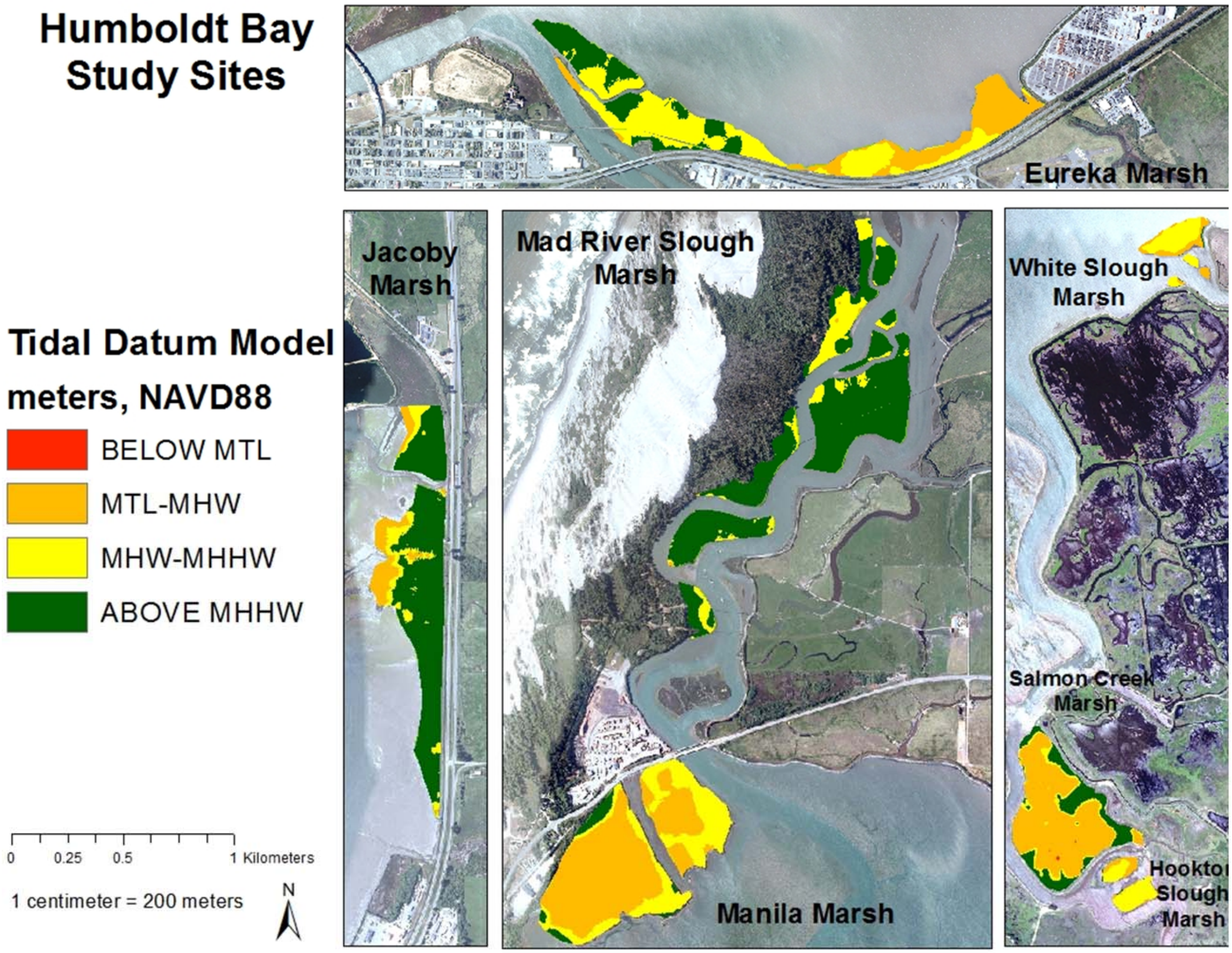

Figure 25. Tidal datums for study sites derived from local inundation data.

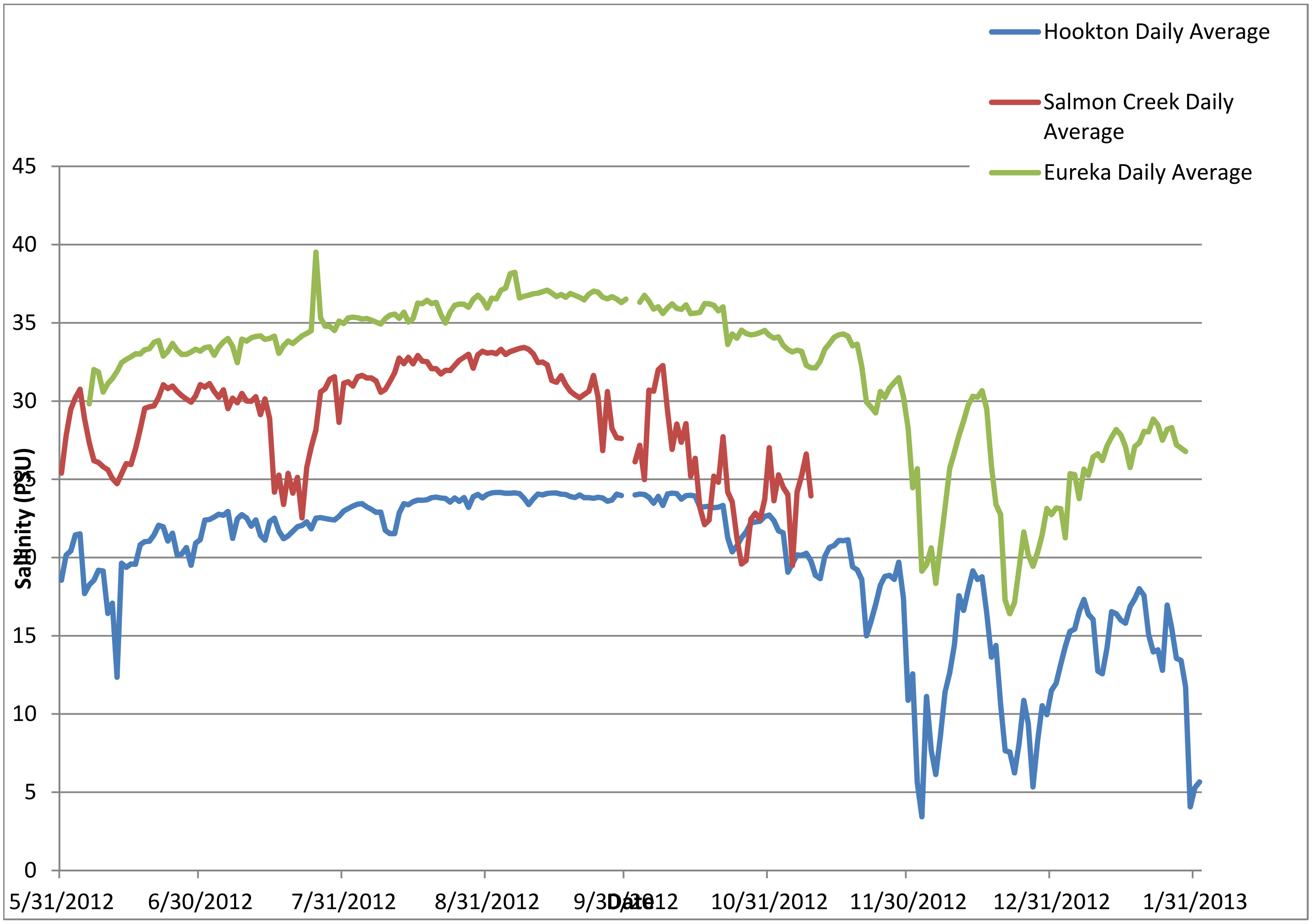

Figure 26. Daily average salinity readings at Eureka, Hookton, and Salmon Creek salinity loggers.

Discussion

Site-specific baseline data and modeling approaches are valuable for resource land managers assessing SLR effects on tidal salt marsh habitats and their species. This first phase report focuses on the collect of site-specific baseline elevation, vegetation, and tidal information to incorporate into SLR marsh response models that will be completed in 2014 under the second phase of the project. Our goal for the project was to characterize the Humboldt Bay tidal marshes and provide land managers with the scientific support necessary to make informed decisions and develop climate change adaptation strategies.

In Humboldt Bay, salt marshes were classified by Eicher (1987) into three types based on their elevation with corresponding differences in vegetation. Eicher (1987) described the lowest elevation marshes as dominated by *S. pacifica*, middle elevation marshes by *S. densiflora*, and high elevation marshes as mixed marshes that contained the greatest diversity of species. *S. densiflora* is a non-native invasive species, but when removed, *S. pacifica* is the dominant species of middle elevation marshes. However, removal of *S. densiflora* has been a recent action, and more time is needed to determine the species composition of the restored marshes.

We found that *S. pacifica* was dominant at lower elevations at our study sites. At middle elevations between 0.05 m and 0.25 m and above MHW (NAVD88), plant communities were more diverse than plant communities at higher marsh elevations. Also, we found that *S. densiflora* had invaded all elevations but was most widespread at middle elevations, although this could reflect removal efforts at lower elevation areas of marsh study sites. The restoration efforts have been shown to set back succession, resulting in a greater proportion of *S. pacifica* than might normally be found at a given tidal elevation (Pickart 2012).

The added effects from climate change on tidal marsh ecosystems could greatly increase threats to vulnerable wildlife and fish populations (Ohlemuller et al. 2008). SLR has the potential to affect water quality in estuary ecosystems including suspended sediment, salinity, temperature, and nutrients which are vital factors influencing salmonid populations and their habitats. Also, increased rates of inundation will be ecologically significant for obligate vegetation and wildlife marsh species.

Next steps

Our Coastal Ecosystem Response to Climate Change (CERCC) program recognizes the importance of extensive and improved integration of physical and biological monitoring that could facilitate the discovery of important trends for SLR and marsh response. Results from our previous work in San Francisco Bay showed that initial elevation, along with tidal range and accretion rates, were key inputs for effectively modeling marsh response from SLR. The collection of sediment cores and installation of surface elevation tables (SETs) were done in fall of 2013 to better understand local sediment accretion rates in Humboldt Bay.

Intertidal marshes are part of a dynamic ecotone which experiences regular inundation containing sediment for deposition on the marsh platform, and that inundation is a critical component of the processes by which marshes maintain elevation (Callaway, 1996). Sediment accretion can partially offset increased SLR; thus, collection of sediment data will be important to reflect the current rate of sediment accumulation at Humboldt Bay. A better understanding of the spatial variability of available suspended sediment and deposition rates for both organic matter and sediment would greatly improve these site-specific results.

We believe that baseline data collection at a local scale can be used to identify and prioritize restoration sites and land acquisitions that can be good candidates for marsh perpetuation in light of projected SLR. In addition, the continued risk to listed species and plant communities needs to be assessed by better understanding response to increased inundation. Consistent with the goal of the USGS Science Strategy, the CERCC program supports models that predict ecosystem change and assess consequences of climate change and its effects on coastal ecosystems, and it will do so at a bottom-up local level appropriate for land managers developing adaptation plans.

Acknowledgments

The authors would like to thank the USGS Western Ecological Research Center and the USGS National Climate Change and Wildlife Science Center for funding support and other contributions from the U. S. Fish and Wildlife Service North Pacific Landscape Conservation Cooperative, and USFWS Region 8 Inventory and Monitoring Program, and USFWS Science Applications Program. The authors would like to thank Eric Nelson, Kenneth Griggs, Andrea Pickard and other Refuge staff for assistance and accommodating USGS technicians at the refuge bunkhouse. Helpful review comments were provided by G. Block and A. Pickard. The authors would also like to thank L. Curry for assistance with project fieldwork.

References Cited

Bengtsson, L., Hodges, K. I., and Keenlyside. N., 2009, Will extratropical storms intensify in a warmer climate?: Journal of Climate, v. 22, p. 2276–2301.

Bindoff, N. L., Willebrand J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, K., Le Quéré, C., Levitus, S., Nojiri, Y., Shum, C. K., Talley, L. D., and Unnikrishnan, A., 2007, Observations: Oceanic Climate Change and Sea Level: *In* Climate Change 2007: The Physical Science Basis. Contribution of

Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, eds. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Avery, T, M. Tignor and H. L. Miller New York: Cambridge University Press.

Brittain, R. A., Craft, C. B., 2012, Effects of Sea-Level Rise and Anthropogenic Development on Priority Bird Species Habitats in Coastal Georgia, USA: Environmental Management, v. 49, p. 473–482.

Callaway, J.C., Borgnis, E.L, Turner, R.E., and Milan, C.S., 2012, Carbon sequestration and sediment accretion in San Francisco Bay tidal wetlands: Estuaries and Coasts, v. 35, no. 5, p. 1163–1181.

Callaway, J., Nyman, J. A., and DeLaune, R. D., 1996, Sediment accretion in coastal wetlands: A review and simulation model of processes: Current Topics in Wetland Biogeochemistry, v. 2, p. 2–23.

Callaway, J., Parker, V. T., Vasey, M. C., and Schile L. M. 2007, Emerging issues for the restoration of tidal marsh ecosystems in the context of predicted climate change: Madroño, v. 54, no. 3, p 234-248.

Cayan, D., Bromirski, P., Hayhoe, K., Tyree, M., Dettinger, M. and Flick, R., 2005, Projecting Future Sea Level: California Climate Change Center Report (CEC-500-2005 202-SD), December 2005. http://www.energy.ca.gov/2005publications/2005_pubs_alpha_order.html

Cayan, D., Luers, A. L., Hanemann, M., Franco, G., and Croes, B., 2006, Scenarios of climate change in California: An overview. Sacramento, Calif.: California Climate Change Center (CEC-500-2005-186-SF), 53 p. http://www.climatechange.ca.gov/climate_action_team/reports/index.html

Cayan, D. R., Bromirski, P. D., Hayhoe, K., Tyree, M., Dettinger, M. D., and Flick, R. E., 2008, Climate change projections of sea level extremes along the California coast: Climate Change, v. 87, p. S57–S73.

Cayan D., Tyree M., Dettinger M., Hidalgo H., Das T., Maurer E., Bromirski P., Graham N., and Flick R., 2009, Climate change scenarios and sea level rise estimates for California 2008 climate change scenarios assessment: California Climate Change Center, CEC-500-2009-014-F.

Curcó, A., Ibañez, C., Day, J. W., and Prat, N., 2002, Net primary production and decomposition of salt marshes of the Ebre Delta (Catalonia, Spain): Estuaries, v. 25, p. 309–324.

Deverel, S. J., Drexler, J. Z., Ingrum, T., and Hart, C., 2008, Simulated Holocene, recent, and future accretion in channel marsh islands and impounded marshes for subsidence mitigation, Sacramento - San Joaquin Delta, California, USA. REPEAT Project Final Report to the CALFED Science Program of the Resources Agency of California, 60 pp.

Emanuel, K., 2005, Increasing destructiveness of tropical cyclones over the past 30 years: Nature v. 436, p. 686–688.

Foxgrover, A. C., Finlayson, D. P., Jaffe, B. E., Takekawa, J. Y., Thorne, K. M., and Spragens, K. A., 2011, 2010 Bathymetric survey and digital elevation model of Corte Madera Bay, California: U.S. Geological Survey Open-File Report 2011-1217, 20 p., available at http://pubs.usgs.gov/of/2011/1217/.

Geden, K. B., Kirwan, M. L., Wolanski, E., Barbier, E. B., and Silliman, B. R., 2011, The present and future role of coastal wetland vegetation in protecting shorelines: Answering recent challenges to the paradigm: Climate Change, v. 106, p. 7–29.

Goals Project, 1999, Bayland ecosystem habitat goals. A report of habitat recommendations prepared by the San Francisco Bay Area Wetlands Ecosystems Goals Project. Joint publication of the U.S. Environmental Protection Agency, San Francisco, California, and San Francisco Bay Regional Water Quality Control Board, Oakland, Calif.

Greenberg, R., Maldonado, J. E., Droege, S., and McDonald, M. V., 2006, Tidal marshes: a global perspective on the evolution and conservation of their terrestrial vertebrates: Bioscience, v. 56, p. 675–685.

Grinsted, A., Moore, J. C., and Jevrejeva, S., 2010, Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD*:* Climate Dynamics, v. 42, p. 461–472.

Hamlet, A. F., and Lettenmaier, D.P., 2007, Effects of 20th century warming and climate variability on flood risk in the western U.S.: Water Resources Research, v. 43, p. W06427.

Hansen, J., Sato, M., Ruedy, R., Lo, K., Lea, D.W., and Medina-Elizade, M., 2006, Global temperature change: *Proceedings of the National Academy of Science, v.* 103, p. 14288–14293.

Holgate, S. J., and Woodworth, P. L., 2004, Evidence for enhanced coastal sea level rise during the 1990s: Geophysical Research Letters, v. 31, p. L07305.

International Panel on Climate Change, 2007, Summary for Policymakers: In Climate Change 2007: The Physical Science Basis. Contribution Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jevrejeva, S., Moore J. C., and Grinsted, A., 2010, How will sea level respond to changes in natural and anthropogenic forcings by 2100?: Geophysical Research Letters, v. 37, p. L07703.

Jevrejeva, S., Moore J. C., and Grinsted, A., 2012, Sea level projections to AD2500 with a new generation of climate change scenarios: Global and Planetary Change, v. 80–81, p. 14–20.

Kemp, A. C., Horton, B. P., Donnelly, J. P., Mann, M. E., Vermeer, M., and Rahmstorf, S., 2011, Climate related sea-level variations over the past two millennia: Proceedings of the National Academy of Science of the United States of America: v. 108, p. 11017–11022.

Kirwan M. L., and Guntenspergen, G. R., 2010, Influence of tidal range on the stability of coastal marshland: Journal of Geophysical Research, v. 115, no. F2, p. 1–11.

Leatherman, S. P., Zhang, K., and Douglas, B. C., 2000, Sea level rise shown to drive coastal erosion: Eos Trans. AGU, v. 81, no.6, p. 55.

Mancera, J. E., Meche, G. C., Cardona-Olarte, P. P., Castaneda-Moya, E., Chiasson, R. L., Geddes, N. A., Schile, L. M., Wang, H. G., Guntenspergen, G. R., and Grace, J. B., 2005, Fine-scale spatial variation in plant species richness and its relationship to environmental conditions in coastal marshlands: Plant Ecology, v. 178, p. 39–50.

Morris, J.T., Sundareshwar, P. V., Nietch, C. T., Kjerfve, B., and Cahoon, D. R., 2002, Responses of coastal wetland to rising sea level: Ecology, v. 83, p. 2869–2877.

Ohlemuller, R., Anderson, B. J., Araujo, M. B., Butchart, S. H. M., Kudrna, O., Ridgely, R. S., and Thomas, C. D., 2008, The coincidence of climatic and species rarity: high risk to small-range species from climate change: Biology Letters, v. 4, p. 568–572.

Robbins, J. A., 1978, Geochemical and geophysical applications of radioactive lead: *In* Biogeochemistry of Lead in the Environment, ed. J. O. Nriagu,p. 285–393, Amsterdam:Elsevier Scientific.

Ruhl, C. A., and Schoellhamer, D. H., 2004, Spatial and temporal variability of suspended-sediment concentration in a shallow estuarine environment: San Francisco Estuary and Watershed Science, v. 2, article 1.

Scarton, F., Day, J. W., and Rismondo, A., 2002, Primary production and decomposition of *Sarcocornia fruticosa* (L.) Scott and *Phragmites australis* Trin. Ex Steudel in the Po Delta, Italy: Estuaries, v. 25, p. 325–336.

Schmid, K. A., Hadley, B. C., and Wijekoon, N., 2011, Vertical accuracy and use of topographic LiDAR data in coastal marshes: Journal of Coastal Research, v. 27, p. 116–132.

Spautz, H., Nur, N., Stralberg, D., and Chan, Y., 2006, Multi-scale habitat relationships of tidal-marsh breeding birds in the San Francisco Bay estuary: Studies in Avian Biology, v. 32, p. 247–269.

Stralberg, D., Brennan, M., Callaway, J. C., Wood, J. K., Schile, L. M., Jongsomjit, D., Kelly, M., Parker, V. T., and Crooks, S., 2011, Prospects for tidal marsh sustainability in San Francisco Bay: Spatial habitat scenarios and sensitivity analysis: *PLoS ONE, v.* 6, no. 11, p. e27388.

Takekawa, J. Y., Woo, I., Spautz, H., Nur, N., Grenier, J. L., Malamud-Roam, K., Nordby, J. C., Cohen, A. N., Malamud-Roam, F., and Wainwright-De La Cruz, S. E., 2006, Environmental threats to tidal marsh vertebrates in the San Francisco Bay estuary: Studies in Avian Biology, v. 32, p. 176–197.

Takekawa J. Y., Woo, I., Thorne, K. M., Buffington, K. J., Nur, N., Casazza, M. L., Ackerman, J. T., 2011, Bird communities: effects of fragmentation, disturbance, and sea level rise on population viability: *In* Ecology, conservation and restoration of tidal marshes: the San Francisco Bay estuary, UC Press., p. 175–194

U.S. Fish and Wildlife Service, 2009, Draft Recovery Plan for Tidal Marsh Ecosystems of Northern and Central California. Sacramento, California, xviii 636 p.

Vermeer, M., and Rahmstorf, S., 2009, Global sea level linked to global temperature: Proceedings of the National Academy of Science of the United States of America, v. 106, p. 21527–21532.

Webster, P. J., Holland, G. J., Curry, J. A., and Chang, H. R., 2005, Changes in tropical cyclone number, duration, and intensity in a warming environment: Science, v. 309, p. 1844–1846.

Woodrey, M.S., Rush, S.A., Cherry, J.A., Nuse, B.L., Cooper, R.J., Lehmicke, A.J.J., 2012. Understanding the potential impacts of global climate change on marsh birds in the Gulf of Mexico region. Wetlands, 32, 35-49

Appendices:

Results by site

Site-specific data are available

John Y. Takekawa, PhD
U.S. Geological Survey
Western Ecological Research Center
505 Azuar Dr.
Vallejo, CA 94592
tel: (707) 562-2000
john_takekawa@usgs.gov

Karen M. Thorne, PhD
U.S. Geological Survey
Western Ecological Research Center
3020 State Univ. Dr. East, 2007 Modoc Hall
Sacramento, CA 95819
tel: (916)-278-9417
kthorne@usgs.gov

Appendix A

Salmon Creek Marsh

Introduction

Located in the southern portion of Humboldt Bay (Fig. 1), Salmon Creek Marsh (hereafter, “Salmon Creek”) was historically tidally influenced, with freshwater contributions from runoff and from Salmon Creek during floods. However, the hydrology of this 21.4 hectare (ha) area was altered over 100 years ago with the construction of dikes. This area is now part of the Salmon Creek restoration project which modified tidal gates and breached dikes to allow muted tidal influence, enhanced fish passage, and salt marsh restoration through the placement of fill to raise the elevation of the diked tidelands (Fig. A). The majority of this marsh is located behind a levee, which makes it unique compared to our other sites. Although this site has ongoing restoration and had sediment added in 2010 to increase elevation, the area was significantly lower than other marshes measured in Humboldt Bay. Salmon Creek is recognized as an important stopover for migratory birds along the Pacific Flyway.

Figure A. Salmon Creek Marsh

Results

Elevation surveys

A total of 382 elevation measurements were taken at Salmon Creek in June 2012 (Fig. A-1). The elevation range was 0.58-1.80 m, with a mean of 1.11 m (NAVD88). The majority (66%) of survey points across Salmon Creek Marsh are located at elevations below mean high water (MHW; Fig. A-2). Salmon Creek is a highly altered marsh and is the second lowest marsh surveyed in this study, relative to NAVD88. A 5-m horizontal resolution elevation model was developed in ArcGIS 10 Spatial Analyst using the kriging method (ESRI, Redlands, Calif., Fig. A-3). This baseline elevation model was used as the initial state for tidal inundation models.

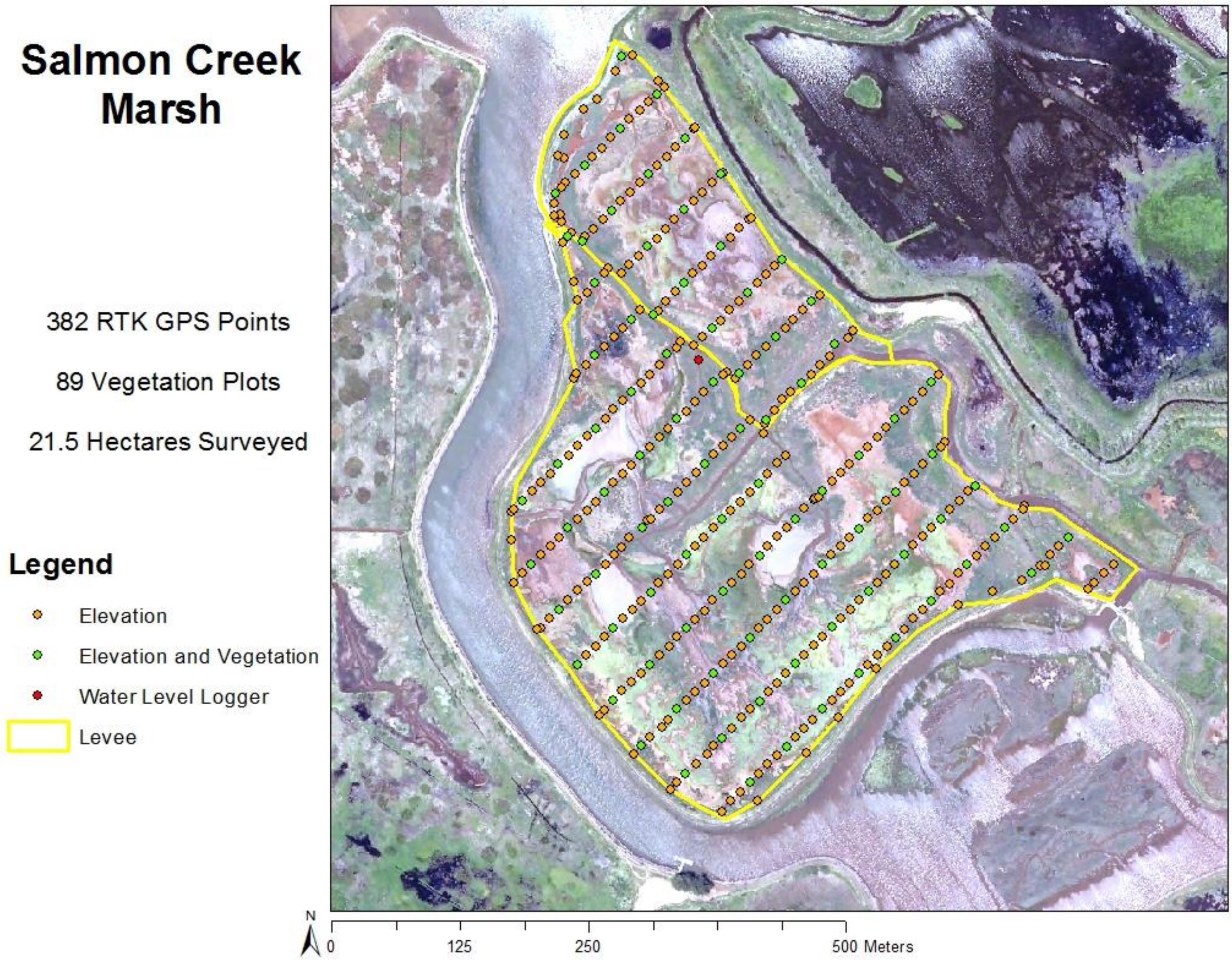

Figure A-1. Salmon Creek Marsh with 2012 elevation and vegetation survey points and water logger locations.

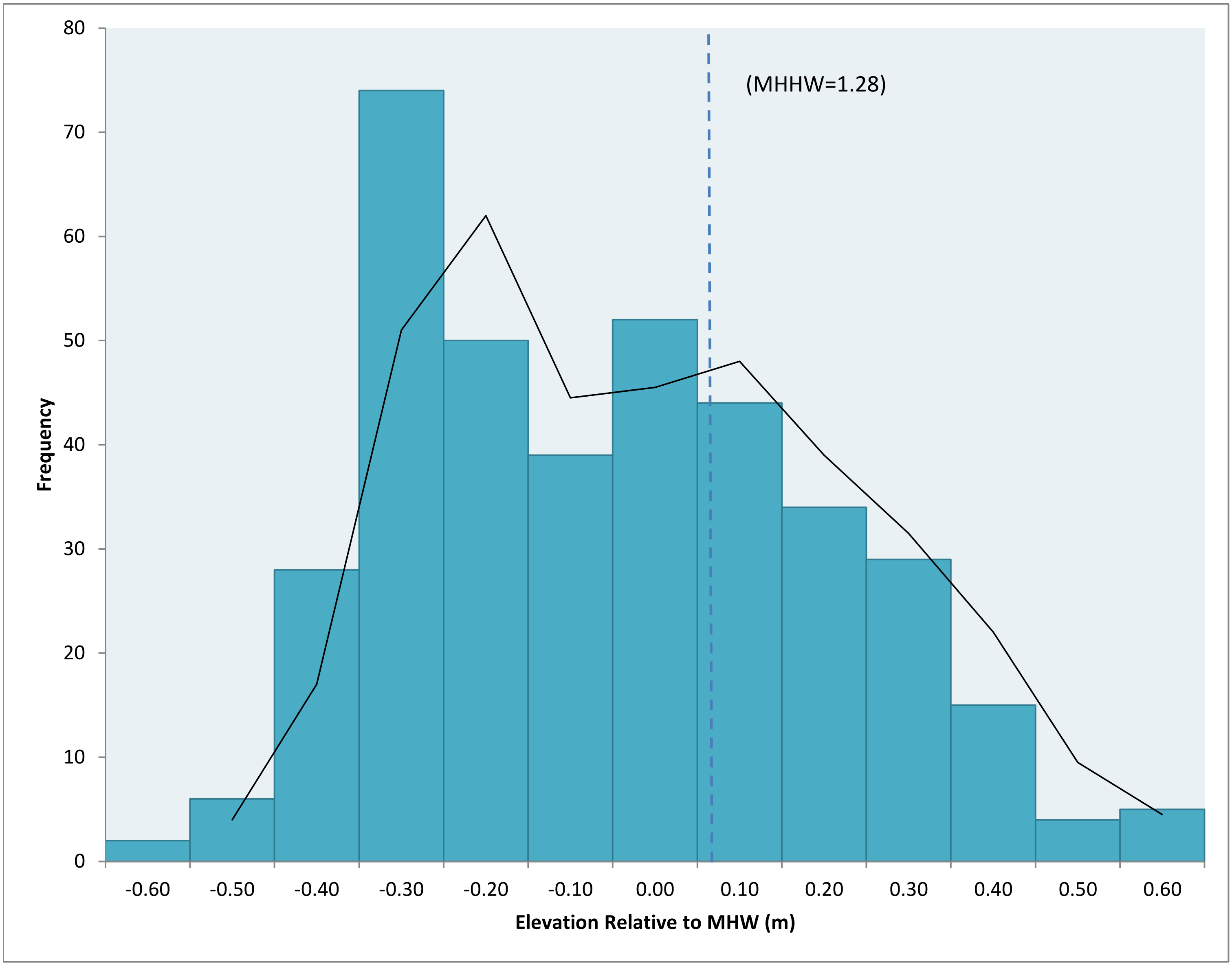

Figure A-2. Frequency distribution of elevation data points (n =382) at Salmon Creek marsh relative to local mean high water (MHW=1.22), in meters (m). Dotted vertical line indicates MHHW, relative to MHW.

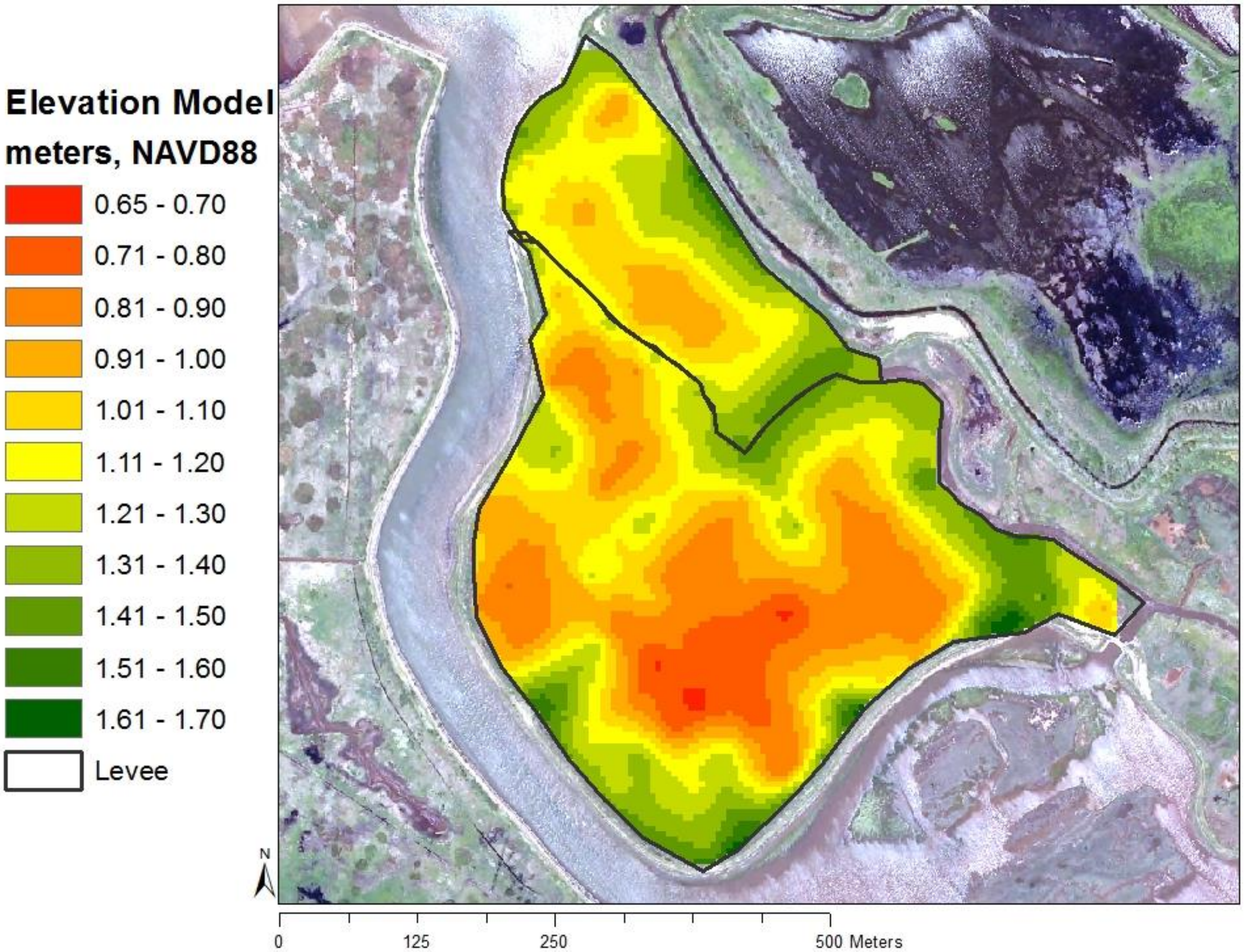

Figure A-3. Elevation model of Salmon Creek marsh (5-m horizontal resolution) developed from ground RTK GPS elevation data. Parameters were optimized to produce minimal root-mean-square (RMS) error.

Vegetation surveys

Vegetation and elevation surveys were conducted concurrently in June 2012. This study site underwent restoration projects and our vegetation surveys were performed at the earlier stages of re-vegetation. These restoration projects included S. *densiflora* removal, beginning in 2010, restoration of tidal influence with the construction of tide gates and the deposition of sediment behind the levee.

A total of 89 locations (Fig A-1) were measured for vegetation composition, height (cm), and percent cover (Table A-1). Salmon Creek marsh was dominated by two species; *S. pacifica* (53% frequency) and *D. spicata* (19%). A total of 15 species were detected, two of which are non-native (*C. coronopifolia* and *S. densiflora*). Vegetation in salt marshes is generally structured by inundation and salinity gradients. In Salmon Creek marsh, zonation of vegetation species relative to MHW was observed (Table A-2; Fig. A-4, 5).

Table A-1. Marsh plant community characteristics at Salmon Creek marsh in 2012.
[cm, centimeter; n, number of quadrats where species was observed]

Species	Frequency (%)	Mean Height (cm)	Mean Height SD	Max Height (cm)	Max Height SD	Mean Cover %	Mean Cover % SD	n
S. pacifica	53.13	18	9	23	10	53	35	51
D. spicata	19.79	28	7	32	7	62	37	19
D. cespitosa	8.33	47	19	56	25	59	41	8
J. carnosa	7.29	12	6	14	6	24	28	7
**C. coronopifolia*	7.29	4	3	7	5	13	15	7
P. anserina	7.29	21	7	29	13	12	10	7
S. macrotheca	5.21	3	2	3	2	8	7	5
H. brachyantherum	4.17	29	4	35	9	10	13	4
T. concinna	3.13	16	3	17	3	17	13	3
Alopecurus	2.08	2	1	15	6	28	4	2
A. prostrata	2.08	12	12	13	14	3	3	2
S. cernuus	1.04	2	-	3	-	3	-	1
Oroboanchaceae	1.04	8	-	17	-	5	-	1
S. maritimus	1.04	27	-	29	-	5	-	1
**S. densiflora*	1.04	68	-	75	-	15	-	1

*non-native species

Table A-2. Presence (n=number of quadrats in which species occurred), mean elevation, minimum elevation, maximum elevation, and elevation range for all species sampled at Salmon Creek marsh relative to MHW (m).

Species	Mean Elevation Relative to MHW (m)	Elevation Relative to MHW (SD)	Maximum Elevation Relative to MHW (m)	Minimum Elevation Relative to MHW (m)	Elevation Range (m)	n
Oroboanchaceae	0.47	-	-	-	-	1
T. concinna	0.33	0.43	0.67	-0.15	0.82	3
Alopecurus	0.33	0.09	0.39	0.27	0.12	2
S. cernuus	0.27	-	-	-	-	1
D. cespitosa	0.20	0.03	0.24	0.15	0.09	8
J. carnosa	0.18	0.34	0.67	-0.18	0.85	7
A.prostrata	0.16	0.15	0.27	0.05	0.22	2
**C. coronopifolia*	0.15	0.16	0.39	-0.09	0.48	7
S. macrotheca	0.14	0.11	0.27	0.02	0.25	5
P. anserina	0.13	0.12	0.23	-0.13	0.36	7
**S. densiflora*	0.07	-	-	-	-	1
H. brachyantherum	0.04	0.22	0.23	1.04	-0.81	4
D. spicata	-0.04	0.26	0.67	0.9	-0.23	19
S. pacifica	-0.07	0.26	0.67	0.76	-0.09	51
S. maritimus	-0.16	-	-	-	-	1

*non-native species

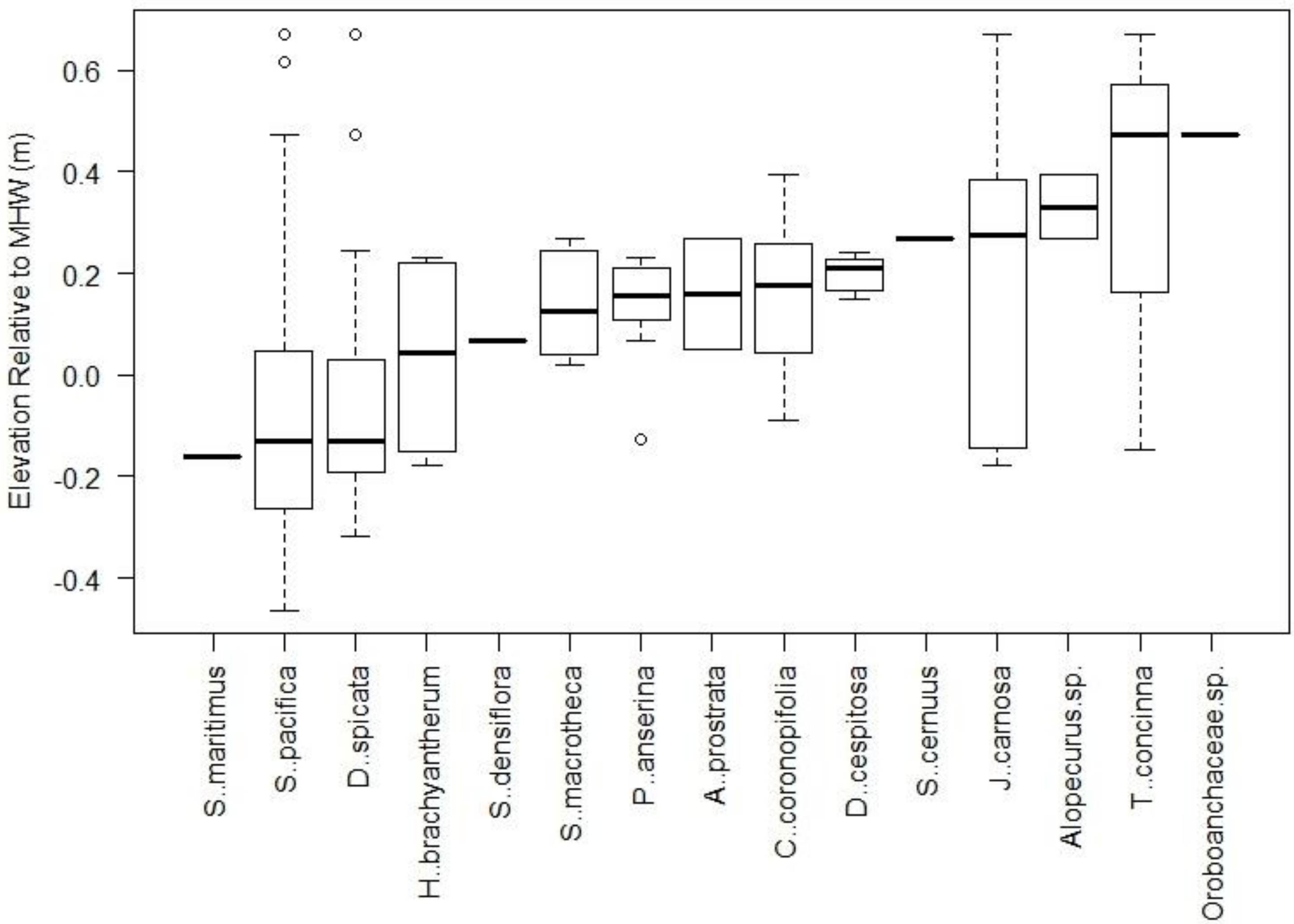

Figure A-4. Elevation of plant species relative to mean high water (MHW), in meters (m), at Salmon Creek Marsh. Median (solid line), 25 and 75 percentiles (box), and 1.5 interquartile range (whiskers).

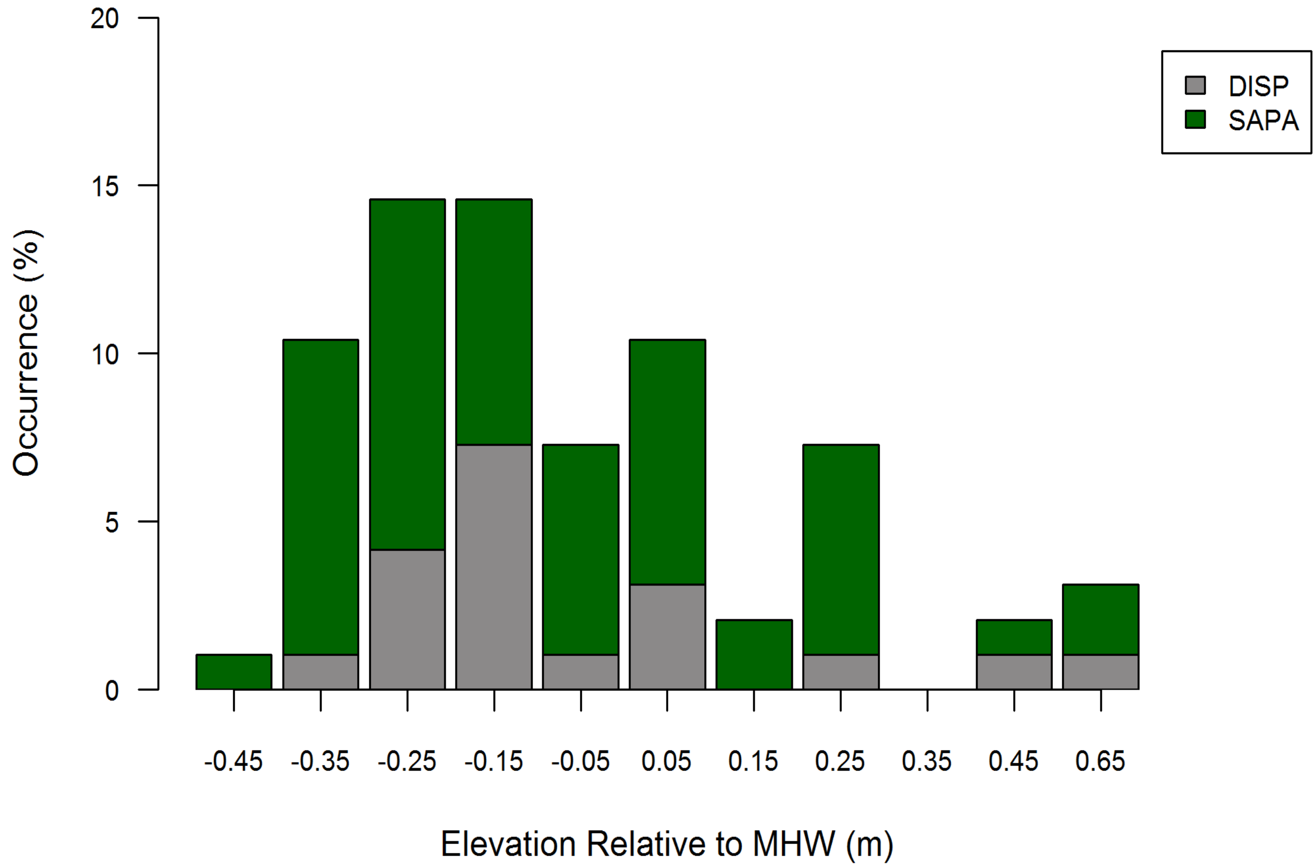

Figure A-5. Percent occurrence of the most common species at Salmon Creek (>10 % of the plots) by elevation. Species codes are: DISP = *Distichlis spicata*; SAPA = *Sarcocornia pacifica*.

Water monitoring

Site-specific water level has been monitored at Salmon Creek from May 2012 to present. Water level was measured by three data loggers, one behind the levee, one at the mouth of a first order channel of Salmon Creek, and one further up-stream in a second order channel of Salmon Creek. We used data from the logger behind the levee to develop a local tidal datum for the Salmon Creek site. Mean tide level (MTL) was 0.68 m, mean high water (MHW) was 1.22 m, and mean higher high water (MHHW) was 1.28 m. This marshes measured tidal datum was different from other sites monitored in Humboldt Bay because of its location behind a levee and the muted tidal flow it receives from managed tide gates. When looking at tidal inundation, Salmon Creek marsh was the fourth lowest marsh surveyed in Humboldt Bay with 74% of elevation measurements below MHHW. The salt marsh platform (defined by the mean marsh elevation) was inundated most often during December 2012 due to large amounts of rainfall (Fig. A-5). Based on the tidal data, a tidal datum model was produced (Fig A-6) which gives insight into what portions of the marsh are covered by water during different tidal periods.

We included more detailed hydrographs of three of the loggers within the Salmon Creek watershed (Fig. A-7-9). The hydrology of this area is of particular interest due to the restoration that occurred during our monitoring and the importance of Salmon Creek to the local salmon populations. These hydrographs represent the seasonal and spatial variation of the hydrology within this site.

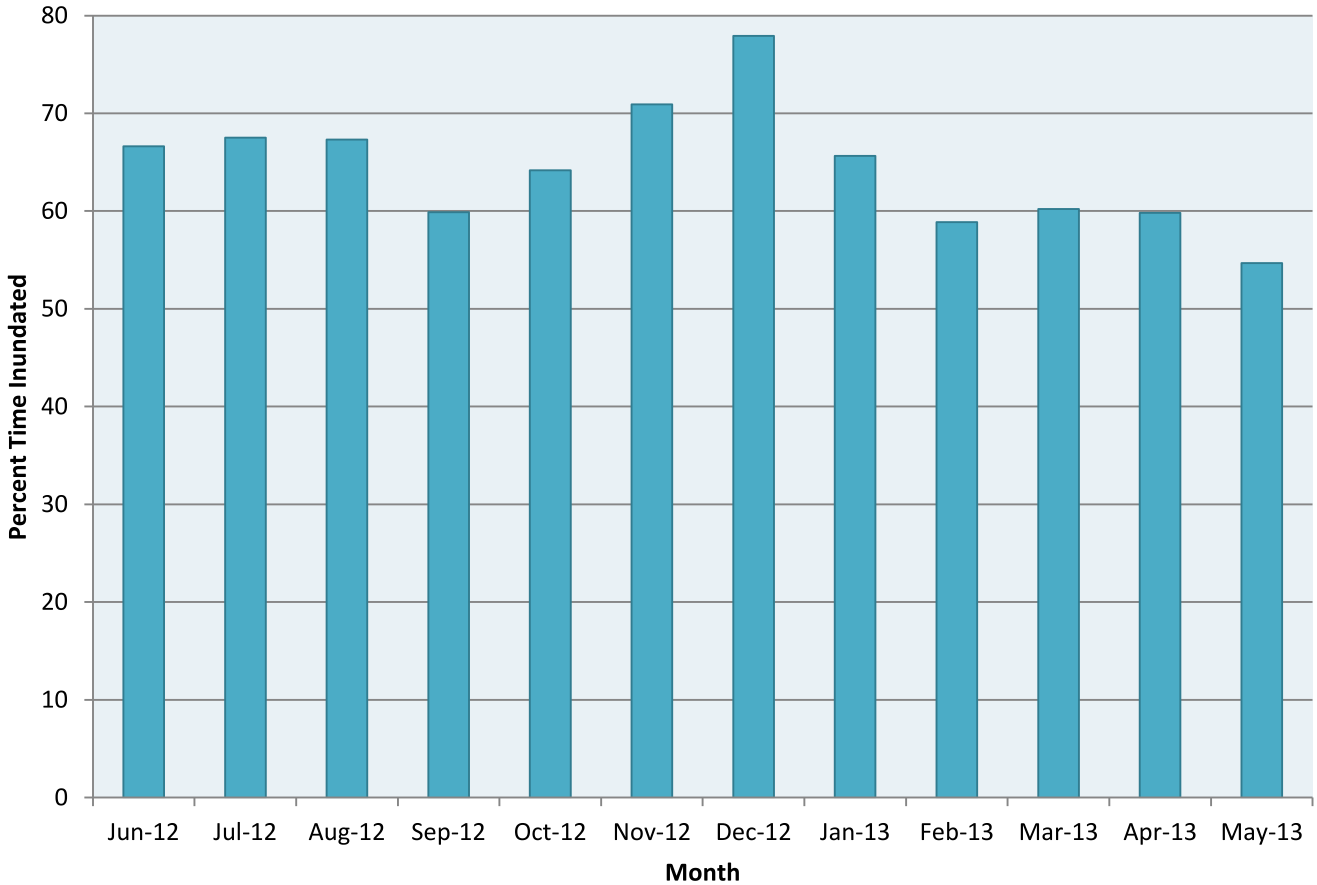

Figure A-5. Percent of time Salmon Creek marsh was inundated monthly, based on the mean elevation of the marsh platform.

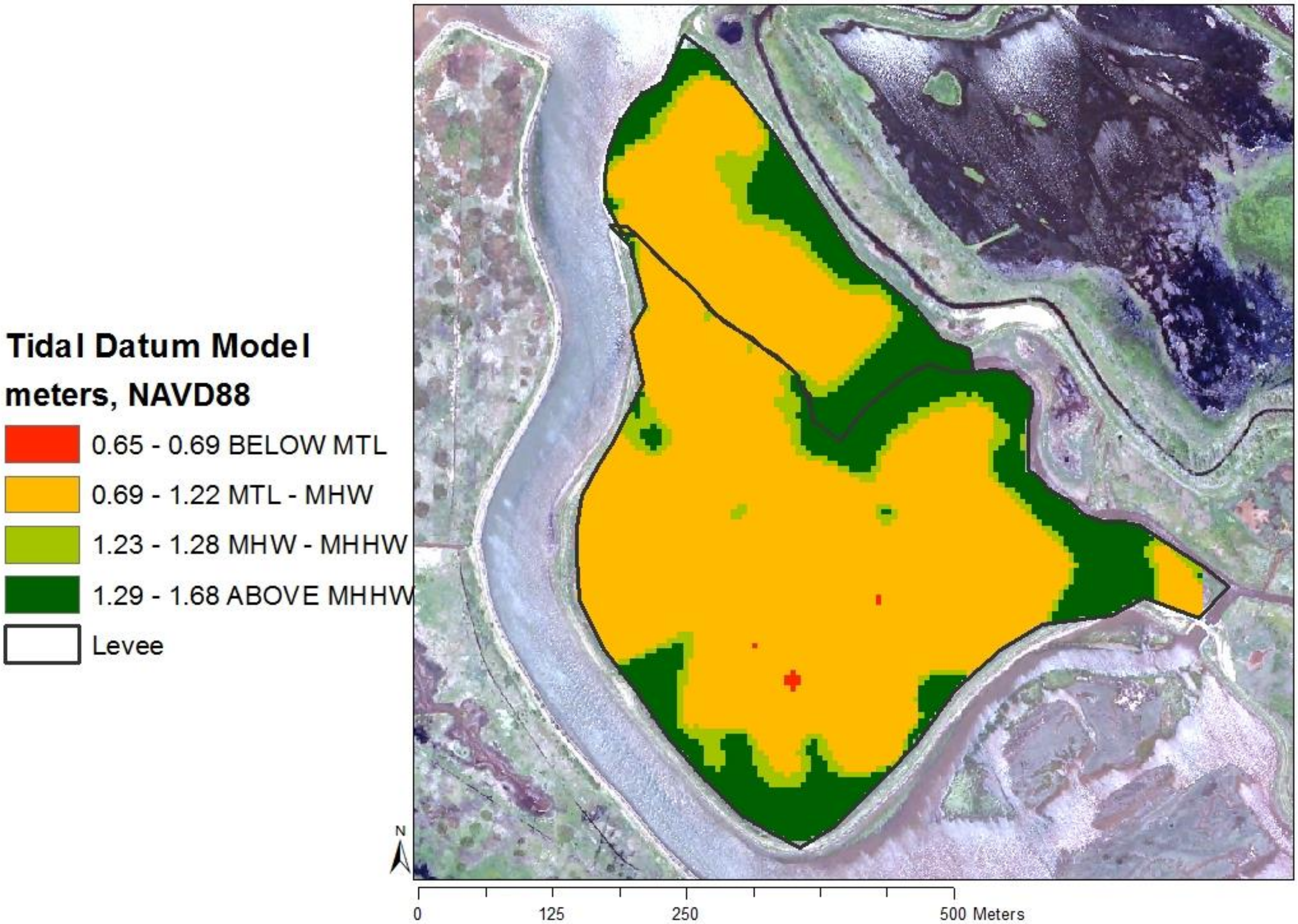

Figure A-6. Tidal datum results for Salmon Creek based on local tidal data from water loggers.

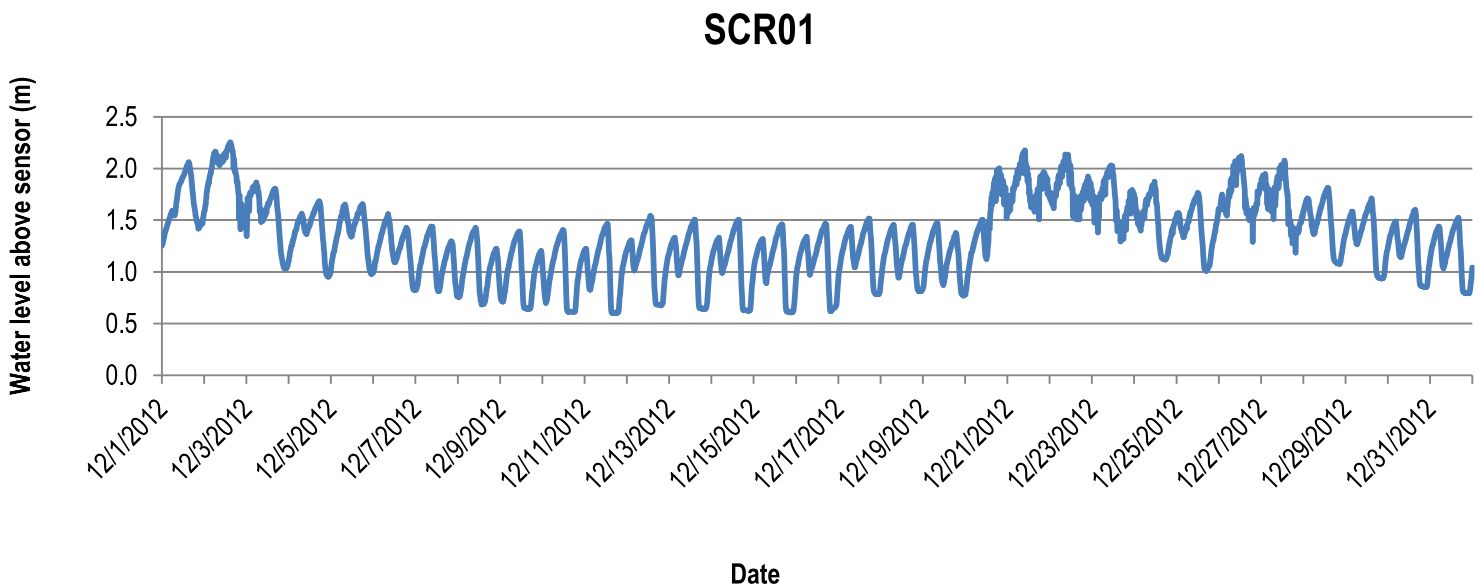

Figure A-7. Water level above water level logger sensor (~0.05 m high) in December 2012 for Salmon Creek Restoration water level logger (SCR01).

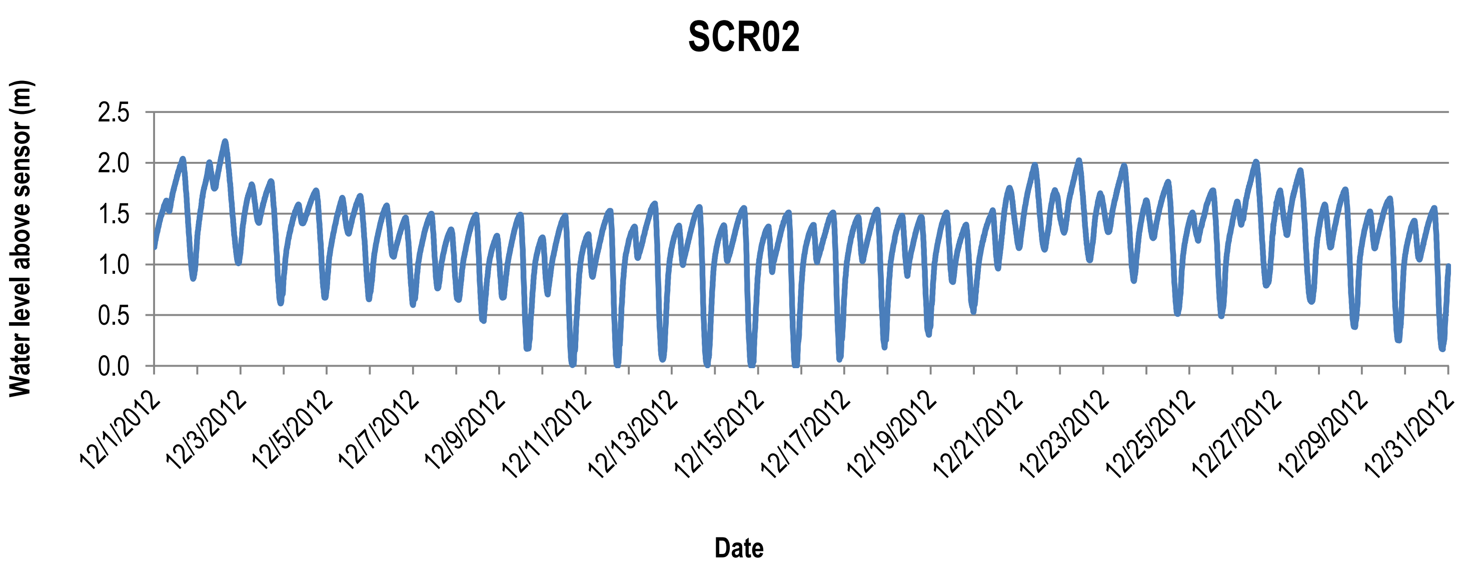

Figure A-8. Water level above water level logger sensor (~0.05 m high) in December 2012 for Salmon Creek Restoration water level logger (SC02).

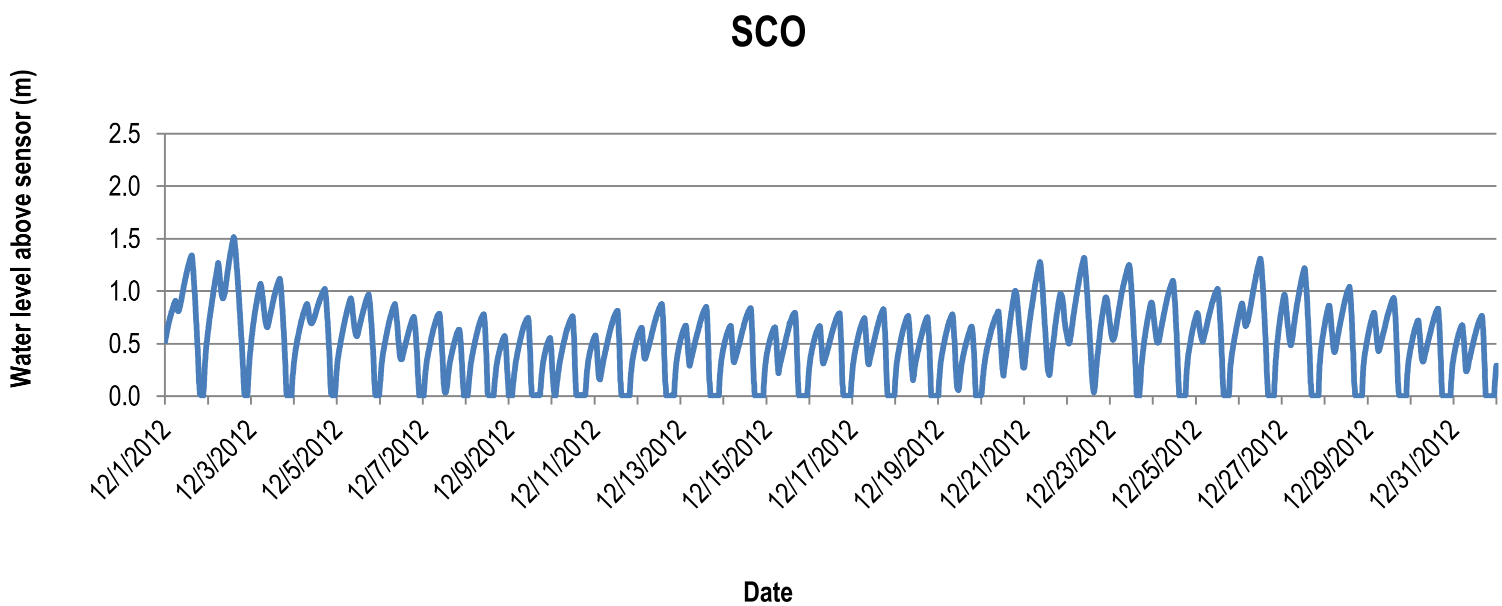

Figure A-9. Water level above water level logger sensor (~ 0.05 m high) in December 2012 for Salmon Creek Overflow logger (SC0).

Appendix B

Hookton Slough Marsh

Introduction

This study site is comprised of two islands totaling 3.2 hectares (ha) of tidal marsh within Hookton Slough marsh (hereafter referred to as Hookton Slough) and is adjacent to the Salmon Creek Restoration site. This site is fully tidal and connected to Humboldt Bay and is also near the Salmon Creek drainage.

Figure B. Hookton Slough Islands

Results

Elevation surveys

A total of 83 elevation measurements were taken at Hookton Slough in June of 2012 (Fig B-1). The elevation range was 1.31-2.01 m, with a mean of 1.79 m (NAVD88). Overall, Hookton Slough is a low to medium elevation marsh with 68% of the elevation points located above mean high water (MHW; Fig B-2). A 5-m horizontal resolution elevation model was developed in ArcGIS 10 (ESRI, Redlands, Calif.) Spatial Analyst using the kriging method (Fig. B-3). This baseline elevation model was used as the initial state for tidal inundation models.

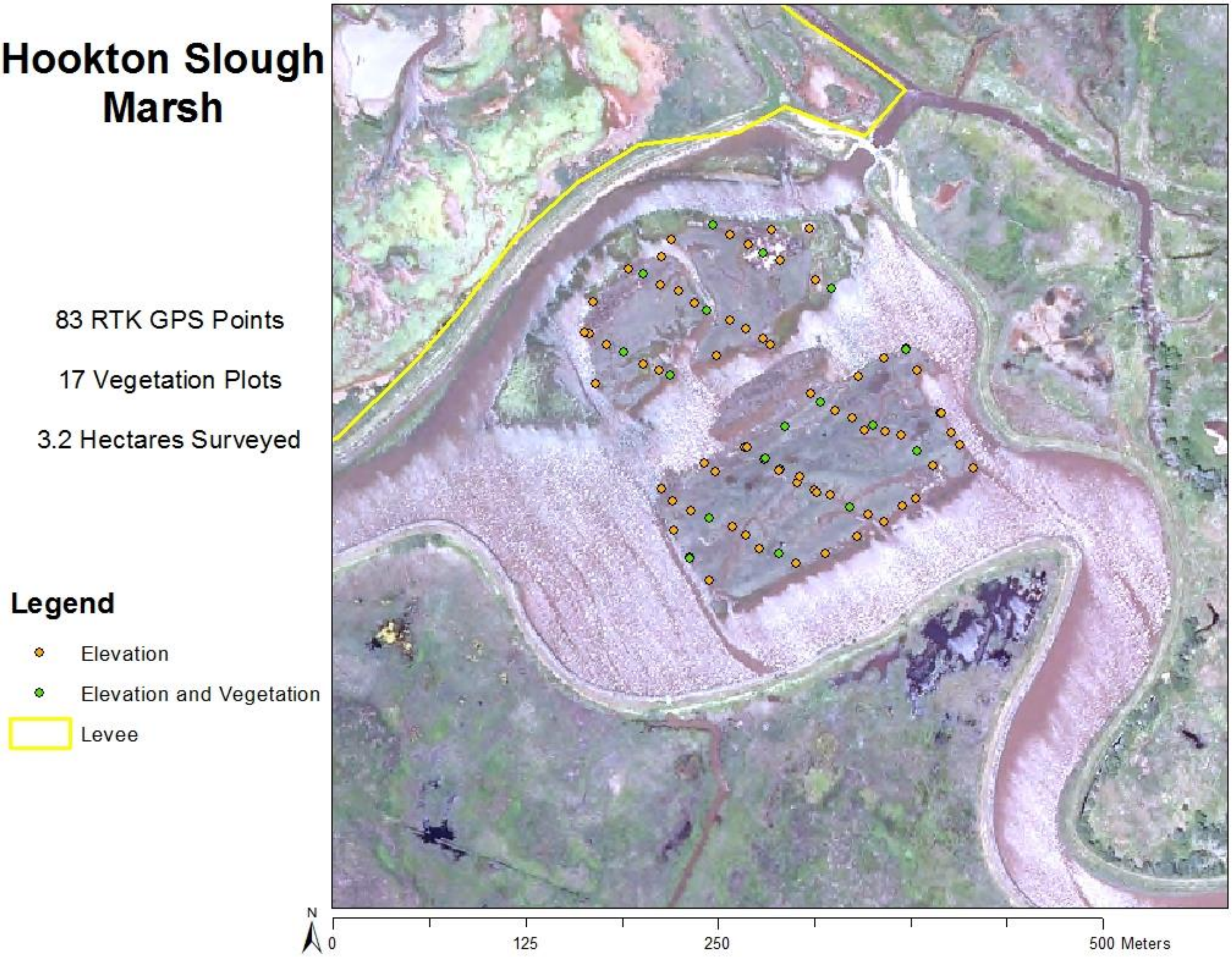

Figure B-1. Hookton Slough with 2012 elevation and vegetation survey points.

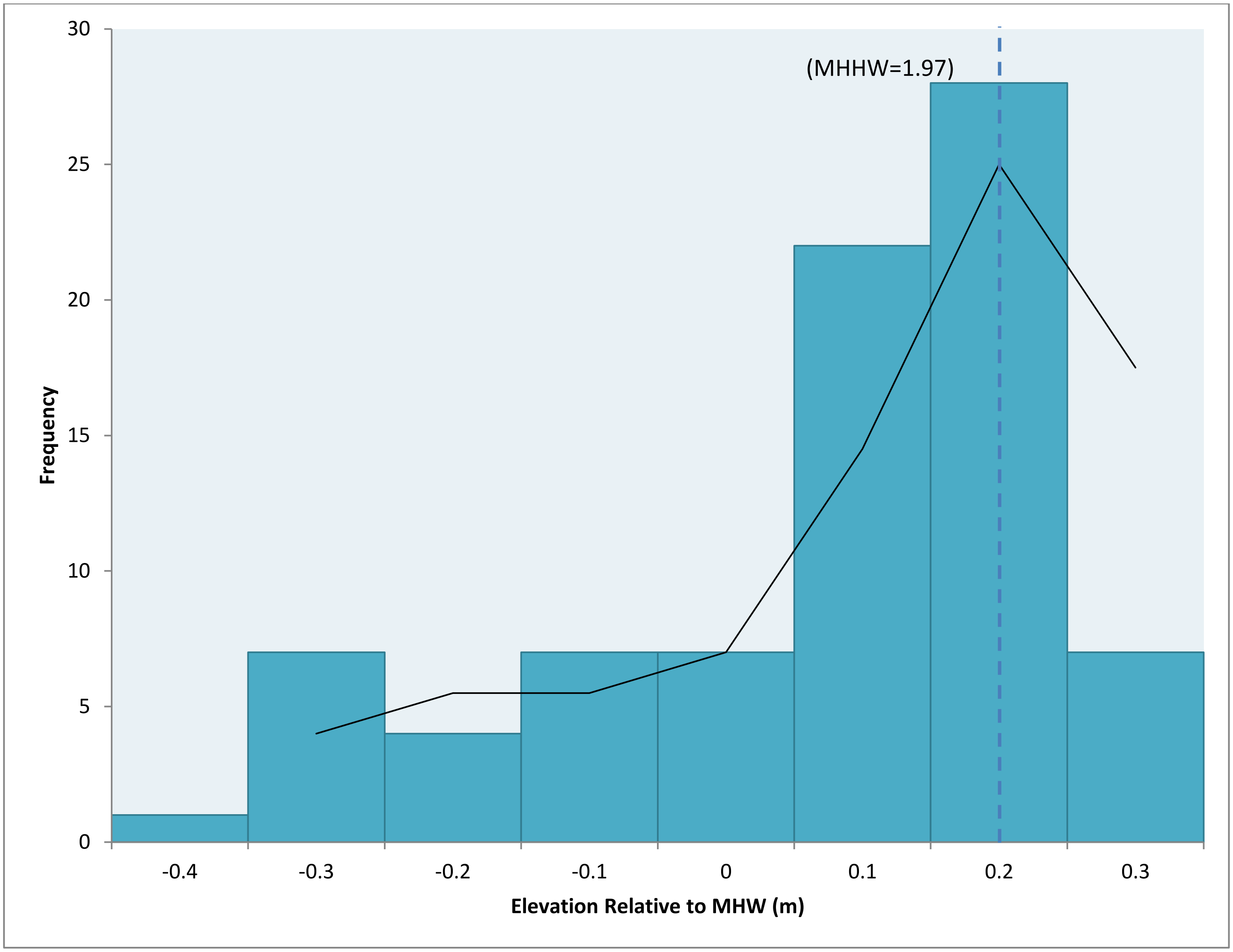

Figure B-2. Frequency distribution of elevation points (n = 83) taken at Hookton Slough Islands relative to mean high water (MHW=1.77), in meters (m). Dotted vertical line indicates MHHW, relative to MHW.

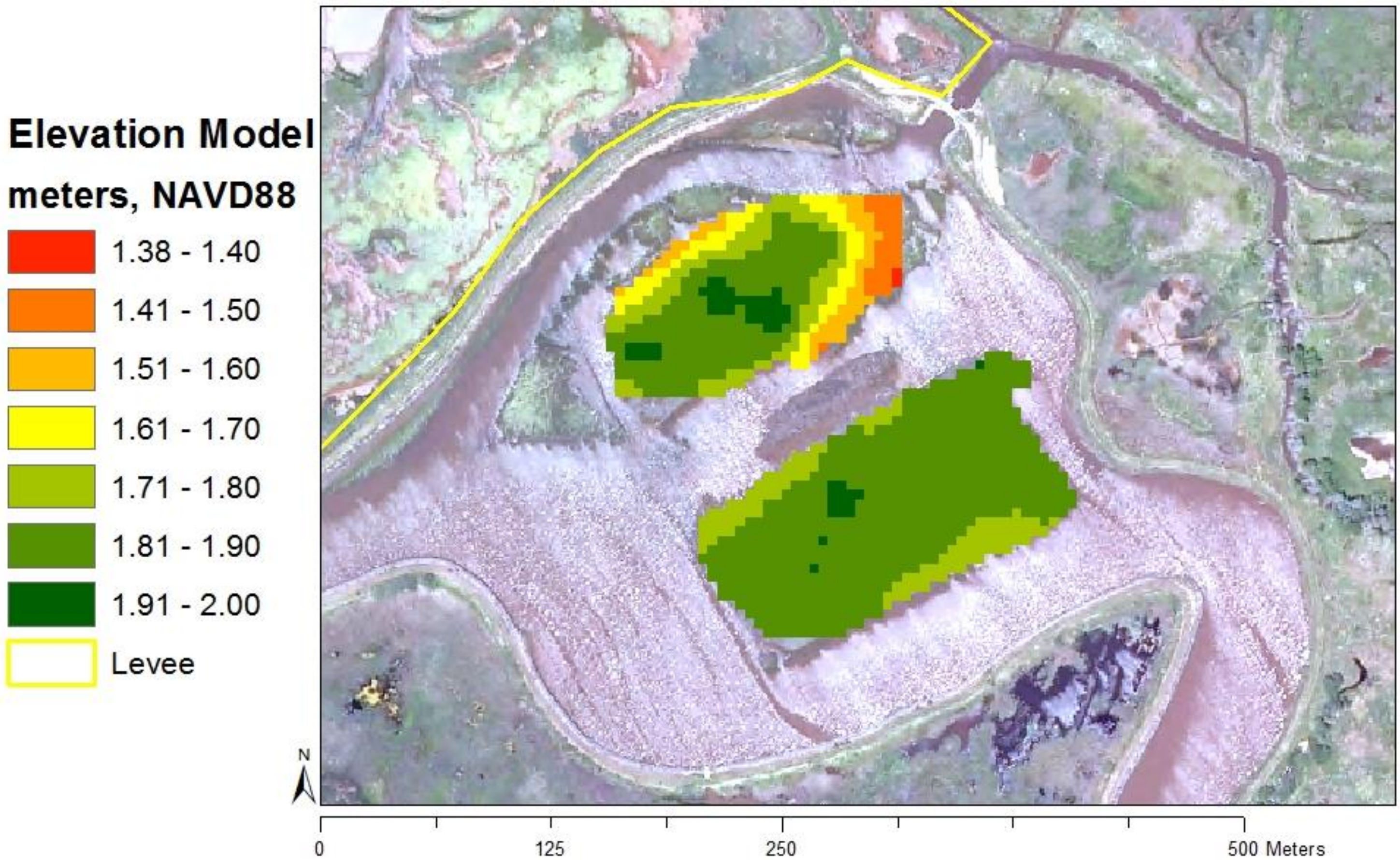

Figure B-3. Elevation model of Hookton Slough Islands (5-m horizontal resolution) developed from ground RTK GPS elevation data. Parameters were optimized to produce minimal root-mean-square (RMS) error.

Vegetation surveys

Vegetation surveys were conducted concurrently with elevation in June 2012. Hookton Slough restoration began in 2010 and included *S. densiflora* removal on the islands. A total of 17 locations (Fig. B-1) were measured for vegetation composition, height (cm), and percent cover (Table B-1, B-2). Hookton Slough was dominated by three species: *S. pacifica* (100% frequency), *D. spicata* (90%), and *J. carnosa* (90%). There were a total of seven detected species.

Table B-1. Marsh plant community characteristics at Hookton Slough marsh in 2012.

[cm, centimeter; n, number of quadrats where species was observed]

Species	Frequency (%)	Mean Height (cm)	Mean Height (SD)	Mean Max Height (cm)	Mean Max Height (SD)	Mean % Cover	Mean % Cover SD	n
S. pacifica	100	14	5	18	5	55	31	10
D. spicata	90	19	3	24	4	63	29	9
J. carnosa	90	8	2	12	2	52	23	9
T. maritima	50	19	5	27	12	41	14	5
P. maritima	20	20	4	23	1	48	25	2
T. concinna	30	15	2	19	1	19	16	3

Table B-2. Presence (n=number of quadrats in which species occurred), mean elevation, minimum elevation, maximum elevation, and elevation range for all species sampled at Salmon Creek marsh relative to MHW (m).

Species	Mean Elevation Relative to MHW (m)	Elevation Relative to MHW (SD)	Minimum Elevation Relative to MHW (m)	Maximum Elevation Relative to MHW (m)	Elevation Range (m)	n
T. concinna	0.00	0.09	-0.09	0.08	0.17	3
S. pacifica	-0.03	0.26	-0.74	0.15	0.90	10
D. spicata	-0.04	0.27	-0.74	0.15	0.90	9
J. carnosa	-0.04	0.27	-0.74	0.15	0.90	9
T. maritima	-0.10	0.37	-0.74	0.15	0.90	5
P. maritima	-0.33	0.58	-0.74	0.08	0.83	2

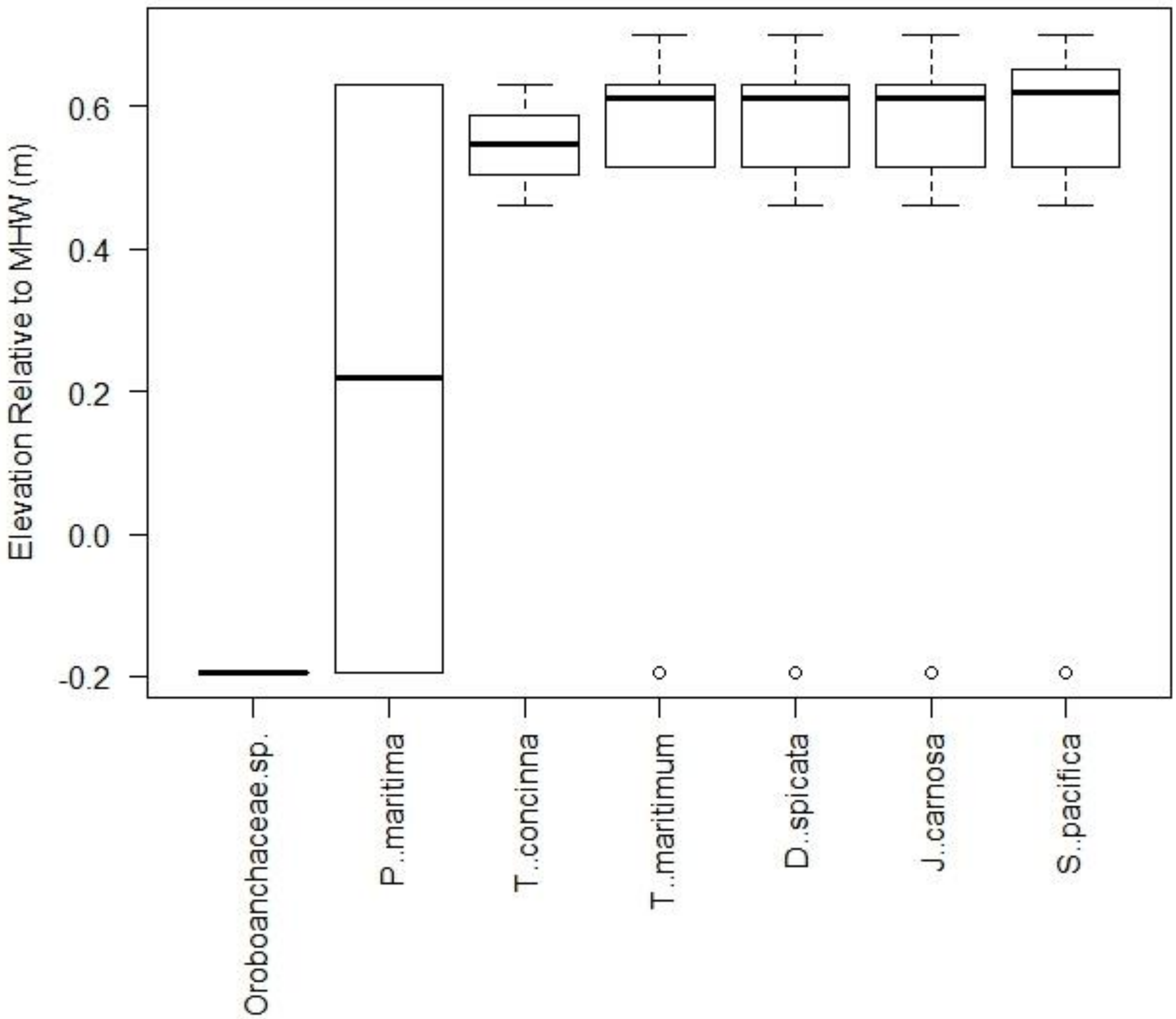

Figure B-4. Elevation of plant species relative to mean high water (MHW), in meters (m), at Hookton Slough Marsh. Median (solid line), 25 and 75 percentiles (box), and 1.5 interquartile range (whiskers).

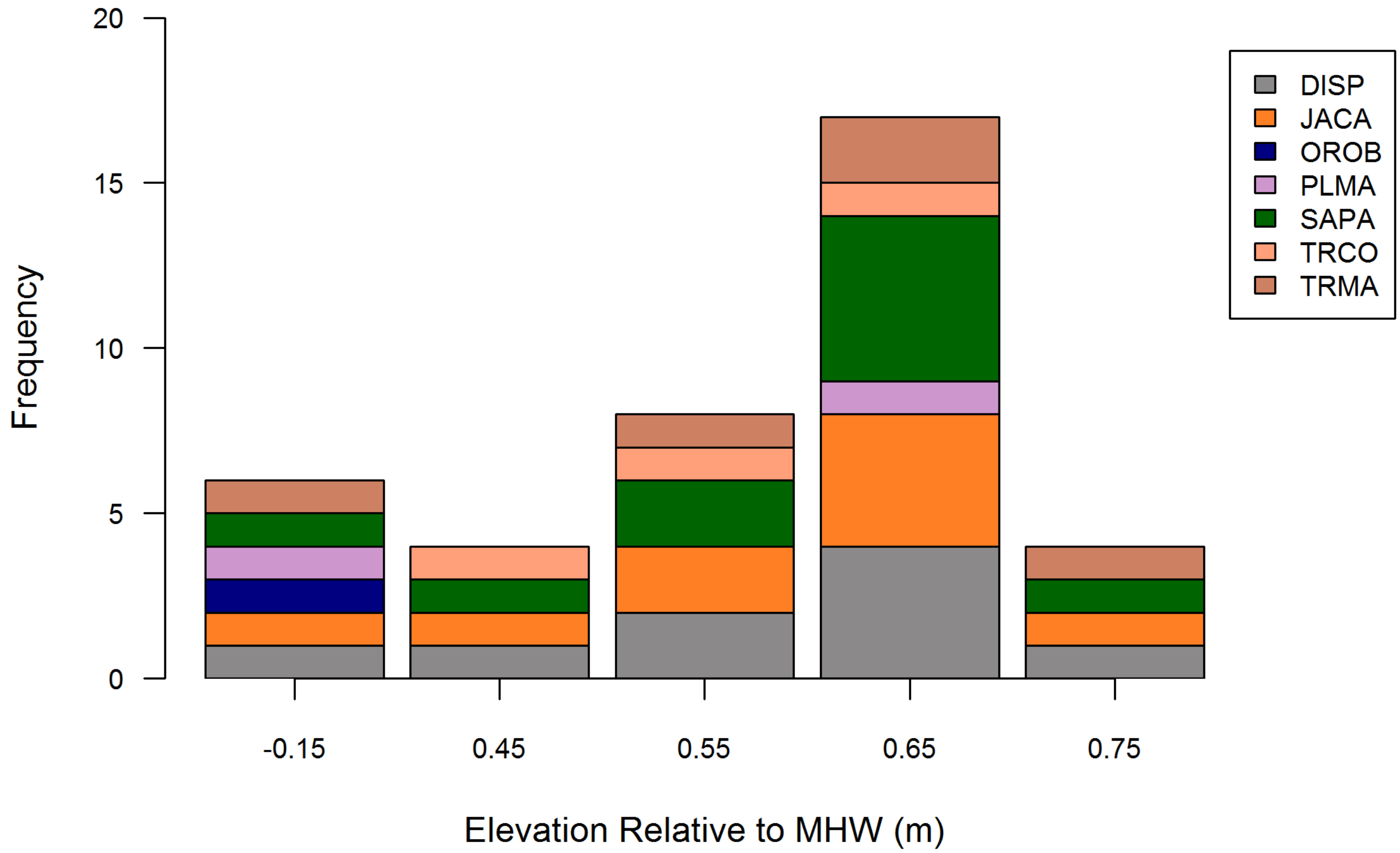

Figure B-5. Distribution of plant species relative to MHW. Species codes are: DISP = *Distichlis spicata*; JACA = *Jaumea carnosa*; OROB = Orobanchaceae; PLMA = *Plantago maritima*; SAPA = *Sarcocornia pacifica*; TRCO = *Triglochin concinna*; TRMA = *Triglochin maritima*.

Water monitoring

Site-specific water levels were monitored by data loggers at two locations in Hookton Slough from May 2012 to present. Loggers were behind the levee, one at the mouth of a first order channel and one in a second order channel on the southern island. We used data from these loggers to develop a local tidal datum. In 2012, mean tide level (MTL) was 1.14 m, mean high water (MHW) was 1.77 m, and mean higher high water (MHHW) was 1.97 m. When looking at tidal inundation, Hookton marsh was the second lowest marsh surveyed in Humboldt Bay with 92% of elevation measurements below MHHW. The salt marsh platform (defined by the mean marsh elevation) was inundated most often during December 2012 due to high amounts of rainfall (Fig. B-6). This site was most affected by rainfall because it is at the drainage of Salmon Creek; we have included a more detailed hydrograph of the logger in the first order channel (Fig. B-7). Based on the tidal data, a tidal datum model was produced (Fig B-8) which gives insight into what portions of the marsh are covered by water during different tidal periods.

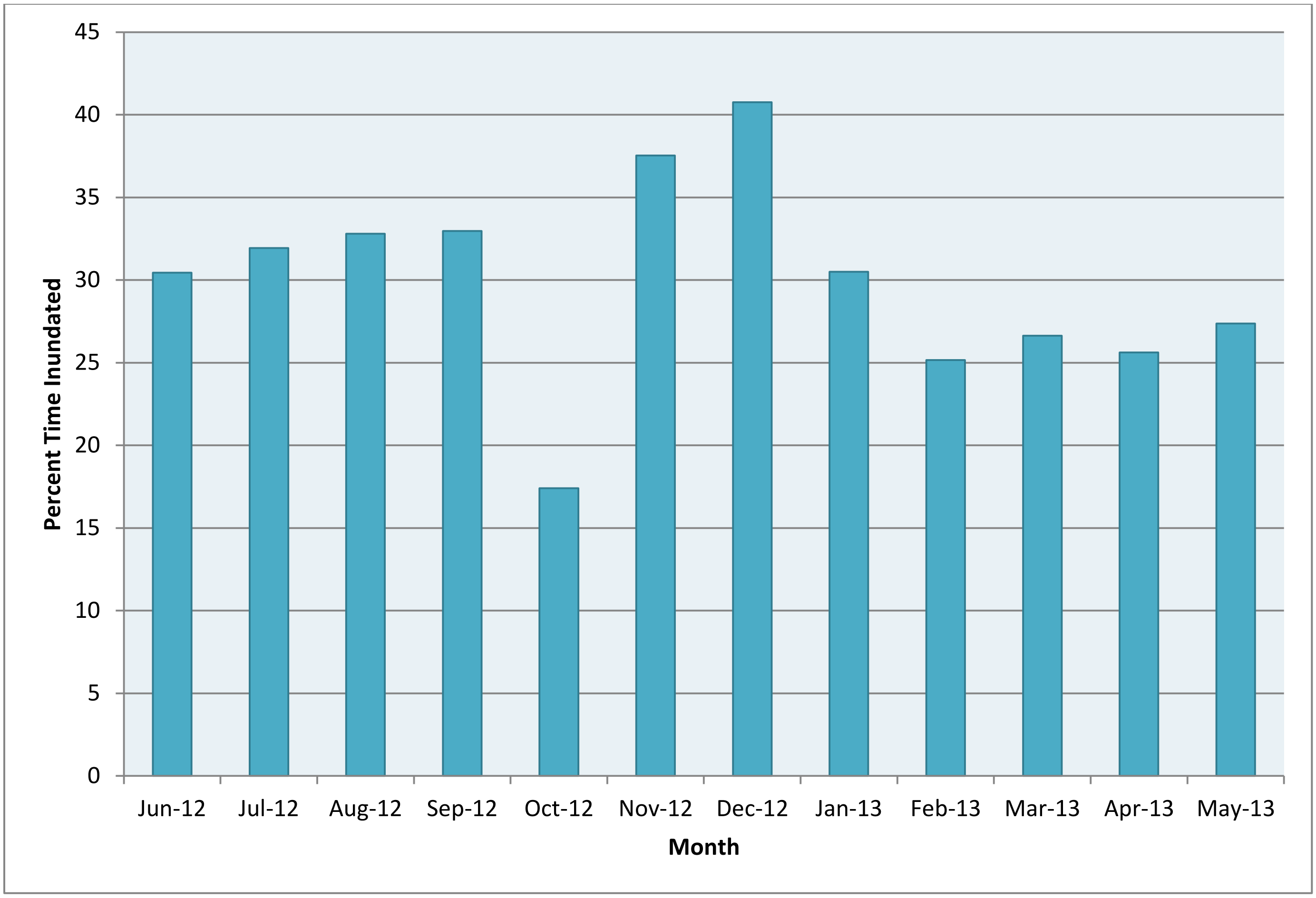

Figure B-6. Percent of time Hookton Slough was inundated monthly based on the mean elevation of the marsh platform.

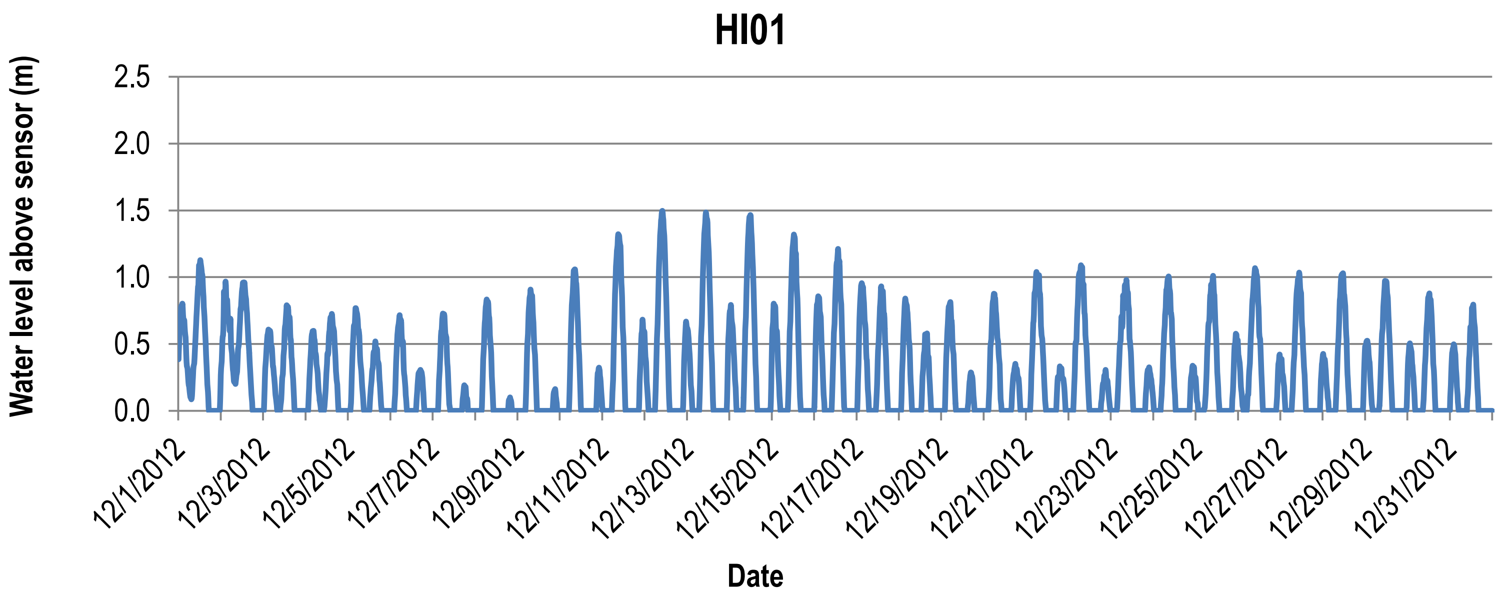

Figure B-7. Water level above water level logger sensor (~ 0.05 m high) in December 2012 for Hookton Island 01.

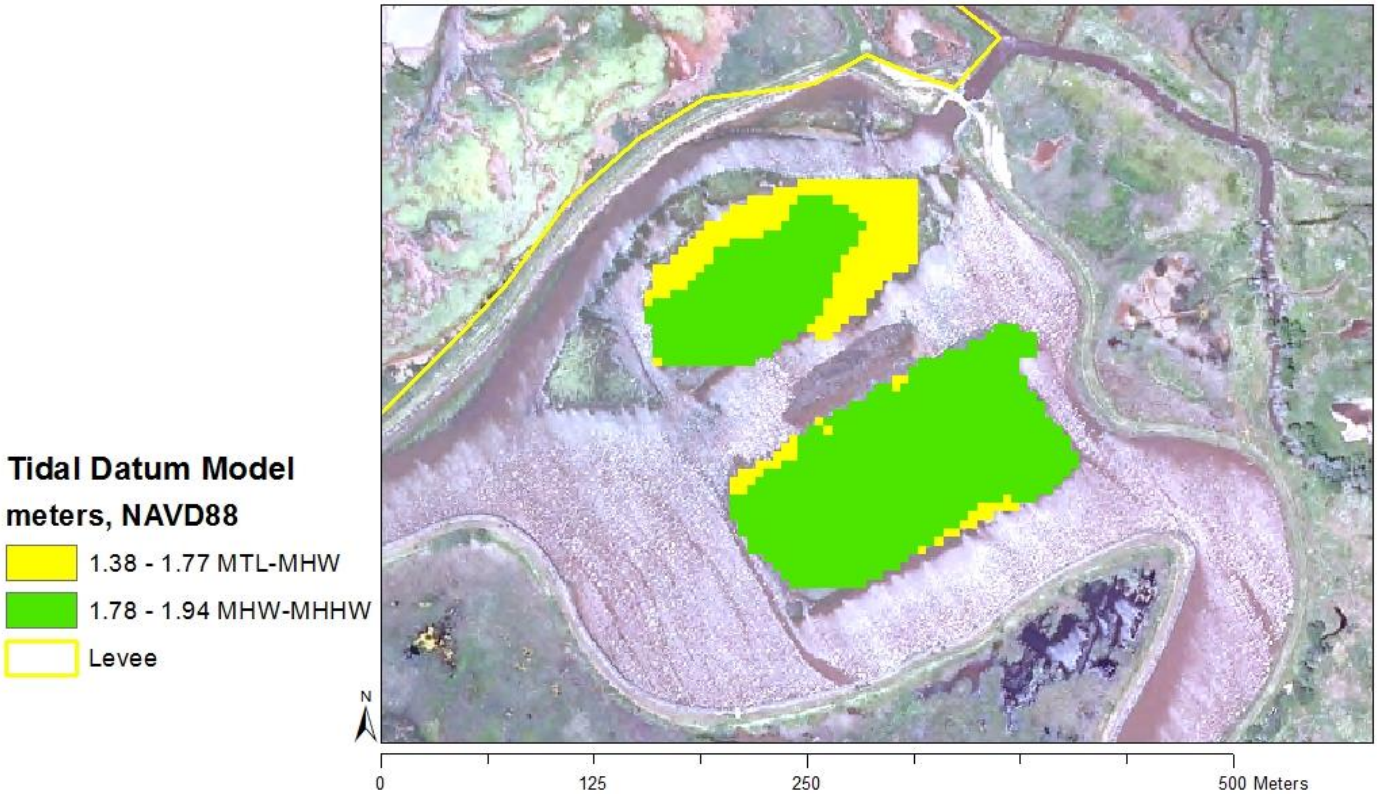

Figure B-8. Tidal inundation model of Hookton Slough marsh based on local tidal data from water loggers.

Appendix C

White Slough Marsh

Introduction

White Slough Marsh (hereafter, White Slough) is a 3.9 hectare (ha) marsh located in southern Humboldt Bay, 2 km north of Hookton Slough (Fig. 1). This is a low elevation marsh that was sparsely vegetated at the time of sampling because of recent *S. densiflora* removal efforts (Fig. C). White Slough is fully tidal and has never been diked.

Figure B. White Slough Marsh June 2012

Results

Elevation surveys

A total of 109 elevation measurements were taken in June 2012 at White Slough (Fig. C-1). The elevation range was 1.52–1.99 meters (m) with a mean of 1.78 m (NAVD88). White Slough had the smallest elevation range of all surveyed sites. Half of all the measured elevations (60%) were above mean high water (MHW; Fig. B-2). A 5-m resolution elevation model was developed in ArcGIS 10 Spatial Analyst using the kriging method (ESRI, Redlands, Calif., Fig. B-3). This baseline elevation model was used as the initial state in tidal datum models.

Figure C-1. White Slough marsh study site with elevation and vegetation survey points in 2012.

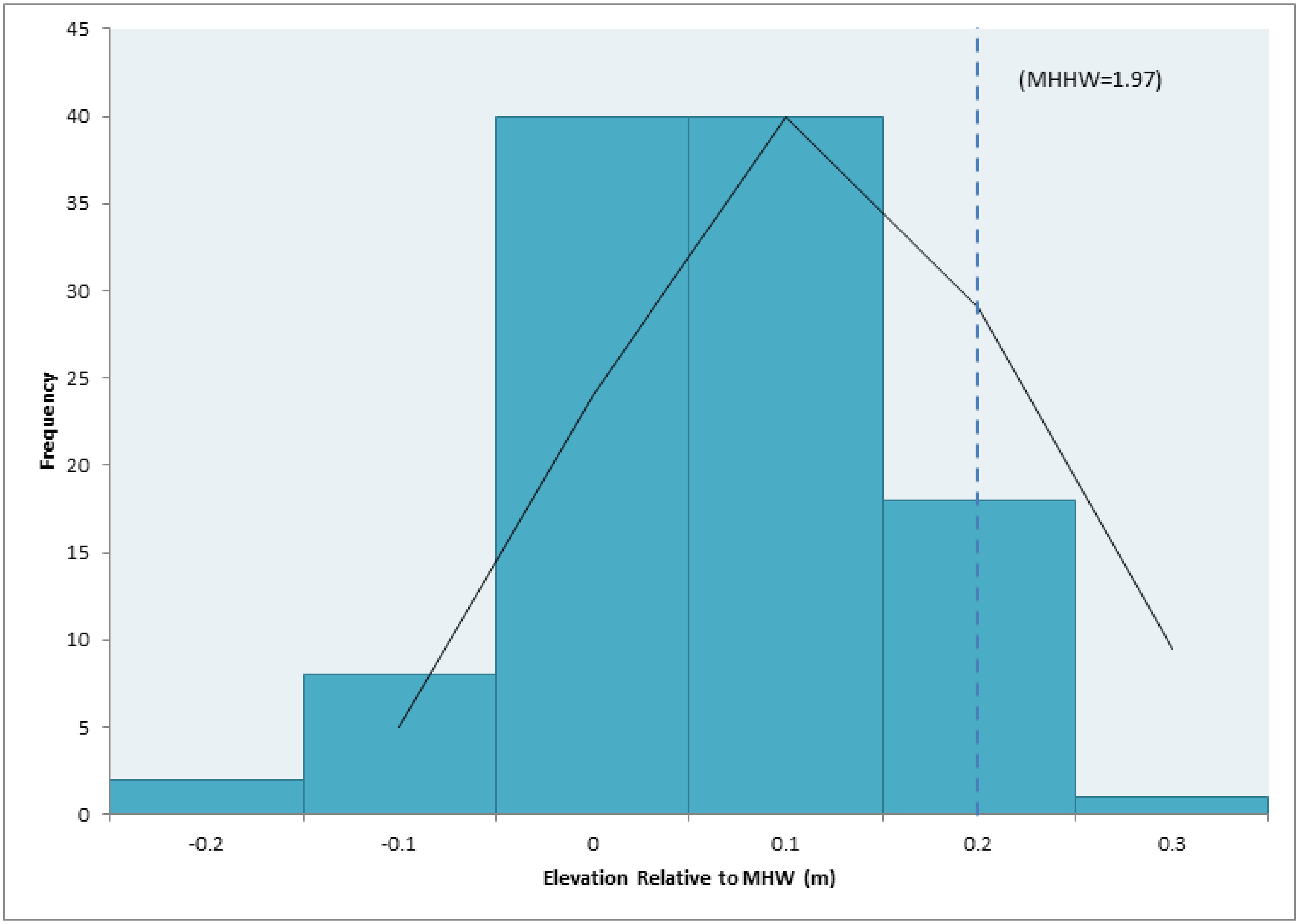

Figure C-2. Frequency distribution of elevation samples (n = 109) taken at White Slough marsh relative to local mean high water (MHW=1.77) in meters (m). Dotted vertical line indicates MHHW, relative to MHW.

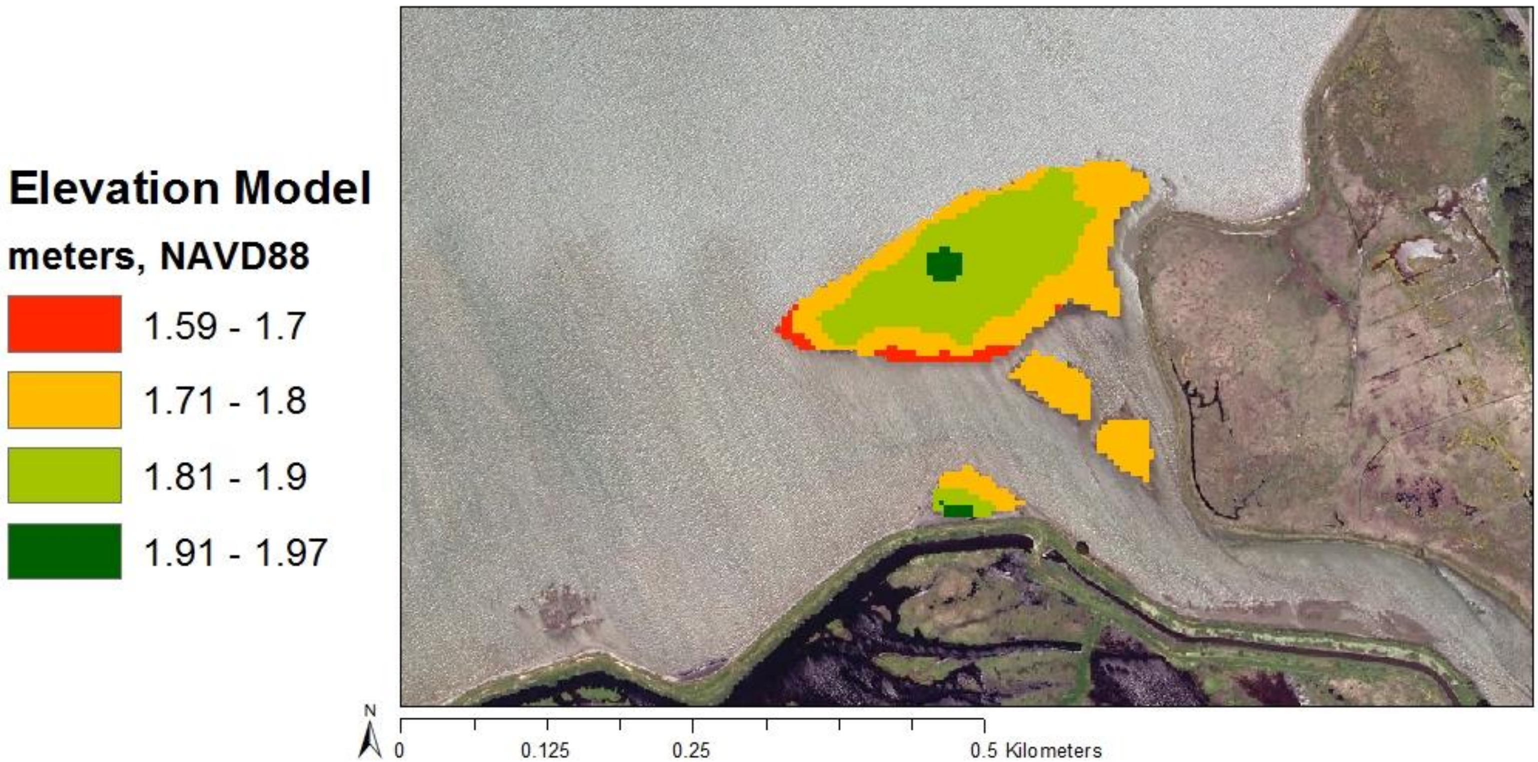

Figure C-3. Elevation model of White Slough (5-meter horizontal resolution) developed from ground RTK GPS elevation data. Parameters were optimized to produce minimal root-mean-square error.

Vegetation surveys

Vegetation and elevation surveys were done concurrently in June 2012. Vegetation at this site was beginning to recover after extensive *S. densiflora* removal in 2010 and 2011, resulting in more exposed bare ground than would be typically present. A total of 25 locations (Fig C-1) were measured for vegetation composition, height (cm), and percentage cover (Table C-1). White Slough was dominated by two species: *S. pacifica* (68% frequency) and *S. densiflora* (32%). This site had the lowest species richness; only 2 species were present, most likely because of the low elevation gradient of the site and vegetation removal efforts. Due to the homogeneity of elevation and plant removal at this site, zonation of vegetation species relative to MHW was not evident (Table C-2; Fig. C-4, 5).

Table C-1. Marsh plant community characteristics at White Slough in 2012.
[cm, centimeter; n, number of quadrats where species was observed]

Species	Frequency (%)	Mean Height (cm)	Mean Height SD	Max Height (cm)	Max Height SD	Mean Cover %	Mean Cover % SD	n
S. pacifica	68	10.3	4.5	15.4	4.6	54.1	30.1	17
D. spicata	32	23.6	7.7	29.5	9.5	13.5	15.2	8

Table C-2. Presence (n = number of quadrats in which species occurred), mean elevation, minimum elevation, maximum elevation, and elevation range for all species sampled at White Slough, relative to MHW (m).

Species code	n	Mean Elevation Relative to MHW (m)	SD Elevation Relative to MHW	Minimum Elevation Relative to MHW (m)	Maximum Elevation Relative to MHW (m)	Elevation Range (m)
Spartina densiflora	8	0.14	0.11	-0.12	0.07	0.19
Sarcocornia pacifica	17	0.13	0.16	-0.19	0.1	0.29

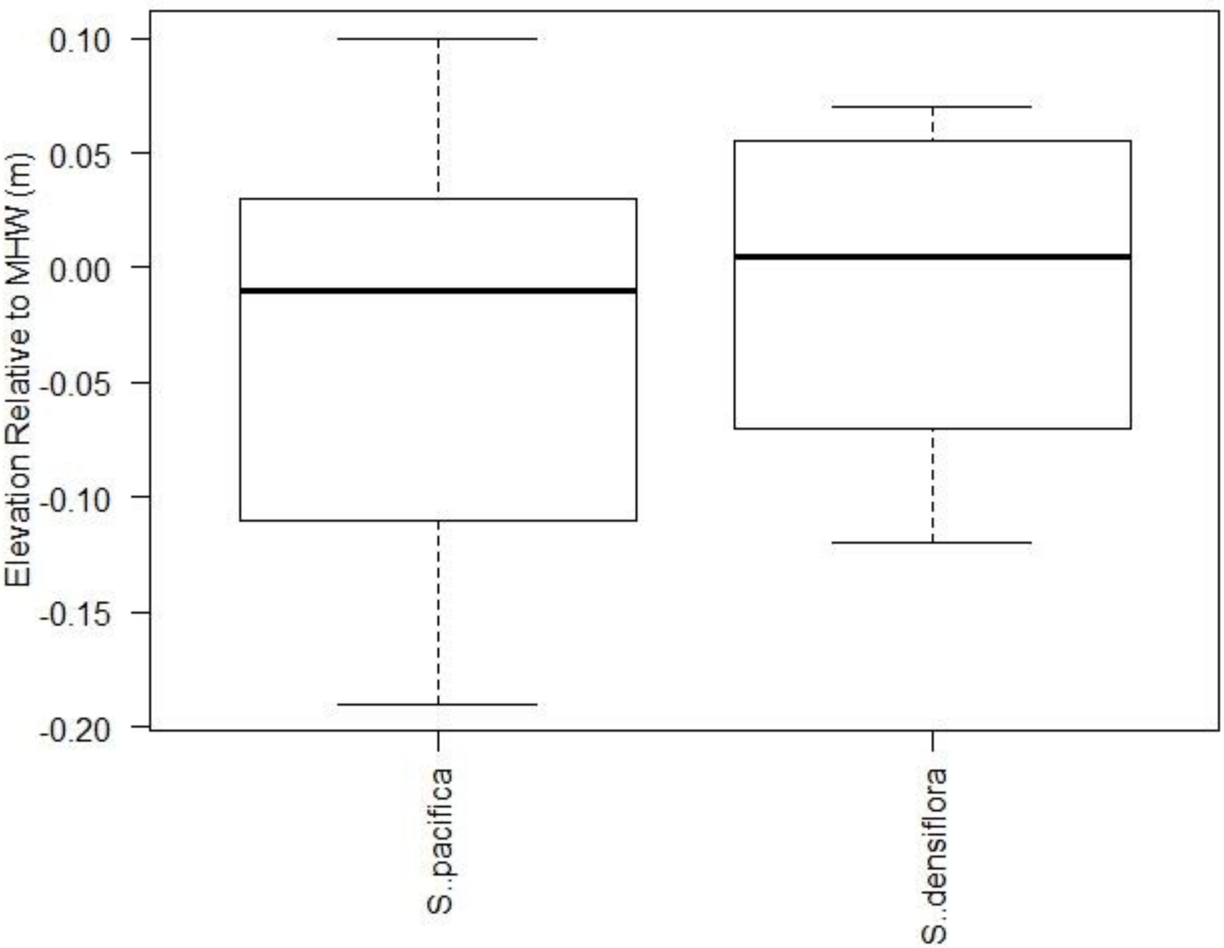

Figure C-4. Elevation of plant species relative to mean high water (MHW), in meters (m), at White Slough Marsh. Median (solid line), 25 and 75 percentiles (box), and 1.5 interquartile range (whiskers).

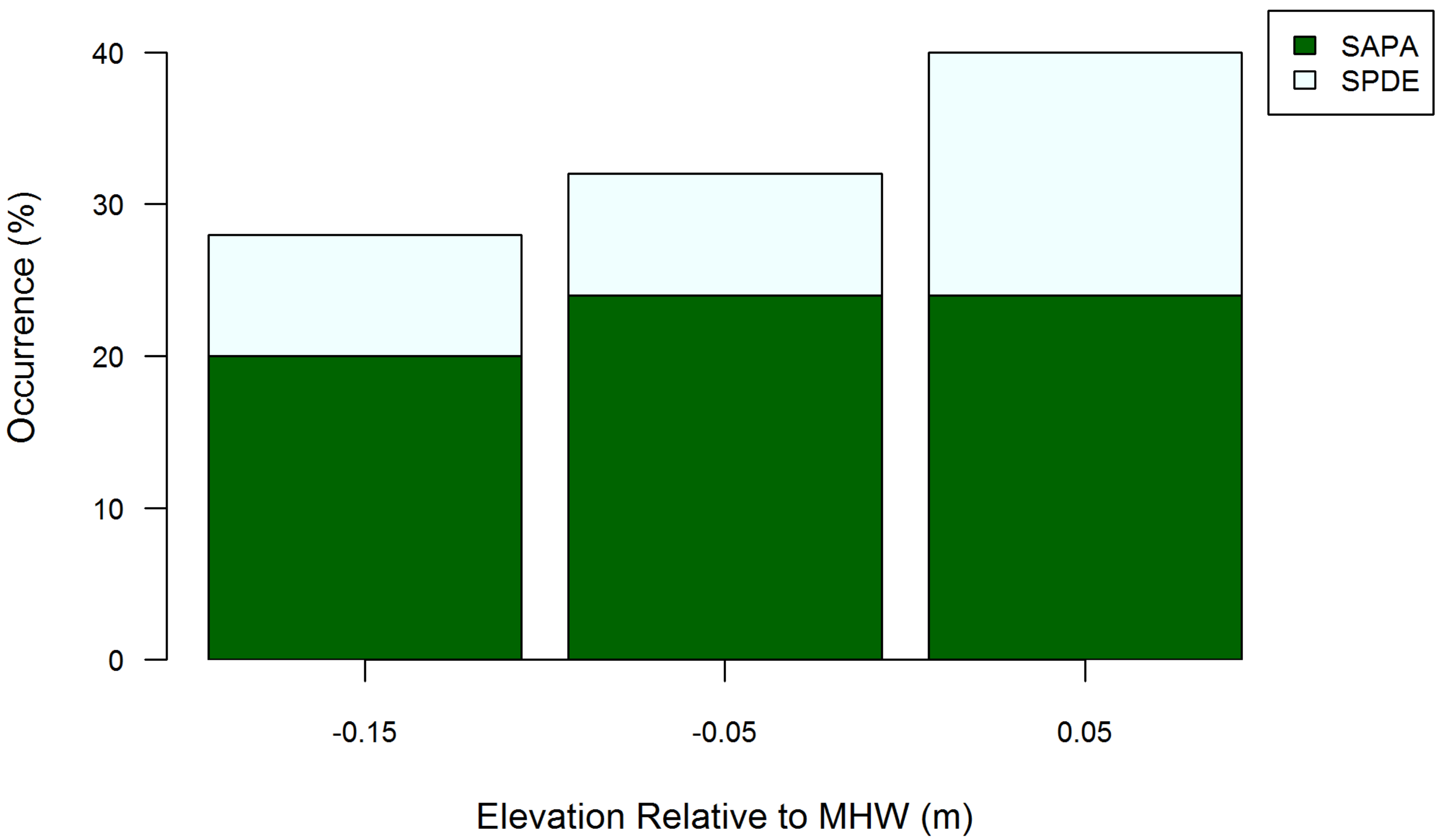

Figure C-5. Frequency distribution of the most common species at White Slough (>10% of the plots) by elevation. Species codes are: SAPA = *Sarcocornia pacifica*; SPDE = *Spartina densiflora*.

Water-level monitoring

Site-specific water level was measured from May 2012 through the present. Water level was measured from nearby (<3 km) Hookton slough marsh. One logger was deployed at the mouth of a primary channel and a second logger was located in the marsh interior. We used data from these loggers to develop a local tidal datum. Mean tide level (MTL) was 1.14 m, mean high water (MHW) was 1.77 m, and mean higher high water (MHHW) was 1.97 m for the site (NAVD88). When looking at tidal inundation, White marsh was the lowest marsh surveyed in Humboldt Bay with only 1% of elevation measurements above MHHW. The salt marsh platform (defined by the mean marsh elevation) was inundated most often during December 2012 due to high amounts of rainfall (Fig. C-6). Based on the tidal data, a tidal datum model was produced (Fig C-7) which gives insight into what portions of the marsh are covered by water during different tidal periods.

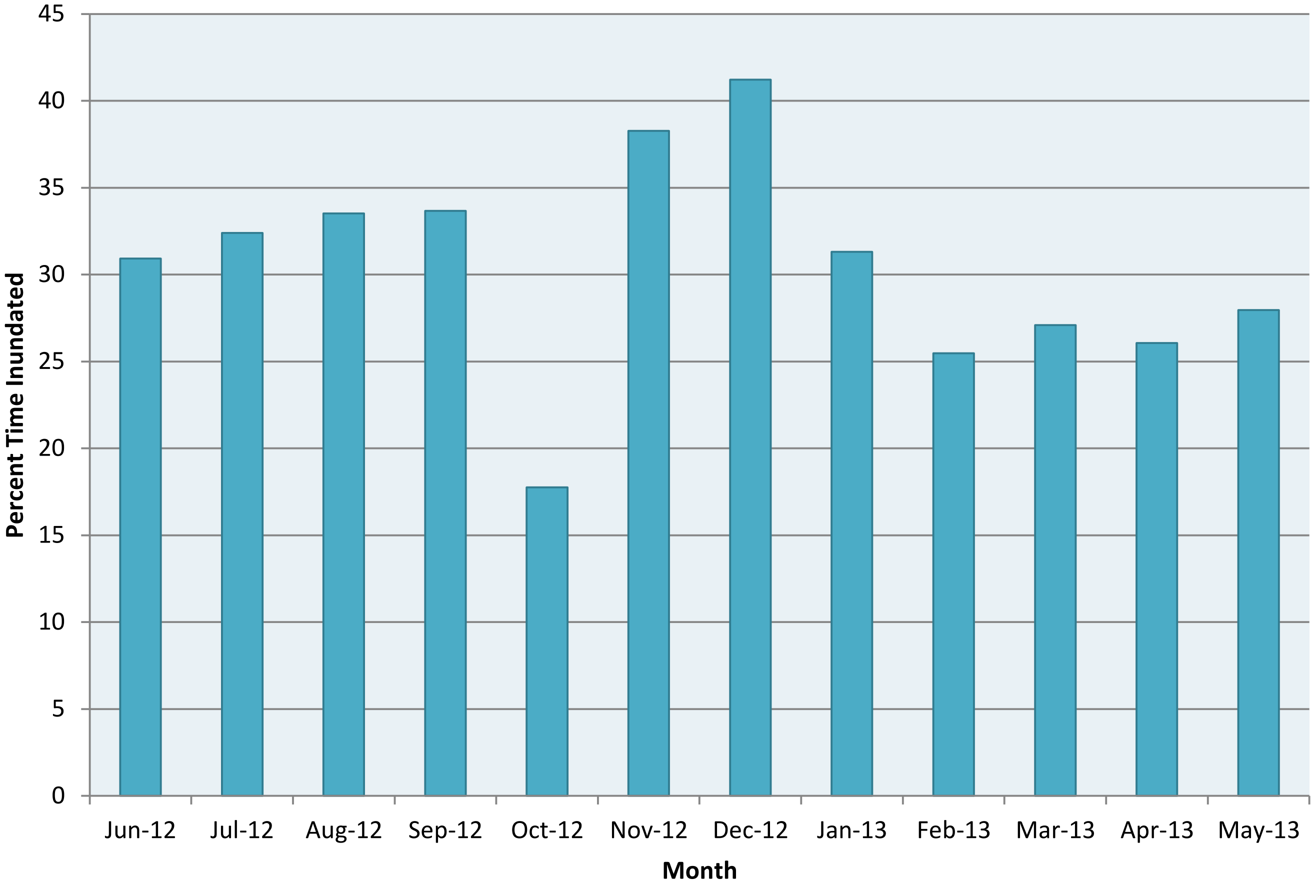

Figure C-6. Percent of time White Slough was inundated monthly, based on the mean elevation of the marsh platform.

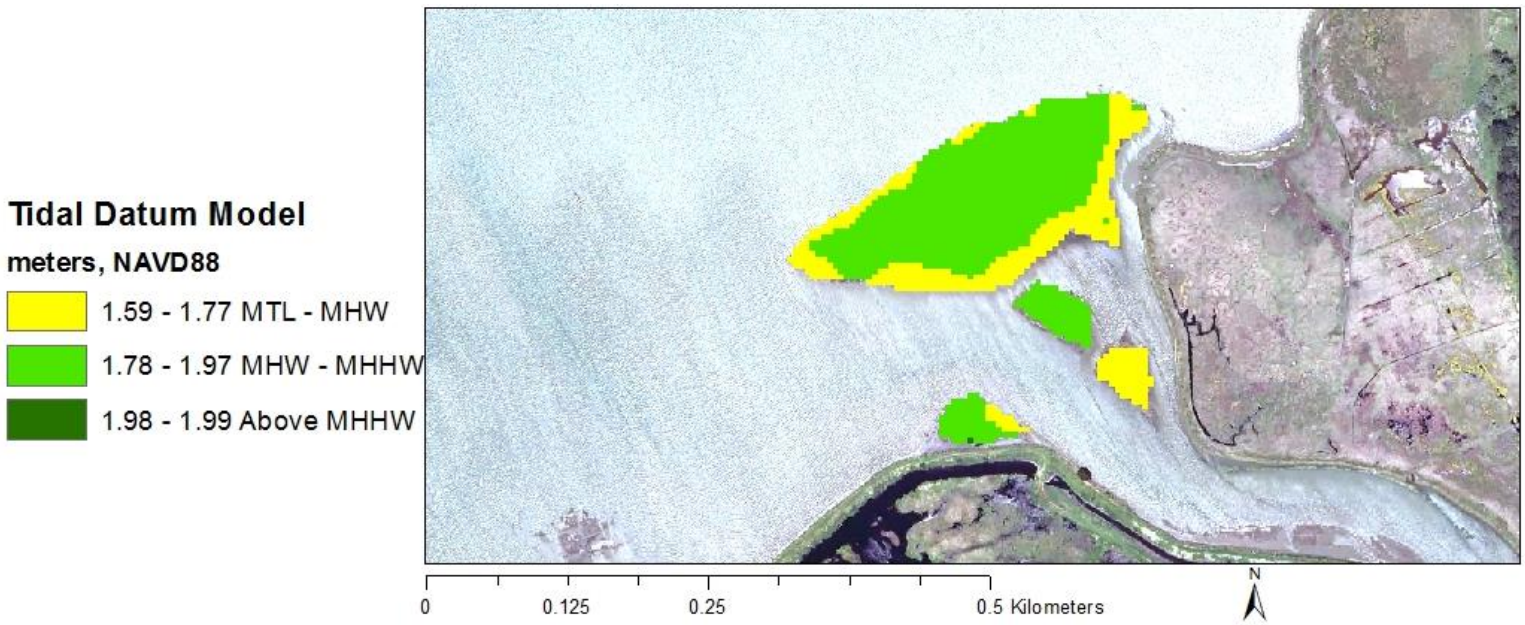

Figure C-7. Tidal inundation model of White Slough marsh based on local tidal data from water loggers.

Appendix D

Eureka Slough Marsh

Introduction

Eureka Slough marsh is a 33.2 hectare (ha) marsh parcel located directly north of the city of Eureka off of U.S. Highway 101. It is surrounded by urban infrastructure, leaving no opportunity for marsh transgression with sea-levels rise. This marsh is tidally influenced and also has freshwater input from Freshwater and Ryan Creeks, which drain into Humboldt Bay at the southwestern edge of the marsh. Eureka Slough marsh is a medium to high elevation marsh that was highly invaded by *S. densiflora* at the time of the survey.

Figure D. Eureka Marsh

Results

Elevation surveys

A total of 686 elevation measurements were taken at the Eureka Slough marsh in May-June 2012 with a RTK GPS (Fig. D-1). The elevation range was 1.18–2.47 m with a mean of 1.96 m

(NAVD88). Over half (70%) of the survey points were within 1.9 m–2.2 m, a 0.3 m range. Eureka Slough marsh was the second highest marsh relative to MHW that was surveyed and exhibited an overall elevation gradient from east (higher) to west (lower). The majority (94%) of survey points were above MHW (Fig. D-2). A 5-m horizontal resolution elevation model was developed in ArcGIS 10 with Spatial Analyst using the kriging method (ESRI, Redlands, Calif., Fig. D-3). This elevation model was used as the initial state for the tidal inundation model.

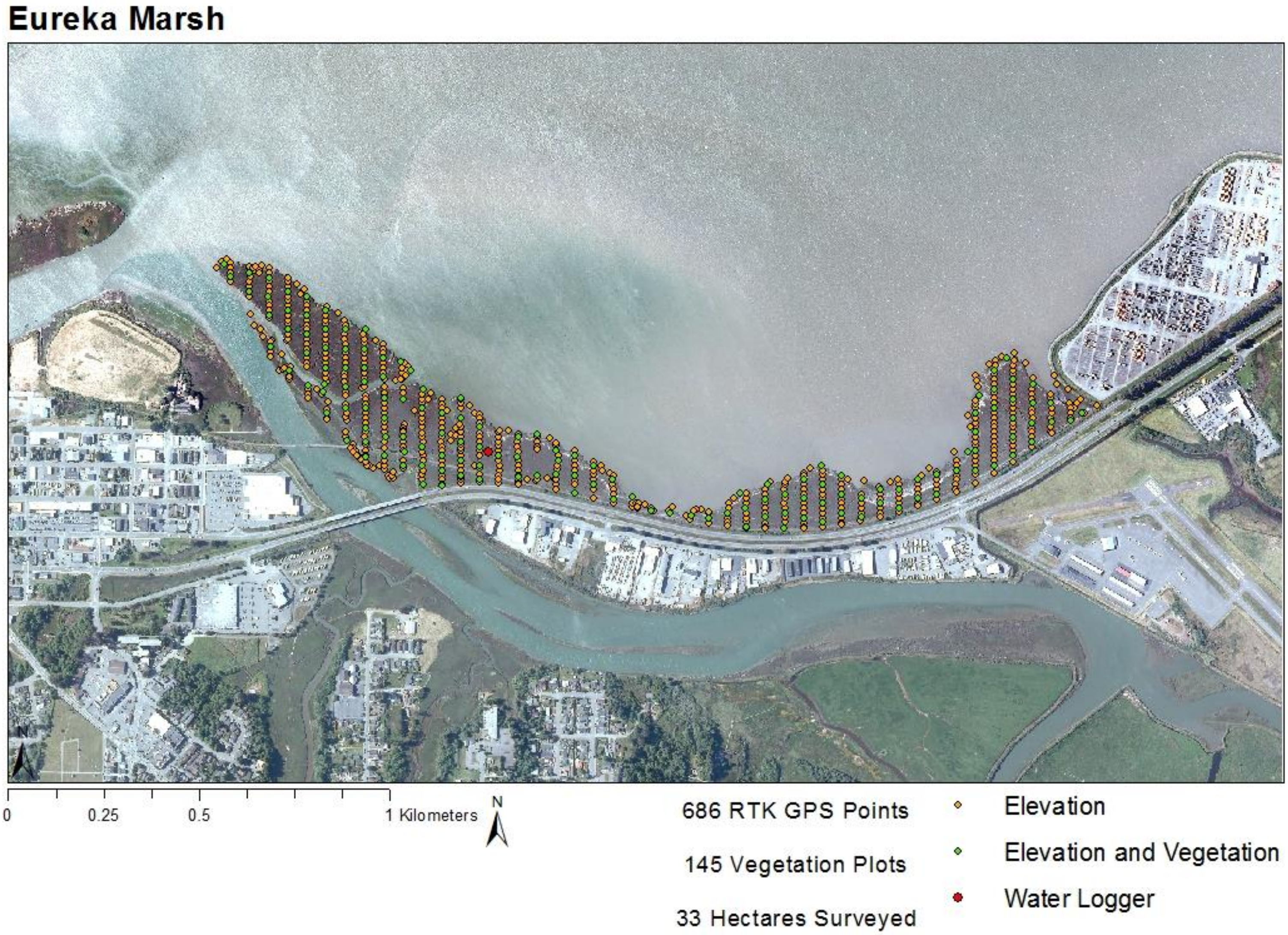

Figure D-1. Eureka Slough marsh with elevation and vegetation survey points and water logger location for 2012.

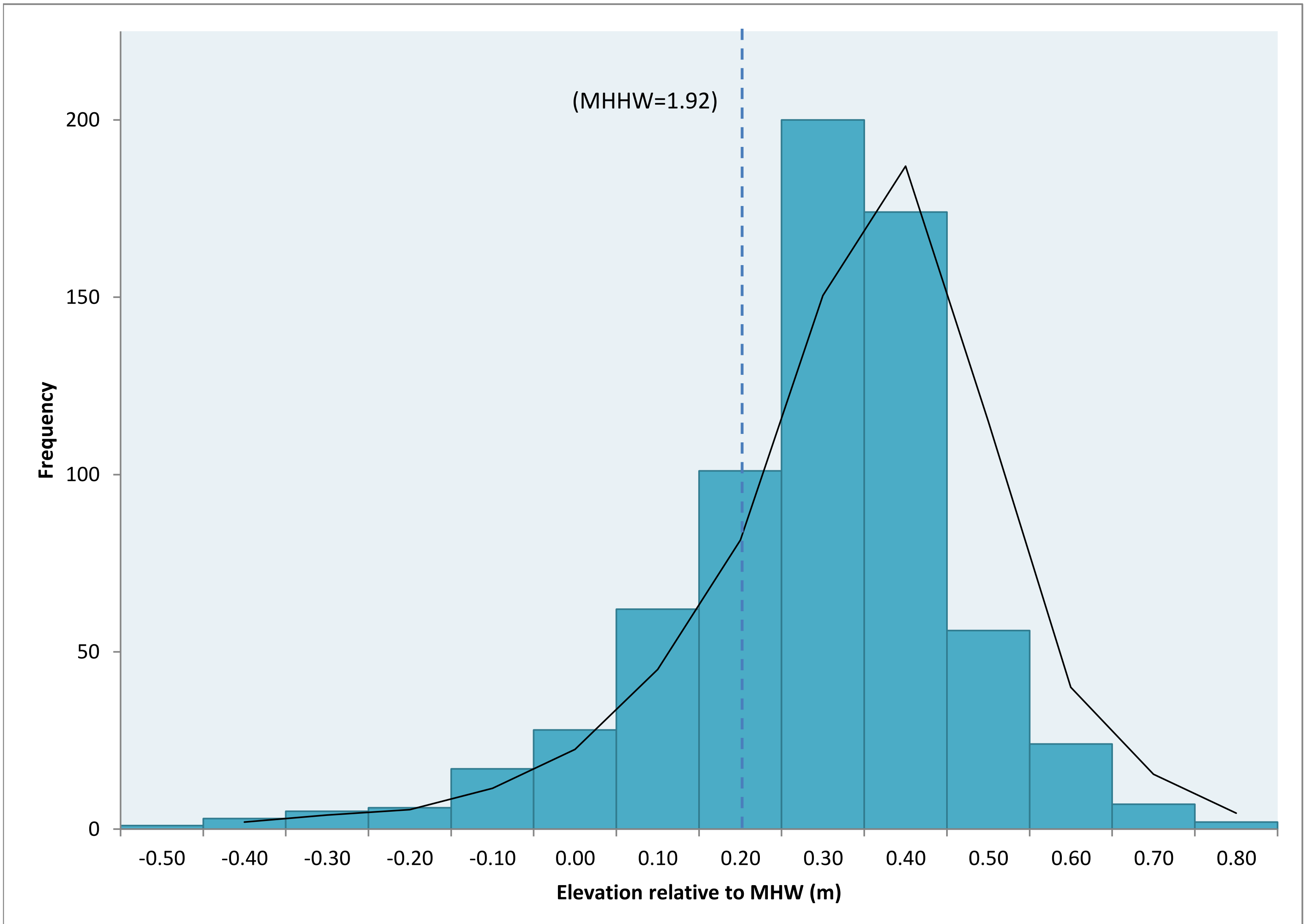

Figure D-2. Frequency distribution of elevation samples (n = 686) taken at Eureka Marsh relative to local mean high water (MHW=1.72) in meters (m). Dotted vertical line indicates MHHW, relative to MHW.

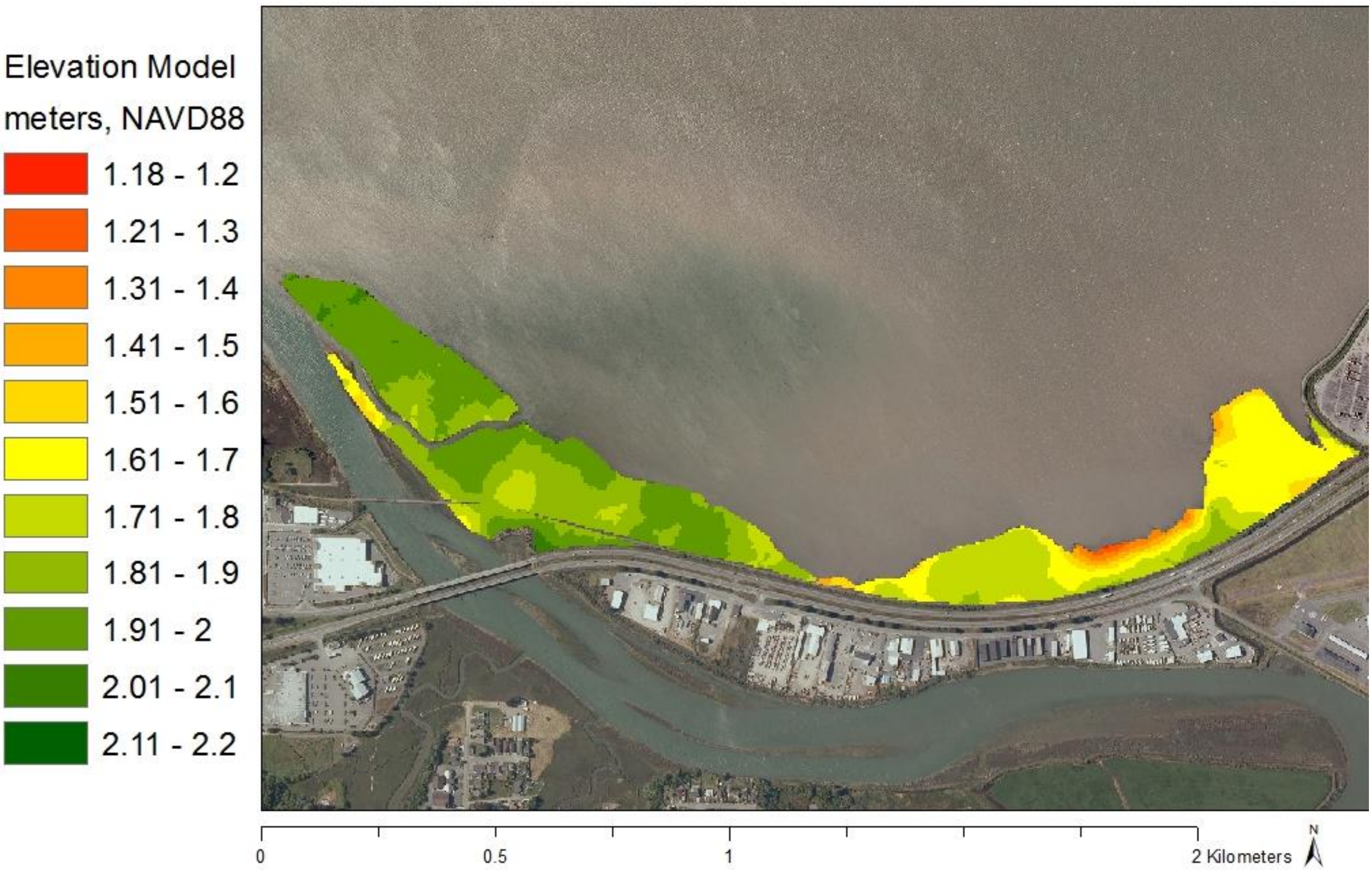

Figure D-3. Elevation model (5-m horizontal resolution) developed from ground RTK GPS data. Parameters were optimized to produce minimal root-mean-square error.

Vegetation surveys

Figure C-4. Marsh master cutting *S. densiflora* at ground level on salt marsh

Vegetation and elevation surveys were done concurrently in June 2012. This marsh was subject to several localized *S. densiflora* removal experiments, including mowing with a marsh master in localized spots in early 2012 before our surveys (Fig. D-4). Since then, efforts have been underway to use a rototiller attachment to more effectively remove *S. densiflora* from this highly infested area. A total of 145 locations (Fig D-1) were measured for vegetation composition, height (cm), and percent cover (Table. D-1). Eureka Slough marsh was dominated by four species: *S. pacifica* (84% frequency), *S. densiflora* (72%), *J. carnosa* (52%), and *D. spicata* (30%). A total of fourteen species of plants were detected in our surveys, including one invasive species (*S. densiflora*). The site had a high presence of well-established *S. densiflora* throughout the marsh platform. The frequency of *S. densiflora* on the Eureka Slough marsh was 72%, whereas its frequency was only 38% across all sites. Vegetation in salt marshes is generally structured by inundation and salinity gradients. In Eureka marsh zonation of vegetation species relative to MHW was observed (Table D-2, Fig. 5, 6).

Table D-1. Marsh plant community characteristics at Eureka Slough in 2012.
[cm: centimeter; n: number of quadrats where species was observed]

Species	Frequency (%)	Mean Height (cm)	Mean Height SD	Max Height (cm)	Max Height SD	Mean % Cover	Mean %Cover SD	n
S. pacifica	84	22	11	28	13	40	30	122
**S. densiflora*	72	48	16	60	18	61	32	104
J. carnosa	52	9	5	12	5	31	27	75
D. spicata	30	20	13	23	10	24	24	43
L. californicum	12	8	3	11	4	11	8	17
Orobanchaceae	9	5	2	7	2	19	22	13
T. concinna	8	10	2	12	2	27	17	11
S. maritimus	6	5	2	7	3	6	4	8
G. stricta	1	42	18	48	20	18	4	2
P. maritima	1	9	-	12	-	10	-	1
A. patula	1	14	-	14	-	1	-	1
A. prostrata	1	13	-	19	-	5	-	1
S. bigelovii	1	4	1	6	2	38	46	2
T. maritima	1	22	6	27	4	15	7	2

*non-native species

Table D-2. Sample number; mean, minimum, and maximum elevation; and elevation range for all species sampled at Eureka Slough marsh relative to MHW (m).

Species	Mean Elevation Relative to MHW (m)	Elevation Relative to MHW (SD)	Minimum Elevation Relative to MHW (m)	Maximum Elevation Relative to MHW (m)	Elevation Range (m)	n
G. stricta	0.60	0.01	0.59	0.60	0.02	2
P. maritima	0.49	-	0.49	0.49	1.46	1
S. bigelovii	0.38	0.04	0.35	0.41	0.06	2
L. californicum	0.36	0.13	0.49	0.49	0	17
S. maritimus	0.36	0.13	0.12	0.54	0.41	8
D. spicata	0.33	0.14	-0.06	0.60	1.83	43
Orobanchaceae	0.33	0.07	0.18	0.41	0.23	13
J. carnosa	0.32	0.13	-0.06	0.60	1.83	75
T. concinna	0.32	0.11	0.12	0.49	0.37	11
T. maritima	0.31	0.18	0.18	0.43	0.25	2
**S. densiflora*	0.28	0.11	-0.01	0.50	1.73	104
S. pacifica	0.27	0.16	-0.29	0.60	1.83	122
A. prostrata	0.74	-	0.74	0.74	0	1
A. patula	0.49	-	0.49	0.49	0	1

* non-native species

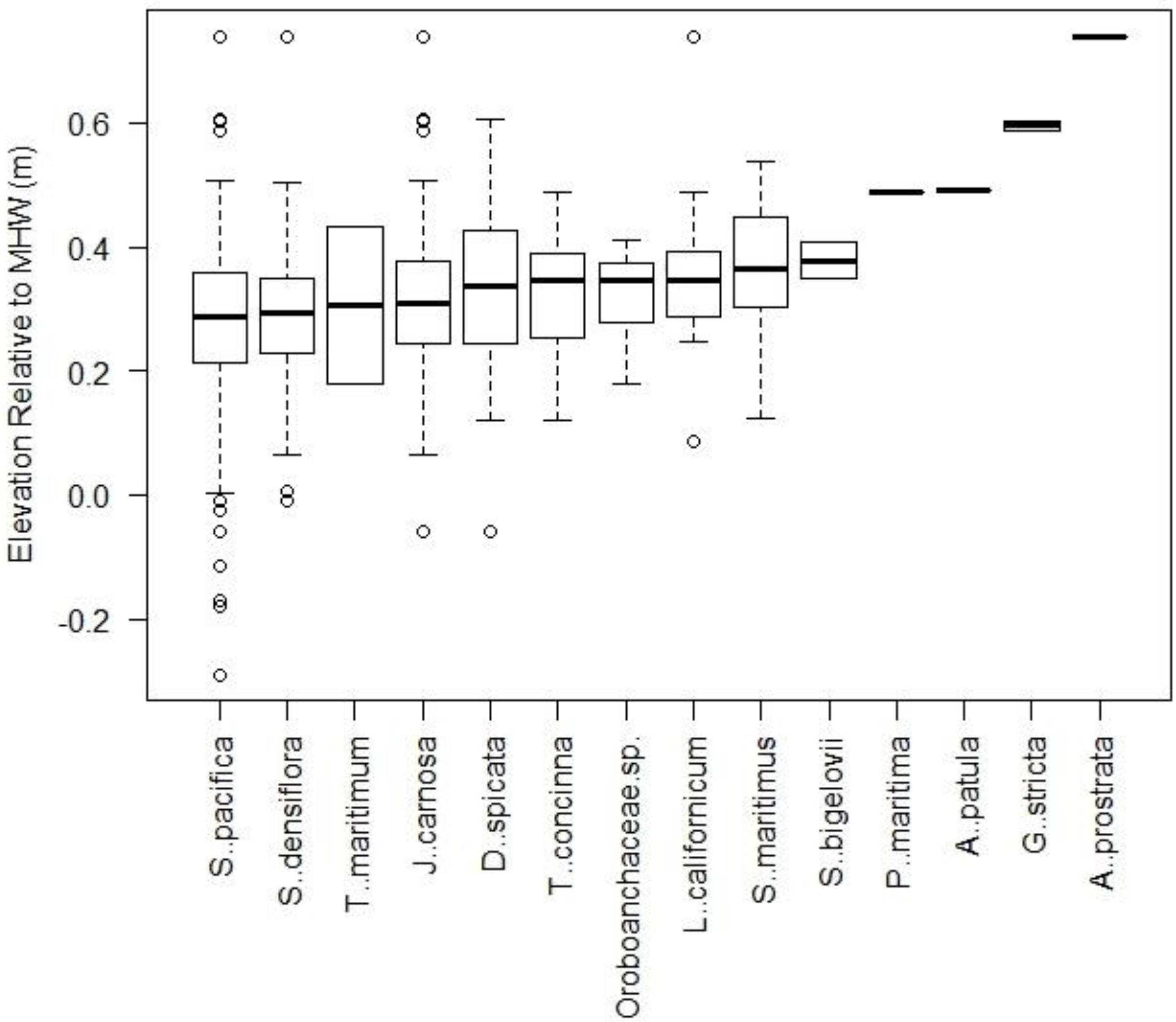

Figure D-5. Elevation of plant species relative to mean high water (MHW) in meters (m). Median (solid line), 25 and 75 percentiles (box), and 1.5 interquartile range (whiskers).

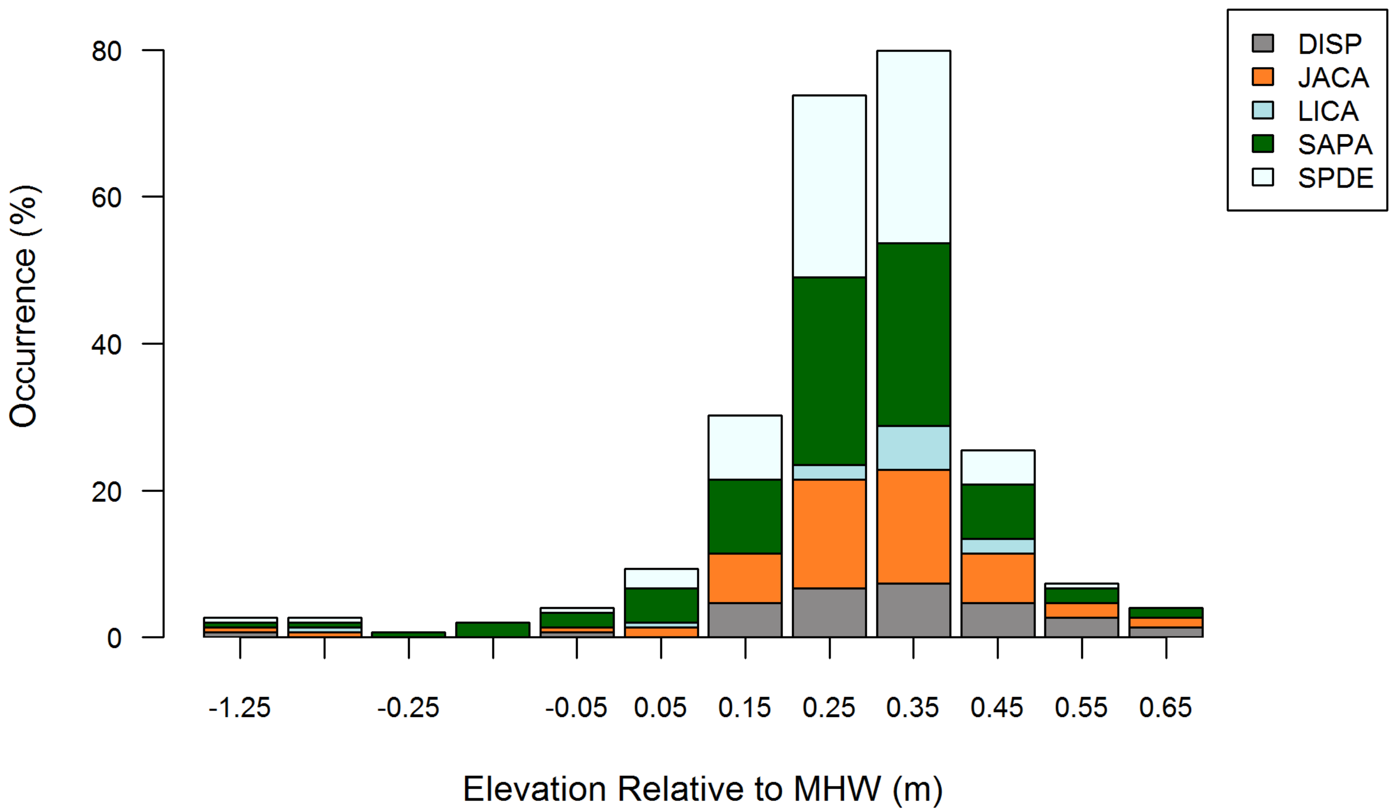

Figure D-6. Percent occurrence of the most common species (>10% of the plots) by elevation. Species codes are: DISP = *Distichlis spicata*; JACA = *Jaumea carnosa*; LICA = *Limonium californicum*; SAPA = *Sarcocornia pacifica*; SPDE = *Spartina densiflora*.

Water-level monitoring

Site-specific water levels were monitored at Eureka Slough marsh for 8 months from June 2012 to January 2013. Water levels were measured by one data logger deployed in a second order channel in the marsh platform (defined by mean marsh elevation). We used data from these loggers to develop a local tidal datum. Mean tide level (MTL) was 0.99 m, mean high water (MHW) was 1.72 m, and mean higher high water (MHHW) was 1.92 m (NAVD88). When looking at tidal inundation, Eureka marsh was the highest marsh surveyed in Humboldt Bay with 91% of elevation measurements above MHHW. The salt marsh platform (defined by the mean marsh elevation) was inundated most often during December 2012 due to large amounts of rainfall (Fig. D-7). 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. A hydrograph was produced from the Eureka water logger for the month of December (Fig. D-9).

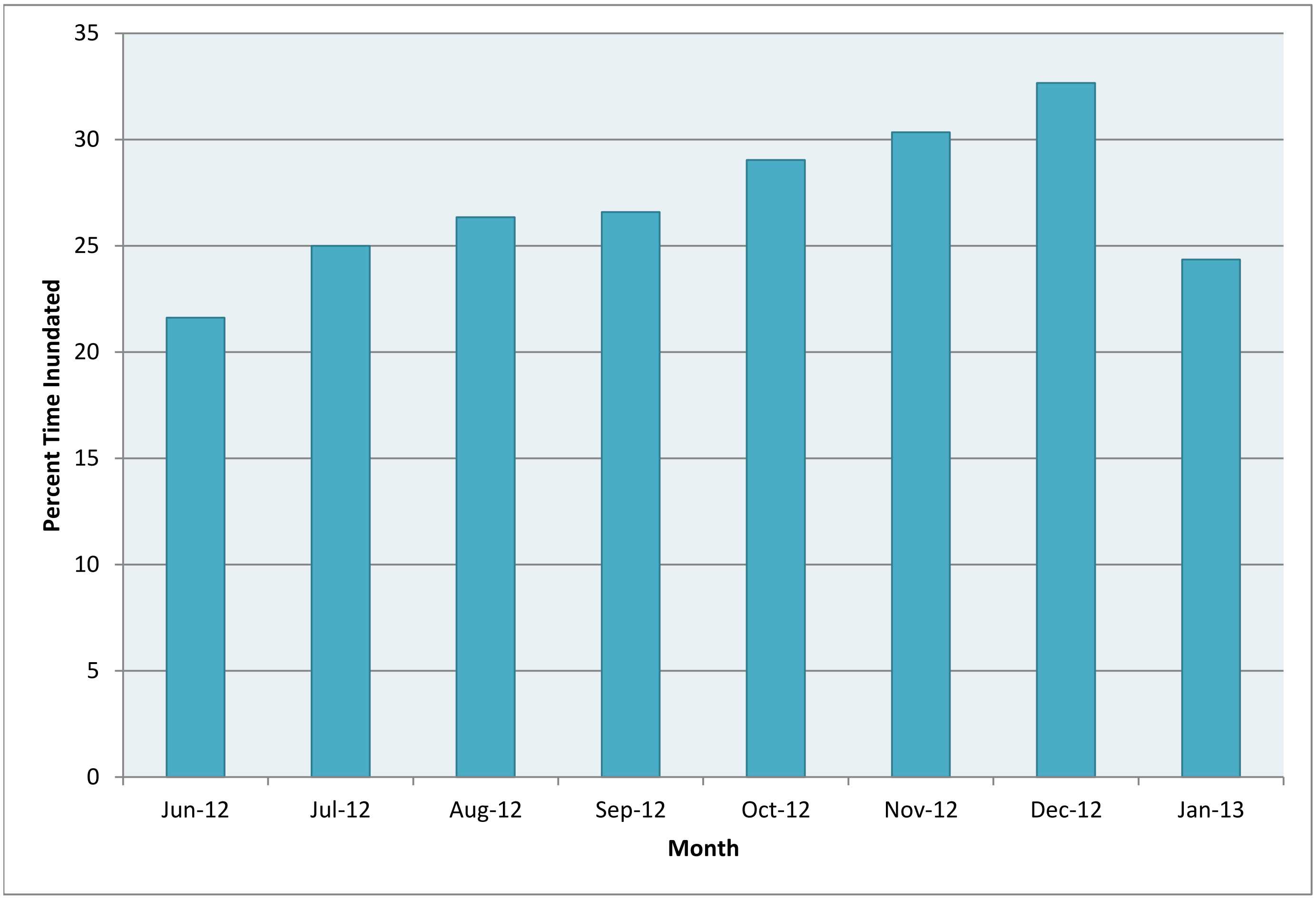

Figure D-7. Percent of time Eureka Slough marsh was inundated monthly, on the basis of the mean elevation of the marsh platform.

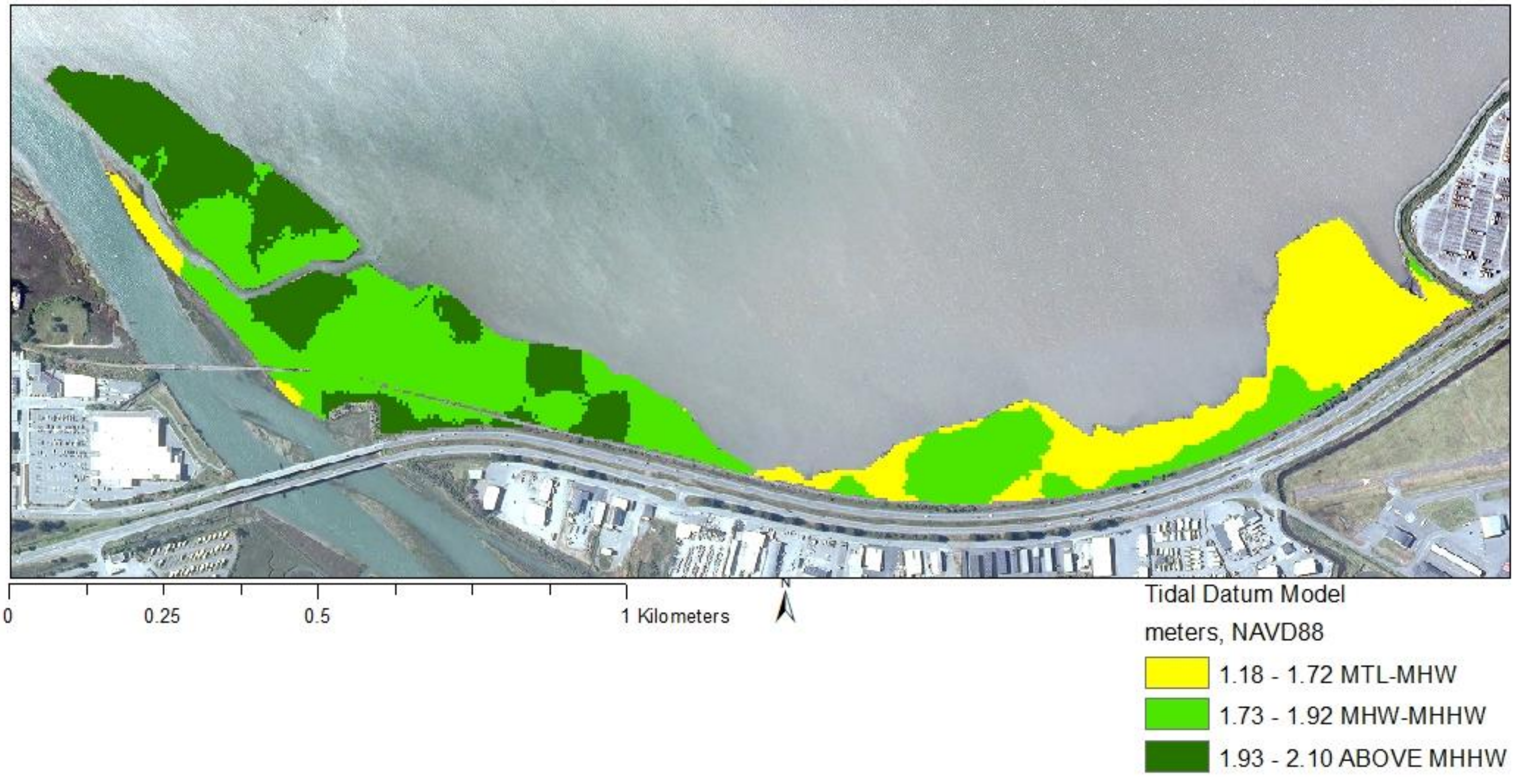

Figure D-8. Tidal inundation model of Eureka Slough marsh based on local tidal data from water loggers.

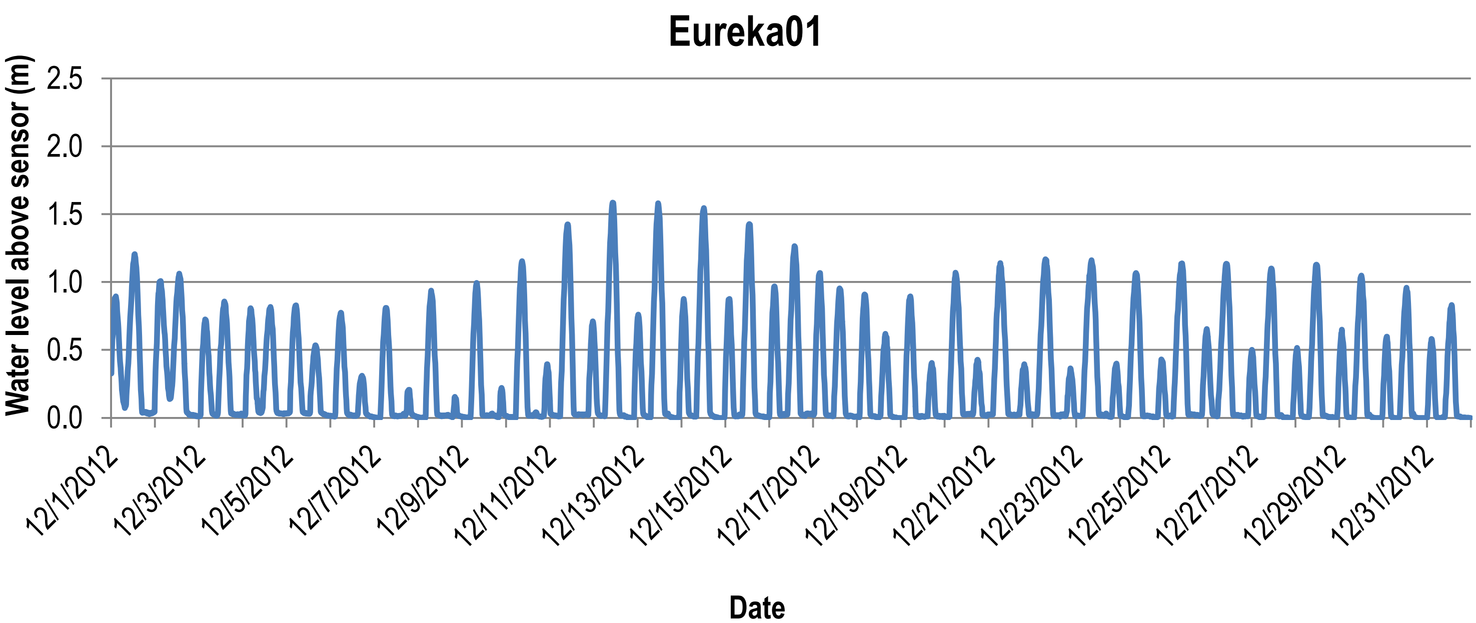

Figure D-9. Water level above sensor (~0.05 m high) in December 2012 for Eureka logger Eureka01.

Appendix E

Jacoby Creek Marsh

Introduction

Jacoby Creek marsh is located in the northeastern portion of Humboldt Bay and is directly west of U.S. Highway 101 (hereafter Hwy 101). This 30.5 hectare (ha) marsh is bordered by Hwy 101 and railroad corridor, which would restrict upslope marsh transgression with sea-level rise. East of Hwy 101 there is a large amount of historic marsh that is currently being used as agricultural wetlands and could potentially transition to tidal marsh if reconnected to the tidal influence and the bay. Jacoby Creek marsh is primarily a high elevation marsh that has tidal influence as well as fresh water input from Jacoby Creek and to a lesser extent Butcher Slough, which split the marsh into three sections at the north end of the study area (Fig. E). A flush of sediment from Jacoby Creek deposited after 1970 expanded the marsh to the west, with *Spartina* quickly colonizing the resulting lower elevation platform.

Figure E. Jacoby Creek surrounded by Jacoby Creek Marsh

Results

Elevation surveys

A total of 558 elevation measurements were taken at Jacoby Creek marsh in late May and early June 2012 using a RTK GPS (Fig. E-1). The elevation range was 1.07–2.64 m with a mean of 2.03 m (NAVD88). The majority (82%) of survey points were located at elevations above mean high water (MHW; Fig. E-2). A 5-m horizontal resolution elevation model was developed in ArcGIS 10 Spatial Analyst using the kriging method (ESRI, Redlands, Calif., Fig. E-3). This baseline elevation model was used as the initial state for the tidal inundation model.

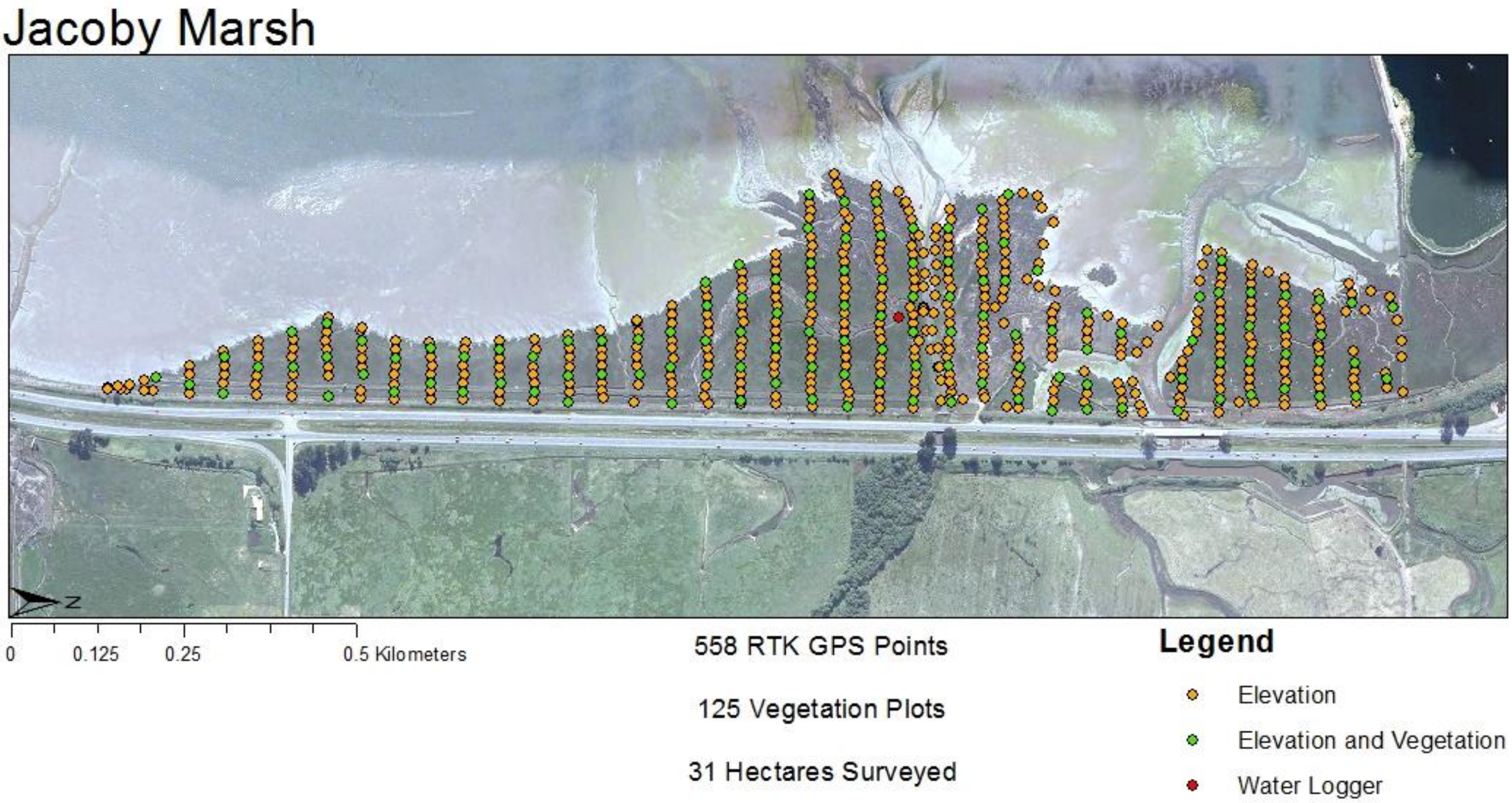

Figure E-1. Jacoby Creek Marsh with 2012 elevation and vegetation survey points and water logger locations.

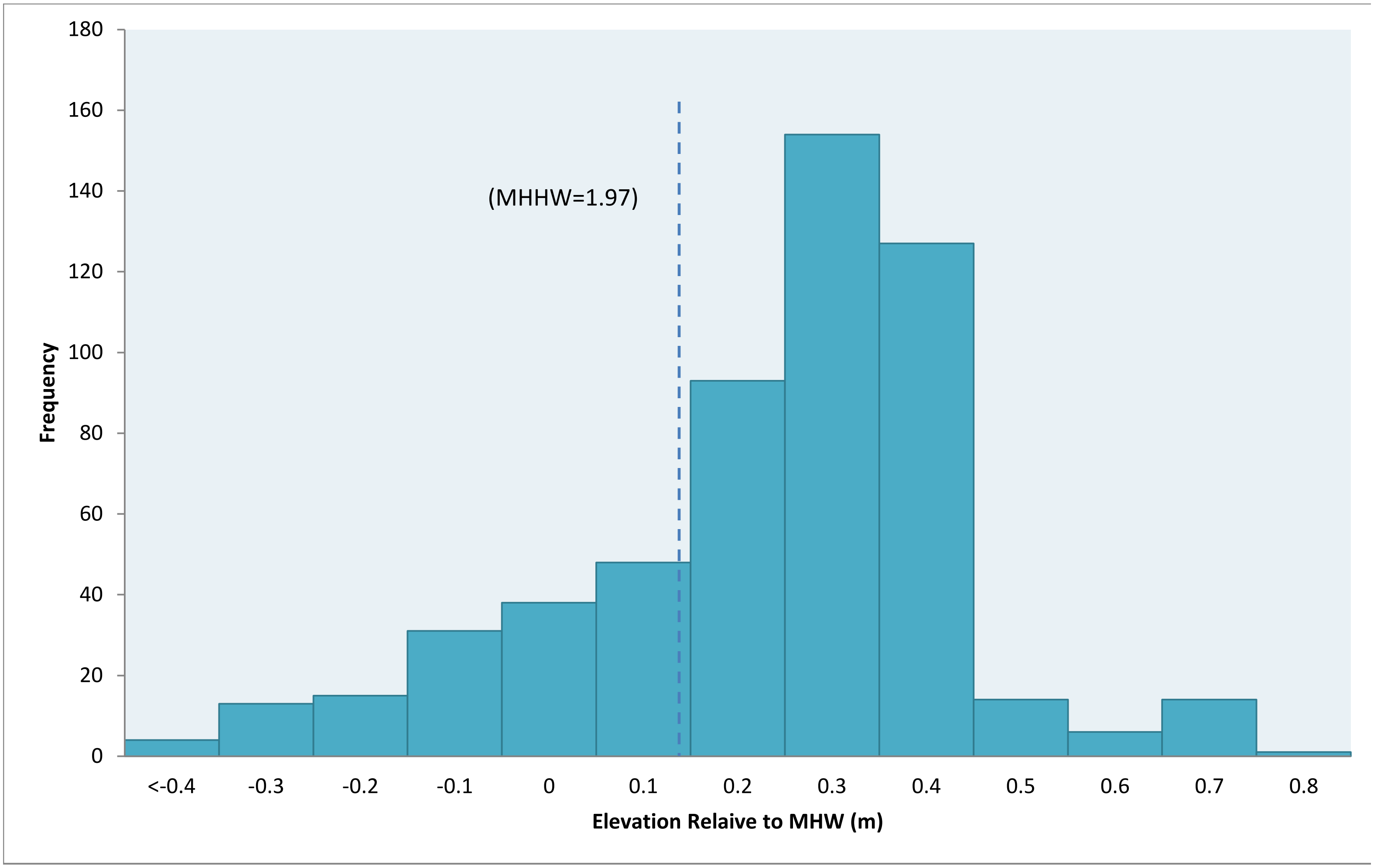

Figure E-2. Frequency distribution of elevation points (n = 585) relative to local mean high water (MHW=1.85), in meters (m). Dotted vertical line indicates MHHW, relative to MHW.

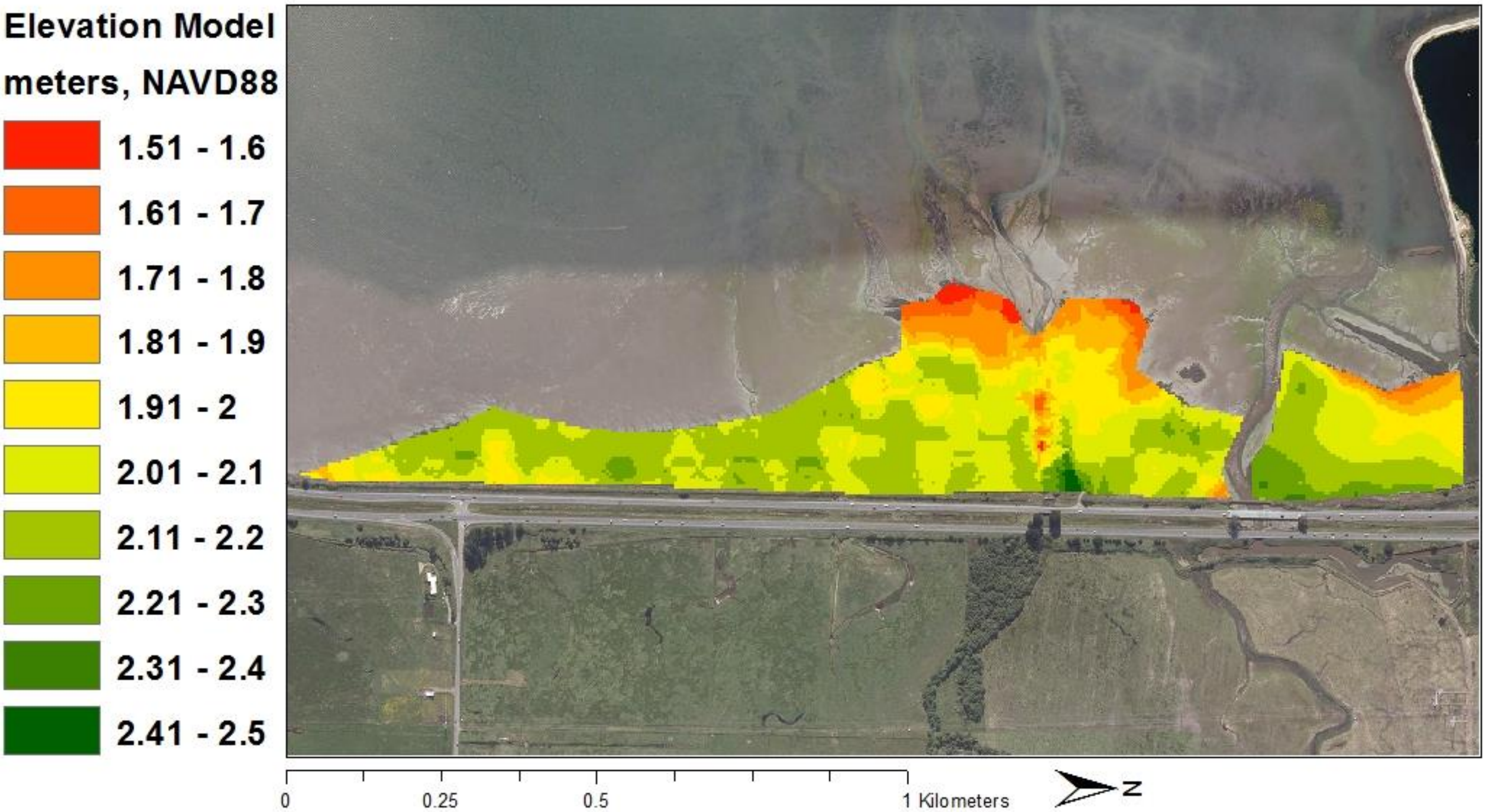

Figure E-3. Elevation model (5-m horizontal resolution) developed from ground RTK GPS elevation data. Parameters were optimized to produce minimal root-mean-square error.

.

Vegetation surveys

Vegetation and elevation surveys were done concurrently in June 2012. This site underwent spot control of *S*. *densiflora* in 2010 in the high elevation areas along the Hwy 101 and river banks. The same removal method was implemented at mid and low elevations throughout 2011.

A total of 125 locations (Fig E-1) were measured for vegetation composition, height (cm), and percent cover (Table E-1). Vegetation was dominated by 8 species: *S. pacifica* (76% frequency), *D. spicata* (73%), *J. carnosa* (58%), *C. ambigua* (50%), *T. maritima* (47%), *S. densiflora* (35%), *L. californicum* (27%), and *P. maritima* (20%). This site had the highest species richness. A total of 18 species were detected, 3 of which are non-native (*S. densiflora*, *C. coronopifolia*, and *P. incurva*). This high diversity could be caused by many factors including the relatively large elevation gradient and the early successional stages caused by *S. densiflora* removal. Vegetation in salt marshes is generally structured by inundation and salinity gradients. In Jacoby marsh zonation of vegetation species relative to MHW was observed (Table E-2; Fig. E-4, 5).

Table E-1. Marsh plant community characteristics at Jacoby Creek marsh in 2012.
[cm, centimeter; n, number of quadrats where species was observed]

Species	Frequency (%)	Mean Height (cm)	Mean Height SD	Max Height (cm)	Max Height SD	Mean Cover %	Mean Cover % SD	n
S. pacifica	76.8	17	8	22	9	40	31	96
D. spicata	73.6	18	6	23	7	51	27	92
J. carnosa	58.4	9	4	13	5	37	30	73
Orobanchaceae	50.4	14	4	17	4	22	23	63
T. maritimum	47.2	28	8	38	15	25	17	59
**S. densiflora*	35.2	22	7	26	8	17	23	44
L. californicum	27.2	9	3	12	3	11	5	34
P. maritima	20.8	15	7	19	8	17	12	26
G. stricta	17.6	23	6	28	11	12	10	22
S. cernuus	12	6	2	9	3	12	10	15
D. cespitosa	10.4	36	12	45	16	33	26	13
S. macrotheca	10.4	10	4	13	5	9	10	13
P. anserina	6.4	19	11	21	12	21	15	8
T. concinna	3.2	16	8	18	8	25	19	4
A. prostrata	1.6	17	1	19	4	3	3	2
**P. incurva*	1.6	2	0	4	1	18	11	2
**C. coronopifolia*	1	1	-	3	-	3	-	1
S. acutus	1	4	-	7	-	5	-	1

* non-native species

Table E-2. Sample number, mean elevation, minimum elevation, maximum elevation, and elevation range for all species sampled at Jacoby Creek marsh relative to MHW (m).

Species	Mean Elevation Relative to MHW (m)	Elevation Relative to MHW (SD)	Minimum Elevation Relative to MHW (m)	Maximum Elevation Relative to MHW (m)	Elevation Range (m)	n
D. cespitosa	0.38	0.19	0.13	0.67	0.55	13
P. anserina	0.31	0.08	0.21	0.46	0.25	8
S. macrotheca	0.3	0.06	0.21	0.44	0.23	13
A. prostrata	0.28	0.04	0.25	0.31	0.05	2
Orobanchaceae	0.28	0.07	0.06	0.44	0.37	63
G. stricta	0.28	0.11	0.06	0.6	0.53	22
L. californicum	0.28	0.06	0.18	0.42	0.24	34
D. spicata	0.27	0.1	-0.17	0.64	0.81	92
P. maritima	0.27	0.07	0.16	0.44	0.28	26
S. cernuus	0.27	0.08	0.13	0.42	0.3	15
T. concinna	0.27	0.06	0.2	0.32	0.12	4
T. maritimum	0.26	0.07	0.06	0.42	0.36	59
J. carnosa	0.25	0.14	-0.47	0.64	1.11	73
S. pacifica	0.24	0.16	-0.47	0.67	1.14	96
**S. densiflora*	0.24	0.12	-0.24	0.44	0.68	44
**P. incurva*	0.18	0.04	0.16	0.21	0.05	2
**C. coronopifolia*	-0.17	-	-0.17	-0.17	0	1
S. acutus	-0.17	-	-0.17	-0.17	0	1

* non-native species

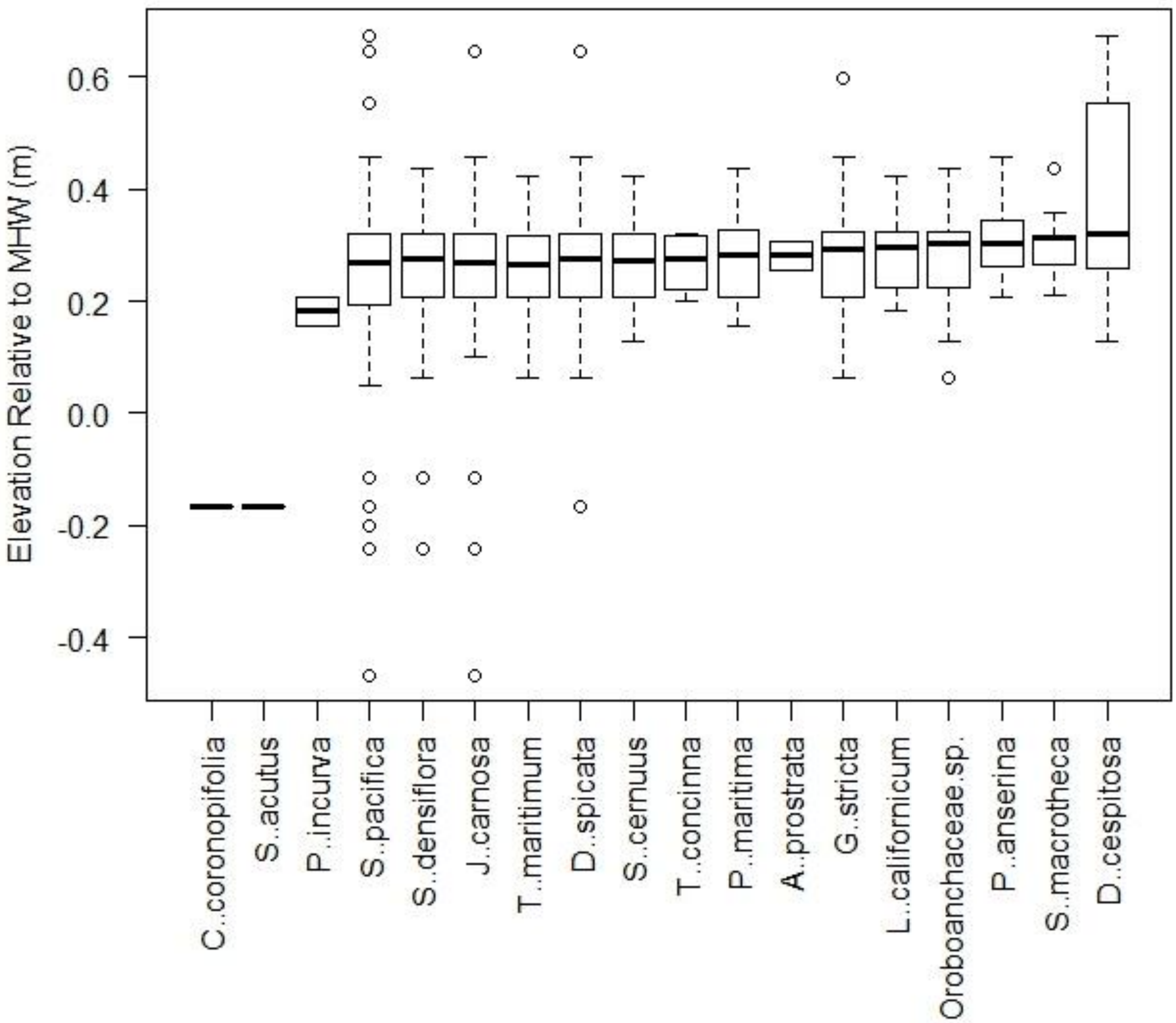

Figure E-4. Elevation of plant species relative to mean high water (MHW), in meters (m), at Jacoby Marsh. Median (solid line), 25 and 75 percentiles (box), and 1.5 interquartile range (whiskers).

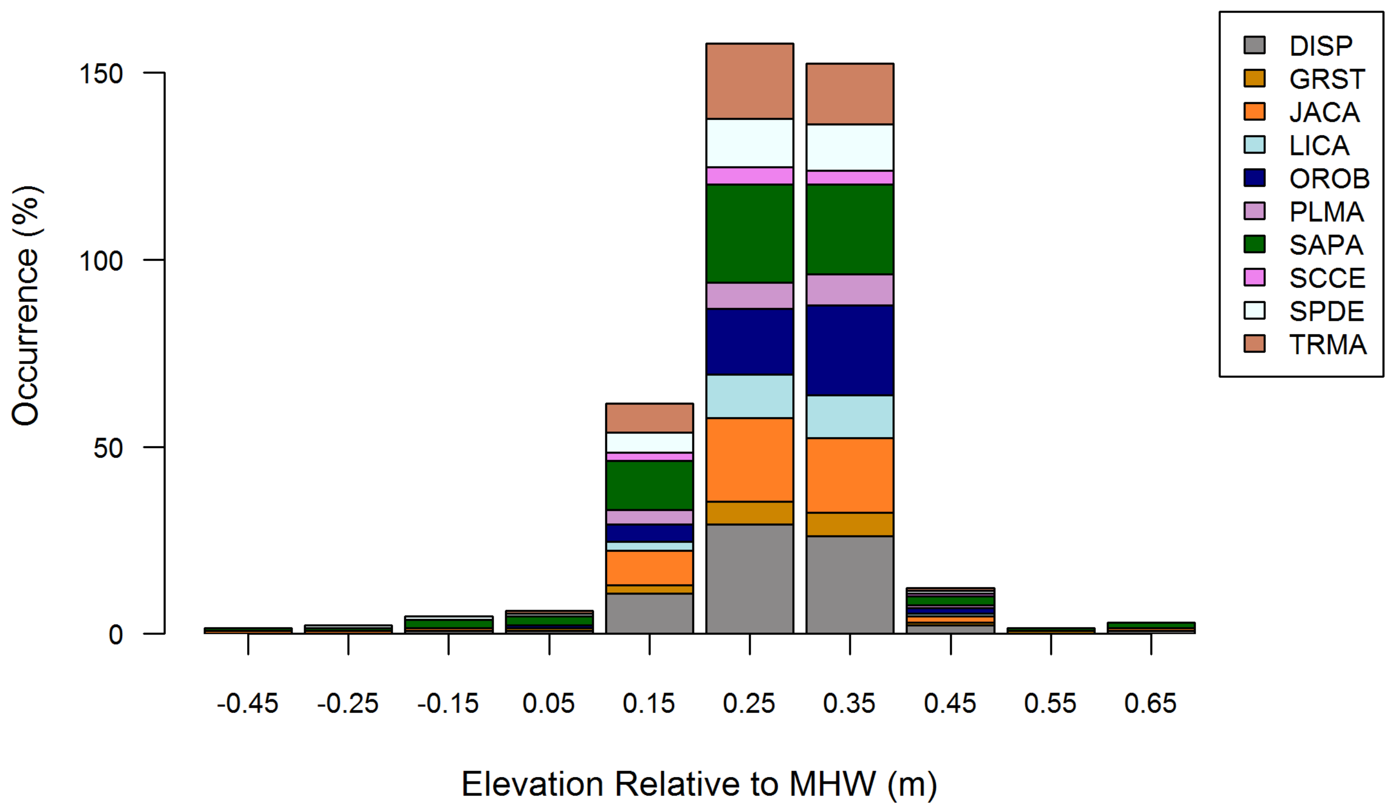

Figure E-5. Percent occurrence of the most common species (>10% of the plots) by elevation at Jacoby Creek marsh. Species codes are: DISP = *Distichlis spicata*; GRST = *Grindelia stricta*; JACA = *Jaumea carnosa*; LICA = *Limonium californicum*; OROB = Orobanchaceae; PLMA = *Plantago maritima* ; SAPA = *Sarcocornia pacifica*; SCCE = *Scirpus cernuus*; SPDE = *Spartina densiflora*; TRMA = *Triglochin maritima*.

Water-level monitoring

Site-specific water level was monitored at Jacoby Creek marsh from June 2012 to September 2012 Water levels were measured by one data logger deployed at the mouth of a second order channel. We used data from this logger to develop a local tidal datum. Mean tide level (MTL) was 1.33 m, mean high water (MHW) was 1.85 m, and mean higher high water (MHHW) was 1.97 m for the site (NAVD88). When looking at tidal inundation, Jacoby marsh was the third highest marsh surveyed in Humboldt Bay, with 81% of elevation measurements above MHHW. The period when the marsh platform (defined as mean elevation) was inundated most often was August 2012; however this was not based on a full year of data (Fig. E-6). A tidal datum model was produced from these data (Fig E-7), which provides insight into what portions of the marsh are covered by water during different tidal periods.

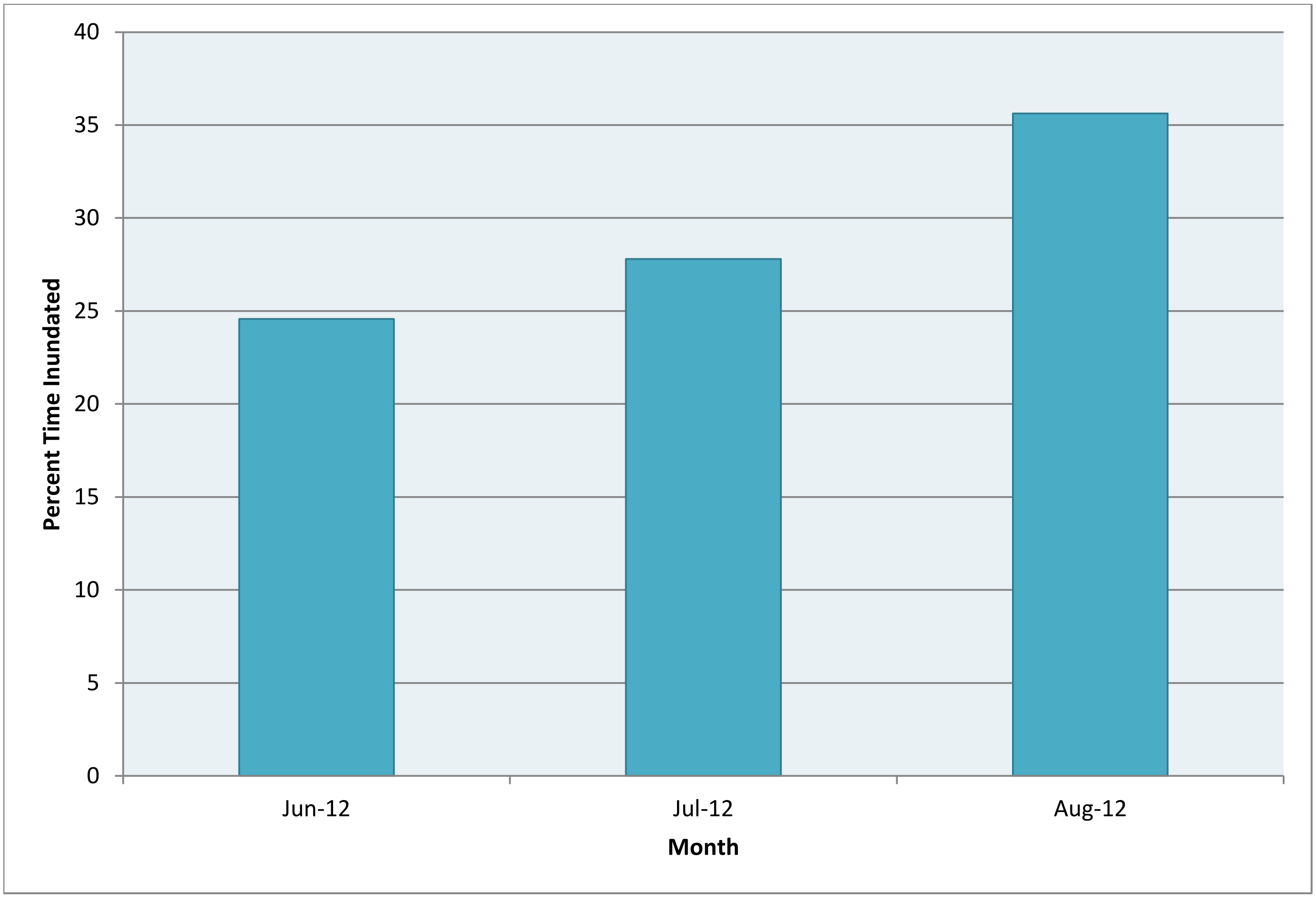

Figure E-6. Percent of time Jacoby Creek marsh was inundated monthly, based on the mean elevation of the marsh platform (water logger stopped working in September).

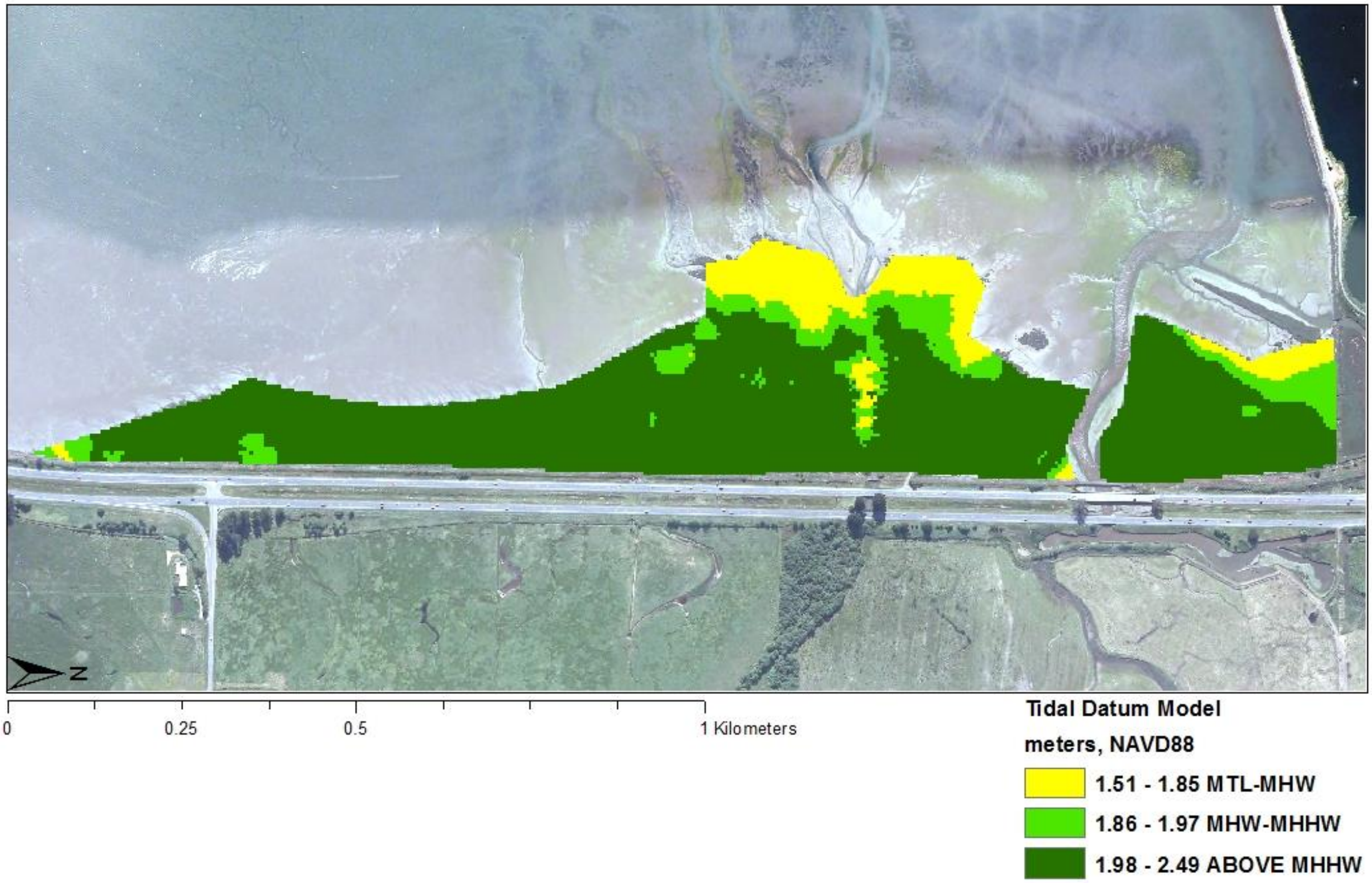

Figure E-7. Tidal inundation model for Jacoby Creek Marsh based on local tidal data from water loggers.

Appendix F

Mad River Slough Marsh

Introduction

Mad River Slough Marsh (hereafter, Mad River) is located in northern Humboldt Bay just east of the Lamphere and Ma-le'l Dunes along the Mad River Slough (Fig. F). This study was focused on 38 hectares (ha) of tidal marsh. Mad River Slough is a large network of marshes occurring as islands as well as lining the dune forest to the west. The slough was not formed by riverine influences; however there is freshwater drainage from the dunes to the west, including a perennial stream that originates at the base of the moving dunes and flows through the forest where it empties into a large tidal creek.

Figure F. Mad River Slough Marsh

Results

Elevation surveys

A total of 852 elevation measurements were taken at Mad River Slough in May 2012 (Fig. F-1). The elevation range was 1.33–2.60 meters (m) with a mean of 2.05m (NAVD88). Over half (73%) of the survey points fell within 2.0–2.3 m, a 0.3 m range. Compared to the other sites it was the highest marsh surveyed with 97% of the elevation points located above mean high water (MHW; Fig F-2). A 5-m horizontal resolution digital elevation model (DEM) was developed in ArcGIS 10 Spatial Analyst using the kriging method (ESRI, Redlands, Calif., Fig. F-3). This baseline elevation model was used as the initial state in the tidal inundation model.

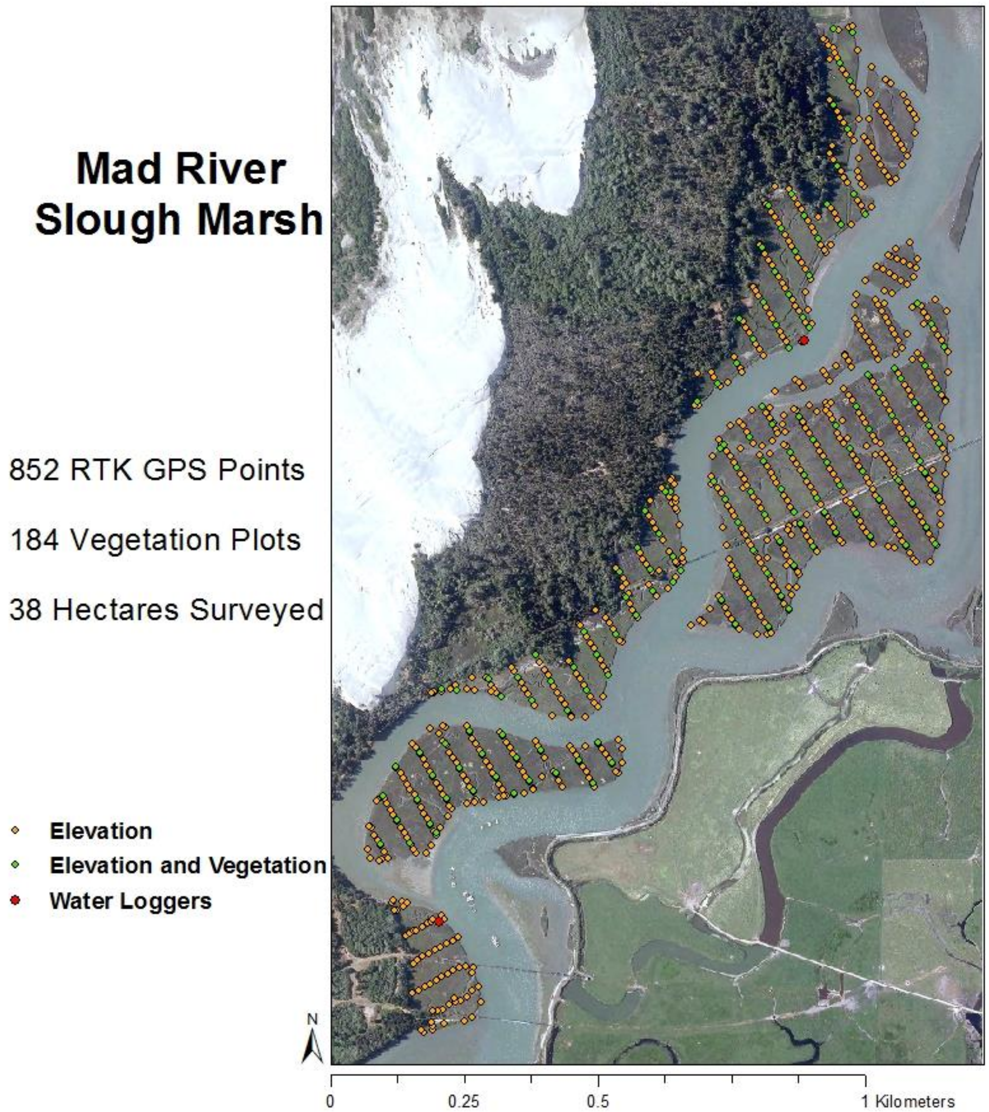

Figure F-1. Mad River Slough marsh with 2012 elevation and vegetation survey points and water logger locations.

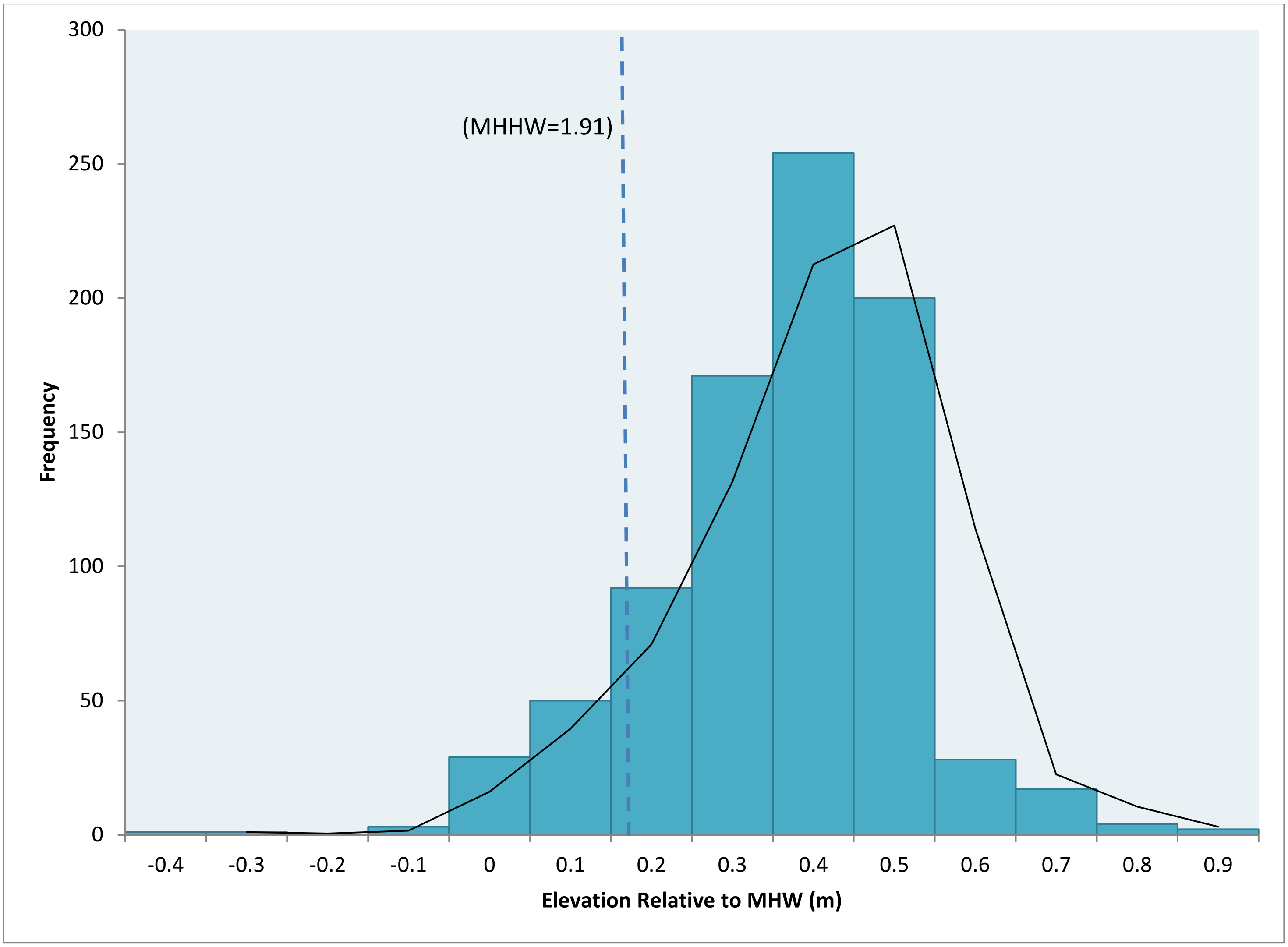

Figure F-2. Frequency distribution of elevation points relative to mean high water (MHW=1.74), in meters (m). Dotted vertical line indicates MHHW, relative to MHW.

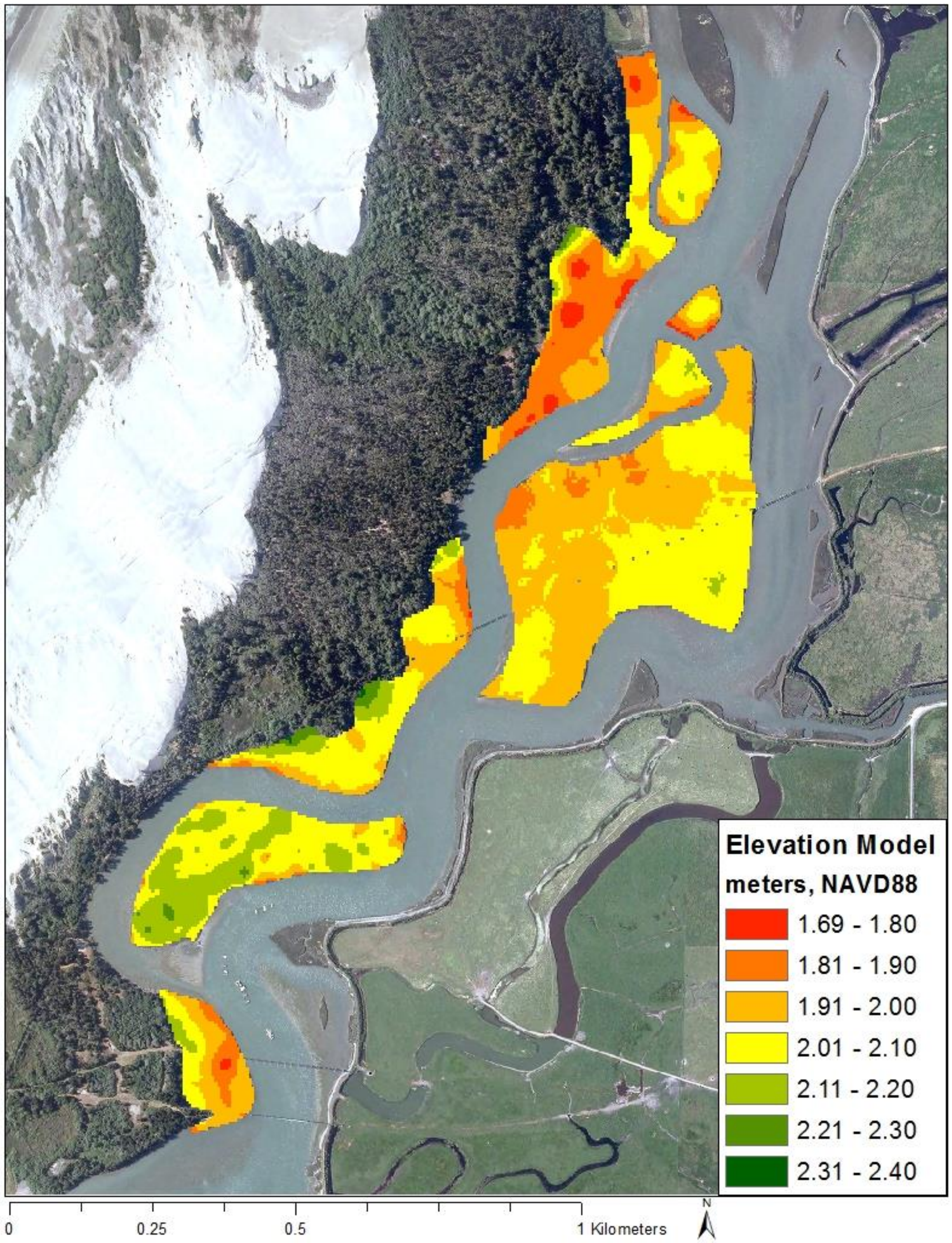

Figure F-3. Digital elevation model (DEM) (5-meter resolution horizontal) developed from ground RTK GPS data.

Vegetation surveys

Vegetation and elevation surveys were done concurrently in May 2012. *Spartina densiflora* removal was done in two stages at the Mad River Slough site. The northern half of the marsh was treated in 2006, while the southern half was treated in 2008. Vegetation canopy had closed by the time of this study, although species composition may still be changing along a successional trajectory.

A total of 184 vegetation plots (Fig. F-1) were analyzed for vegetation composition, height (cm), and percent cover (Table. F-1). Mad River Slough was dominated by nine species; S. *pacifica* (91%), D. *spicata* (89%), J. *carnosa* (72%), Orobanchaceae (39%), L. *californicum* (39%), *T. concinna* (37%), S. *densiflora* (35%), P. *maritima* (34%), and *T. maritima* (20%). This site had the highest plant diversity. There were 22 plant species detected, 1 of which was nonnative (*S. densiflora*). The high diversity could be attributed to a number of factors including the high elevation gradient, the freshwater influence on the mainland marshes, the stage of restoration, predominance of high marsh and the history of protection and management (Table F-2; Fig. F-4,5).

Table F-1. Marsh plant community characteristics at Mad River Slough in 2012.
[cm, centimeter; n, number of quadrats where species was observed]

Species	Frequency (%)	Mean Height (cm)	Mean Height (SD)	Mean Max Height (cm)	Mean Max Height (SD)	Mean % Cover	Mean % Cover SD	n
S. pacifica	91.76	19	6	23	7	33	27	167
D. spicata	89.01	20	6	25	7	50	30	162
J. carnosa	72.53	9	4	11	4	25	23	132
Orobanchaceae	39.56	11	4	15	5	13	18	72
L. californicum	39.01	10	2	13	5	10	7	71
T. concinna	37.91	17	7	22	9	34	24	69
**S. densiflora*	35.16	29	15	35	19	19	24	64
P. maritima	34.07	16	4	20	4	16	15	62
T. maritima	20.33	36	14	45	18	17	17	37
S. macrotheca	13.74	6	3	8	3	6	9	25
G. stricta	7.69	24	12	28	15	7	7	14
J. lesueurii	5.49	55	15	70	18	61	39	10
S. bigelovii	5.49	4	1	6	2	8	11	10
P. anserina	3.3	30	15	36	21	8	4	6
S. canadensis	3.3	15	3	17	4	10	8	6
A. prostrata	2.75	17	4	18	4	9	7	5
S. cernuus	1.65	6	2	10	3	27	19	3
C. lyngbyei	1.1	50	6	63	17	20	7	2
G. maritima	1.1	28	18	31	13	4	1	2
S. acutus	1.1	162	30	207	44	98	4	2
F. rubra	0.55	51	-	51	-	1	-	1
H. brachyantherum	0.55	37	-	39	-	5	-	1

* non-native species

Table F-2. Presence (n = number of quadrats in which species occurred), mean elevation, minimum elevation, maximum elevation, and elevation range for all species sampled at Mad River Slough marsh relative to MHW (m).

Species	Mean Elevation Relative to MHW (m)	Elevation Relative to MHW (SD)	Minimum Elevation Relative to MHW (m)	Maximum Elevation Relative to MHW (m)	Elevation Range (m)	n
P. anserina	0.69	0.08	0.62	0.83	0.22	6
G. stricta	0.64	-	0.64	0.64	0	14
H. brachyantherum	0.60	0.01	0.59	0.61	0.02	1
J. lesueurii	0.58	0.2	0.09	0.83	0.75	10
A. prostrata	0.57	0.19	0.24	0.71	0.47	5
F. rubra	0.56	-	0.83	0.83	0	1
C. lyngbyei	0.51	0.18	0.39	0.64	0.25	2
S. cernuus	0.49	0.02	0.47	0.5	0.03	3
G. maritima	0.41	0.12	0.24	0.64	0.4	2
P. maritima	0.41	0.13	0.18	1	0.82	62
S. acutus	0.4	0.12	0.31	0.48	0.16	2
Orobanchaceae	0.39	0.11	0.14	1	0.86	72
S. macrotheca	0.38	0.08	0.18	0.48	0.3	25
L. californicum	0.37	0.11	0.01	0.68	0.67	71
S. bigelovii	0.37	0.07	0.22	0.48	0.26	10
**S. densiflora*	0.37	0.14	0.01	1	0.99	64
T. concinna	0.37	0.12	0.14	1	0.86	69
T. maritima	0.37	0.18	-0.24	0.68	0.92	37
S. canadensis	0.36	0.18	0.01	0.48	0.47	6
J. carnosa	0.35	0.13	-0.24	1	1.24	132
D. spicata	0.34	0.14	-0.24	1	1.24	162
S. pacifica	0.34	0.15	-0.24	1	1.24	167

* non-native species

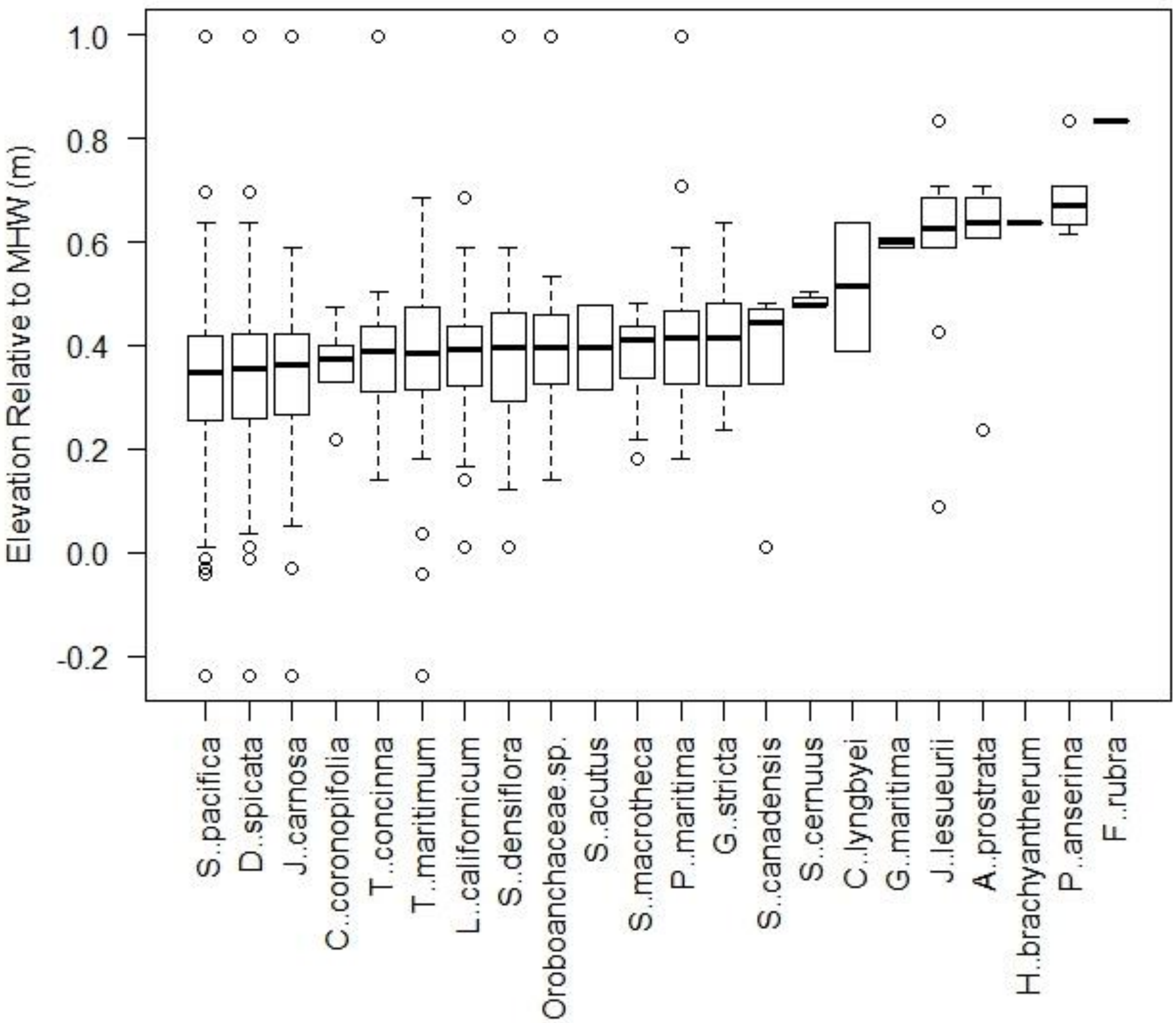

Figure F-4. Elevation of plant species relative to mean high water (MHW), in meters (m), at Mad River Slough Marsh. Median (solid line), 25 and 75 percentiles (box), and 1.5 interquartile range (whiskers).

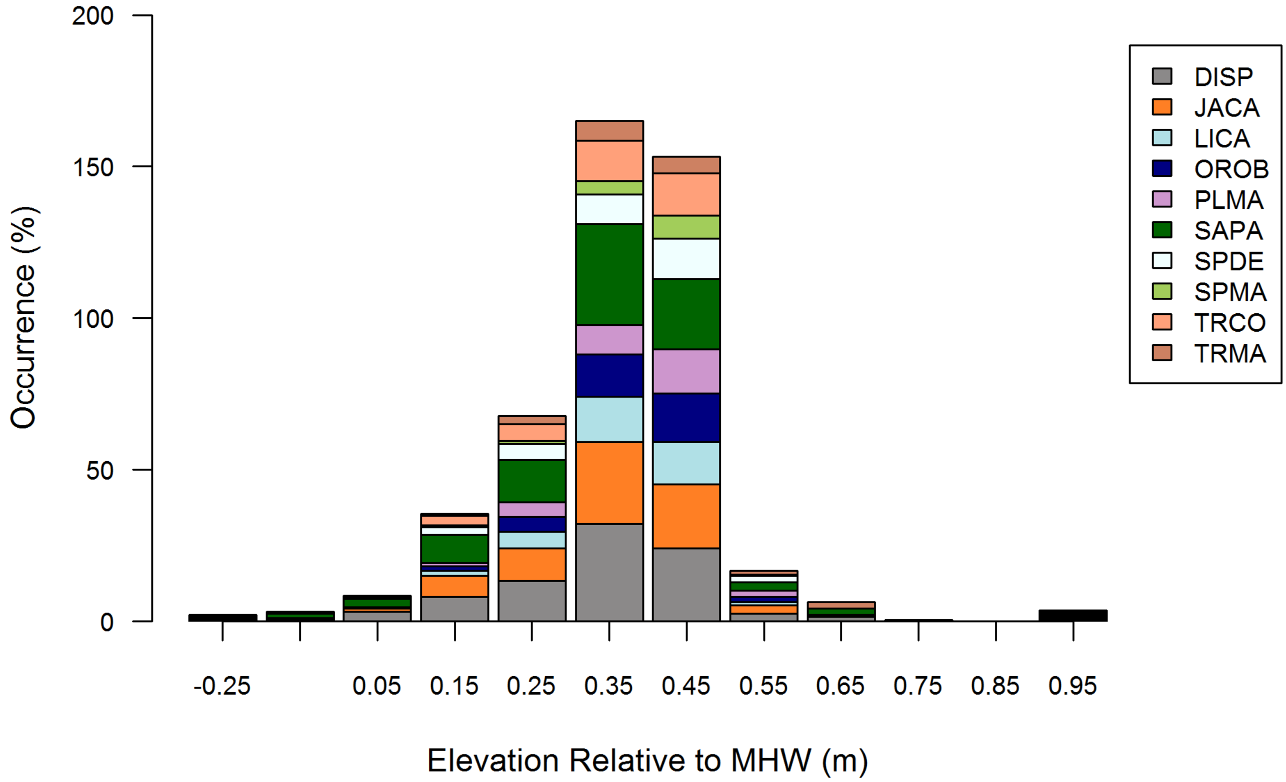

Figure F-5. Percent occurrence of the most common species (>10% of the plots) by elevation relative to MHW (m) at Mad River Slough. Species codes are: DISP = *Distichlis spicata*; JACA = *Jaumea carnosa*; LICA = *Limonium californicum*; OROB = Orobanchaceae; PLMA = *Plantago maritima* ; SAPA = *Sarcocornia pacifica*; SPDE = *Spartina densiflora* ; SPMA = *Spergularia* macrotheta; TRCO = *Triglochin concinna*; TRMA = *Triglochin maritima*.

Water monitoring

Site-specific water level was monitored at Mad River Slough from May 2012 to present. Water level was measured using two loggers, one deployed in a primary channel and another deployed in a secondary channel. We used data from these loggers to develop local tidal datum. Mean tide level (MTL) was 1.16 m, mean high water (MHW) was 1.74 m, and mean higher high water (MHHW) was 1.91 m for the site (NAVD88). When looking at tidal inundation, Mad River Slough marsh was the second highest marsh surveyed in Humboldt Bay with 83% of elevation measurements above MHHW. Water levels were monitored throughout the year to evaluate seasonal patterns in tides. The salt marsh platform (defined by the mean marsh elevation) was inundated most often during December 2012 due to high amounts of rainfall (Fig. F-6). Based on the tidal data, a tidal datum model was produced (Fig F-7) which provides insight into what portions of the marsh are covered by water during different tidal periods. We provide an example hydrograph from the Mad River Slough 02 water logger for the month of December (Fig. F-8).

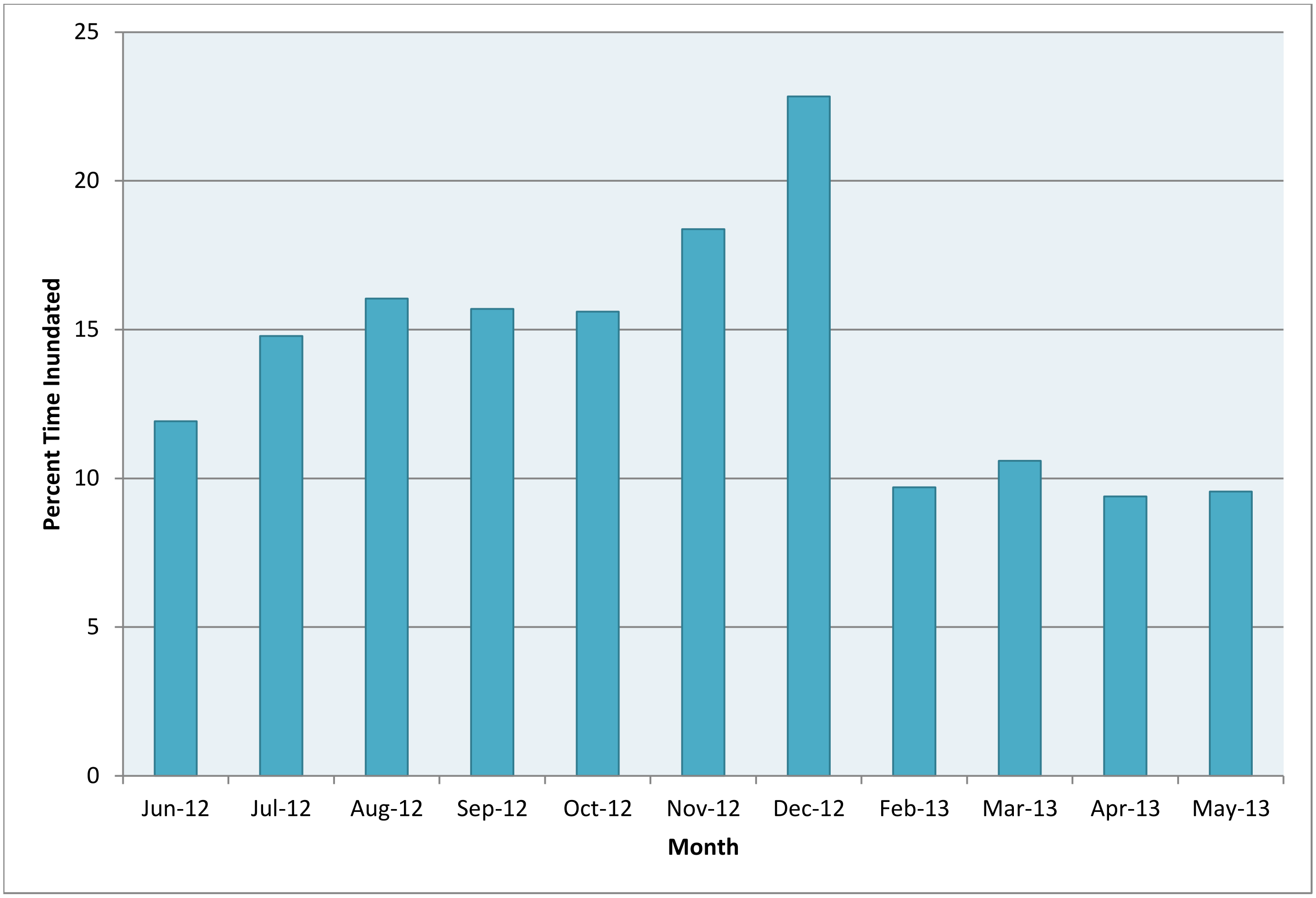

Figure F-7. Percent of time Mad River was inundated monthly based on the mean elevation of the marsh platform.

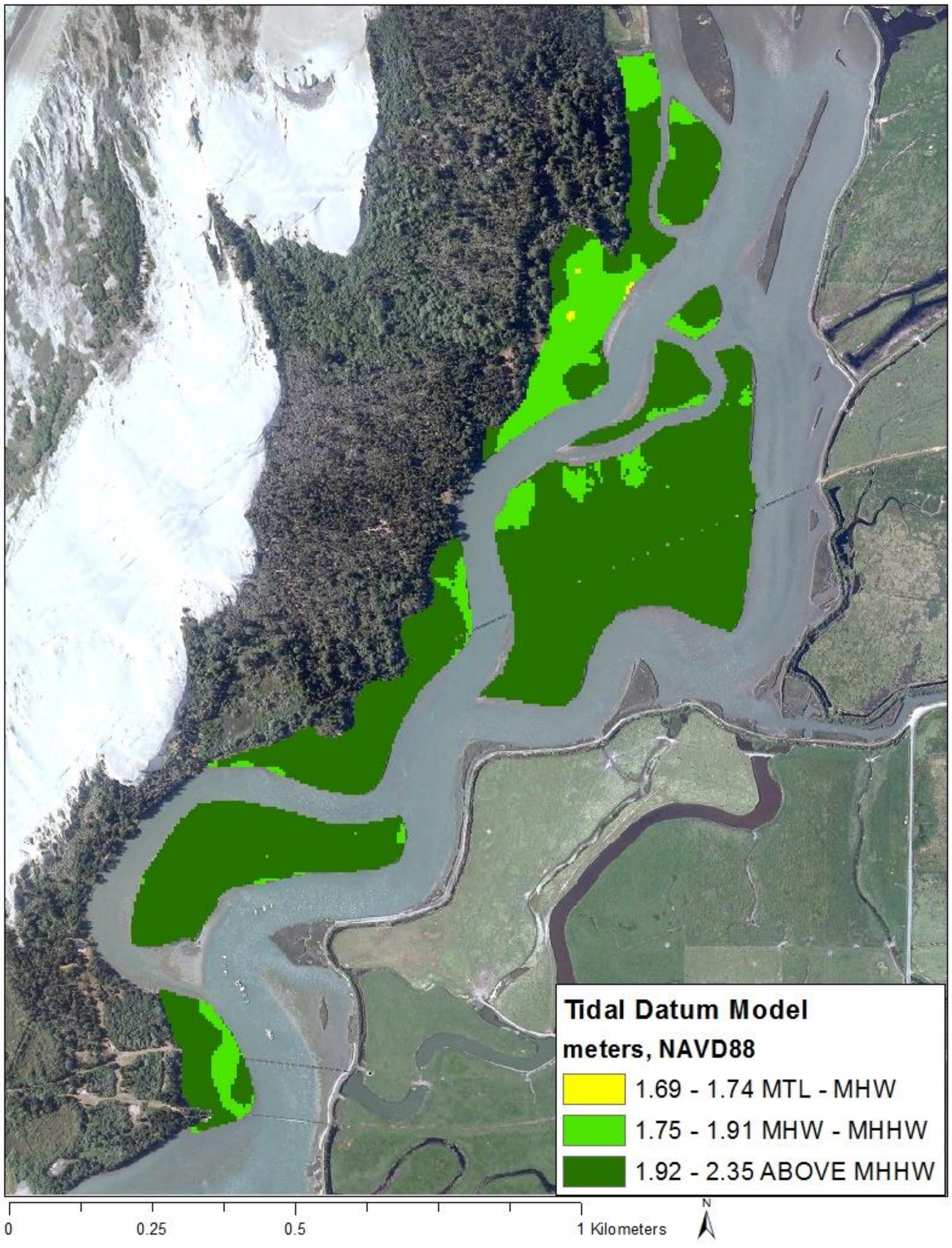

Figure F-6. Tidal inundation model for Mad River based on local tidal data from water loggers.

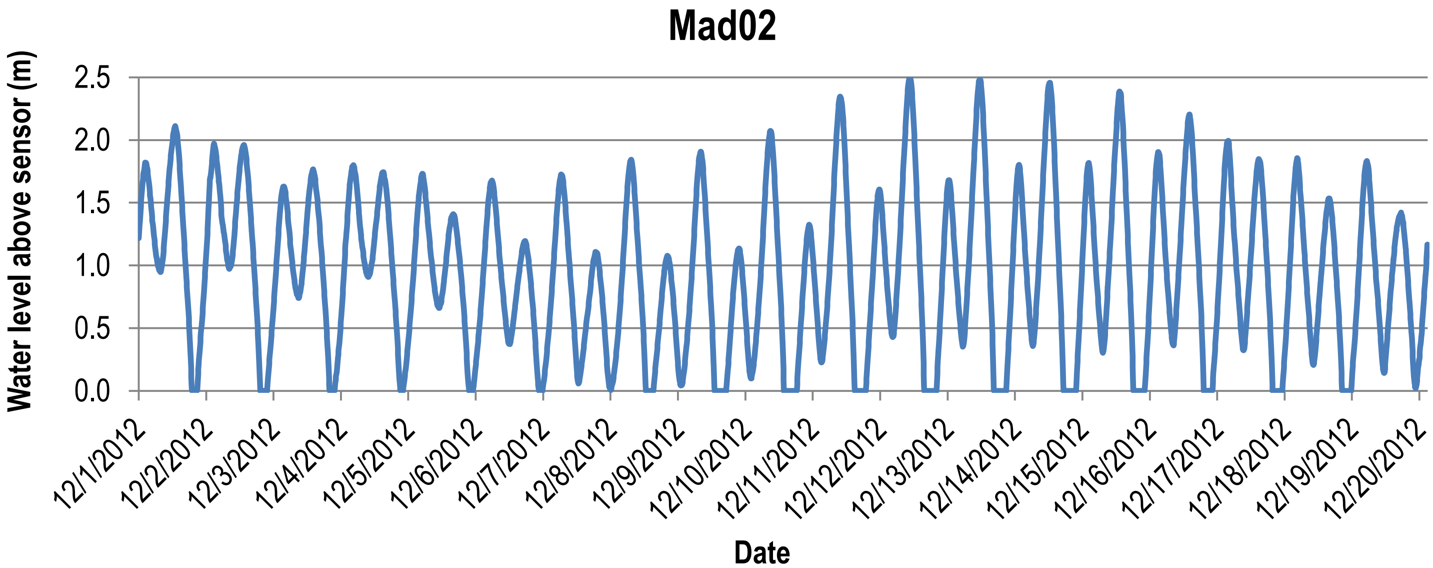

Figure F-8. Water level above the sensor (~0.05 m high) in December 2012 for Mad River Slough logger 02.

Appendix G

Manila Marsh

Introduction


Figure G. Manila Marsh [Photo by C. Freeman]

Manila Marsh (hereafter Manila), is located in northern Humboldt Bay just south of State Highway 255. This study focused on 38 hectares (ha) of tidal marsh, which is managed by the California Department of Fish and Wildlife. This marsh is not part of the Humboldt National Wildlife Refuge. Elevation surveys were conducted in January-February 2013. Although vegetation analysis was performed, it serves more as a baseline for future surveys because the surveys did not coincide with the other sites and most of the vegetation was senescent. While Manila is in close proximity to Mad River Slough Marsh, the data was analyzed separately because management of these marshes has been very different. There has been no *S. densiflora* removal on Manila Marsh. This marsh is also much lower in elevation than the adjacent Mad River Slough Marsh.

Results

Elevation surveys

A total of 732 elevation measurements were taken at Manila in February 2013 (Fig. G-1). The elevation range was 1.09-2.82 m with a mean of 1.73 m (NAVD88). The majority (73%) of survey points across Manila are located at elevations below mean high water (MHW; Fig. G-2). Manila was the second lowest marsh, surveyed in this study, relative to NAVD88. A 5-m horizontal resolution elevation model was developed in ArcGIS 10 (ESRI, Redlands, Calif.) Spatial Analyst using the kriging method (Fig. G-3). This baseline elevation model was used as the initial state for tidal inundation models.

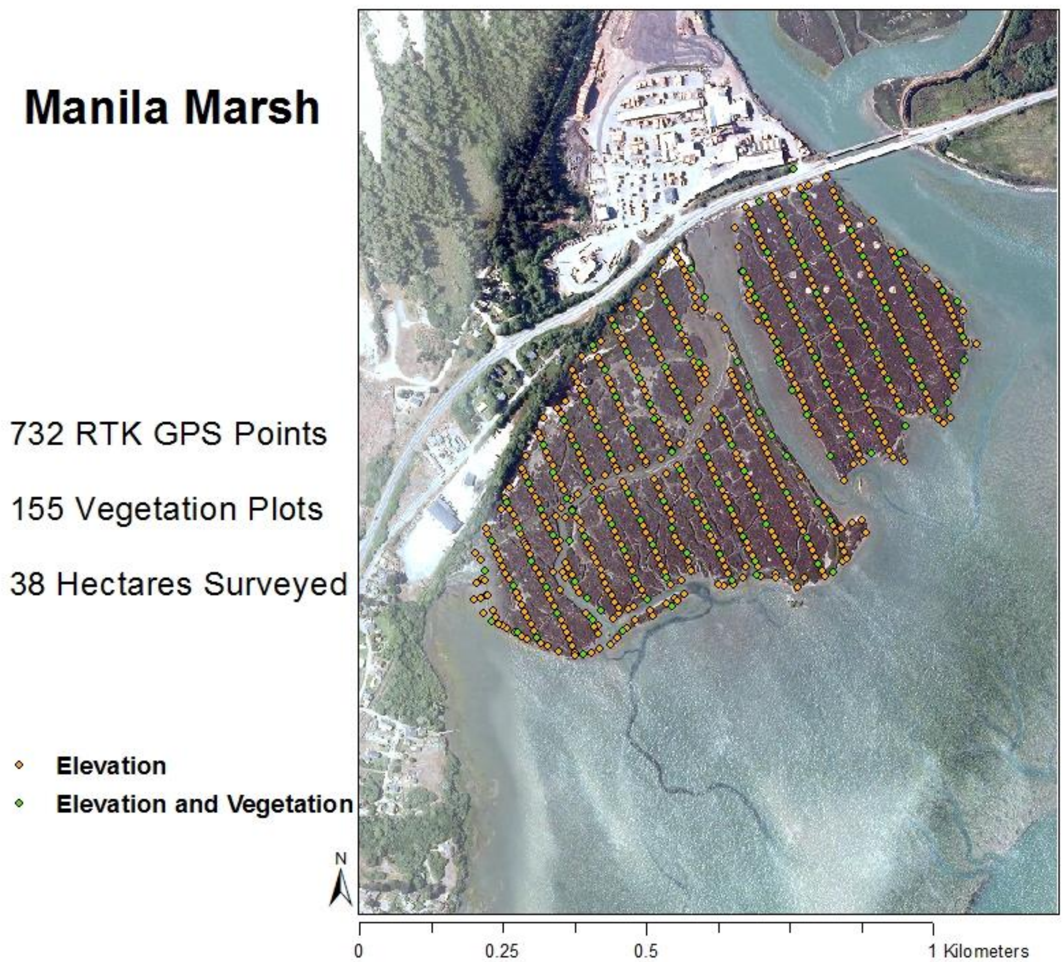

Figure G-1. Manila Marsh with 2013 elevation and vegetation survey points.

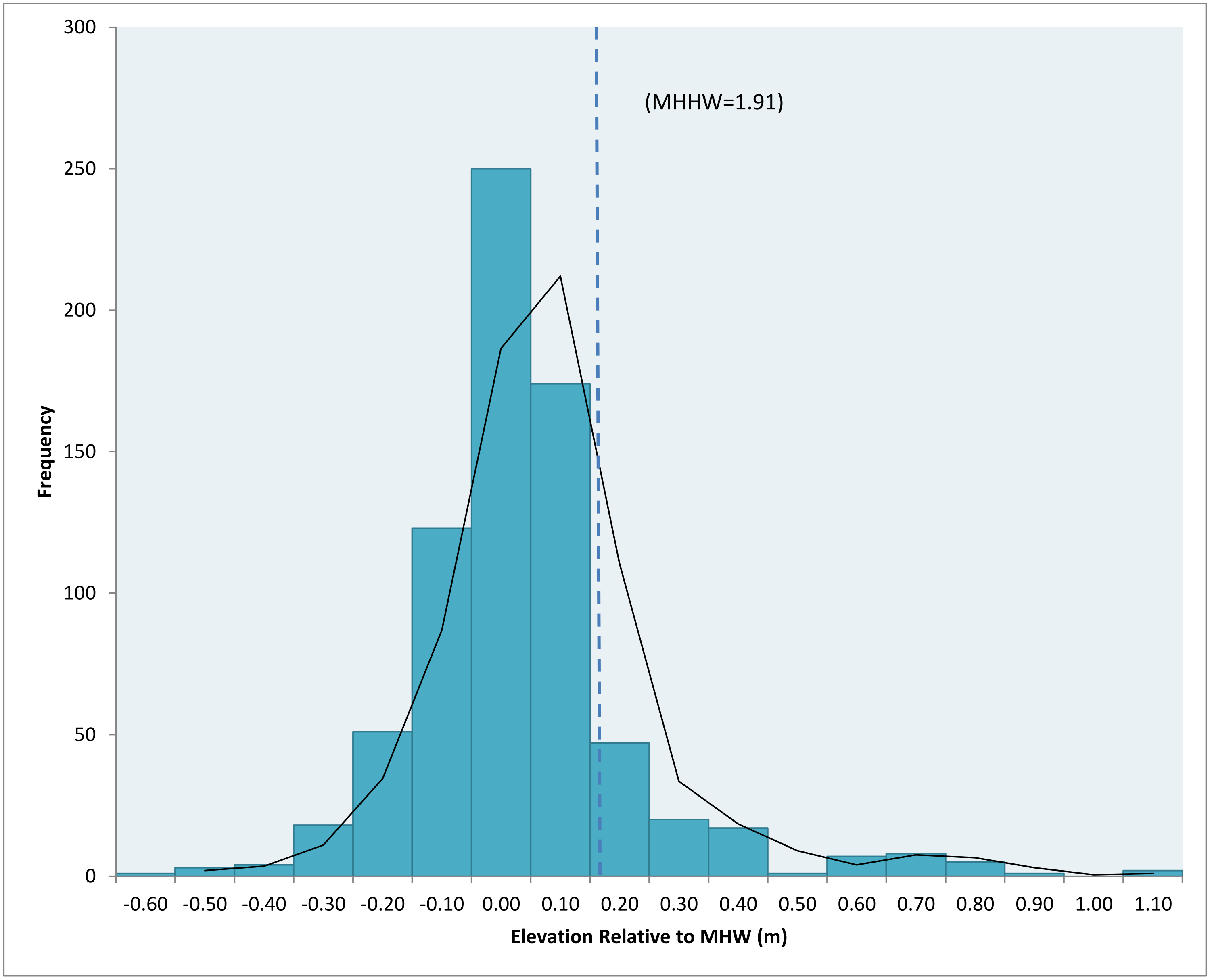

Figure G-2. Frequency distribution of elevation samples (n = 732) taken relative to mean high water (MHW=1.74), in meters (m). Dotted vertical line indicates MHHW, relative to MHW.

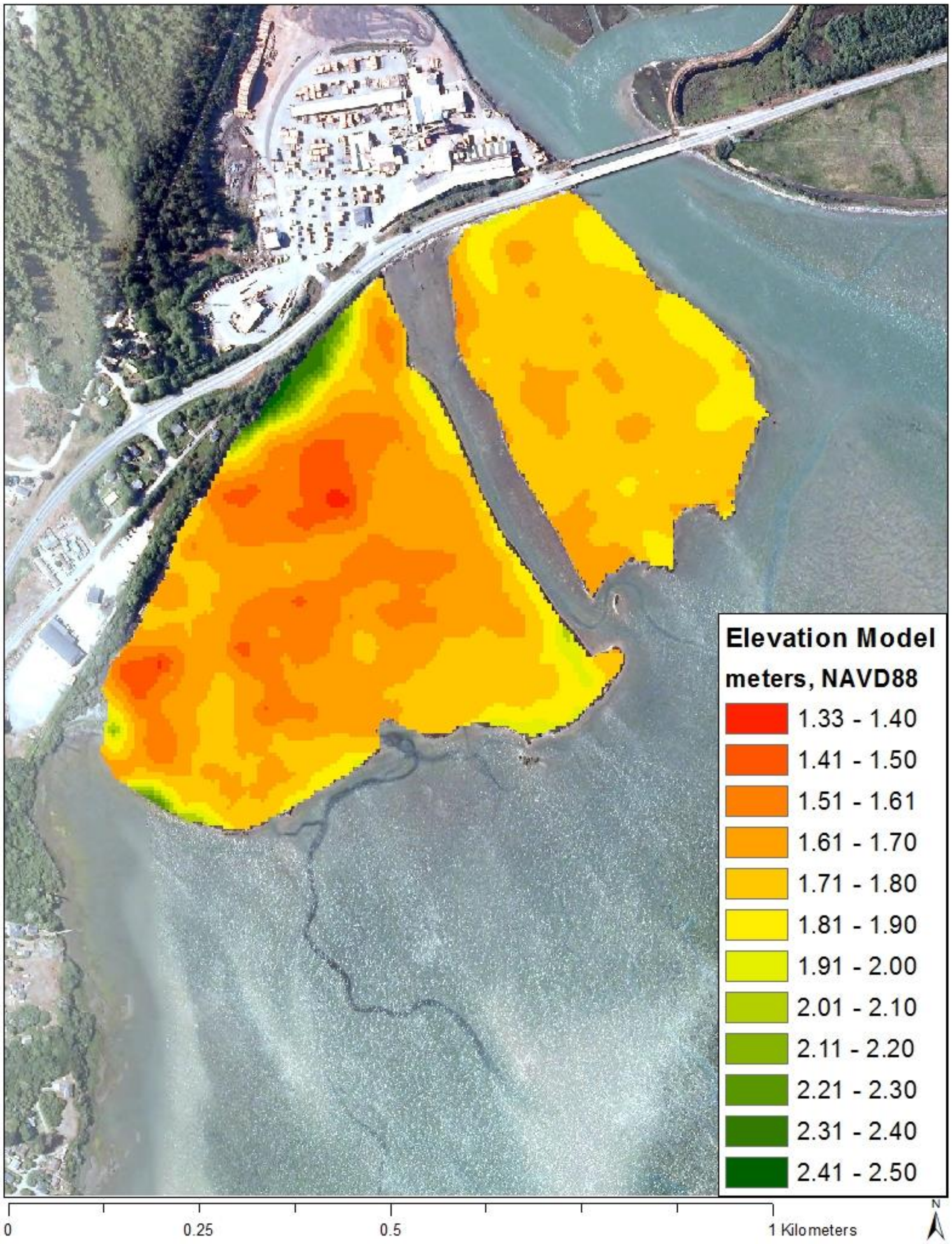

Figure G-3. Digital elevation model (DEM) (5-meter resolution horizontal) developed from ground RTK GPS data.

Vegetation surveys

Vegetation and elevation surveys were done concurrently in February 2013. This was done during a period of senescence which affected species detection.

A total of 155 vegetation plots (Fig. G-1) were analyzed for vegetation composition, height (centimeters), and percent cover (Table. G-1). Four species were detected in Manila marsh; S. *densiflora* (77%), S. *pacifica* (74%), D. *spicata* (6%), and L. *californicum* (1%). The lower diversity could also be attributed to the high *S. densiflora* occurrence, since this is the only site in our study that was not subjected to *Spartina densiflora* removal. Vegetation in salt marshes is generally structured by inundation and salinity gradients. In Manila marsh, zonation of vegetation species relative to MHW was not well observed which could be due to the sites low elevation and narrow gradient. (Table A-2; Fig. A-4, 5).

Table G-1. Marsh plant community characteristics at Manila marsh in 2012.

[cm, centimeter; n, number of quadrats where species was observed]

Species	Frequency (%)	Mean Height (cm)	Mean Height (SD)	Mean Max Height (cm)	Mean Max Height (SD)	Mean % Cover	Mean % Cover SD	n
**S. densiflora*	0.77	53.91	16.14	73.10	19.97	61.60	31.51	118
S. pacifica	0.74	24.20	5.80	29.50	6.70	53.40	34.90	114
D. spicata	0.06	12.56	3.94	15.11	4.62	22.44	26.85	9
L. californicum	0.01	3	-	3	-	5	-	1

Table G-2. Presence (n=number of quadrats in which species occurred), mean elevation, minimum elevation, maximum elevation, and elevation range for all species sampled at Salmon Creek marsh relative to MHW (m).

Species	Mean Elevation Relative to MHW (m)	Elevation Relative to MHW (SD)	Minimum Elevation Relative to MHW (m)	Maximum Elevation Relative to MHW (m)	Elevation Range (m)	n
D. spicata	0.28	0.12	0.14	0.52	0.38	9
L. californicum	0.20	-	0.20	0.20	-	1
**S. densiflora*	-0.01	0.12	-0.31	0.52	0.83	118
S. pacifica	-0.04	0.14	-0.31	0.52	0.83	114

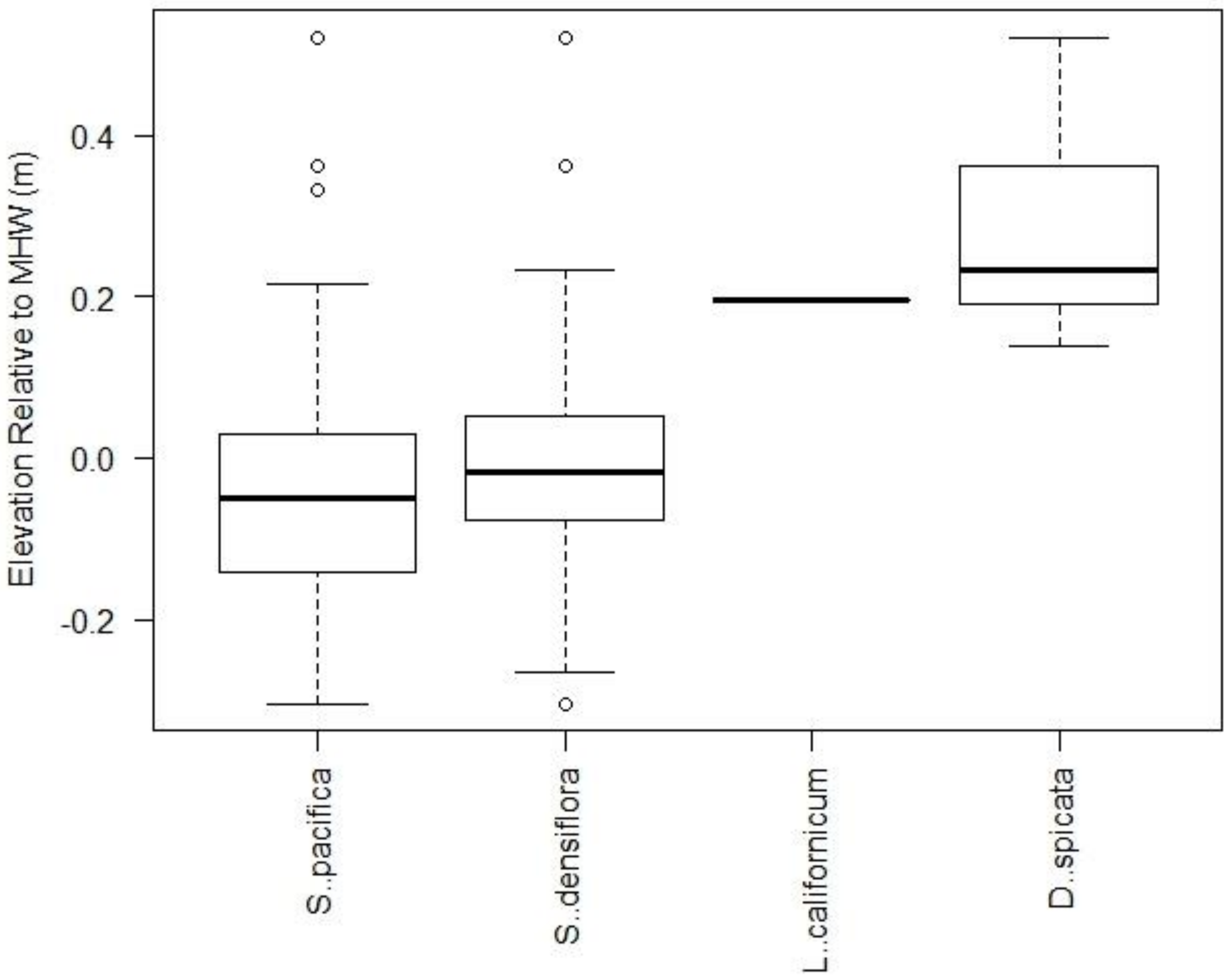

Figure G-4. Elevation of plant species relative to mean high water (MHW), in meters (m), at Manila Marsh. Median (solid line), 25 and 75 percentiles (box), and 1.5 interquartile range (whiskers).

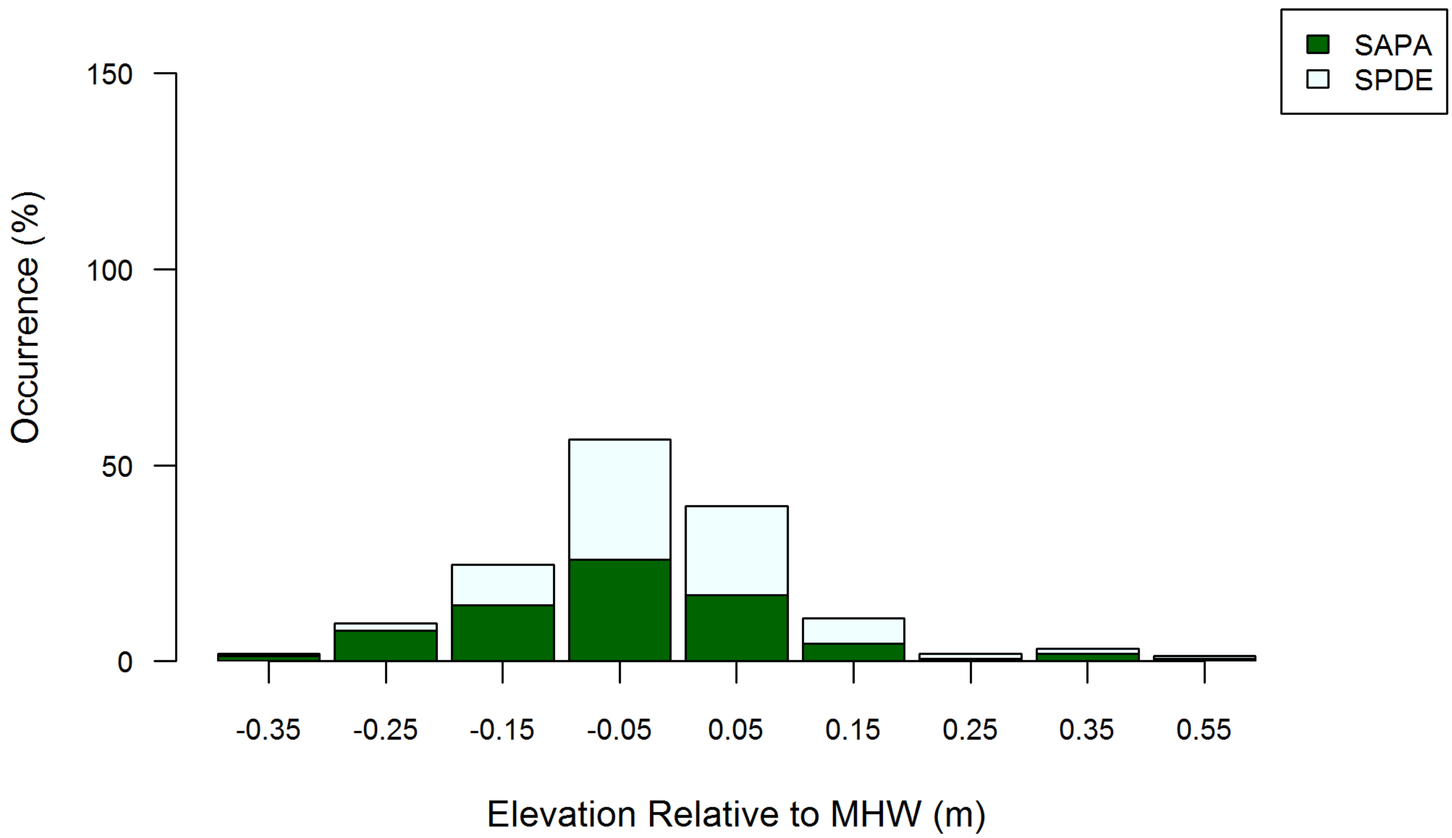

Figure G-5. Percent occurrence of the most common species (>10% of the plots) by elevation relative to MHW (m) at Manila marsh. Species codes are: SAPA = Sarcocornia pacifica; SPDE = *Spartina densiflora*.

Water monitoring

Site-specific water levels were monitored at Manila marsh from May 2012 to present. Water level was measured using two loggers, one deployed in a primary channel and another deployed in a secondary channel. Mean tide level (MTL) was 1.16 m, mean high water (MHW) was 1.74 m, and mean higher high water (MHHW) was 1.91 m (NAVD88). Manila marsh was the third lowest marsh surveyed in Humboldt Bay with 10% of elevation measurements above MHHW. The marsh platform (defined as mean marsh elevation) was inundated most often November thorough December 2012 when rainfall was greatest (Fig. G-6). A tidal datum was produced based on the tidal data (Fig. G-7) and provides insight into what portions of the marsh were covered by water during different tidal periods.

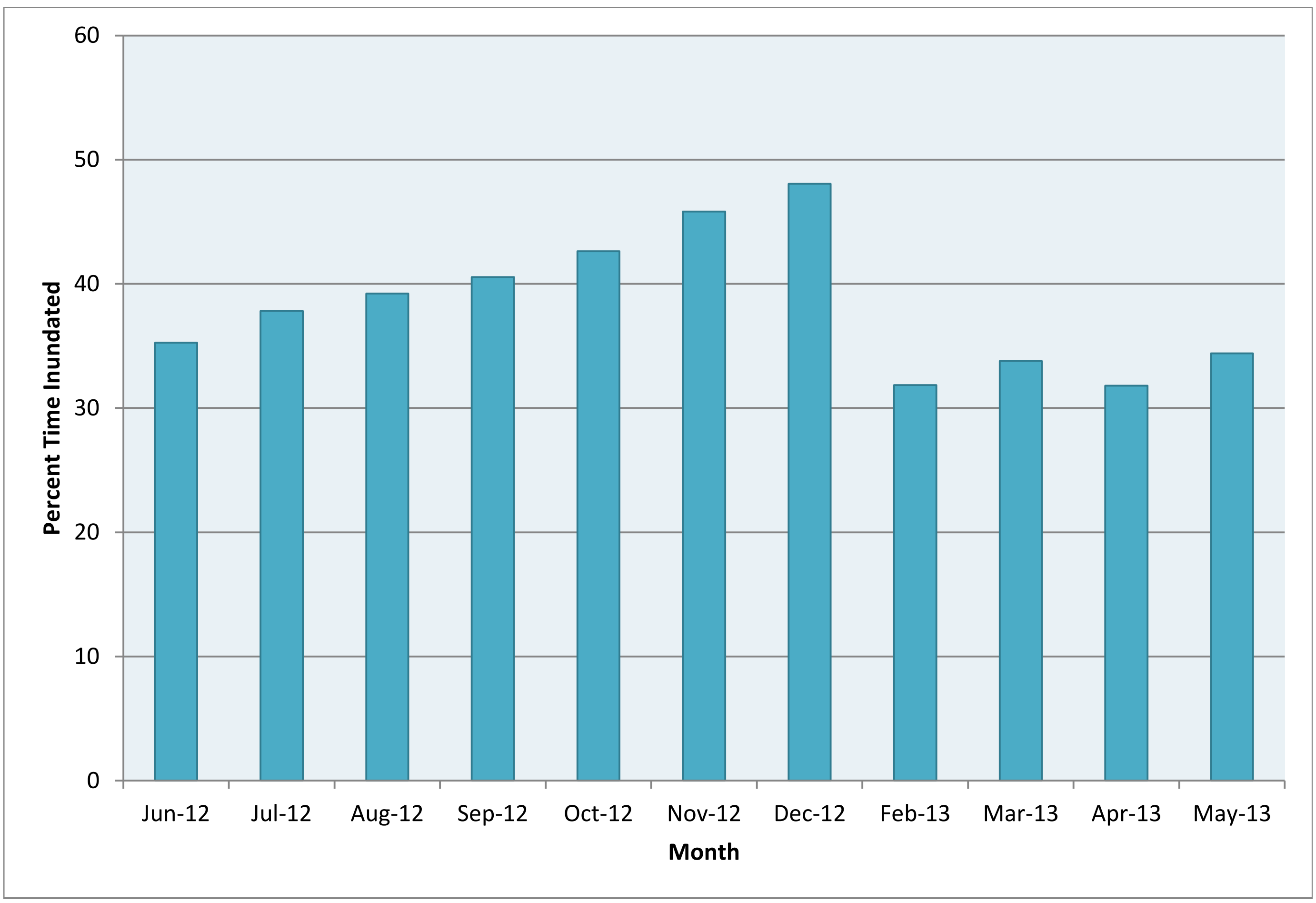

Figure G-6. Percent of time Manila marsh was inundated monthly based on the mean elevation of the marsh platform.

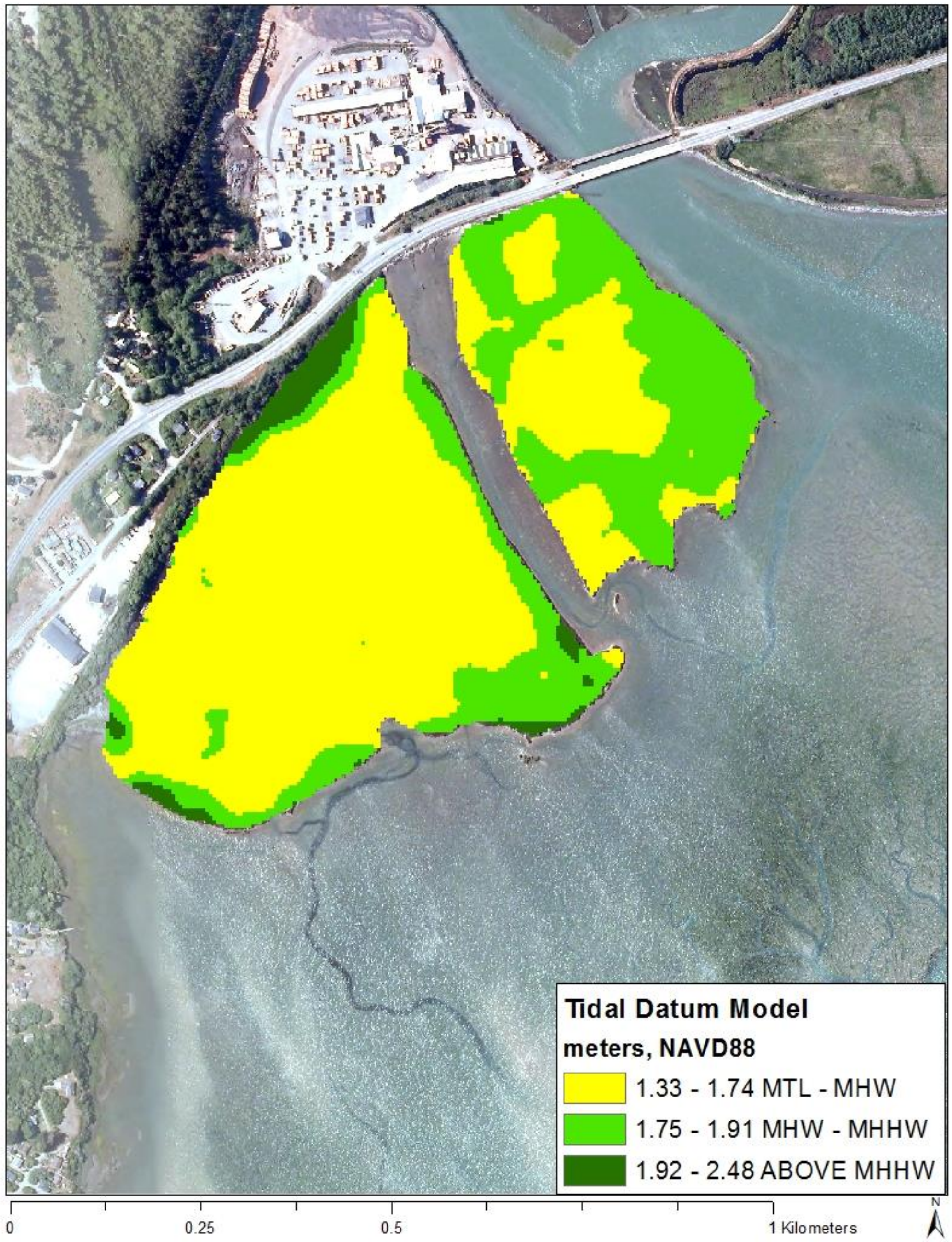

Figure G-7. Tidal inundation model based on local tidal data from water loggers.