An Elevation and Climate Change Assessment of the Tolay Creek Restoration, San Pablo Bay National Wildlife Refuge

U. S. Geological Survey, Western Ecological Research Center

Data Summary Report Prepared for the California Landscape Conservation Cooperative and U.S. Fish & Wildlife Service Refuges

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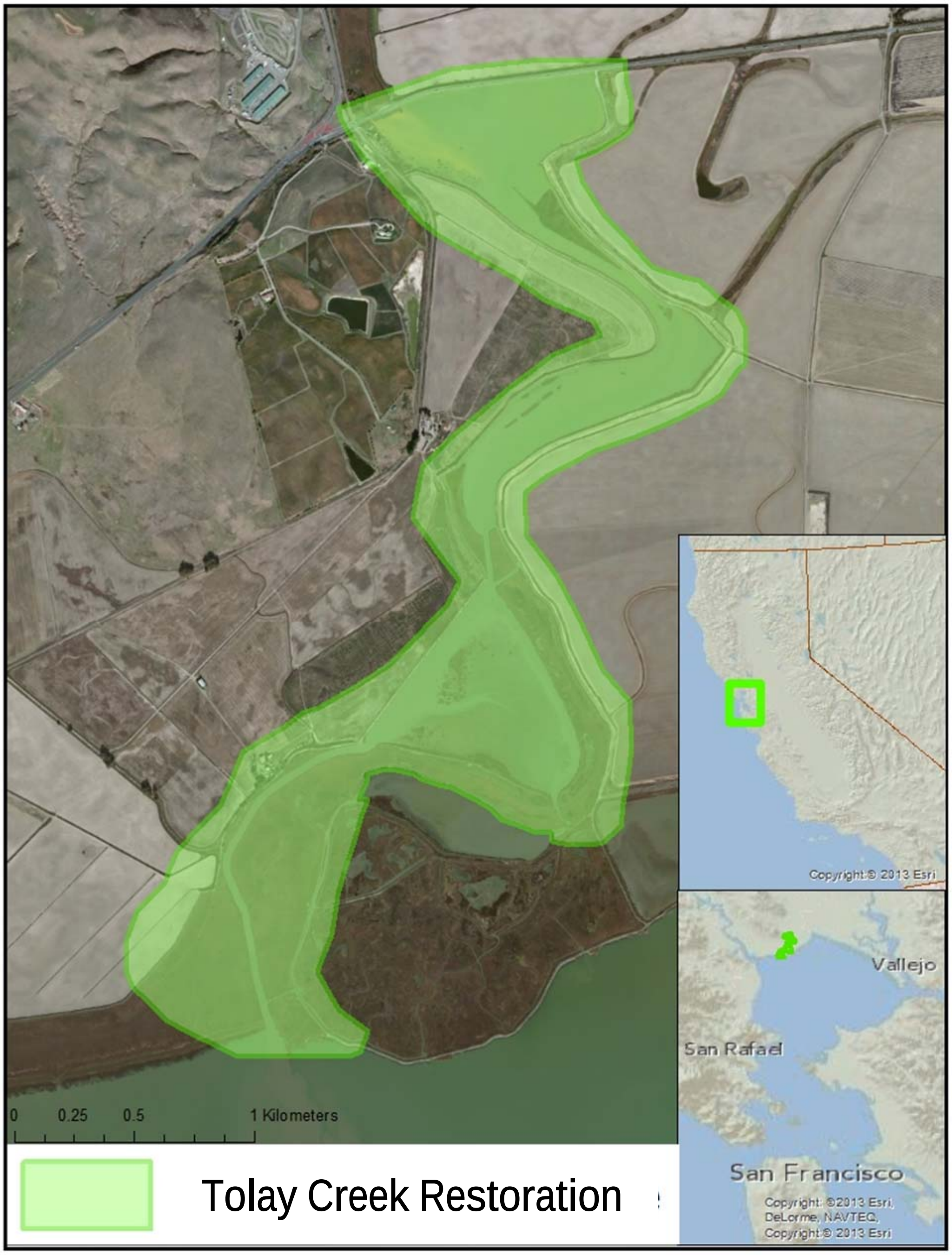

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Executive Summary

- San Francisco Bay tidal marshes will be affected by climate change through sea-level rise and increased frequency and intensity of storms. Restoration of existing baylands may be an effective conservation strategy to increase resiliency of endemic tidal marsh populations and their habitats in anticipation of these projected climate change effects in the next several decades.
- Our Coastal Ecosystem Response to Climate Change (CERCC) program follows a bottom-up approach to provide information for evaluating sea-level rise effects for marsh parcels that is scalable to larger landscapes. Objectives of this report were to: (1) present baseline conditions for the Tolay Creek Restoration, (2) develop a digital elevation model (DEM), and (3) assess changes between 2000 and 2012 to determine if accretion was keeping pace with sea-level rise.
- We surveyed a 75-ha parcel and collected 675 elevation points during 2009 and 2012 with a Real Time Kinematic (RTK, 1 cm x,y, $\pm$2 cm z) GPS unit. Elevation ranged from 0.79 to 2.25 m (mean = 1.60 m). Elevation near the mouth of Tolay Creek ranged from 0.79 to 2.08 m (mean = 1.73 m) in 2009, while elevation at the upper reach ranged from 0.99 to 2.25 m (mean = 1.54 m) in 2012.
- We used a shallow-water, echosounder system to survey 221 ha of the channel and mud flat and collected 49,978 elevation points to create a DEM ranging from -6.60 to 2.10 m (mean = 0.18 m)
- Elevation change for the marsh, channel, and mud flat ranged from - 4.57 m to 10.47 m (mean = 0.96) from 2000 to 2012. Accretion averaged 0.11 m/yr and ranged from 0.09 to 0.15 m/yr.
- The vegetated marsh plain had the smallest amount of accretion. Elevation increased from 0.76 m (range = -1.21 to 2.74 m) in 2000 to 1.54 m (range = 1.11 to 2.09 m) in 2012 or +0.78 m. Most of the elevation change (57%) occurred between 0.5 and 0.9 m.
- Estimated sea-level rise was 2.58 cm from 2000-2012. Our DEM indicated that 95% of the area kept pace with sea-level rise, and most of the area surpassed that rate.
- Marsh vegetation was sampled concurrently with elevation at 341 0.25-m^2 quadrats, and *Sarcocornia pacifica* was the most common species that occurred at 91% of the vegetation plots.
- Water level loggers were deployed at two sites in January 2012 and January 2013. Peak tide levels were averaged to produce site-specific tidal datums for mean tide level (MTL=0.93), mean high water (MHW=1.54), and mean higher high water (MHHW=1.70).
- Thus, although sea-level rise is projected to accelerate after the mid-century, tidal marsh restorations may keep pace in the short term to provide greater resilience for their ecosystems.

Introduction

Marshes 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 since variation in tidal depth and duration plays a major role in structuring plant communities (Brittain and Craft 2012). Marshes will be affected by climate change from sea-level rise (SLR; Holgate & Woodworth, 2004; Kemp et al., 2011), erosion (Leatherman et al. 2000), changes in precipitation patterns (Hamlet and Lettenmaier 2007, Bengtsson et al. 2009) and the frequency and intensity of storms (Emanuel, 2005; Webster, Holland, Curry, & Chang, 2005; IPCC, 2007).

Current SLR projections for California range from 44 – 166 cm, with a mean increase of 93 cm by 2100 (National Research Council 2012). Marshes can keep pace with changes in local sea level through accretion processes that include sediment deposition and organic matter accumulation (Morris et al. 2002, Gedan et al. 2011) if suspended-sediment concentrations and organic production are high enough (Kirwan et al. 2010). However, marshes may be lost if SLR outpaces vertical accretion processes or if transgression is not possible (Morris et al. 2002, Callaway et al. 2007). Restoration efforts can be implemented to offset the effects from climate change if restoration accretion processes can outpace SLR. The San Pablo Bay National Wildlife Refuge (NWR) and the California Department of Fish and Wildlife (CDFW) has been actively rehabilitating or restoring historic tidal wetlands in San Pablo Bay from previously converted agricultural land. The Tolay Creek Restoration was initiated in 1997 to rehabilitate the tidal marsh habitats along the creek with the San Pablo Bay NWR.

Tidal wetland restoration projects have been undertaken to increase the extent of emergent wetlands throughout the San Francisco Bay estuary. However, wetland restoration projects success (Race 1985, Zedler et al. 2001) and persistence are often uncertain due to SLR and understanding the amount of available suspended sediment for accretion processes. We collected baseline data under our Coastal Ecosystem Response to Climate Change (CERCC) program at the Tolay Creek Restoration following a site-specific, bottom-up approach to assess restoration progress since 2000. Our goal was to provide science support for development of local management strategies and adaptation plans for this restoration and surrounding areas (Fig. 1). The objectives of this study were to: (1) establish baseline conditions including elevation, vegetation, and tidal levels, (2) develop digital elevation models (DEM), and (3) assess changes in elevation between 2000 and 2012 to determine if accretion rates kept pace with sea-level rise.

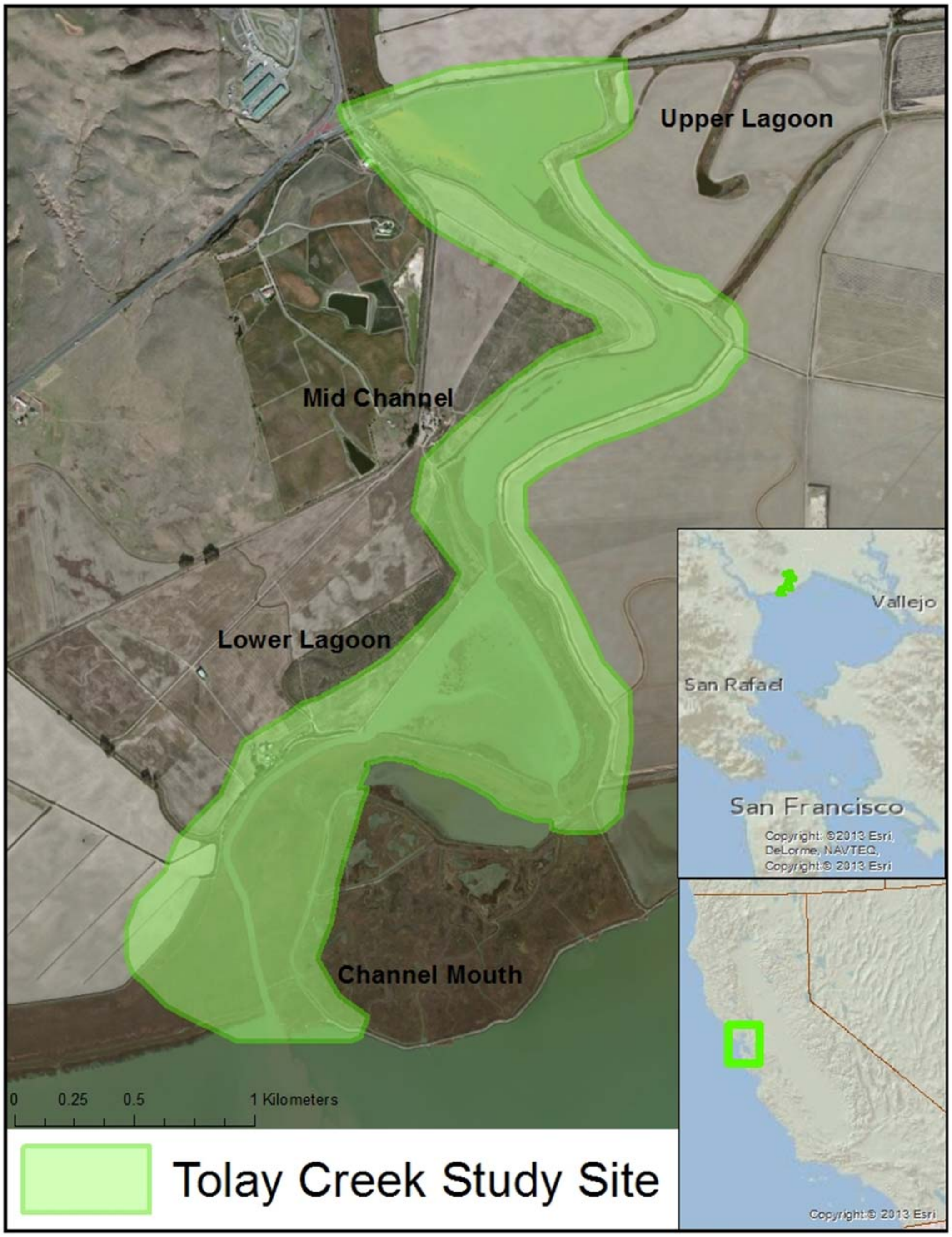

Figure 1. Tolay Creek is located in northern San Pablo Bay and managed by the San Pablo National Wildlife Refuge and California Department of Fish and Wildlife

Study Site

San Pablo Bay, the northern embayment of the San Francisco Bay, comprises the largest remaining expanse of undeveloped baylands. A large proportion of this undeveloped land is diked baylands that have been converted to agricultural use that includes mostly hay or oats. Tolay Creek drains into the northwest side of San Pablo Bay and is co-managed by the San Pablo Bay NWR and CDFW. The NWR manages more than 5,340 ha of wetlands including the southern portion of the Tolay Creek (Fig. 2). The refuge is actively rehabilitating or restoring historic tidal wetlands from previously converted agricultural land including the Tolay Creek Restoration. This area is critical for many endemic and listed species that depend on salt marshes and are under state or federal protection (Harvey et al. 1992) such as Delta Smelt (*Hypomesus transpacificus*), Sacramento Splittail (*Pogonichthys macrolepidotus*), California Clapper Rail (*Rallus longirostris obsoletus*), California Black Rail (*Laterallus jamaicensis coturniculus*), San Pablo Song Sparrow (Melospiza melodia samuelis), Salt Marsh Yellowthroat (*Geothlypis trichas sinuosa*) and Salt Marsh Harvest Mouse (*Reithrodontomys raviventris halicoetes*). These species should benefit from the restoration of tidal salt marshes with plant communities typically dominated by native cordgrass (*Spartina foliosa)* and pickleweed (*Sarcocornia pacifica)*.

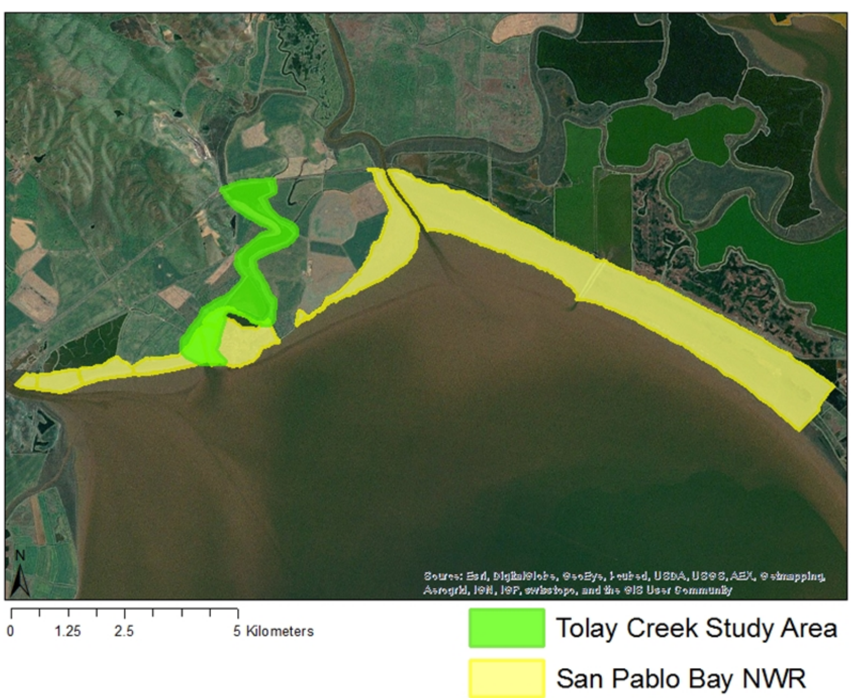

Figure 2. Tolay Creek and the San Pablo Bay NWR.

Historically, Tolay Creek received freshwater input from Tolay Lake and intermittent streams in the Sonoma Mountains (Fig. 3). As it reached lower elevations, Tolay Creek spread out onto a tidal flood plain, creating marsh habitat and tidal linkage to Sonoma Creek before connecting with San Pablo Bay (USFWS 1997). Human activities such as levee construction and conversion to agricultural land dramatically altered the landscape of Tolay Creek, decreasing the size of the tidal flood plain and associated tidal marsh. Tolay Creek entered San Pablo Bay along a remnant wetland corridor on the northwest shore between the Petaluma River and Sonoma Creek, 16 km west of Vallejo on the south side of Highway 37 (Fig. 3). When Tolay Creek was acquired by CDFW in 1981, there was no tidal flow to the upper 3 km of the creek between the north end of the Lower Lagoon and Highway 37. The Tolay Creek Restoration, managed by San Pablo Bay NWR and CDFW, was initiated in 1997 to increase tidal flow to 176 ha of the channelized lower creek and improve habitats for endemic tidal marsh species (USFWS 1997). The restoration included rehabilitation of tidal flow to four areas: the mouth, lower lagoon, mid channel, and upper lagoon (Fig. 1). In December 1998, restoration included removal of a levee to widen the mouth of Tolay Creek and increase flow and creation of a channel to connect the lower lagoon and a mitigation pond. The U. S. Geological Survey began monitoring the restoration in 1998 to assess the effects of the restoration.

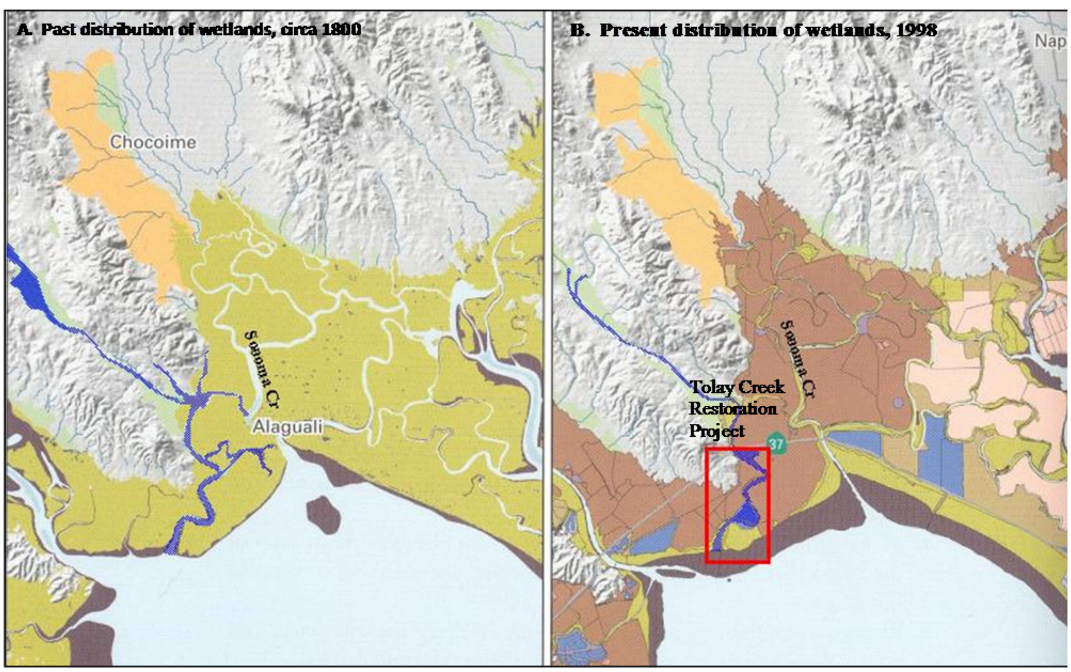

Figure 3. The Tolay Creek drainage (dark blue) in historic (A) and modern (B) times. The modern drainage (outlined in red) is much smaller and lacking Tolay Lake to the northwest and the lower creek network with tidal linkage to Sonoma Creek (Goals Project 1999).

Methods

Marsh Elevation

We conducted survey-grade elevation surveys at Tolay Creek marsh in June and July of 2009 and January of 2012 with a Leica Viva Real Time Kinematic (RTK) Global Positioning System (GPS) rover ($\pm$1 cm x, y, $\pm$2 cm z accuracy; Leica Geosystems Inc., Norcross, GA). The rover positions were received in real time from the Leica Smartnet system through a Code Division Multiple Access (CDMA) modem (www.lecia-geosystems.com). We used the WGS84 ellipsoid model for vertical and horizontal positioning. Positions were referenced to a nearby National Geodetic Survey (NGS) benchmark. The average measured vertical error for the benchmark (X 552 1956 Mare Island) throughout the study was $\pm$2.5 cm, similar to the reported precision for the RTK GPS. Elevation was surveyed along transects perpendicular to the watercourse. The Geoid09 model was used in calculating elevations from 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).

Picture 1. RTK GPS elevation Survey

We synthesized the survey data to create an elevation raster in ArcGIS 10.0 Spatial Analyst (ERSI 2009, Redlands, CA) with Kriging methods (5 x 5 m cell size). We used the exponential model for Ordinary Kriging and adjusted model parameters to minimize the root-mean-square error (RMSE), an internal measure of model performance. We then used the elevation models as the basis for subsequent analysis, such as tidal inundation patterns and vegetation correlations. We coordinated a topographical as-built survey conducted in 2000 by Ducks Unlimited to determine the elevation of the site a few years after restoration. A grid was developed from a series of 1:1,200 aerial photographs, ground-truthed to determine elevation, and rectified into an ArcGIS DEM coverage. This 1 m x 1 m gridcell elevation DEM was used as a baseline to compare to elevation change to 2012.

Channel Bathymetry

Bathymetric data was collected using a shallow-water echo-sounding system (Takekawa et al. 2010) comprised of an acoustic profiler (Reson, Inc.; Slangerup, Denmark, Navisound 210; 1 cm reported accuracy), a Leica RX1200 Real Time Kinematic (RTK) Global Positioning System (GPS) rover unit capable of collecting survey-grade elevation and x,y position data from the Leica Smartnet system (± 3 cm x,y,z accuracy; Leica Geosystems Inc., Norcross, GA), and a laptop computer mounted on a shallow-draft, portable flat-bottom boat (Bass Hunter, Cabelas, Sidney, NE) equipped with an electric trolling motor. We operated a variable frequency single-beam sonar transducer at a frequency of 200 kHz attached to the front of the boat in >30 cm of water. We calibrated the system prior to our surveys with a bar-check plate suspended below the transducer at a known depth and adjusted the sound velocity for salinity and temperature differences.

Picture 2. Bathymetric survey

We averaged 20-depth values generated each second by the echosounder with a program written in SAS 9.1. This process yielded 49,978 data points for the Tolay Creek channel and mud flat during 2012. We used Spatial Analyst in ArcGIS 10.1 (ESRI, Redlands, CA) to create a digital elevation model with 5 m x 5 m gridcells. We used the Inverse-Distance Weighting (IDW) method to interpolate the elevation point data. IDW allows use of a "barrier" polyline file that forces the interpolation to exclude selected points from gridcell elevation calculations to avoid distortion from nearby features such as deep channels or borrow ditches. We created barrier polylines by mapping known pond features from aerial imagery. If a large channel is delimited with a barrier polyline, data points from within the channel are not used to calculate the elevation for gridcells of the adjacent pond bottom. We validated bathymetric and data processing methods by comparing paired elevation estimates at the intersection of east-west and north-south transects. Average differences between points was <2 cm comparable to our earlier studies (e.g. Takekawa et al. 2010). All data were reported in meters with horizontal datum UTM NAD83 and vertical datum NAVD88.

Elevation Change and Sea-level Rise

Separate digital elevation models (DEMs) were developed from the 2000 elevation dataset and the 2009 and 2012 dataset. Elevation models were created with ArcGIS 10.1 Spatial Analyst (ERSI 2009, Redlands, CA) with Kriging methods (5 x 5 m cell size) and model parameters were adjusted to minimize the RMSE. We used the ArcGIS raster math tool to subtract the 2012 from the 2000 DEM to determine elevation changes over 12 years. SLR was based on monthly mean sea level data from 1897 to 2006 from the San Francisco Bay tide gage (http://tidesandcurrents.noaa.gov/sltrends; Cayan et al. 2006) that indicated a maximum increase of 2.58 cm possible over the 12-year study period. Any areas with increasing marsh surface elevations at or above 2.58 cm were considered to be "keeping pace" with SLR.

Marsh Vegetation Surveys

Initial vegetation surveys were conducted by the USGS between 1998 and 2000, which consisted of nine 15-m line transects spaced 500 m apart. The starting point of each 15 m transect was at a fixed location and the direction was randomly determined. A 0.25 m^2 quadrat was placed directly along transects at the beginning (0 m), middle (7 m), and end (9.5 m) of each transect. Quadrat measurements consisted of species identification, estimates of percent cover (total > 100%), maximum height (cm), and density (rooted individuals/m^2). Transect sampling provided information on species identification and canopy cover. This data is summarized as a baseline condition rather than a direct comparison to our data collected in 2009 and 2012. During our 2009 and 2012 surveys we recorded plant species richness and abundance concurrently with elevation surveys at 25% of the elevation points within a 0.25 m^2 quadrat. We measured height (mean, maximum, measured within 0.05 m) and estimated percent cover for each species. We categorized plant species into low, mid, high- marsh, and upland transition by measured elevation relative to mean sea level (MSL; m), which were used to relate to changing elevations.

Picture 3. Vegetation and elevation data were collected concurrently.

Water Level Monitoring

We deployed water level data loggers (Model 3001, 0.01% FS resolution, Solinst Canada Ltd., Georgetown, Ontario) at two locations in the marsh. One logger was placed close to the mouth of Tolay Creek and one logger was placed at the northern reaches of Tolay Creek to capture the local tidal cycle and inundation patterns throughout the channel. We collected continuous data every six minutes during 2012 to develop local hydrographs and inundation rates. Loggers were surveyed with the RTK GPS at

Picture 4. Continuous water-level data was collected.

the time of deployment and at each data download to correct for any movement. Water levels were corrected for local barometric pressure with data from independent barometric loggers (Model 3001, 0.05% FS accuracy, Solinst Canada Ltd., Georgetown, Ontario).

The local water level data was used to develop elevation and tidal datum relationships. Water level peaks throughout 2012 were averaged to create mean tide level (MTL), mean high water (MHW), and mean higher high water (MHHW) datums relative to NAVD88 for Tolay Creek. The development of local mean sea level (MSL) and mean low water (MLW) tidal datums were not possible because of the relative elevation of the water loggers in the marsh channels. All results are reported relative to local MHW calculated from local water data. However, MHW and MHHW are the most important metrics for understanding tidal marsh plant communities and their relationship to tides. Inundation was also compared between logger tidal datums, because inundation changes from the mouth to the upstream section of Tolay Creek. A tidal datum was also estimated for 2000 on the basis of our 2012 datum back cast to the year 2000 applying a mean sea-level rise of 0.00201 mm/year for the San Francisco Bay.

Results

Marsh Elevation Surveys

During 2009 and 2012, we conducted elevation surveys and collected 675 points in the marsh. The 2009 survey included 165 points located near the creek mouth, whereas the 2012 survey included 510 points located at the upstream near the upper lagoon (Fig. 4, 5). The interpolated DEMs had a root-mean-square error (RMSE) of 0.1 m (Table 2). Elevation surveys ranged from 0.79 to 2.25 m (mean = 1.60 m). Points ranged from 0.79 to 2.08 m (mean = 1.73 m) near the mouth and from 0.99 to 2.25 m (mean = 1.53 m; Table 1) upstream. Overall, elevation was within a narrow range, as 74% of surveyed points fell between 1.5 and 1.8 m (NAVD88; Fig. 7). At the mouth, 67% of the points were between 1.7-1.9 m, whereas at the mouth, 77% were between 1.5-1.7 m (NAVD 88; Fig. 9, 11, 13). Tolay Creek is considered a high elevation marsh, and we found 84% of the marsh located above MHW at an average of 1.54 m (Fig. 8). Since tidal datums differed between the Tolay Creek mouth and loggers located in the northern lagoon, comparison was made comparing MHW (Fig. 10, 12, 14). The upstream marsh was at lower elevation relative to MHW and was inundated more often than the area near the creek mouth.

Table 1. Summary of elevation and vegetation data collected at Tolay Creek [ha, hectare, m, meter; n, num]

Year	Site	Area (ha)	Elevation (n)	Mean Elevation (m)	Elevation Range (m)	Vegetation (n)
2009	**mouth**	49.2	222	1.73	1.29	222
2012	**upstream**	25.9	447	1.53	1.26	119
Combined	**overall**	75.1	669	1.60	1.46	341

Table 2. ArcGIS elevation model root-mean-square error (RMS) and standard error (SE) by area.

Year	Area	Model RMS	Model Mean SE
2009	**mouth**	0.154	0.13
2012	**upstream**	0.156	0.13

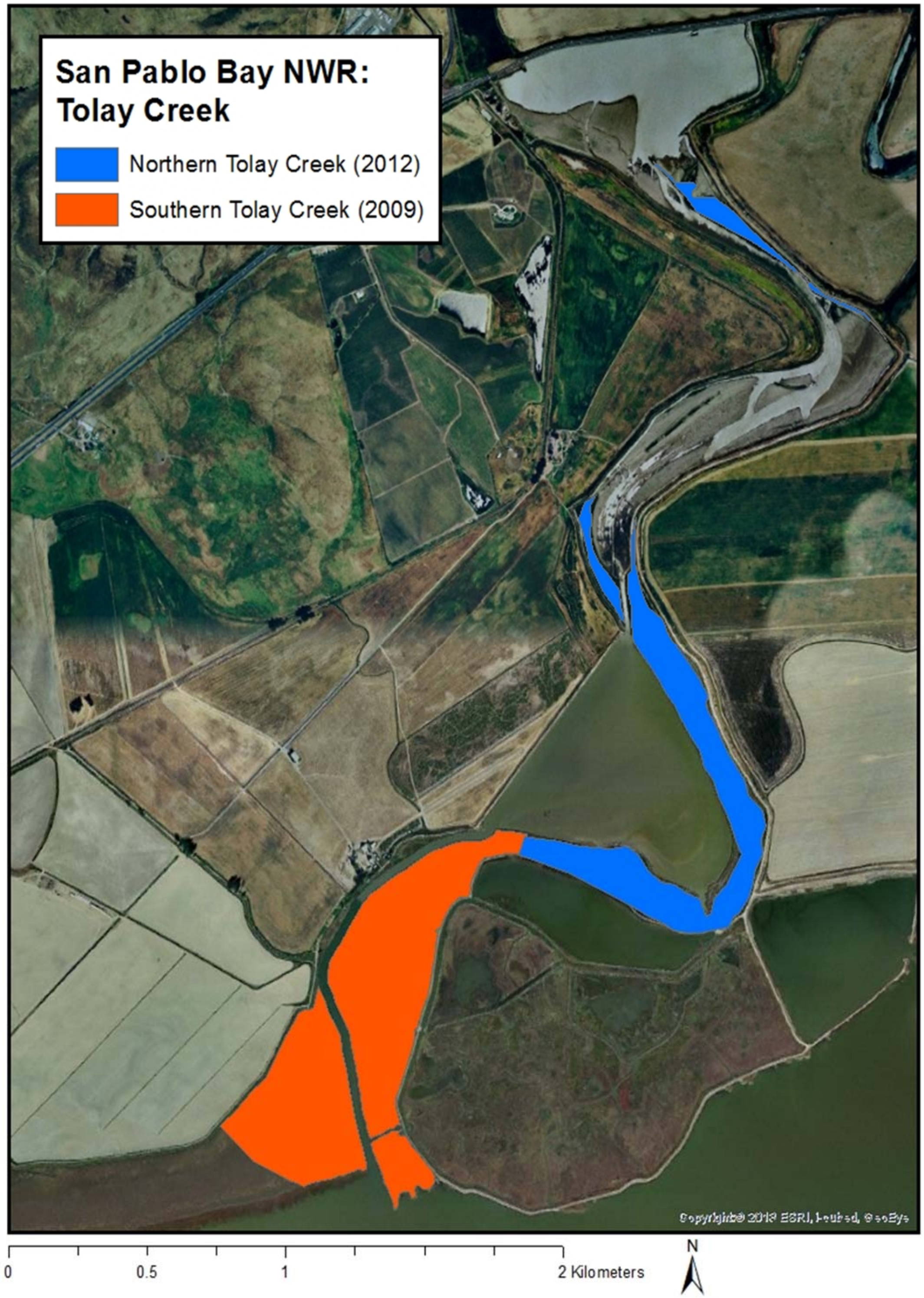

Figure 4. Tolay Creek mouth and upstream marsh parcels

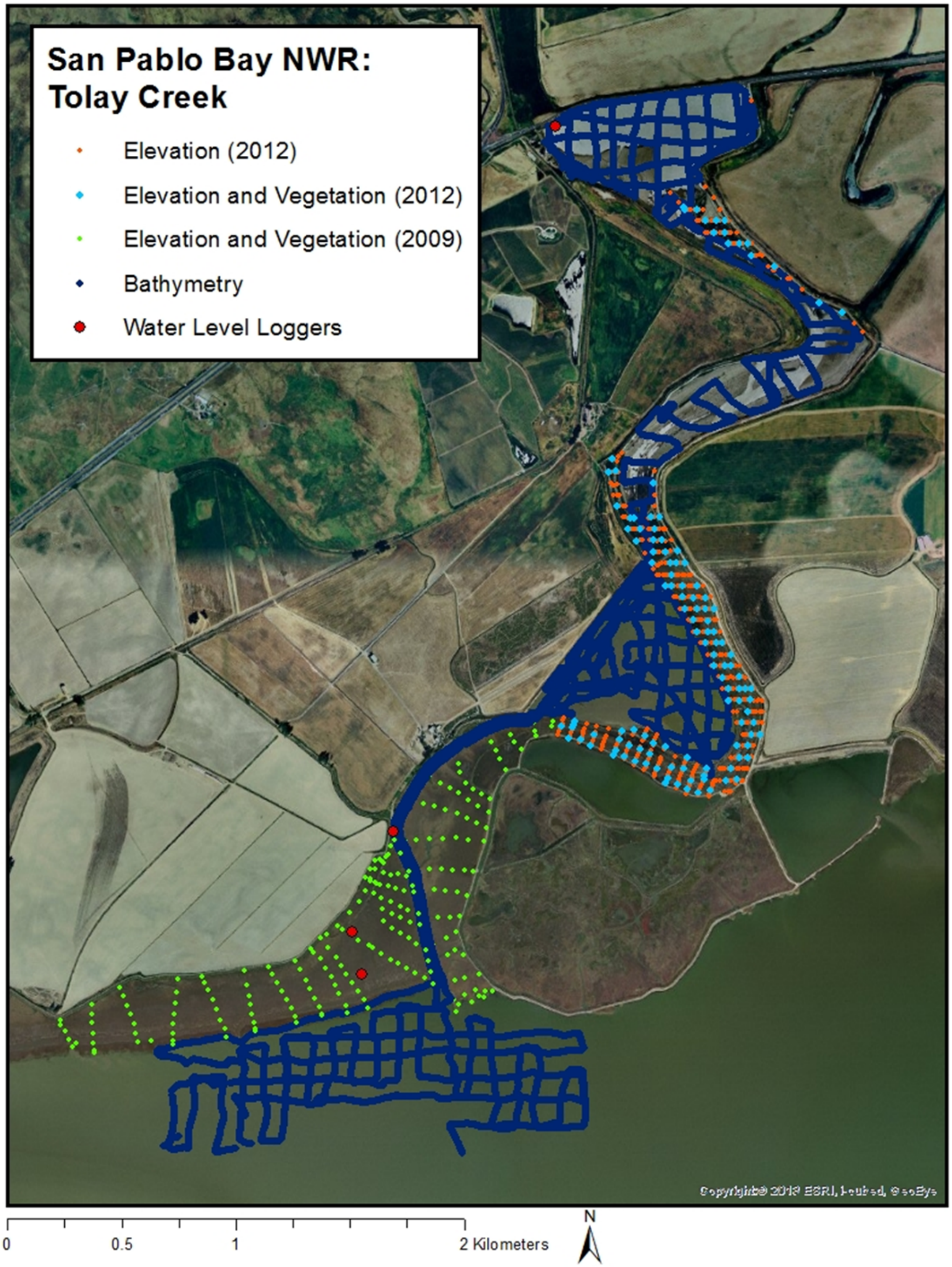

Figure 5. Elevation, vegetation, and tidal level samples collected at Tolay Creek.

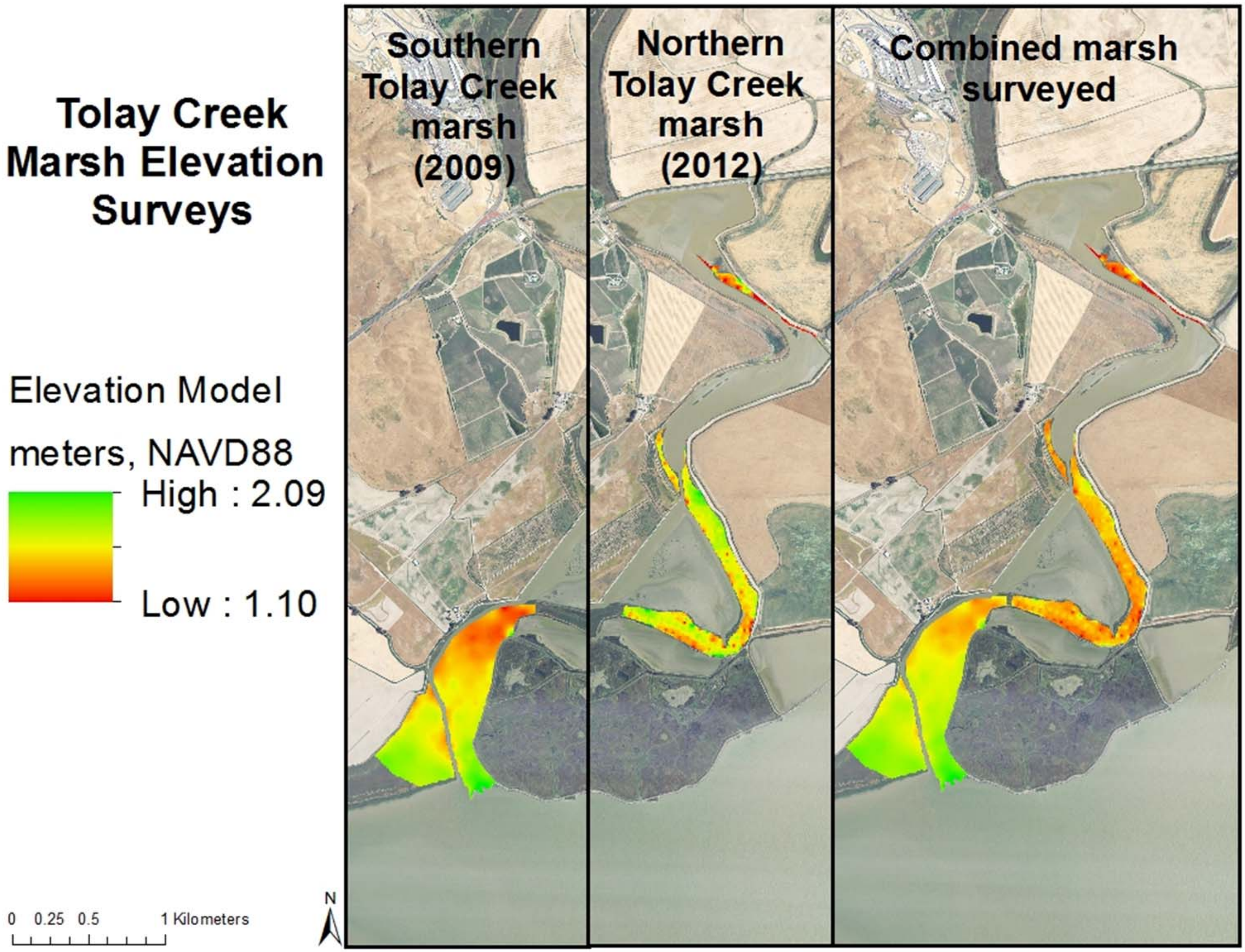

Figure 6. DEMs for 2009 (mouth) and 2012 (upstream) elevation surveys at Tolay Creek.

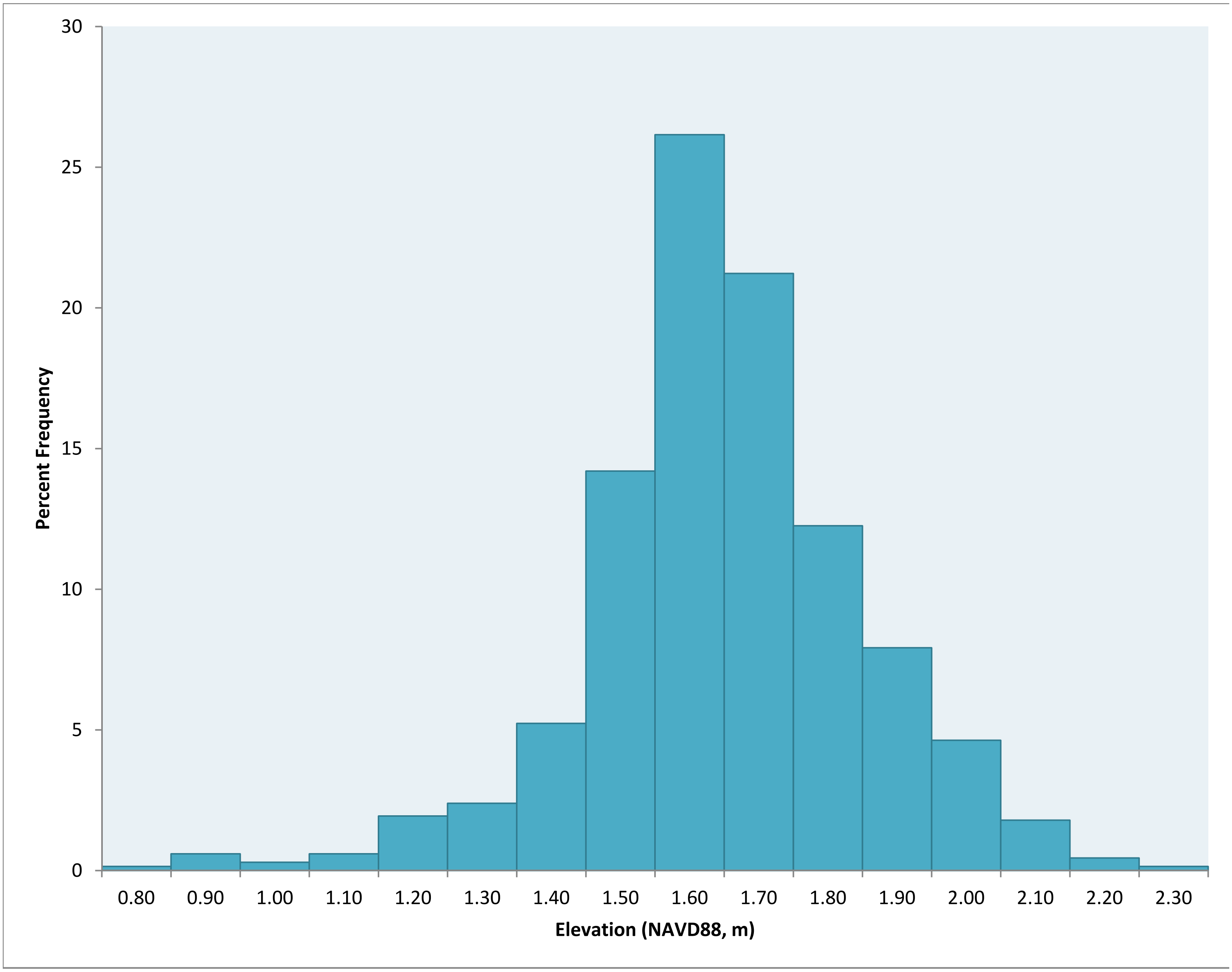

Figure 7. Percent frequency of RTK GPS elevation points (meters, NAVD88) for the Tolay Creek marsh plain.

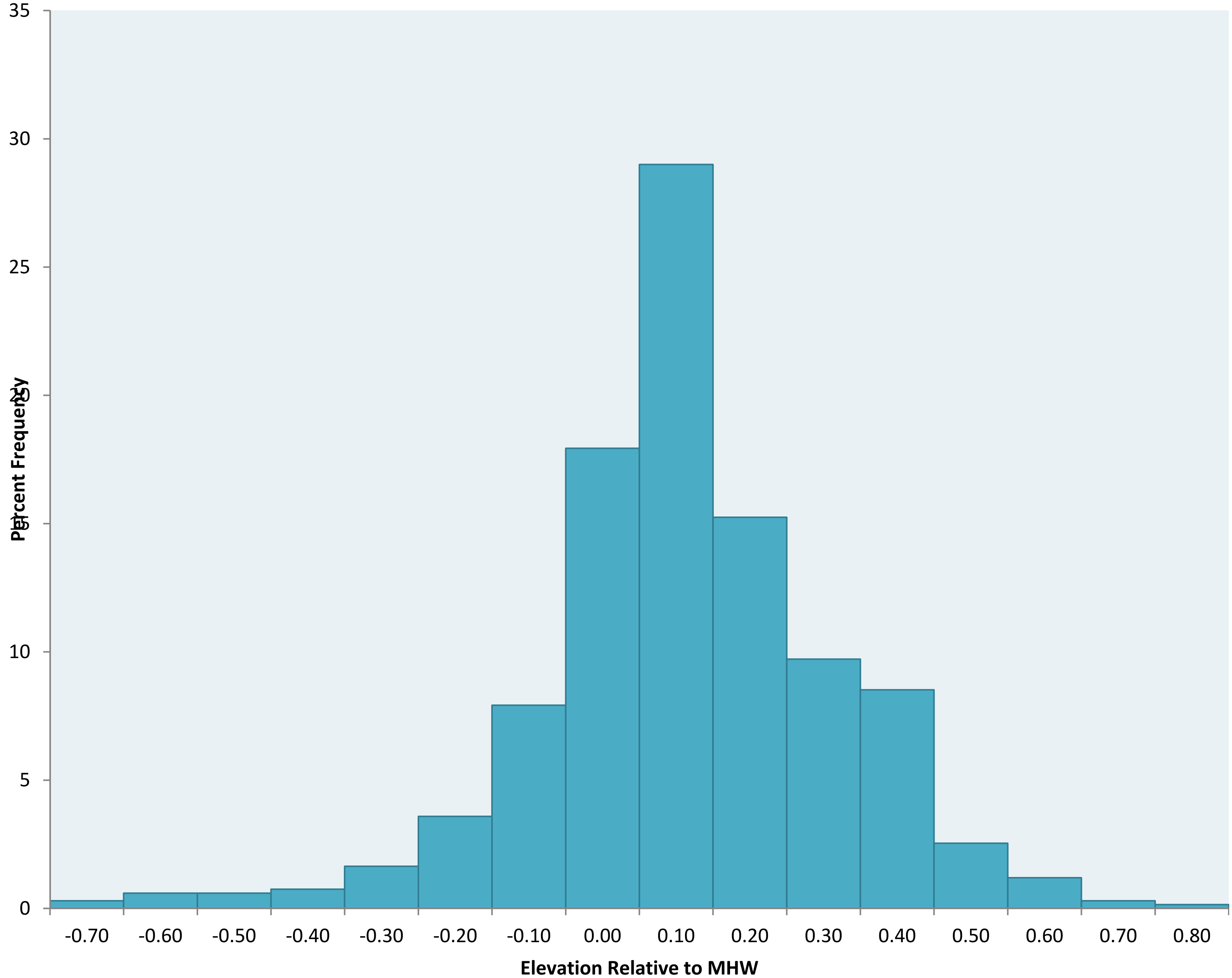

Figure 8. Percent Frequency of all marsh RTK GPS elevation measurements taken relative to an averaged MHW of the upper and lower Tolay Creek water level loggers (MHW=1.54 m).

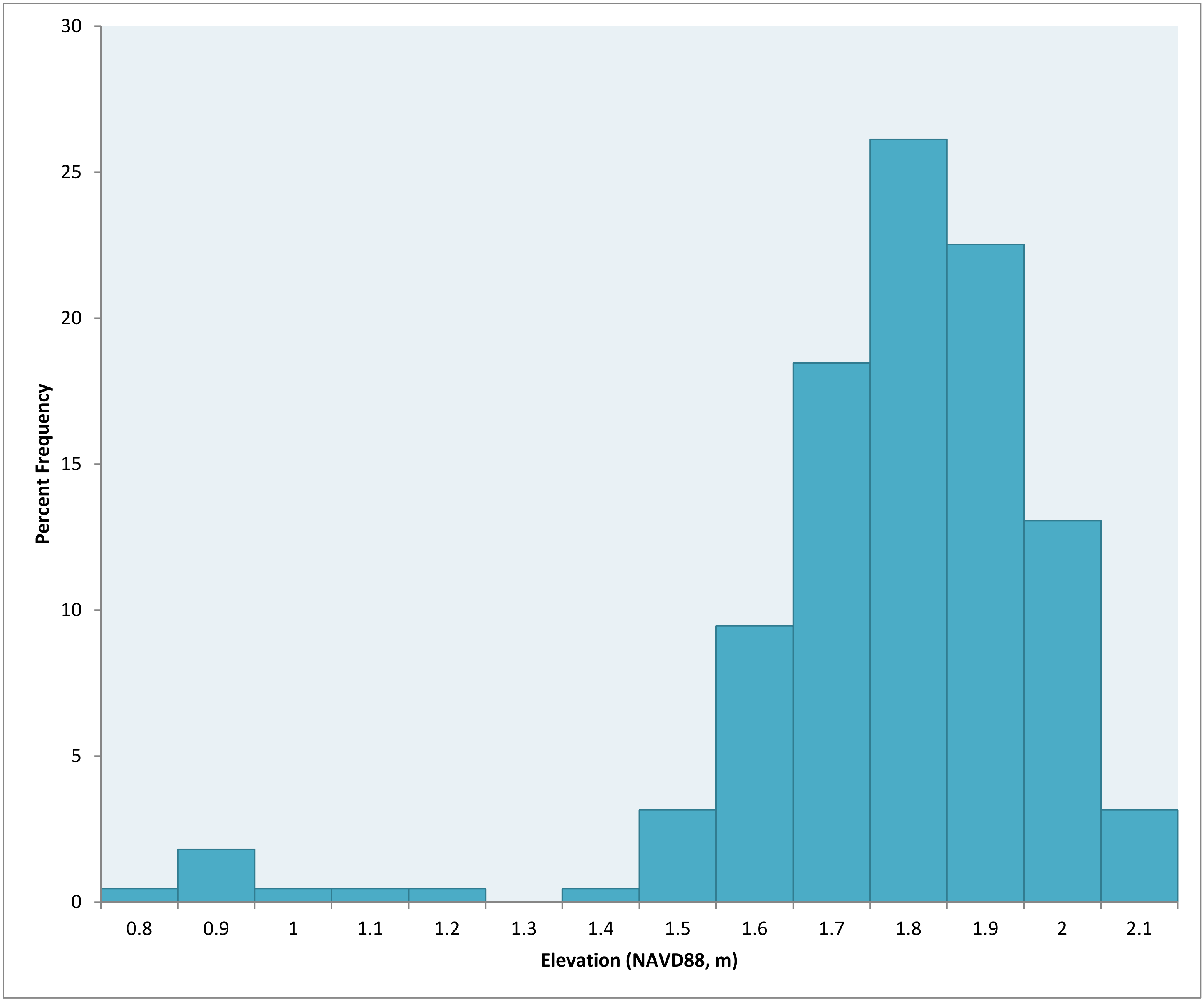

Figure 9. Percent frequency of marsh elevation points measured by RTK GPS (meters, NAVD88) at the Tolay Creek mouth.

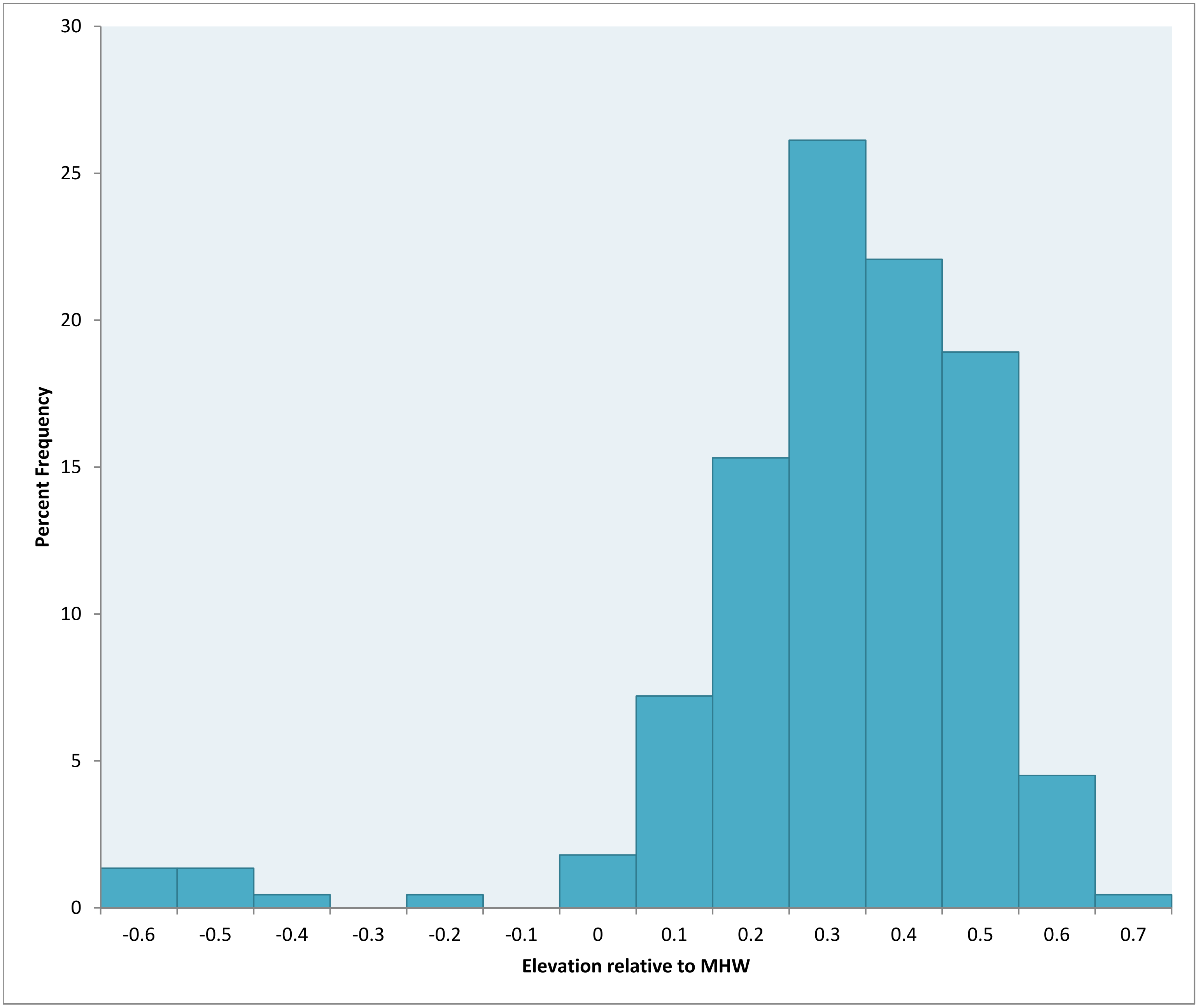

Figure 10. Percent frequency of marsh RTK GPS elevation points measured during 2009 at Tolay Creek mouth relative to MHW measured at the adjacent logger (MHW= 1.47).

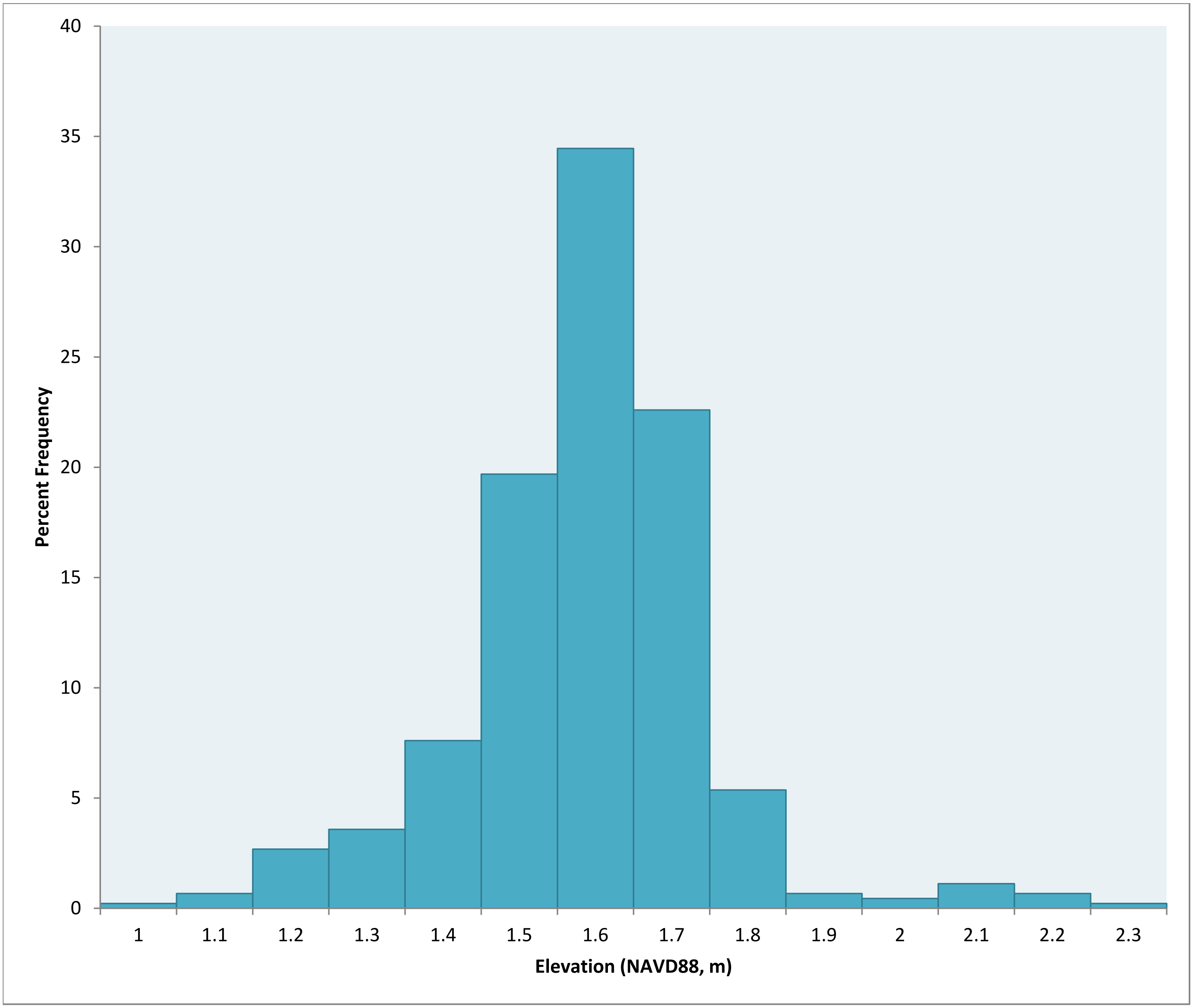

Figure 11. Percent frequency of marsh RTK GPS elevation points (meters, NAVD88) measured during 2012 at northern Tolay Creek upstream marsh.

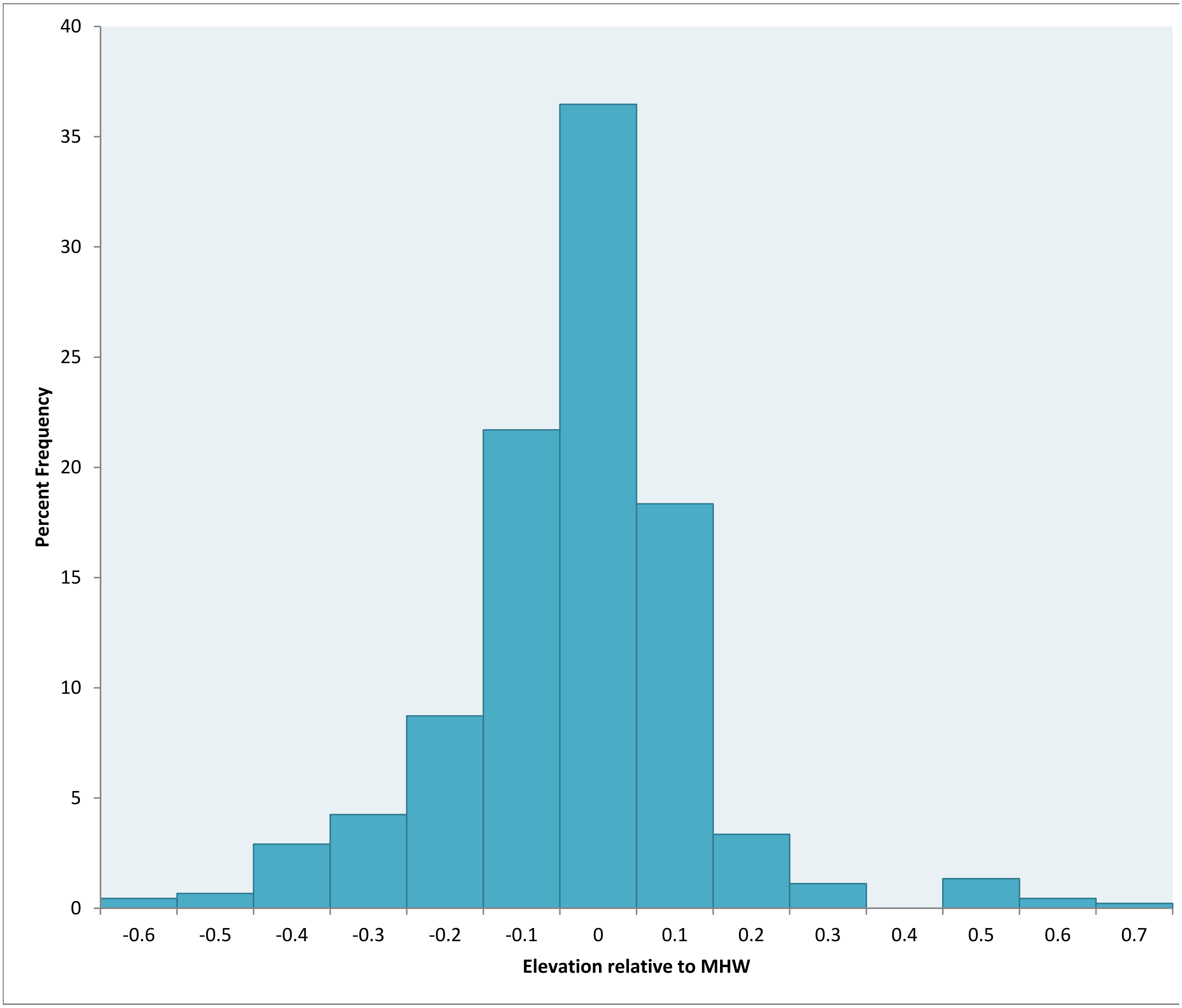

Figure 12. Percent frequency of marsh RTK GPS elevation measurements taken during 2012 at northern Tolay Creek marsh relative to MHW measured at northern Tolay Creek logger (MHW=1.62).

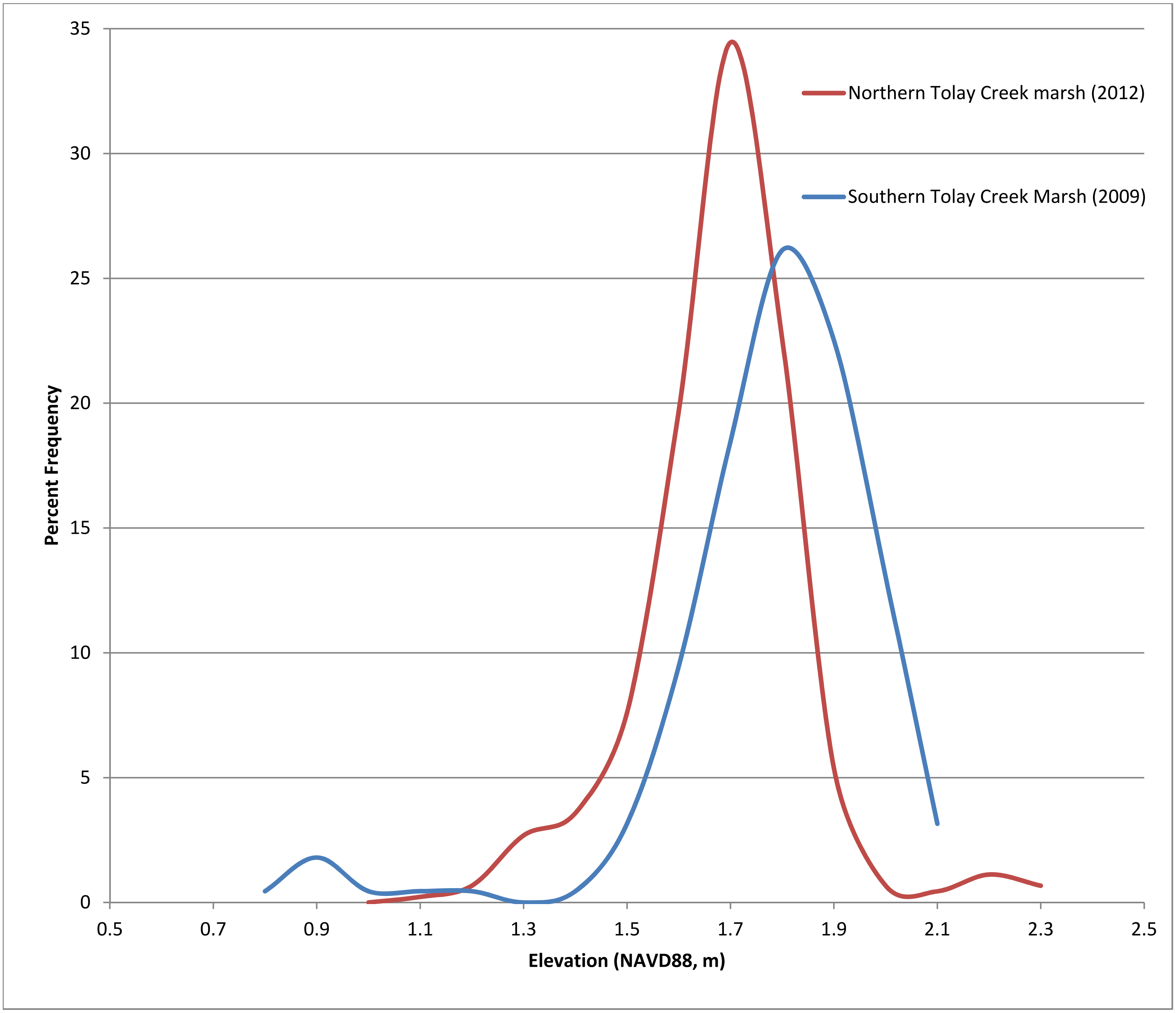

Figure 13. Comparison between southern mouth and northern upstream marsh elevation measurements (meters, NAVD88) at Tolay Creek.

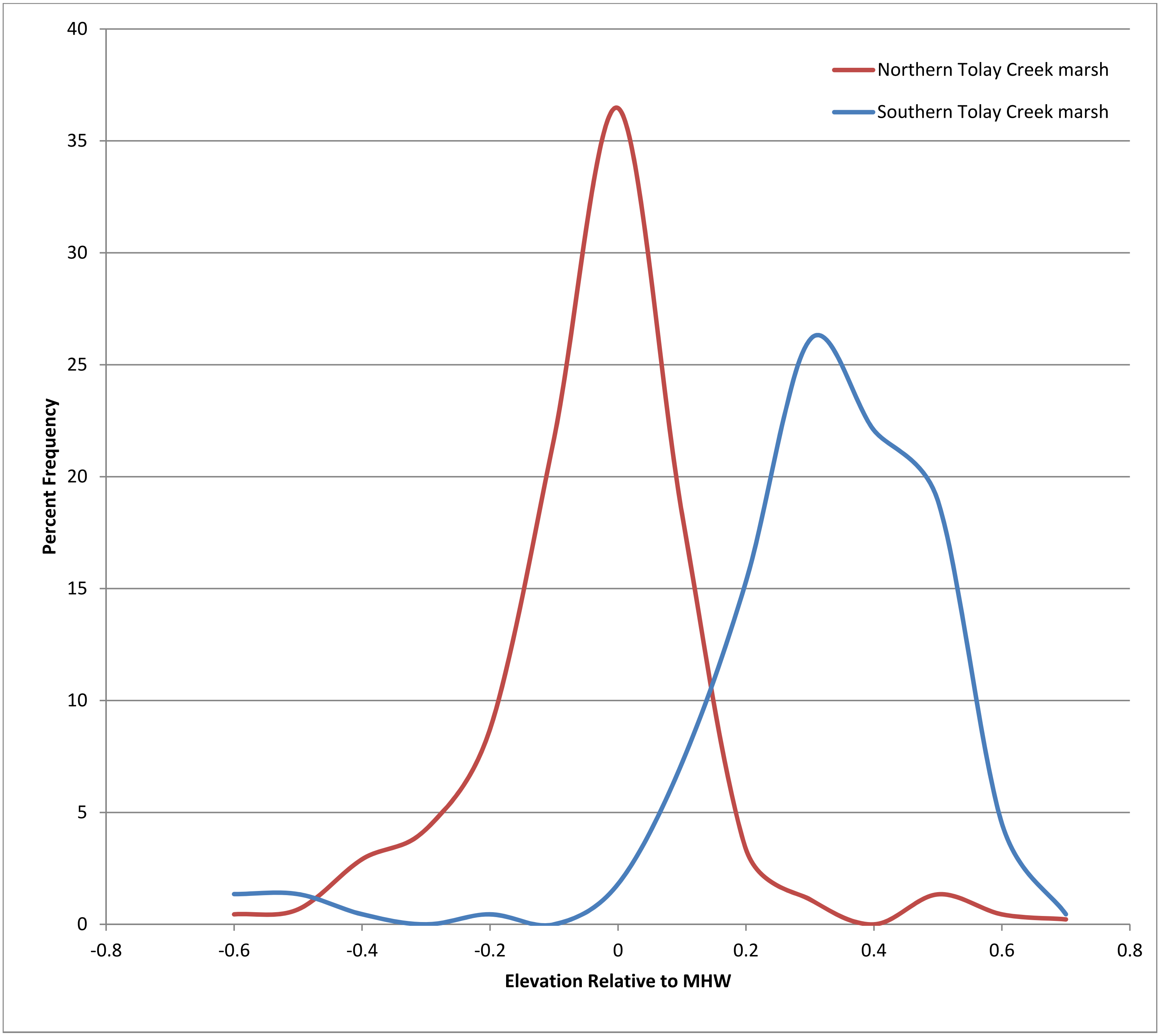

Figure 14. Percent frequency of Tolay Creek elevation points taken at the southern mouth section that was inundated less frequently than the northern upstream section relative to MHW measured at nearby mouth (MHW=1.47) and upstream (MHW=1.62) water level loggers.

2000 Elevation Survey

The DEM for 2000 ranged from -3.22 to 15.64 m with a mean of 0.03 m. The northern upstream section of the marsh had a range of -1.22 to 2.74 m (mean = 0.78 m), whereas the southern mouth section had a range from -0.75 to 2.39 m (mean = 1.04 m). This model gave us the baseline to compare elevation change of the Tolay Creek marshes, mudflats, and upland areas.

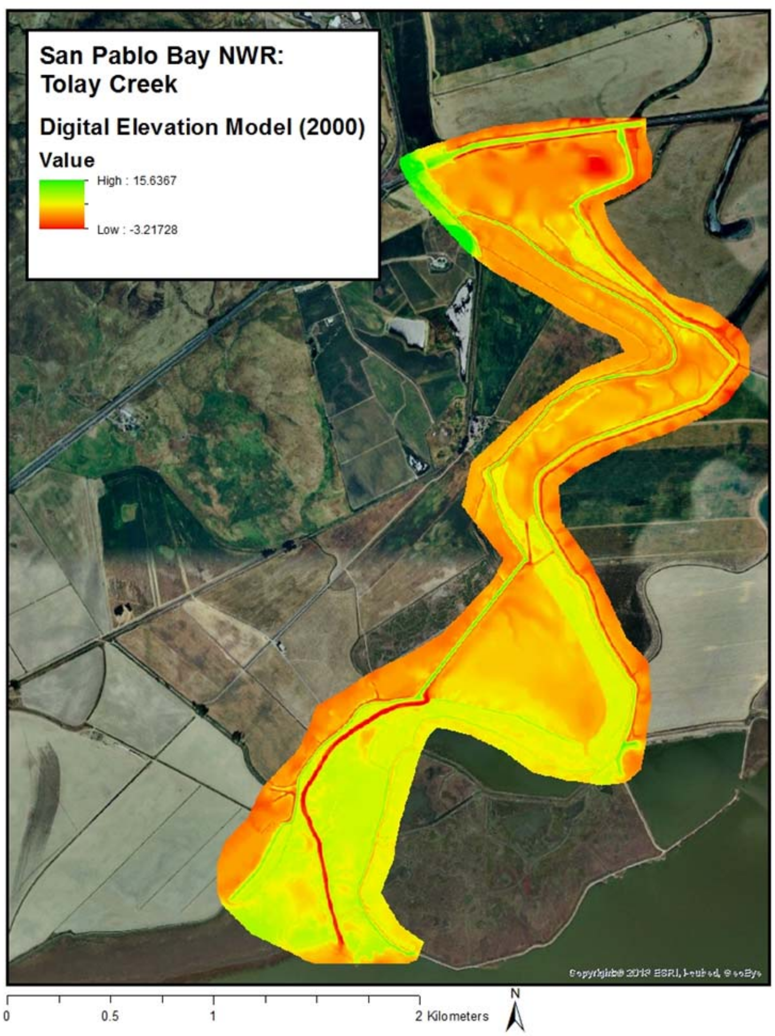

Figure 15. Post restoration (2000) digital elevation model conducted by Ducks Unlimited.

Channel Bathymetry

Bathymetry surveys were conducted on 221 hectares of Tolay Creek channel and mud flat during high tide (Fig. 5, 16). During the survey, 49,978 data points were used to create DEM coverage which had an elevation range from -6.60 to 2.10 (mean = 0.18 m; Fig. 16-17). Compared to the local tidal datum, 60% of the data points were below mean tide level (MTL) and 98% of the points were below MHW (Fig. 18; NAVD88, m). The 2% of elevation points that were above MHW were located in the northern lagoon that has been accumulating sediment. Bathymetry surveys of the mud flat showed an elevation range of - 2.0 to 2.1 m (mean = 1.03 m). Only 5% of data points in the mud flats were above MHW (Fig. 19, 20).

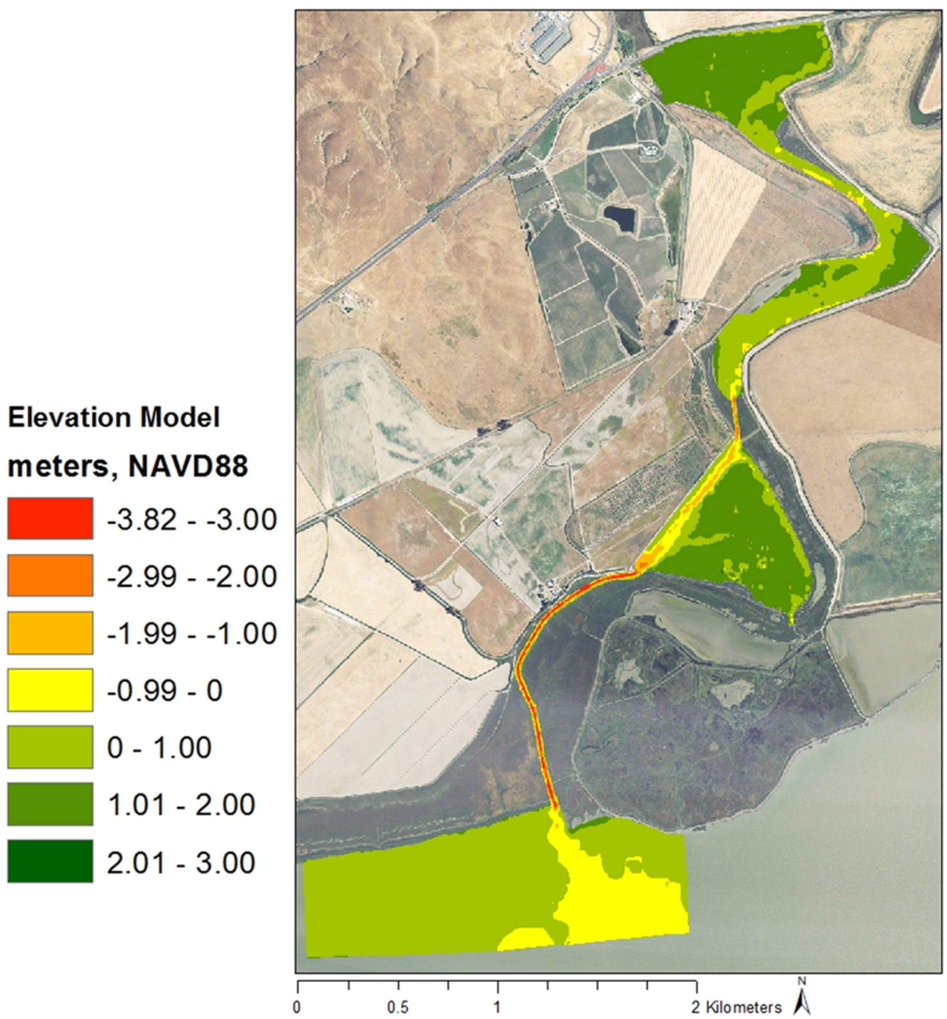

Figure 16. Bathymetric survey of Tolay Creek and adjacent shoals.

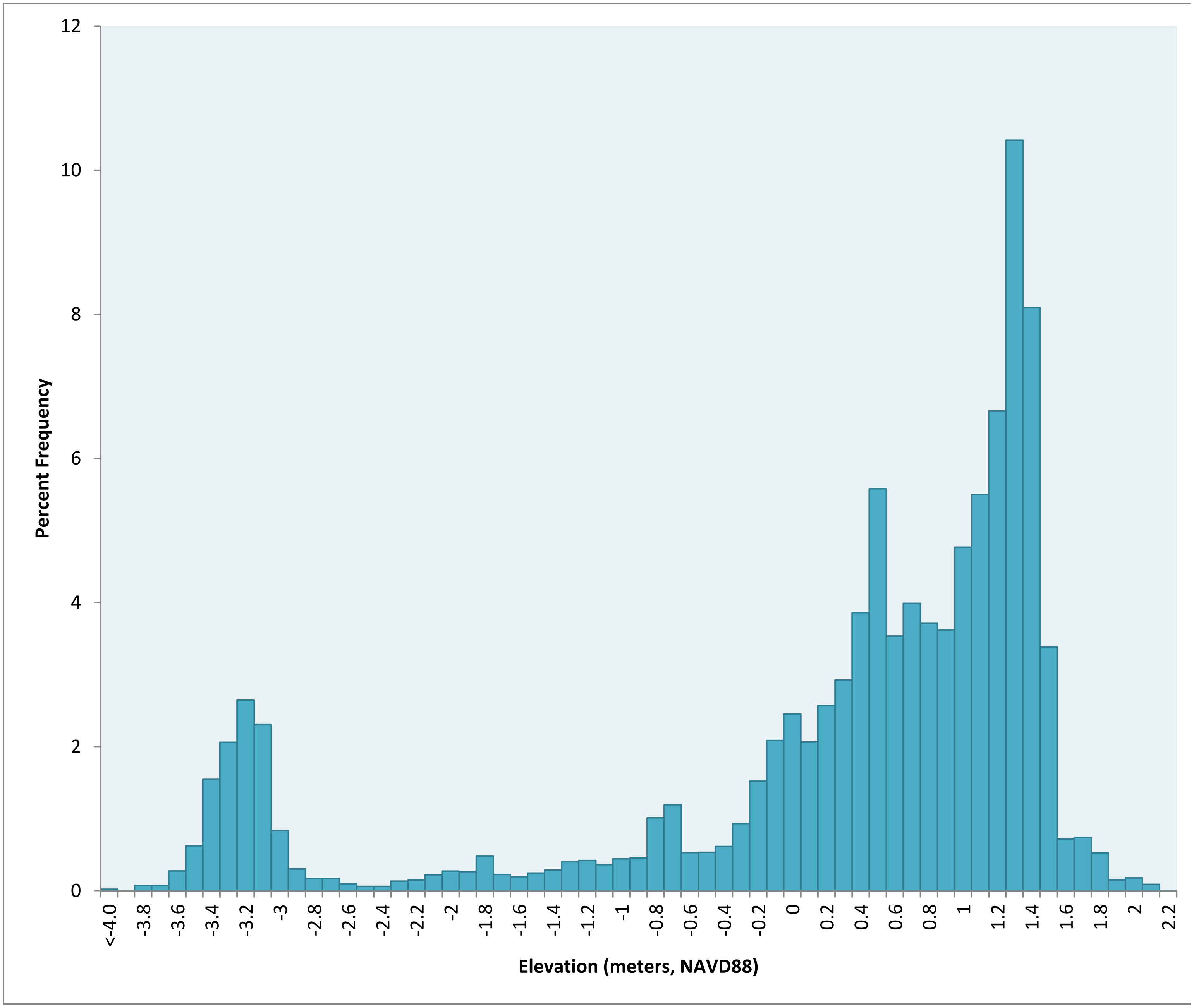

Figure 17. Percent frequency of bathymetric measurements of Tolay Creek and adjacent shoals during 2012 surveys (meters, NAVD88).

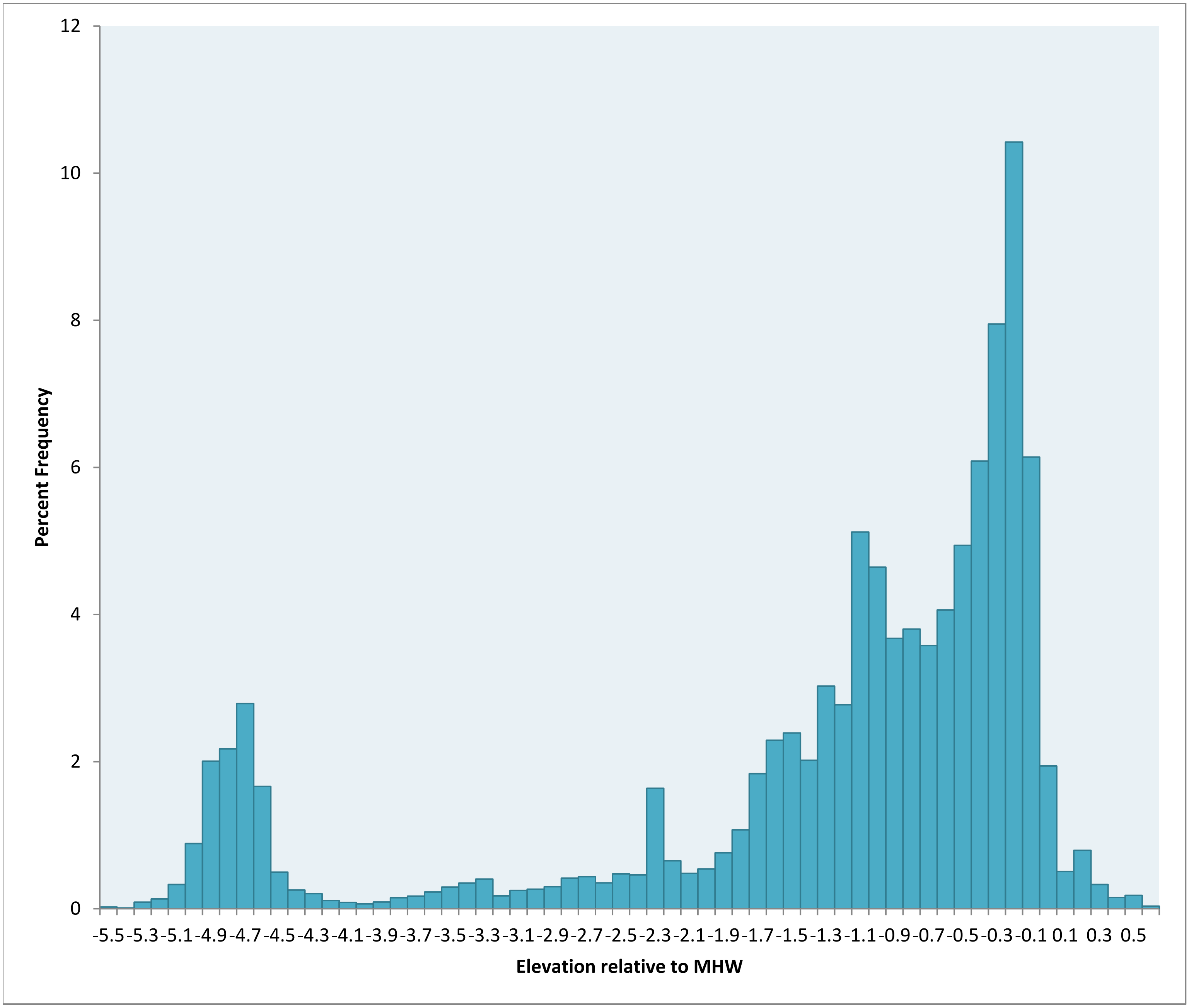

Figure 18. Percent frequency of bathymetric measurements of Tolay Creek and adjacent shoals during 2012 surveys relative to MHW (meters, NAVD88).

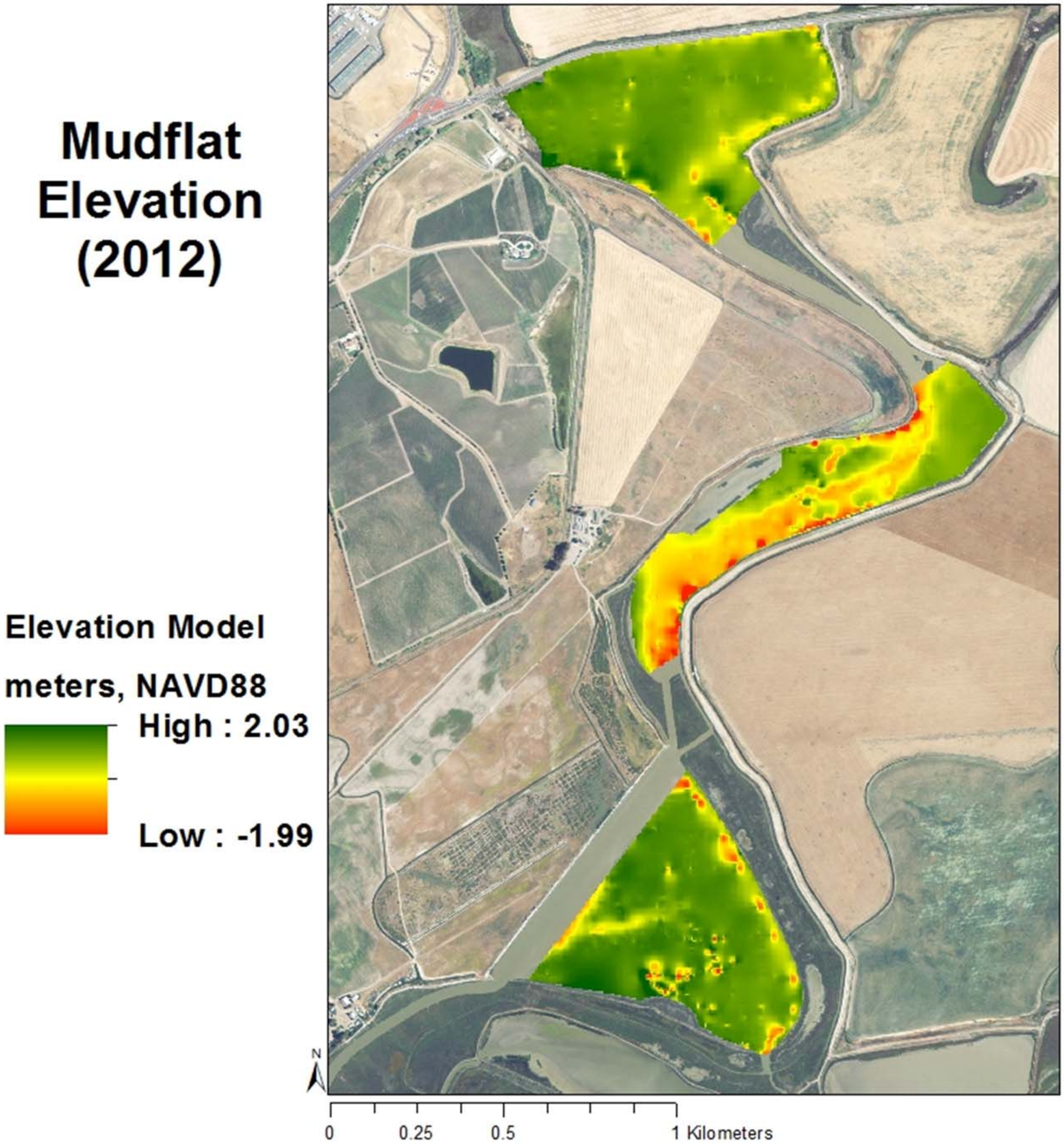

Figure 19. DEM of Tolay Creek mudflats created from 2012 bathymetric survey.

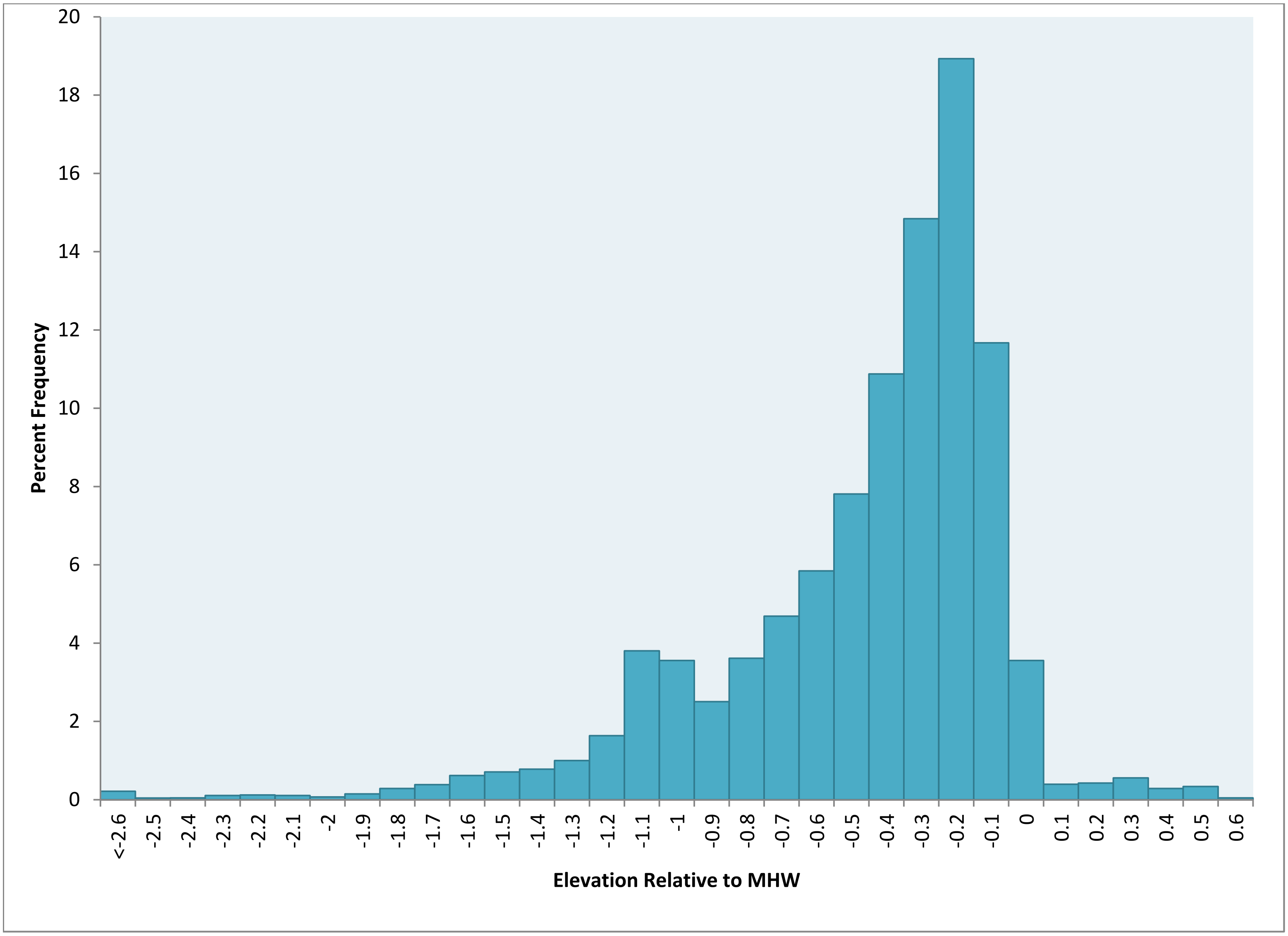

Figure 20. Percent Frequency of elevation measurements of Tolay Creek mud flats relative to MHW (MHW=1.54, average between upper and lower Tolay Creek water level loggers).

Restoration Elevation Change

To assess twelve years of restoration progress, elevation data collected during 2012 was compared to the elevation data collected in 2000. The Tolay Creek study area showed a post restoration elevation increase. The overall area had a change in elevation that ranged from - 4.57 m to 10.47 m with a mean change of 0.96 m (Fig 21-23). There was an increase in elevation at 96% of the DEM gridcells showing accretion throughout most of the area (Fig. 21). The majority of the elevation change (54%) fell between 0.6 m and 1.2 m, with a range of 0.6 m (Fig. 21).

The mudflat zone showed the largest elevation increase when compared to the vegetated marsh and upland zones. Overall, mud flats increased in elevation and especially in the northern lagoon section. In 2000, the mean elevation of the mud flat was -0.41 m ranging from -2.84 m to 2.50 m, whereas in 2012, the mean elevation was 1.05 m ranging from -2.0 m to 2.05 m. This was an increase in mean elevation of +1.47 m for the mud flat between 2000 and 2012 (Fig. 24-26). The majority (53%) of the elevation change fell between 1.1 and 1.8 meters with a range of 0.7 meters (Fig. 25).

As would be expected the vegetated marsh showed the smallest increase in elevation. In 2000, the mean elevation for the salt marsh was 0.76 m ranging from -1.21 to 2.74 m, whereas in 2012, the mean elevation was 1.54 m ranging from 1.11 to 2.09 m. This is an increase in mean elevation of +0.78 m (Fig. 27-29). The majority (57%) of the change was between 0.5 m and 0.9 m or a range of 0.4 meters (Fig. 28).

Comparison of the upland agricultural zone was conducted with the 2000 DEM compared with LiDAR elevations from 2012. The upland agricultural zone had the second largest increase in elevation change of the three zones. In 2000, the mean elevation for the upland agriculture land was -0.16 ranging from -3.15 m to 15.64 m, but in 2012, the mean elevation was 0.75 m ranging from -3.48 m to 21.64 m. This was an increase in mean elevation of +0.91 m (Fig. 30-32), and 57% of the upland elevation change was between 0.6 m and 1.00 m (Fig. 31).

Sea-level Rise

When the 12-year elevation change was compared to local rates of SLR during the same time period we found that 95% of the area outpaced SLR (Fig. 33). Most of the restoration area experienced accretion rates that were 20-50 times greater than SLR during the same time period (Fig. 34). Deep water portions of the Tolay Creek channel experienced a decrease in elevation probably due to increased channelization from tidal flow. The upper lagoon experienced accretion rates 50 times greater than SLR, but the majority of the area and surrounding marsh had 21-50 times greater than SLR.

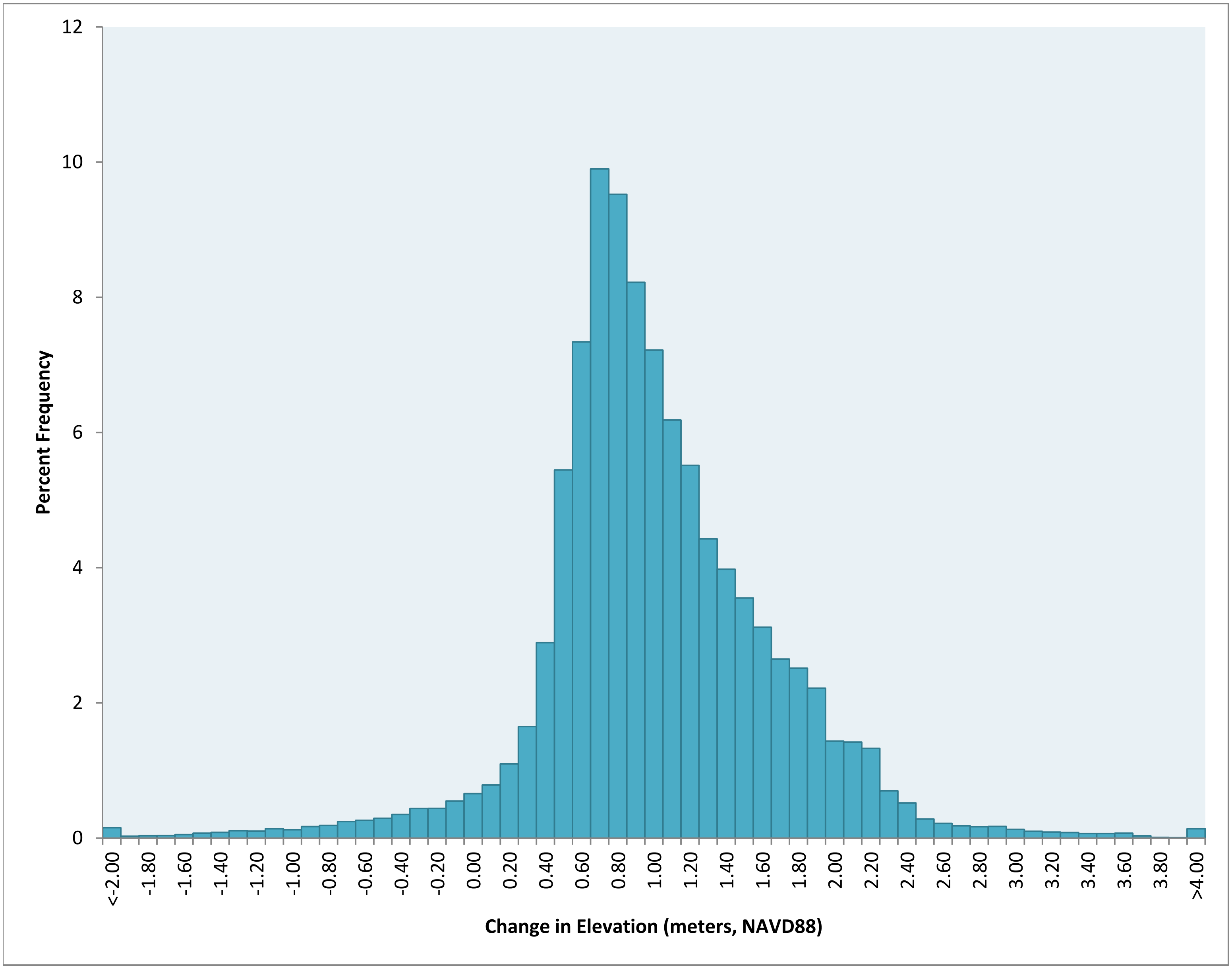

Figure 21. Percent frequency of overall elevation change of the entire Tolay Creek study area between 2000 and 2012.

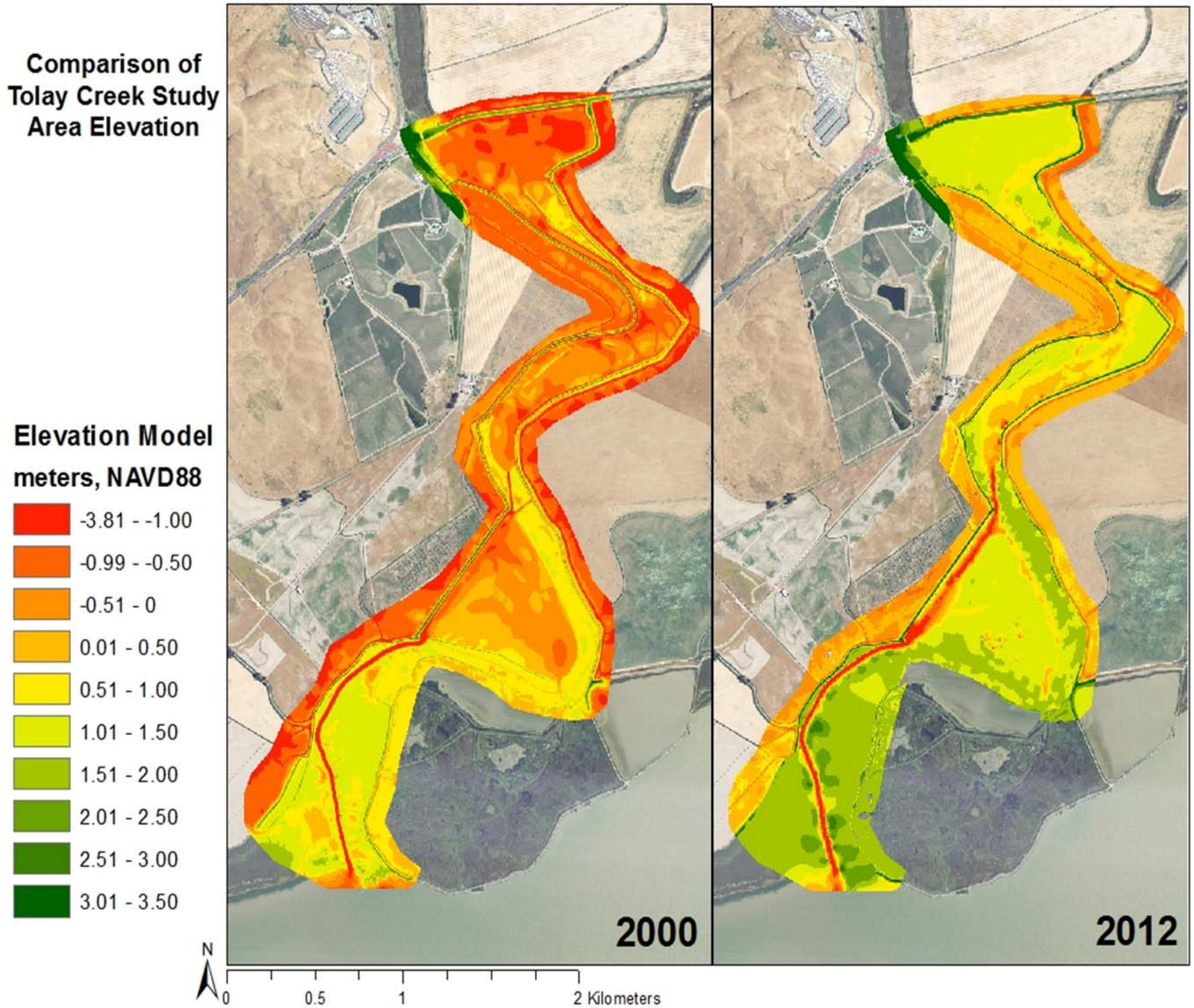

Figure 22. Digital elevation model of Tolay Creek study area comparing elevation between 2000 and 2012.

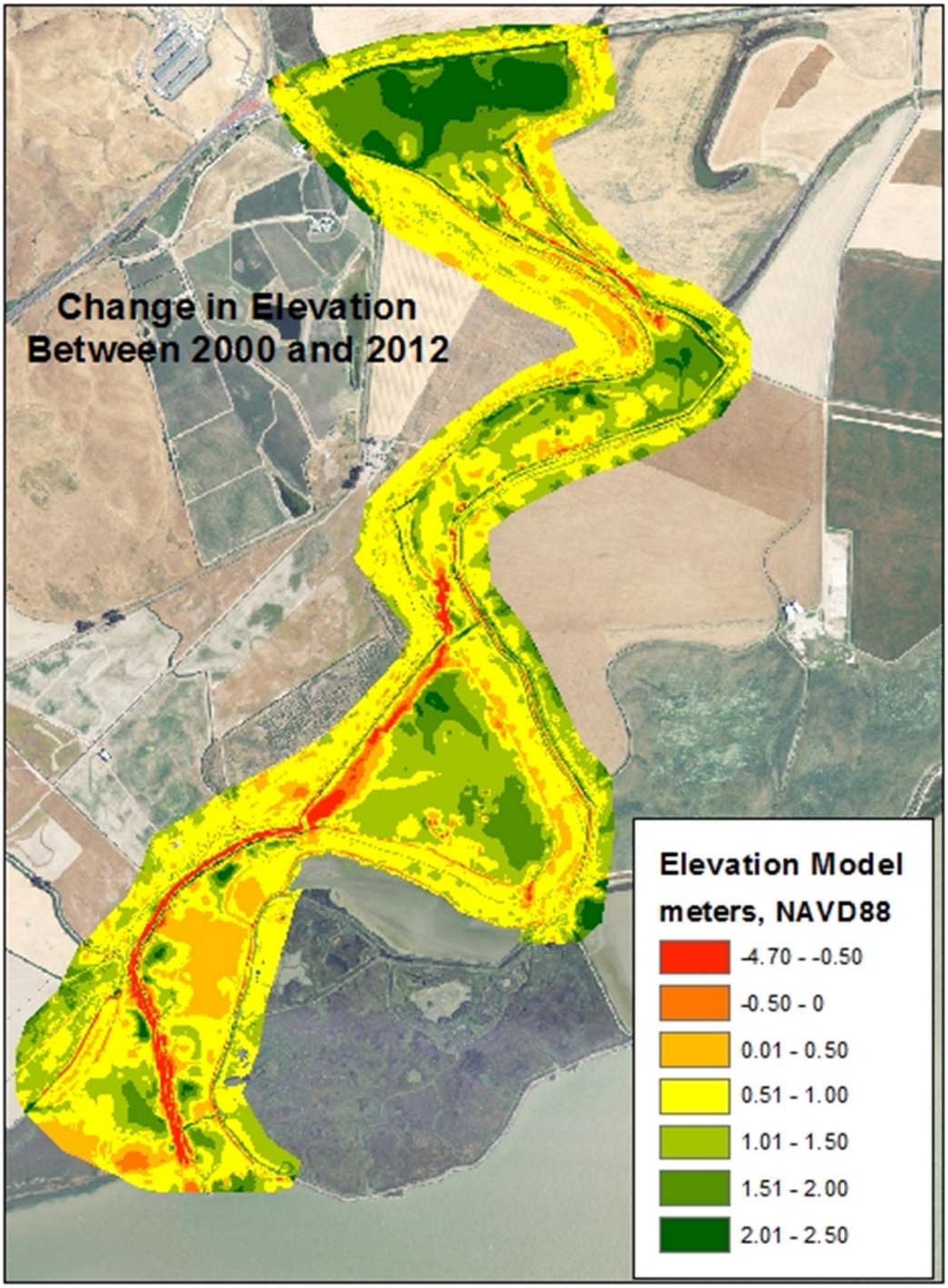

Figure 23. Digital Elevation model showing elevation change for the entire Tolay Creek study area between 2000 and 2012.

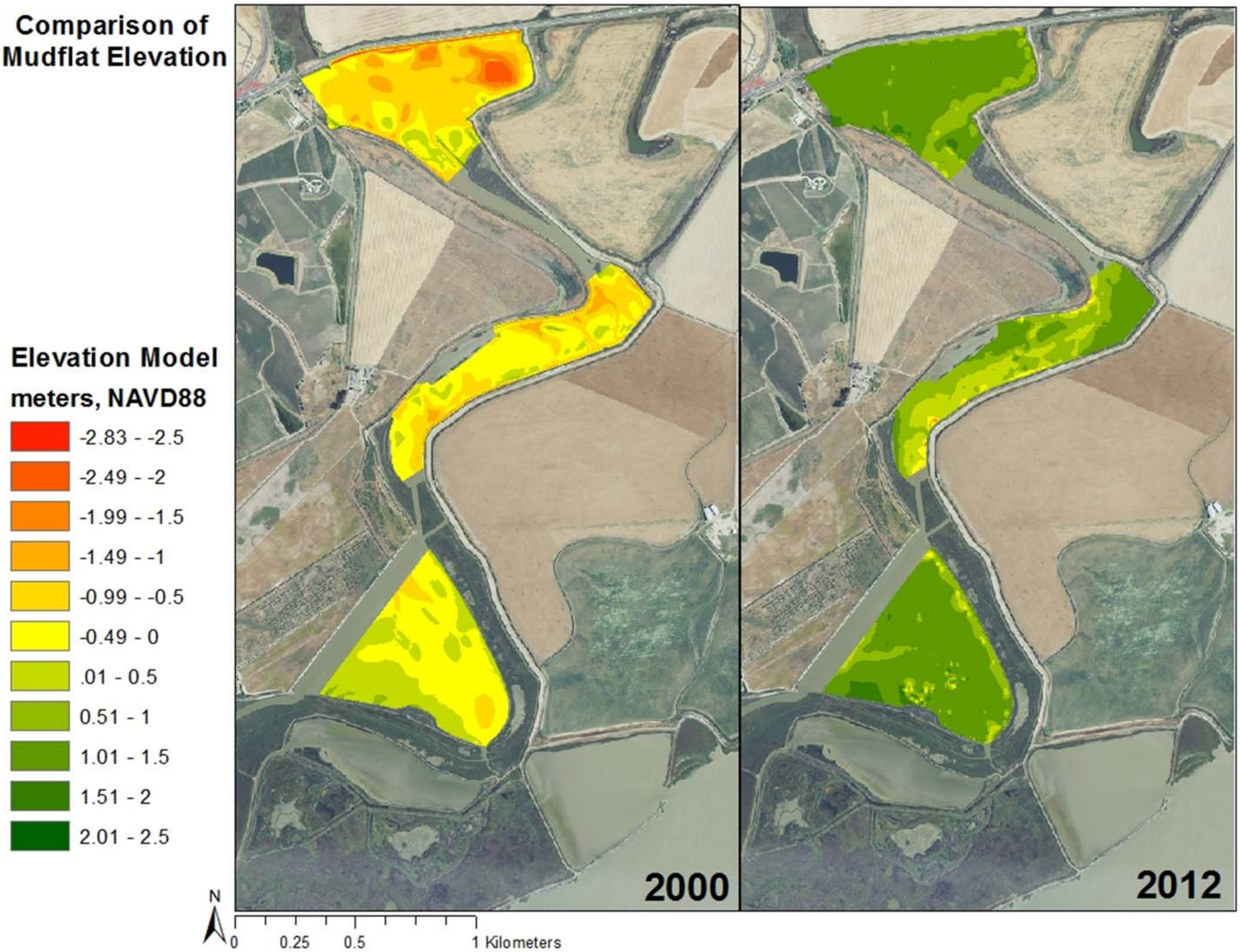

Figure 24. Digital elevation model of Tolay Creek mud flat comparing 2000 to 2012.

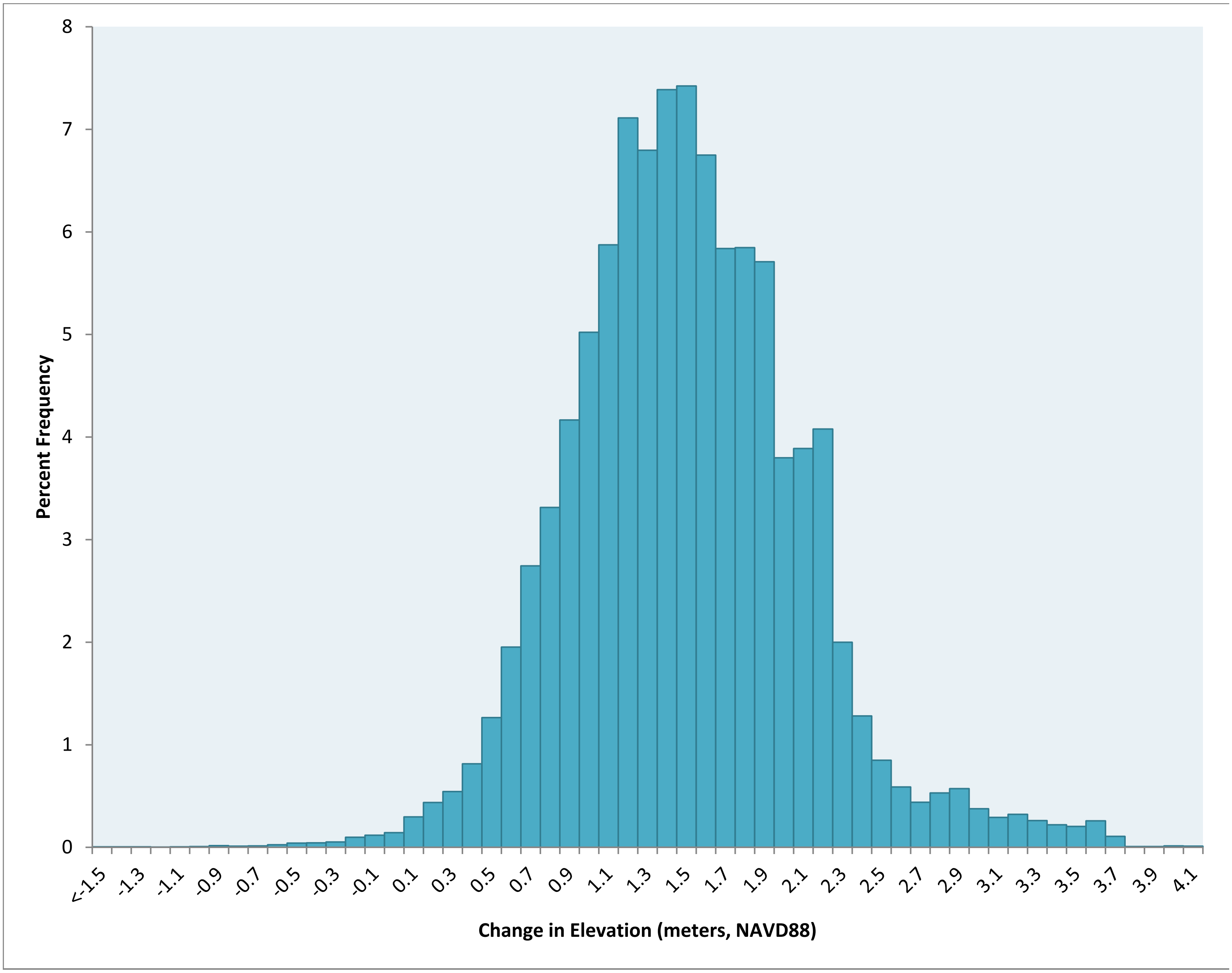

Figure 25. Change in elevation of Tolay Creek mudflat between 2000 and 2012.

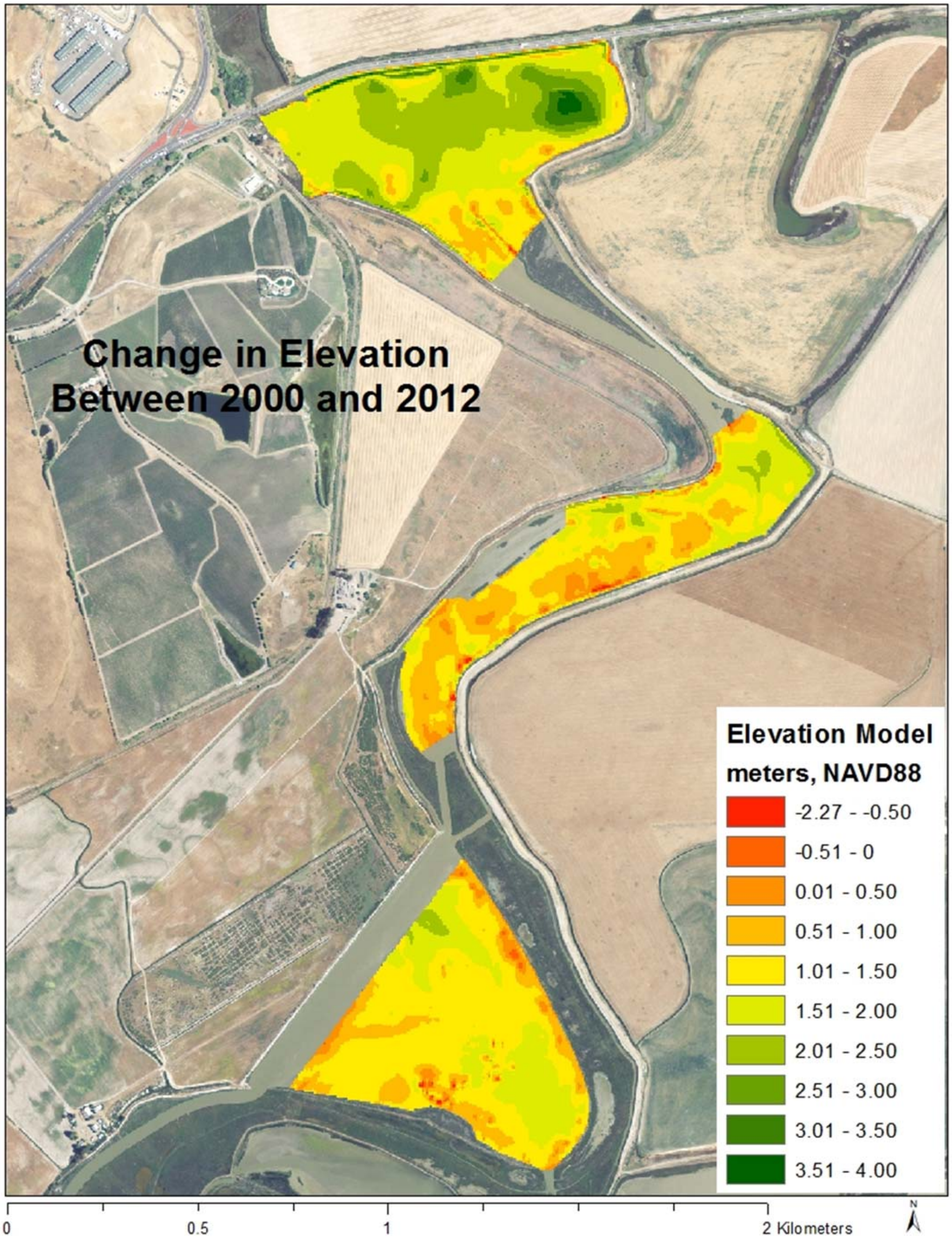

Figure 26. Digital elevation model of Tolay Creek mud flats showing elevation change between 2000 and 2012. Overall mud flats increased in elevation especially in the northern lagoon.

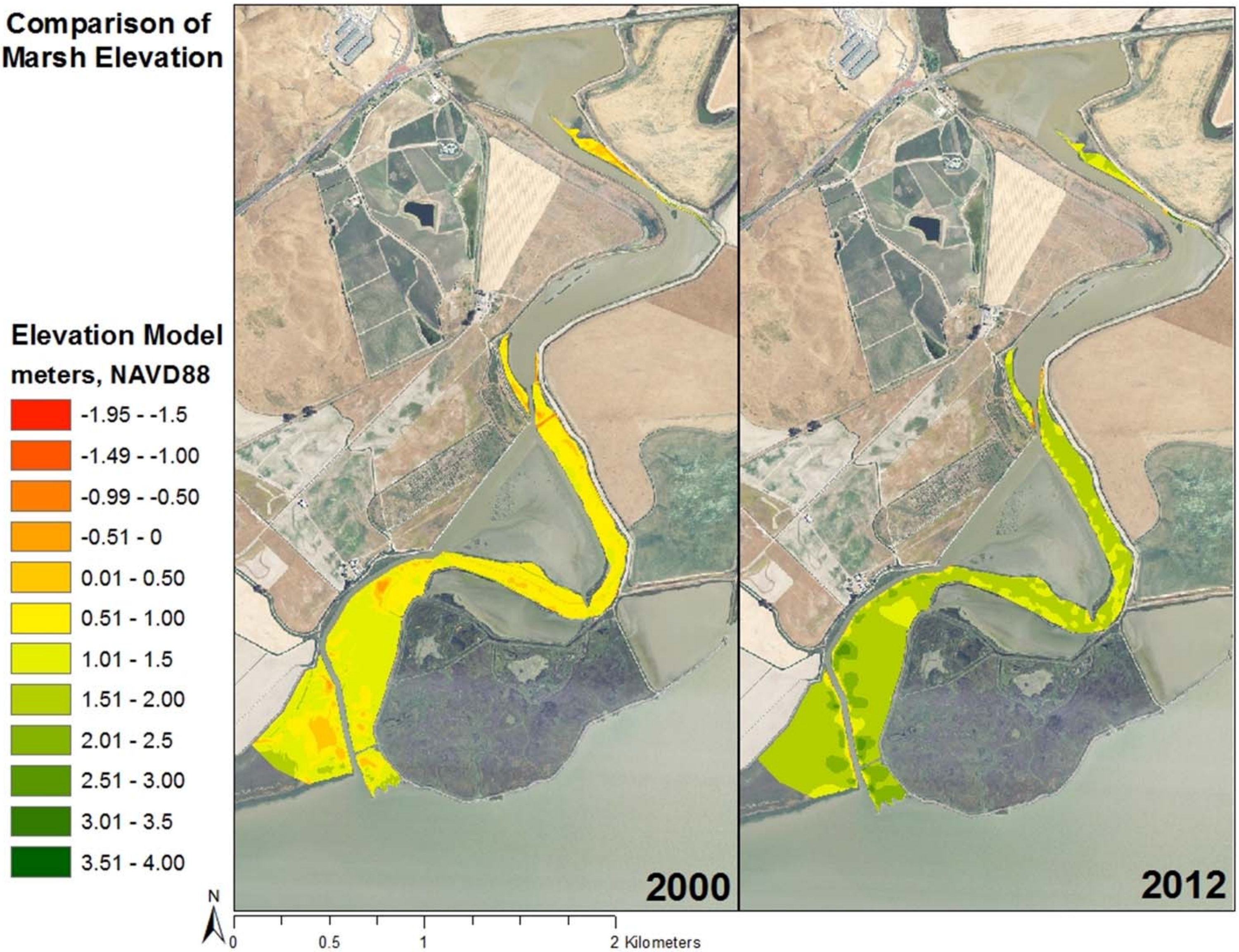

Figure 27. Digital elevation model of Tolay Creek vegetated fringe marsh comparing 2000 to 2012.

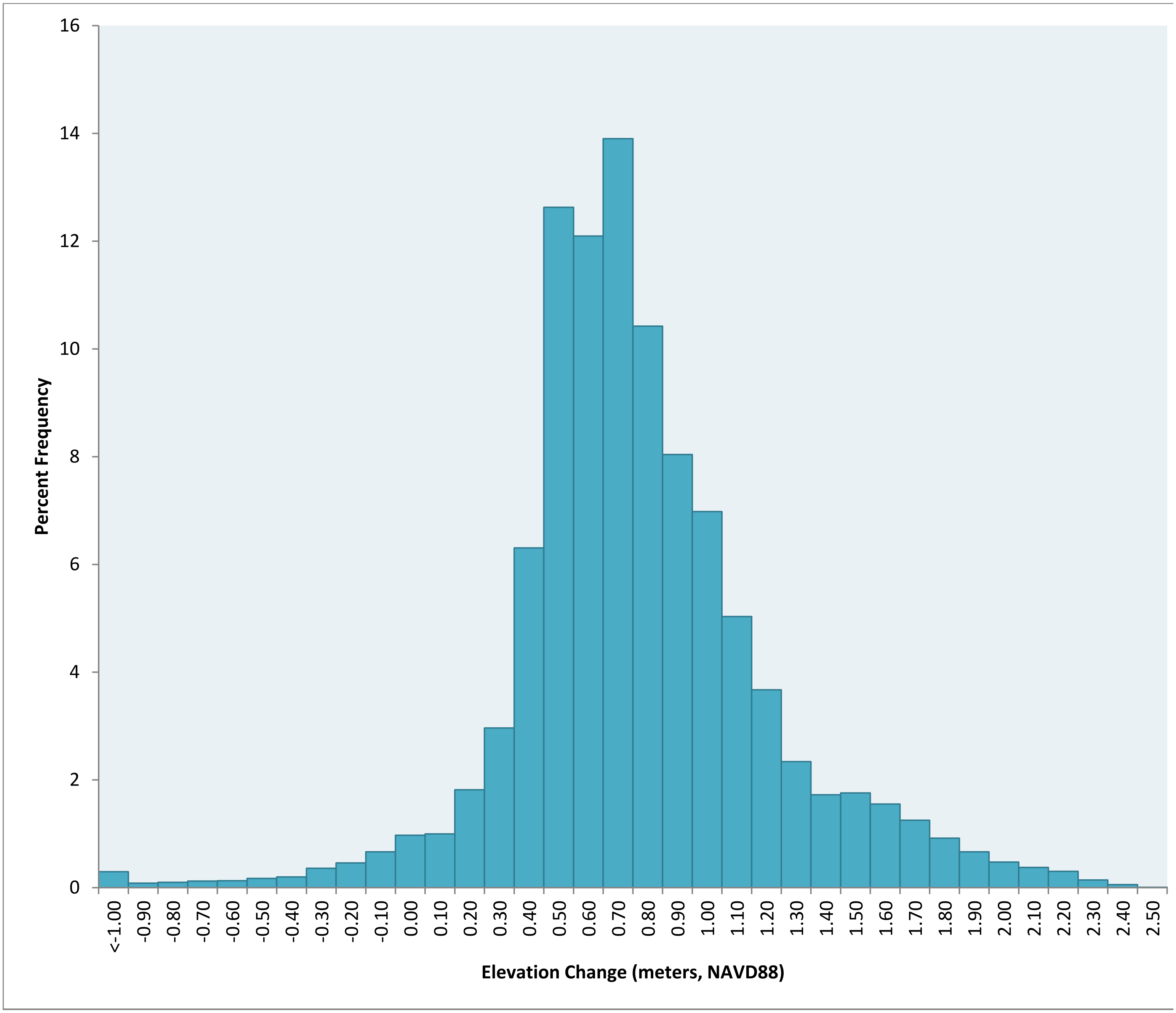

Figure 28. Percent frequency of elevation change at Tolay Creek vegetated fringe marsh between 2000 and 2012.

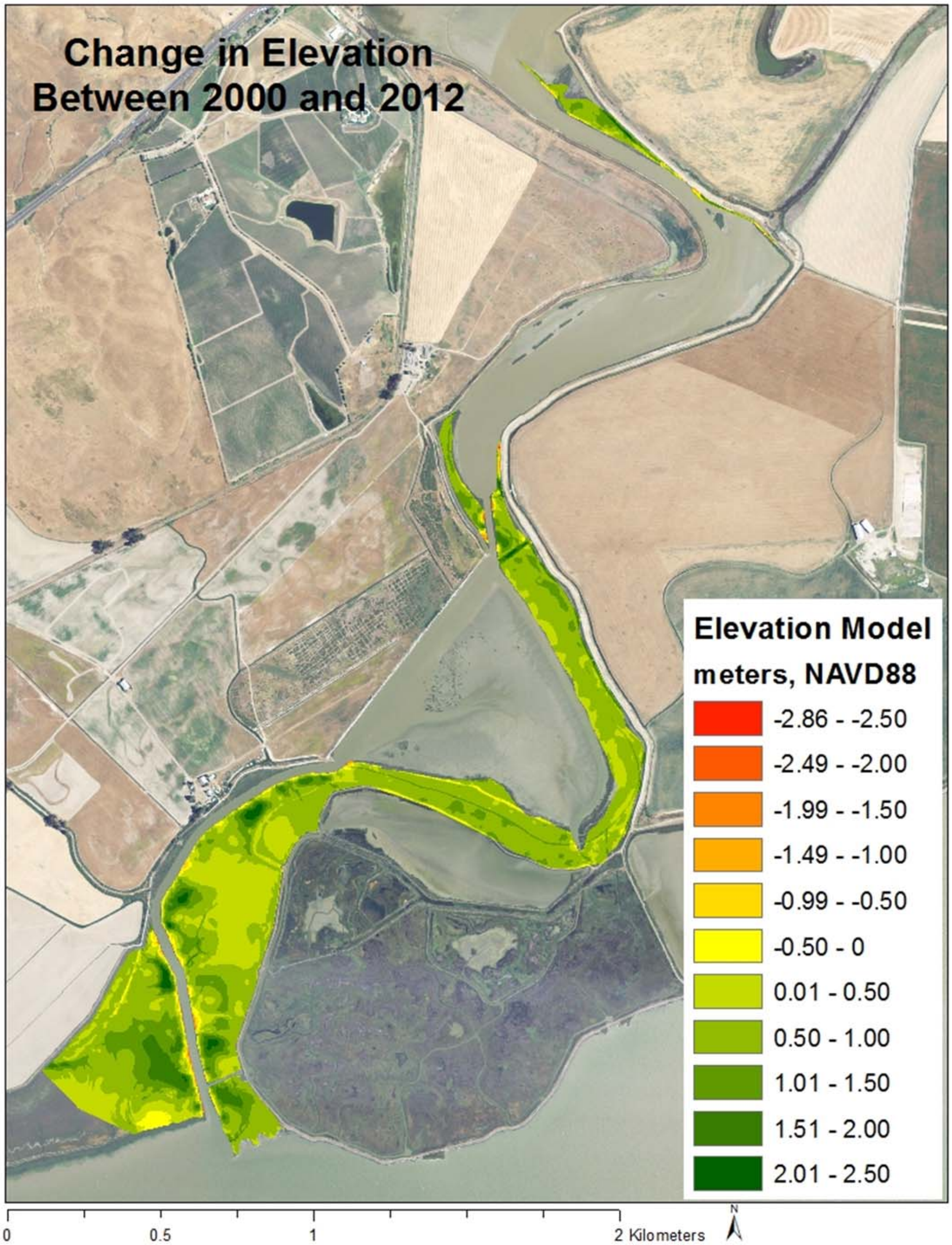

Figure 29. Digital elevation model of Tolay Creek marsh showing elevation change between 2000 and 2012. Vegetated fringe marsh showed an increase in elevation from 2000 to 2012.

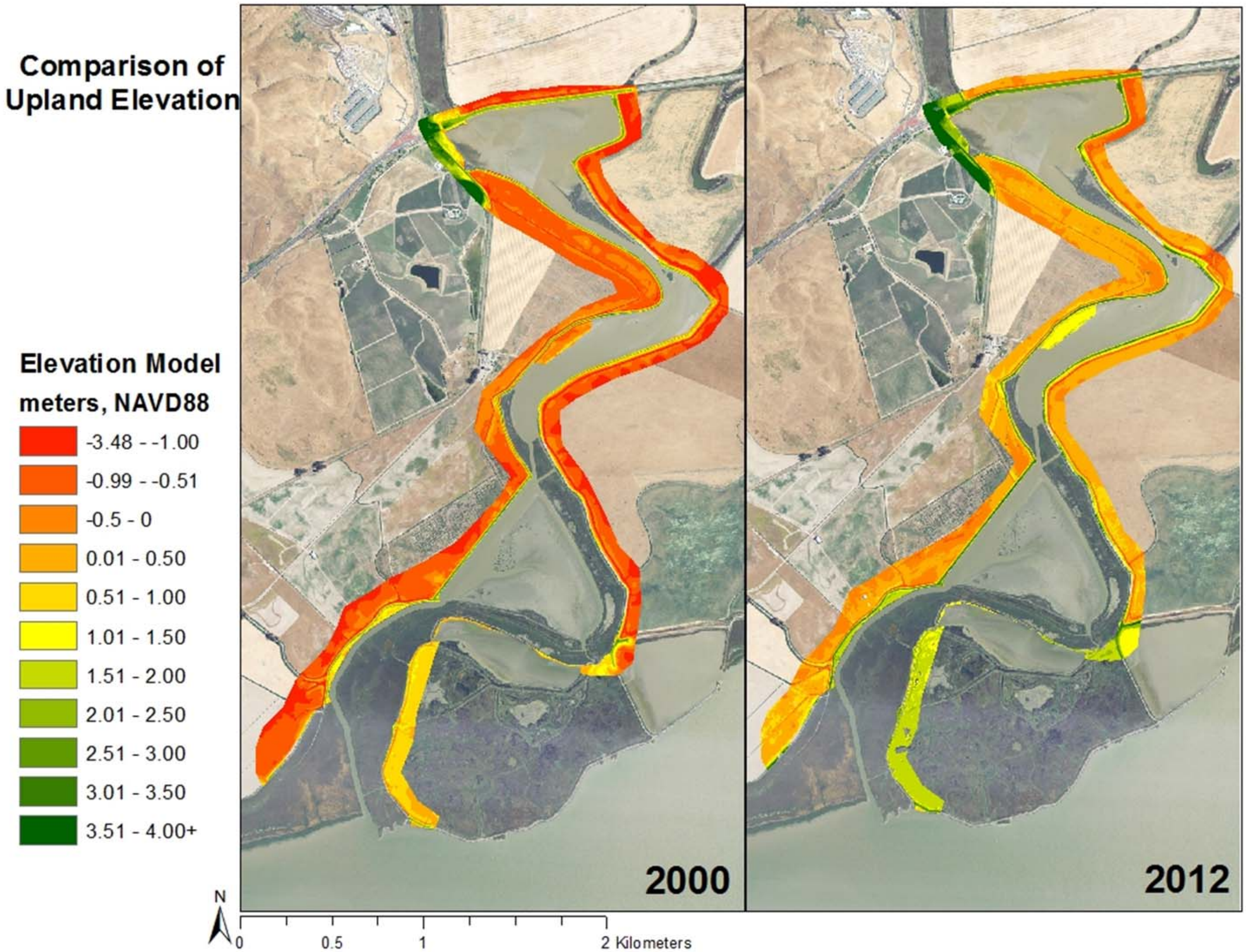

Figure 30. Digital elevation model of Tolay Creek upland comparing 2000 to 2012.

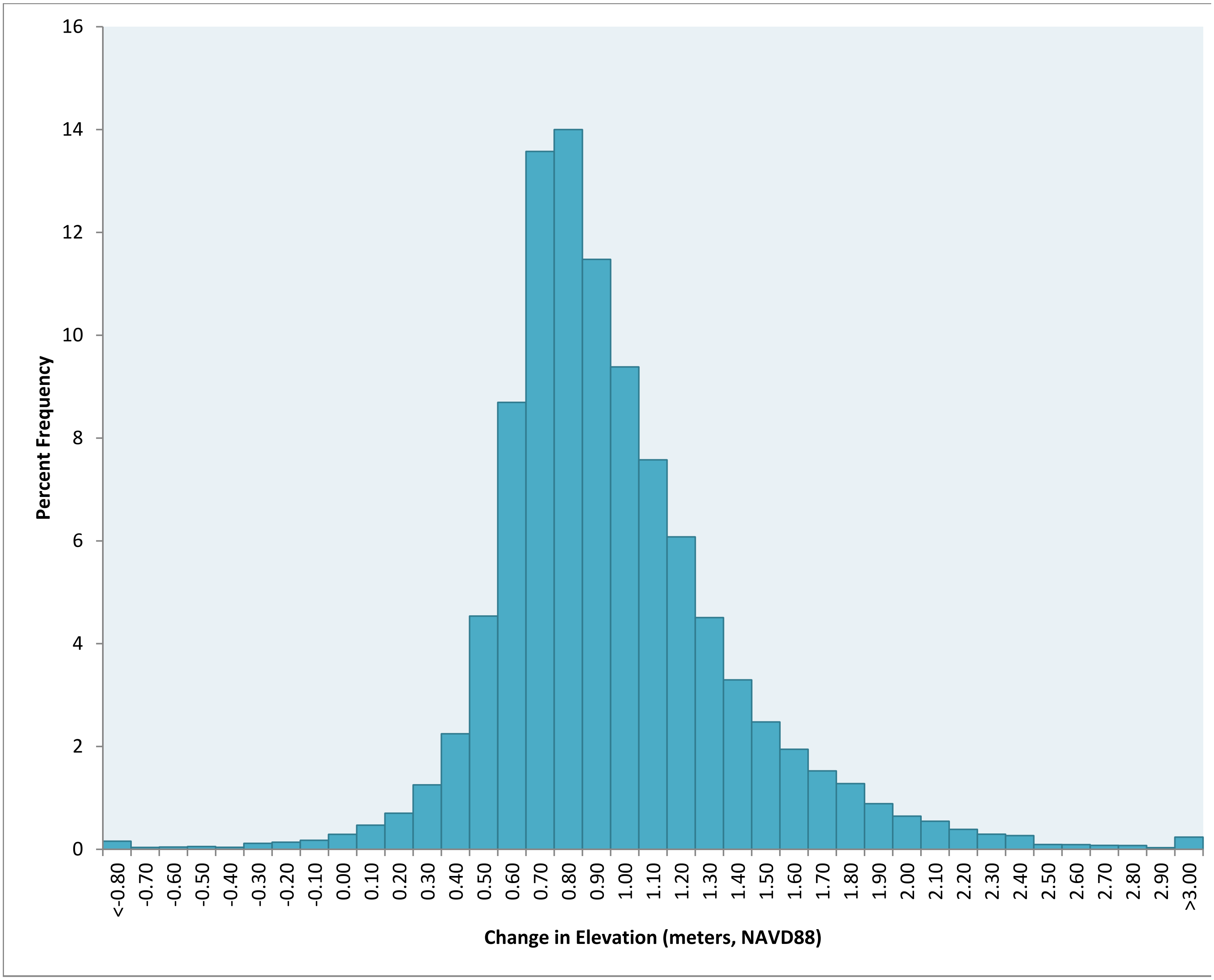

Figure 31. Percent frequency of elevation change at Tolay Creeks upland areas between 2000 and 2012.

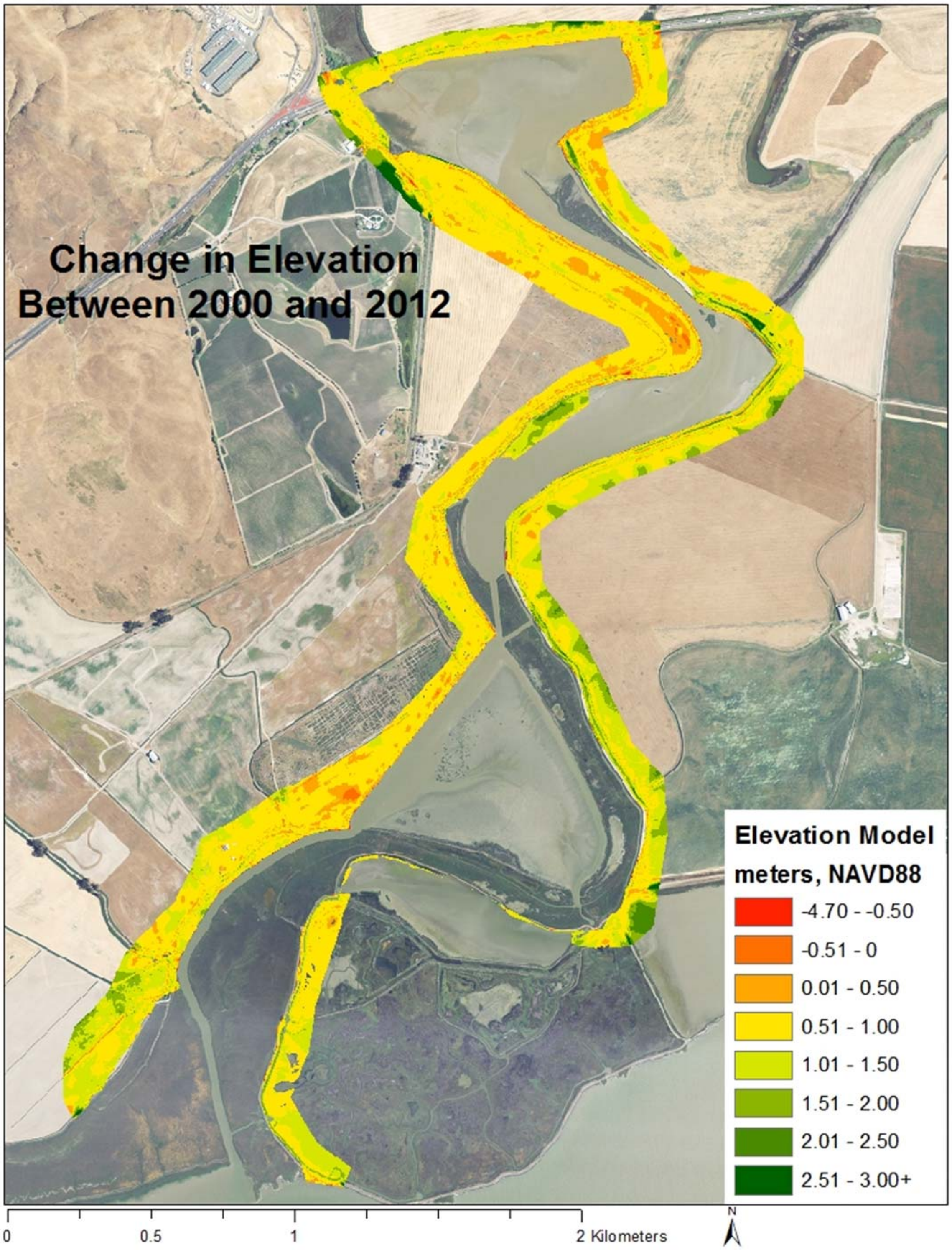

Figure 32. Digital elevation model of Tolay Creek upland showing elevation change from 2000 to 2012

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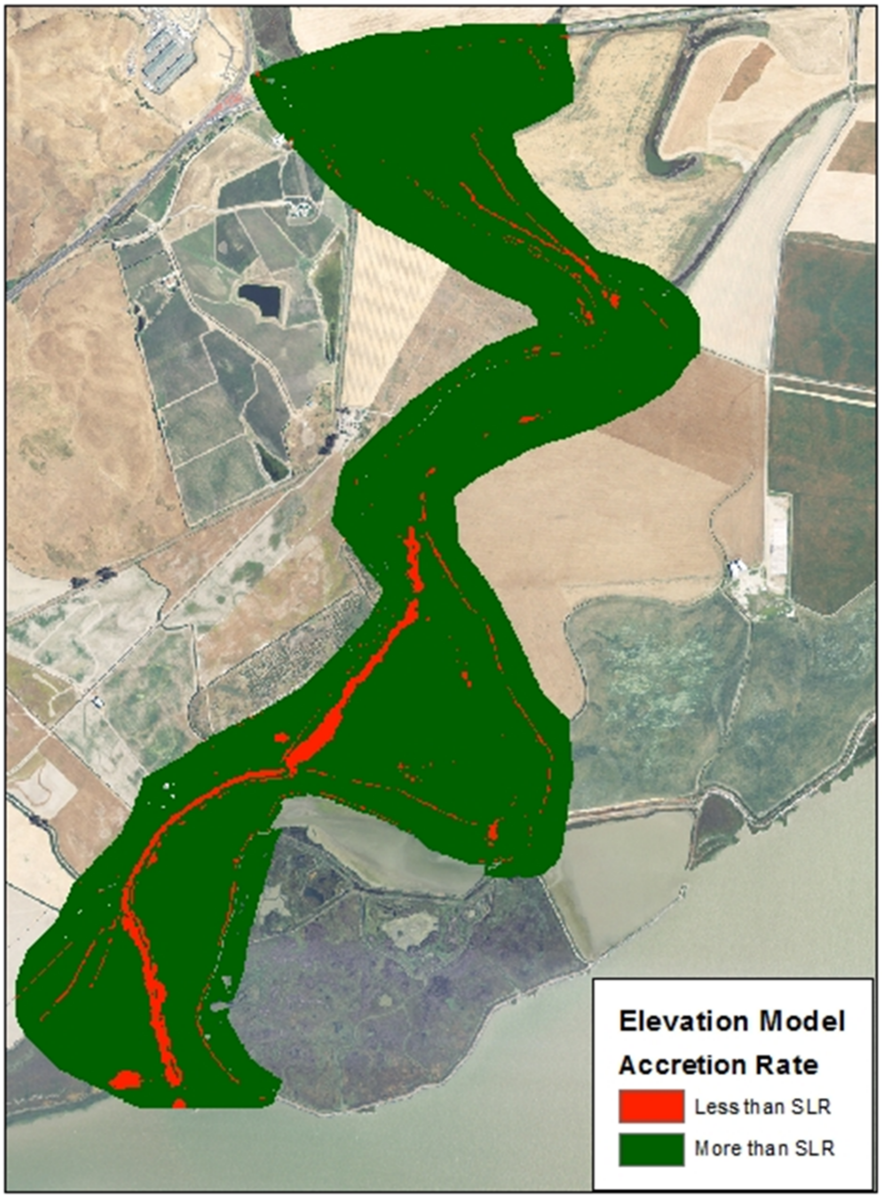

Figure 33. Elevation change analysis compared to local rate of sea-level rise during the same period. 95% of the study area including the restoration and fringe marsh had accretion rates that outpaced sea-level rise

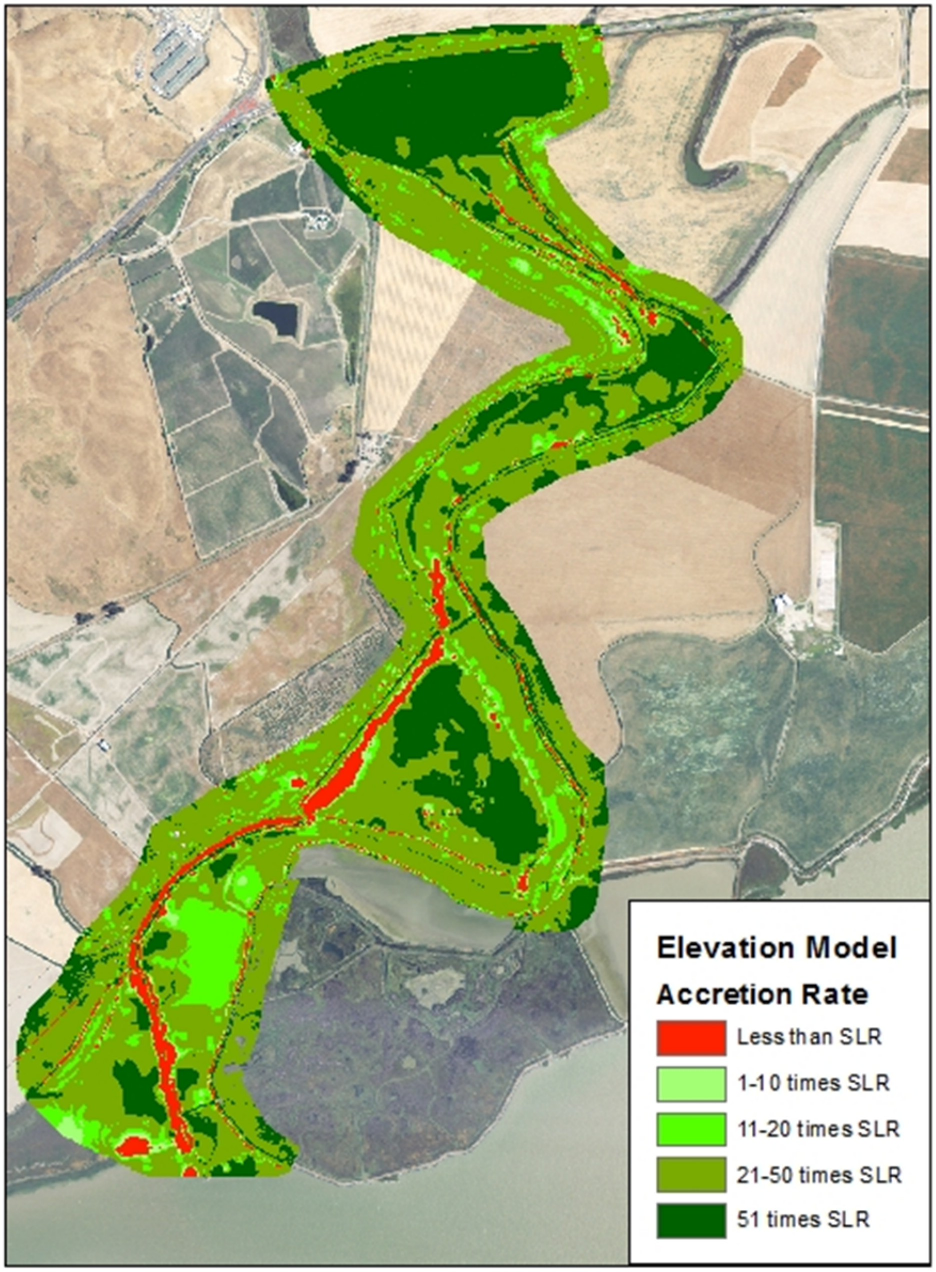

Figure 34. Most of the restoration and fringe marsh experienced much higher rates of accretion when compared with local SLR during the same time period.

Marsh Vegetation Surveys

Pre-breach vegetation surveys in the upper lagoon of Tolay Creek area consisted primarily of grasses and ruderal species while pickleweed dominated the lower reaches of Tolay Creek. Other common salt marsh species experienced a gradual decline through time, except for alkali heath (*Frankenia salina*) and parasitic dodder. During our current study vegetation surveys where done concurrently with elevation surveys and a total of 341 vegetation plots were measured. During the 2009 survey vegetation plots were measured at every elevation point for a total of 222 plots; whereas during the 2012 survey vegetation was sampled at a quarter of the elevation points for a total of 119 vegetation plots (table 1, Fig 4). Distinct zonation in plant communities was observed in relation to MHW because plants are typically restricted by their inundation tolerance and soil salinities; most of the surveyed marsh was typified by high marsh vegetation (table 4, Fig 33-36).

During the 2009 survey *Sarcocornia pacifica* was the most common species occurring at 91% of the vegetation plots. *Grindelia stricta* was the second most common species occurring at 13% of the vegetation plots, followed by *Spartina* spp*.* (66%), *F. salina* (4.8%), *Jaumea carnosa* (3.9%), *Distichlis spicata* (2.2%), *B. pilularis* (1.3%), and *L. latifolium* (0.4%). In 2012, S. *pacifica* was also the most common species occurring at 91% of the vegetation plots. *Spartina* spp*.* was the second most common species occurring at 25% of the vegetation plots, followed by *Distichlis spicata and Jaumea carnosa* both occurring at 8.4%, and *F. salina* (6.7 percent), *G. stricta* (5.8 percent), and *A. millefolium* (0.84%).

Table 3. Vegetation species recorded during surveys of Tolay Creek during 2009 and 2012.

Scientific Name	Common Name
Achillea millefolium	Common Yarrow
Baccharis pilulrais	Coyote Brush
Distichlis spicata	Saltgrass
Frankenia salina	Alkali Heath
Grindelia stricta	Coastal Gumplant
Jaumea carnosa	Marsh Jaumea
Lepidium latifolium	Perennial Pepperweed
Sarcocornia pacifica	Pickleweed, Pacific Swampfire
Spartina spp.	Cordgrass

Table 4. Sample number, mean marsh elevation relative to mean high water (MHW, 1.47 m), average, and max height, percentage cover with standard deviations (SD), and presence by species at Tolay Creek mouth. See Table 3 for scientific name. [cm, centimeter; m, meter; n, sample number]

Species	n	Mean Elevation Relative to MHW (m)	SD Elevation Relative to MHW	Mean Avg. Height (cm)	Mean Avg. Height SD	Mean Max Height (cm)	Mean Max Height SD	Mean Cover %	Mean Cover % SD	Presence (%)
B. pilulrais	3	0.44	0.33	92.00	15.72	101.67	17.56	53	23.09	1.33
F. salina	11	0.43	0.18	27.45	13.26	31.45	14.65	40	32.67	4.87
D. spicata	5	0.42	0.11	8.80	8.50	10.80	7.79	44	32.53	2.21
S. pacifica	205	0.29	0.14	46.94	11.35	54.90	11.99	86	25.12	90.71
J. carnosa	9	0.28	0.14	14.78	12.86	18.00	15.64	50	29.58	3.98
G. stricta	30	0.26	0.12	68.43	17.60	74.33	20.12	41	28.03	13.27
L. latifolium	1	0.13	-	80	-	80	-	2	-	0.44
Spartina spp	15	-0.47	0.25	74.60	13.36	79.93	15.35	42	20.21	6.64

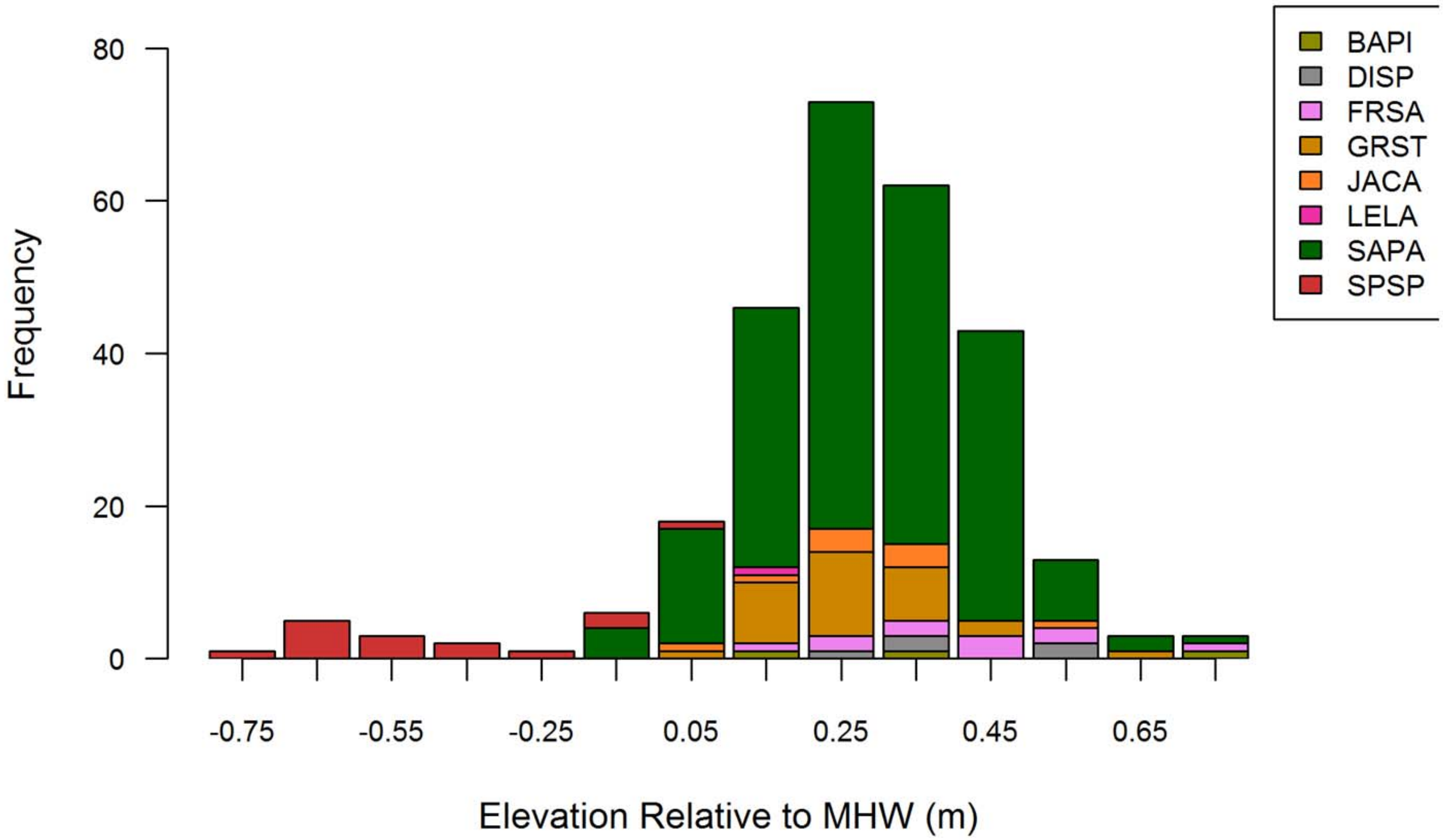

Figure 35. Vegetation survey of lower Tolay Creek marsh during 2009. Stratification of plant species distribution was observed relative to MHW. Species codes are: BAPI = *Baccharis pilulrais*; DISP = *Distichlis spicata*; FRSA = *Frankenia salina*; GRST = *Grindelia stricta*; JACA = *Jaumea carnosa*; LELA = *Lepidium latifolium*; SAVI = *Sarcocornia pacifica*; SPSP = *Spartina species*.

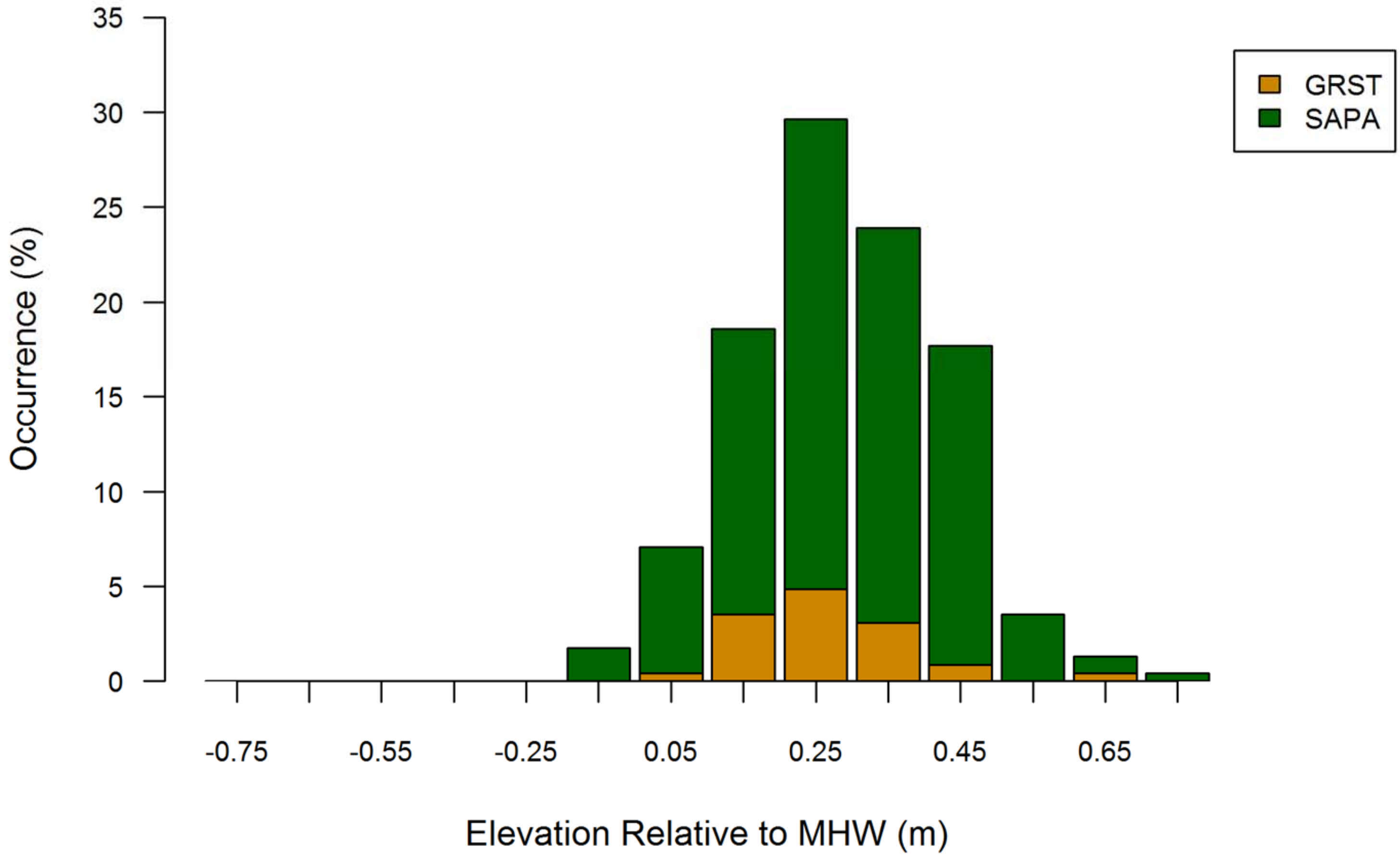

Figure 35. Vegetation survey of lower Tolay Creek marsh during 2009. Occurrence (percent) of the most common species (>10 % of the plots) by elevation. Species codes are: GRST = *Grindelia stricta*; SAPA = *Sarcocornia pacifica*.

Table 5. Sample number, mean marsh elevation relative to mean high water (MHW, 1.62 m), average, and max height, percentage cover with standard deviations (SD), and presence by species at the northern upstream section of Tolay Creek during 2012. See Table 3 for scientific names. [cm, centimeter; m, meter; n, sample number]

Species	n	Mean Elevation Relative to MHW (m)	SD Elevation Relative to MHW	Mean Avg. Height (cm)	Mean Avg. Height SD	Mean Max Height (cm)	Mean Max Height SD	Mean Cover %	Mean Cover % SD	Presence (%)
F. salina	8	0.13	0.28	23.38	11.26	35.50	13.49	43.8	36.9	6.72
G. stricta	7	0.02	0.11	50.00	16.58	65.57	21.10	27.9	32.0	5.88
D. spicata	10	0.02	0.05	27.50	9.79	40.30	14.72	74.0	24.1	8.40
A. millefolium	1	-0.04	-	95.00	-	105.00	-	15.0	-	0.84
S. pacifica	108	-0.07	0.18	38.35	10.69	57.90	13.60	80.9	27.5	90.76
J. carnosa	10	-0.10	0.19	16.80	7.83	21.10	8.33	42.3	33.9	8.40
Spartina spp.	30	-0.14	0.20	51.17	24.08	69.47	26.04	38.3	28.4	25.21

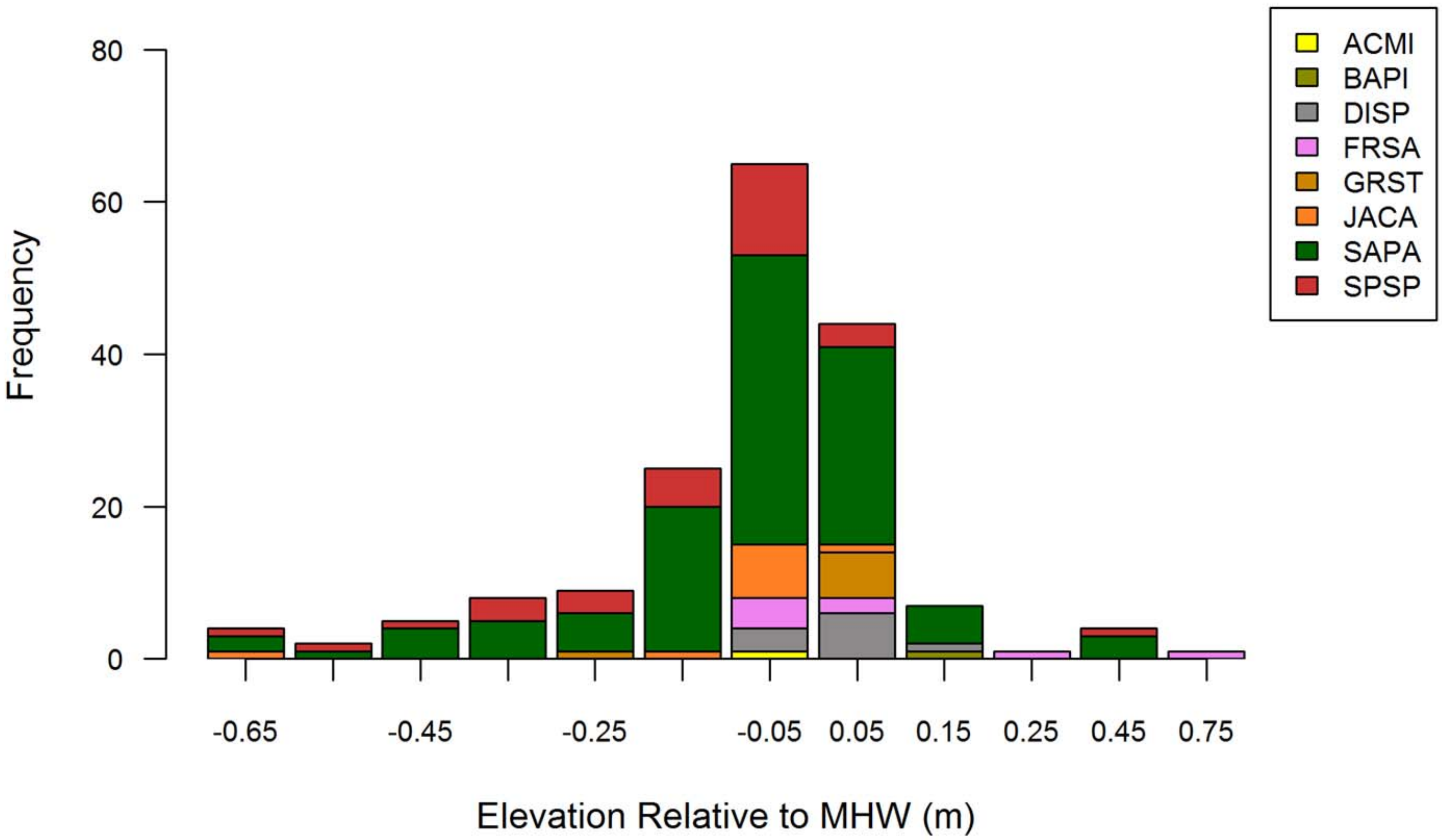

Figure 36. Vegetation survey of upper Tolay Creek marsh during 2012. Stratification of plant species distribution was observed relative to MHW. Species codes are: ACMI = *Achillea millefolium*; BAPI = *Baccharis pilulrais*; DISP = *Distichlis spicata*; FRSA = *Frankenia salina*; GRST = *Grindelia stricta*; JACA = *Jaumea carnosa*; SAPA = *Sarcocornia pacifica*; SPSP = *Spartina species*.

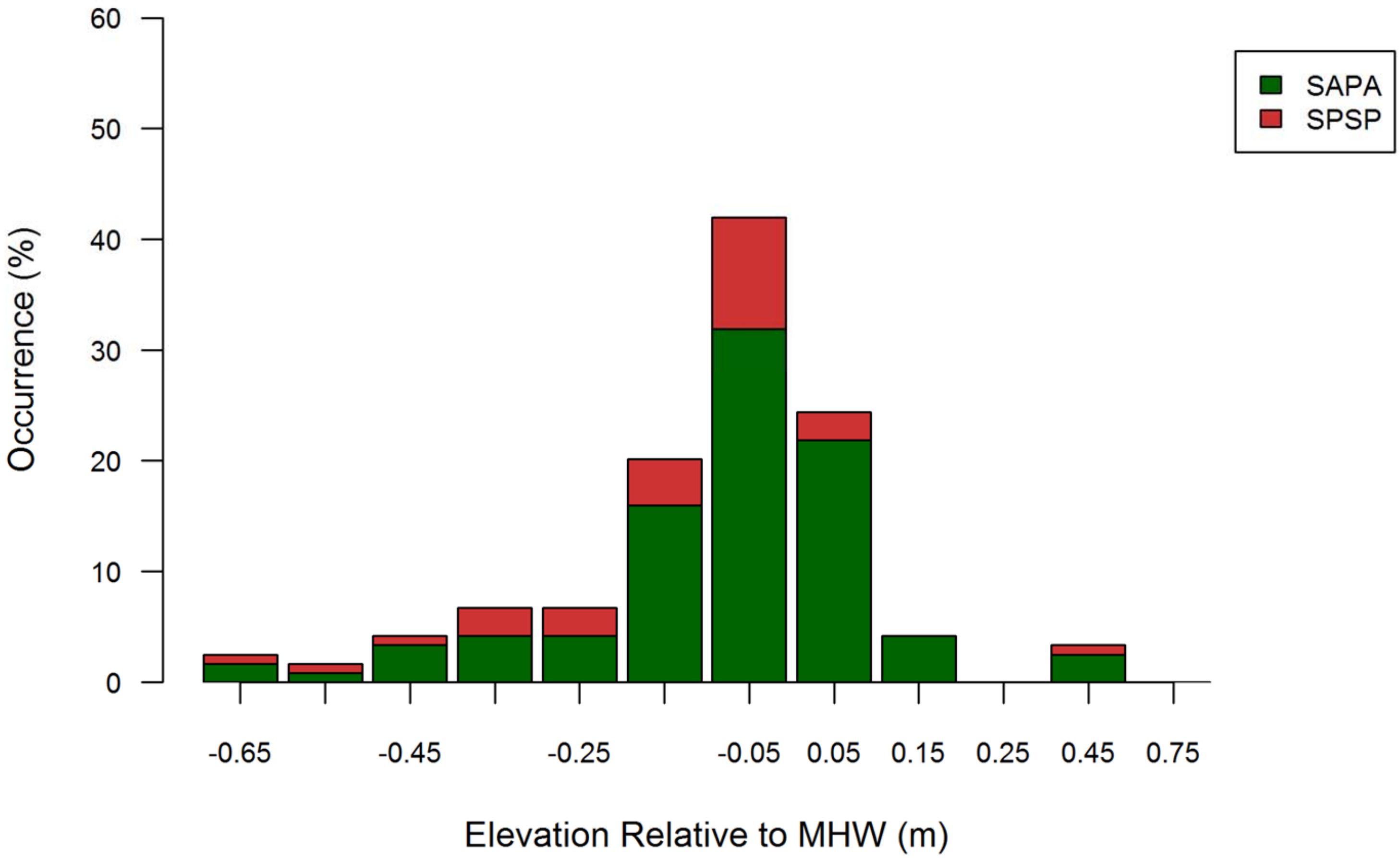

Figure 37. Vegetation survey of upper Tolay Creek marsh during 2012. Occurrence (percent) of the most common species (>10 % of the plots) by elevation. Species codes are: SAPA = *Sarcocornia pacifica*; SPSP = *Spartina* spp.

Water level monitoring

Site specific water level was monitored at Tolay Creek from January 2012 to January 2013. Mean tide level (MTL) was 0.73 m, Mean High Water (MHW) was 1.47 m, and mean higher high water (MHHW) was 1.64 m for the lower channel; whereas MTL was 1.13 m, MHW was 1.62 m, and MHHW was 1.77 m was measured for the northern lagoon (NAVD88, table 6). Inundation was compared between logger tidal datums (Fig. 37), and between 2000 and 2012 (Fig. 38). The period when the marsh platform (defined as mean marsh elevation) was inundated most often was during winter and spring months which were defined as December to April (Fig. 39-40).

Table 6. Water elevations (NAVD88), in meters (m), for 2012.

[Mean Tide-level (MTL), Mean high water (MHW) and mean higher high water (MHHW) were calculated from *in situ* data loggers.]

	MHHW	MHW	MTL
Tolay 01 (southern)	1.64	1.47	0.73
Tolay 02 (northern)	1.77	1.62	1.13
Average	1.705	1.545	0.93
Estimated Datum: year 2000	1.68	1.52	0.906

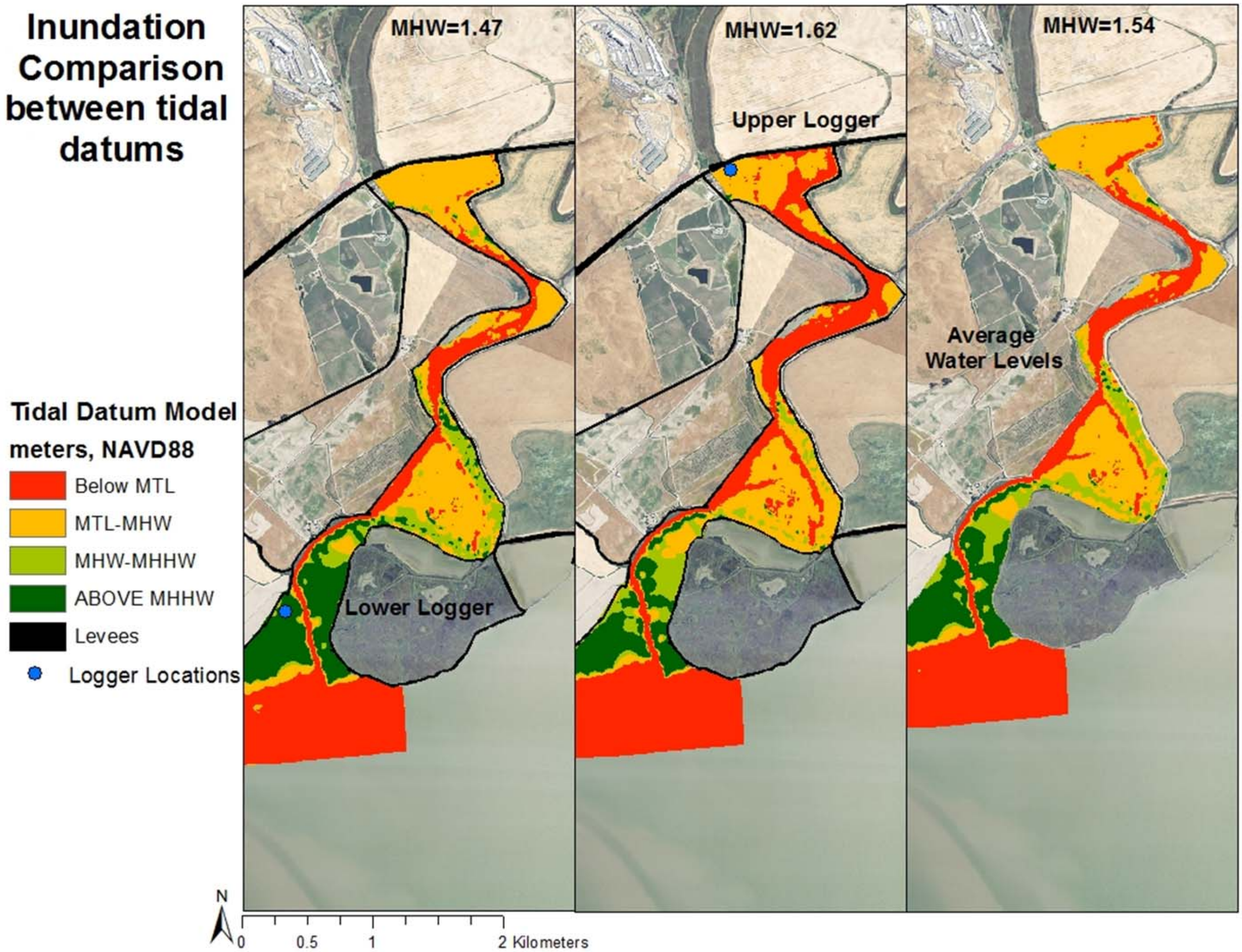

Figure 38. Tidal datum of Tolay Creek comparing the southern logger, northern lagoon logger, and the average of both datums.

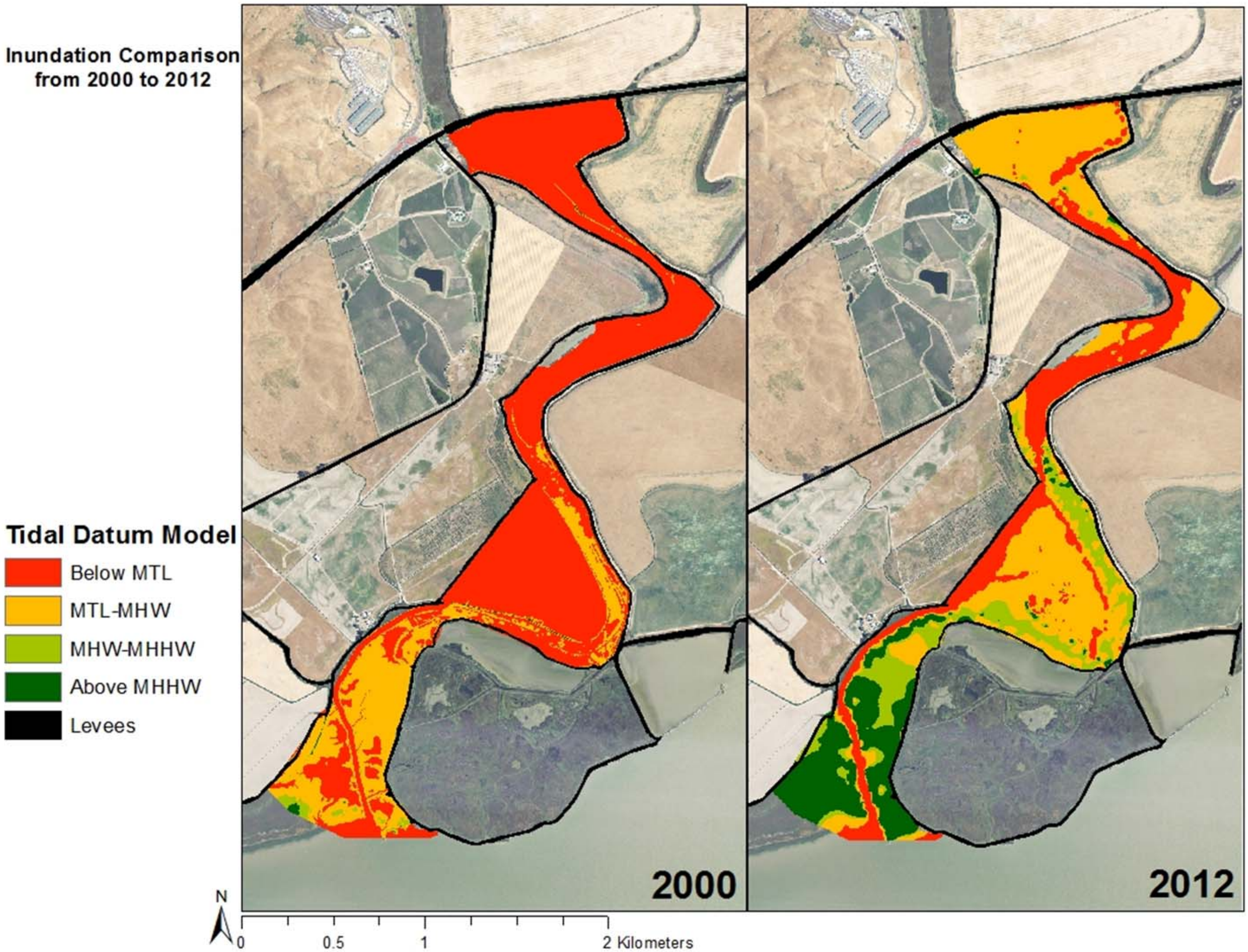

Figure 39. Tidal datum comparing Tolay Creek inundation between 2000 and 2012. Tidal Datum used for 2012 is based off the average from the upper and lower water level loggers.

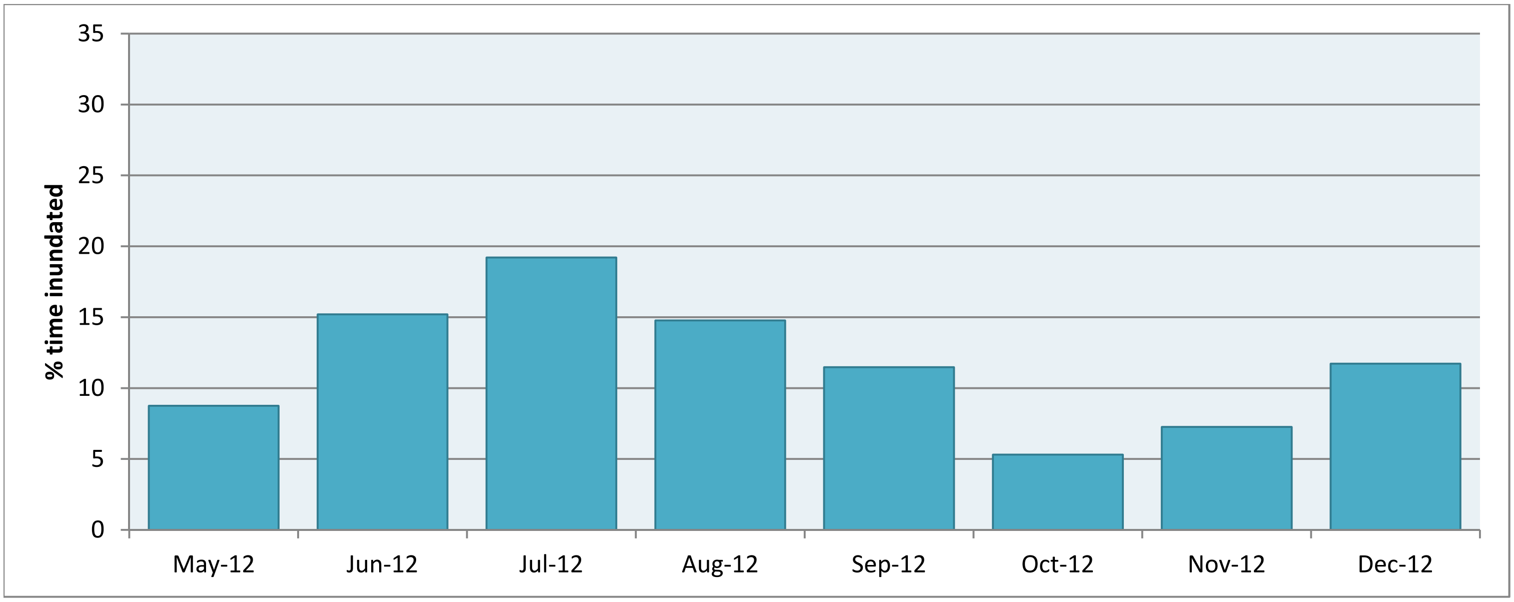

Figure 40. Percentage of time Tolay Creek vegetated marsh was inundated monthly, based on the mean elevation of the marsh platform and tidal data from the Tolay 01 logger located in the southern portion of the creek near the mouth.

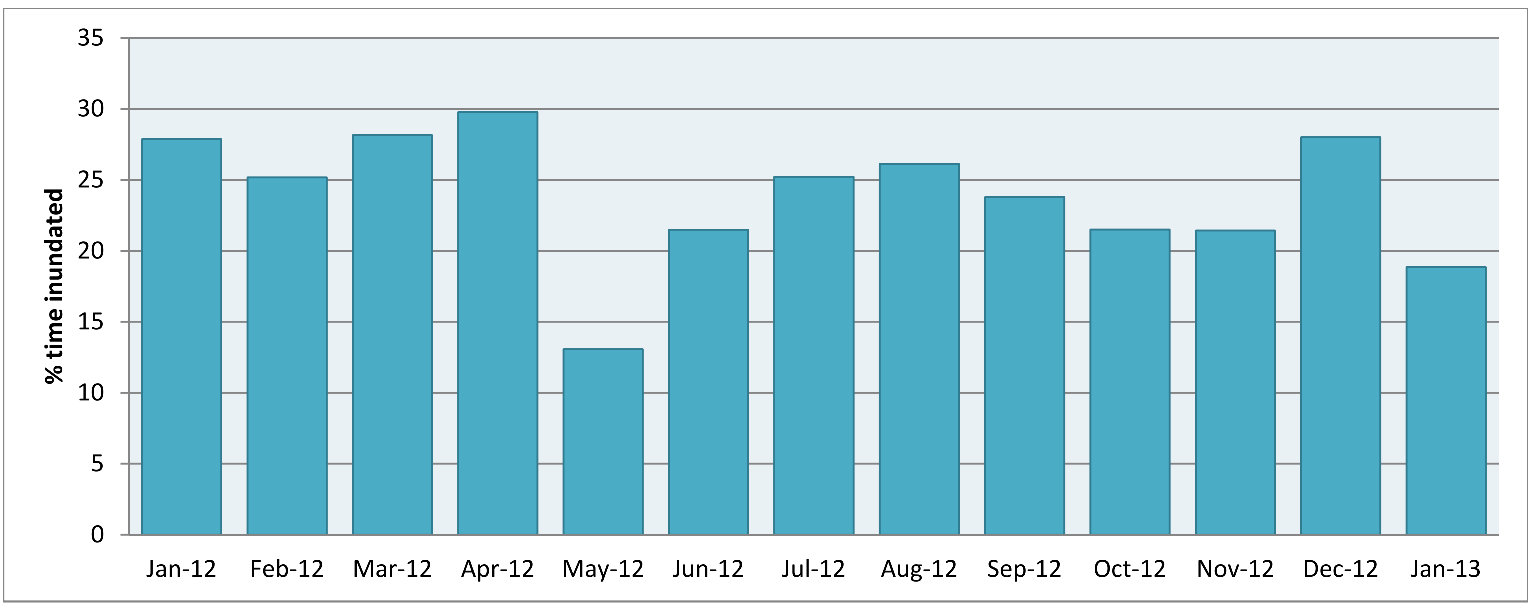

Figure 41. Percentage of time Tolay Creek vegetated marsh was inundated monthly, based on the mean elevation of the marsh platform and tidal data from the Tolay 02 logger located in the northern portion of the creek upstream.

Discussion

Resource land managers need site-specific baseline data to assess restoration efforts and resiliency to SLR and other climate change effects for the protection of tidal marsh wildlife and fish species and their habitats. In this project, our focus was to collect site-specific baseline elevation, vegetation, and tidal data to assess elevation change over 12 years for the Tolay Creek restoration. Our goal in characterizing restoration progress was to provide land managers with the scientific support necessary to make informed decisions and develop climate change adaptation strategies.

These results indicate that the tidal marshes and mudflats along Tolay Creek were accreting sediment during the past 12 years, and most of the restoration site had accretion rates that outpaced SLR during the study period. Thus, the area may keep pace with SLR over the near-term of the next few decades; however, the longer-term effects of SLR are expected to rise exponentially, and sediment accretion is much less likely to keep pace. Early monitoring and assessment will help to support models that can determine if and how long a restoration project is accreting sediment at a pace that exceeds SLR.

The monitoring of Tolay Creek was initiated in 1998 and is one of only a few restoration projects in the region with comprehensive long-term monitoring datasets. Monitoring biological and physical parameters is a critical component to improve wetland restoration and rehabilitation projects (CALFED Bay-Delta Program 1997). The Tolay Creek Restoration has provided an opportunity to develop a general framework for wetland monitoring and to create understanding of restoration efforts in light of SLR. Documentation of change, including by what magnitude and in which direction an ecosystem is responding to restoration, is critical for assessment of restoration benefits and development of adaptive management strategies. Wetland projects like the Tolay Creek Restoration should improve the resiliency of endemic populations over the next few decades which should allow more opportunities to mitigate the effects of SLR into the next century.

Next Steps

Our Coastal Ecosystem Response to Climate Change (CERCC) program uses integration of physical and biological monitoring to facilitate understanding and identification of climate change effects. Results from our previous work in San Francisco Bay showed that initial elevation, along with tidal range and suspended-sediment availability, were key inputs for effectively modeling marsh response from SLR. Ongoing work on San Pablo Bay NWR includes annual monitoring of surface elevation tables (SETs) to better understand local sediment accretion rates at Tolay Creek and continuous monitoring of water level loggers to assess inundation rates and to measure the frequency and severity of storms.

Intertidal marsh habitats 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. Sediment accretion can partially offset increased SLR; thus, the monitoring of accretion rates will be important to reflect the current rate of sediment accumulation at Tolay Creek and surrounding marshes. It also will be critically important to monitor the frequency and severity of storms to better understand their effects which may be the major issue in tidal marsh management over the next few decades.

We believe baseline data collection at a local scale across a gradient of sites can be used to identify and prioritize restoration sites and land acquisitions that can be good candidates for marsh perpetuation in light of SLR. In addition, the continued risk to listed species needs to be assessed by better understanding wildlife response to increased inundation over the near and long-term. Consistent with the goal of the USGS Science Strategy, the CERCC program will support 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

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