San Francisco Estuary Wetland Regional Monitoring Program: Standard Operating Procedures for Hydrogeomorphic Monitoring

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Executive Summary

The Technical Advisory Committee (TAC) of the Wetland Regional Monitoring Program (WRMP) recommends to the WRMP Steering Committee (SC) the enclosed Standard Operating Procedures (SOPs) for monitoring hydrogeomorphic variables (Hydrogeomorphic SOP) in the brackish and saline tidal marshes of the San Francisco Estuary (SFE). The SOP was developed through the TAC by the WRMP's Hydrogeomorphic (HGM) Workgroup.

Hydrogeomorphic monitoring, including topography, accretion, tidal inundation, salinity, suspended sediment, channels/ponds/pannes expansion, and dissolved oxygen, is crucial for understanding and tracking changes in tidal marshes. Not only do these physical parameters determine where tidal marshes occur, but these hydrogeomorphic variables significantly shape the form and function of these habitats and determine which species can live within these ecosystems. For example, tidal marsh vegetation is highly influenced by a range of hydrogeomorphic factors, including elevation, sedimentation, inundation, and salinity regimes. Therefore, monitoring hydrogeomorphic variables at a regional scale is indispensable for comprehending the physical and biological characteristics of the SFE. Additionally, establishing a close connection between hydrogeomorphic and biological variables is crucial because they often exert a mutual influence. The WRMP Plan is focused on tracking changes in the tidal marsh ecosystem due to management actions, including restoration, and climate change. The Plan recognizes the need for hydrogeomorphic monitoring in both regards. This SOP helps meet this need by providing detailed guidance for monitoring the following key aspects of tidal marsh hydrogeomorphology at sites that vary in their age and human interventions (including historical wetlands and restoration projects): topography, accretion, tidal inundation, salinity, suspended sediment, dissolved oxygen, channels, ponds and pannes, and shoreline change.

To achieve this comprehensive hydrogeomorphic monitoring, the TAC of the WRMP recommends remote sensing, regional sensors, field surveys, and special studies. Remote sensing is particularly useful for tracking large-scale, plan-form change (i.e., 2D spatial change) within the landscape, including the expansion or reduction of ponds, pannes, and channels and changes in shoreline shape and position. In these regards, this Hydrogeomorphic SOP leverages the recommended Geospatial SOP and the resulting baylands habitat map (Baylands Change Basemap[1]). Remote sensing is also recommended for SFE-wide elevation mapping through incorporation of LiDAR (Light Detection and Ranging) to accurately model elevation across the region.

Regional sensors such as NOAA tide-gauges[2] should be leveraged to track sea level rise and tidal regimes in near-by wetlands. Field survey methods are recommended to calibrate LiDAR and provide detailed information on site-specific ground surface and water surface elevation, accretion, suspended sediment, and salinity at selected Benchmark, Reference, and restoration Project sites (see monitoring site hierarchy of the WRMP Plan). Establishing local horizontal and vertical control points will be necessary to attain the needed resolution and accuracy of the hydrogeomorphic data.

Lastly, special studies are suggested to further develop hydrogeomorphic indicators and analyze monitoring results. For example, conducting comparisons of surface water, porewater, and shallow groundwater salinity can enhance our understanding of their interrelationships. Additionally, in the context of accretion, sediment deposition pads could be deployed as a cost-effective method for assessing spatial and temporal trends in surface accumulation within and across wetlands, and their influence on the distribution and abundance of tidal marsh flora and fauna.

The production of this document and the related efforts to integrate monitoring across elements of the WRMP in an initial Monitoring Plan are funded by a San Francisco Bay Restoration Authority Grant to the San Francisco Estuary Institute - Aquatic Science Center (SFEI-ASC) in partnership with the San Francisco Estuary Partnership (SFEP).

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[1] Name subject to change

[2] This instrument is spelled both gauge (more commonly) and gage (e.g. USGS) with the same meaning

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WRMP Background

The Wetland Regional Monitoring Program (WRMP, www.wrmp.org) is a multi-agency effort to coordinate the monitoring of estuarine wetland habitats within the San Francisco Estuary (SFE) and inform wetland restoration, conservation, and adaptive management. The mission of the WRMP is to deliver coordinated regional monitoring of the San Francisco Estuary's wetlands to (1) inform science-based decision-making for wetland restoration and adaptive management and (2) increase the cost-effectiveness of permit-driven monitoring associated with wetland restoration projects. To accomplish this mission the WRMP is working to (1) understand how landscape-scale drivers, such as climate change, are affecting these ecosystems across space and time and (2) support decision-making informed by the best available science.

The Technical Advisory Committee (TAC) of the SFE WRMP provides scientific and technological advice to the Steering Committee (SC) of the WRMP.

Purpose of This Document

The purpose of this document is to recommend Standard Operating Procedures (SOPs) for monitoring the status and trends of key hydrogeomorphic (HGM) variables in tidal marshes over space and time. These SOPs will be referenced in the WRMP Monitoring Plan (expected in December 2023) that will propose which Level 1, 2, and 3 indicators[3] should be monitored (and, in the case of historical data, synthesized).

The SOPs are methods documents to inform WRMP monitoring, and while they can be used to inform and design project monitoring, they are not designed to be used wholesale as permit requirements.

The TAC and its HGM Workgroup selected methods to capture relevant hydrogeomorphic dynamics that answer the WRMP Management Questions outlined in the WRMP Program Plan (WRMP, 2020) (see Section 3 below). The methods have been selected based on present practice and experience in the Bay, historical data collection, conceptual and empirical models, peer-reviewed literature, and consensus-based professional judgment of the TAC.

While monitoring elements of the WRMP are outlined individually in separate SOPs, they are interrelated and will be integrated in the WRMP Monitoring Plan. For instance, field surveys of vegetation should be co-located with elevation, salinity, and tidal inundation monitoring stations. In this way the trends and patterns seen in vegetative cover and species composition over time can be correlated with important abiotic factors to improve understanding of the regional factors driving tidal marsh change. Similarly, field surveys can be coordinated with regional monitoring and habitat mapping efforts in order to ground-truth remote-sensed products.

Geographic Focus and Scope

The SOPs are designed to be implemented across a regional scale and within sites that vary in their history of human impact and restoration. The WRMP Priority Monitoring Site Memo (WRMP 2023) identifies six Priority Monitoring Site Networks that span the five sub-embayments of the San Francisco Estuary (Suisun, North Bay, Central Bay, South Bay, and Lower South Bay) where historical monitoring data can be synthesized and where new monitoring can be focused (Figure 1).

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[3] The WRMP science framework is based on the Wetland and Riparian Area Monitoring Plan (WRAMP) framework established by the California Water Quality Monitoring Council, which describes how to integrate Level 1 (remote sensing), Level 2 (qualitative field assessment), and Level 3 (quantitative field assessment) data.

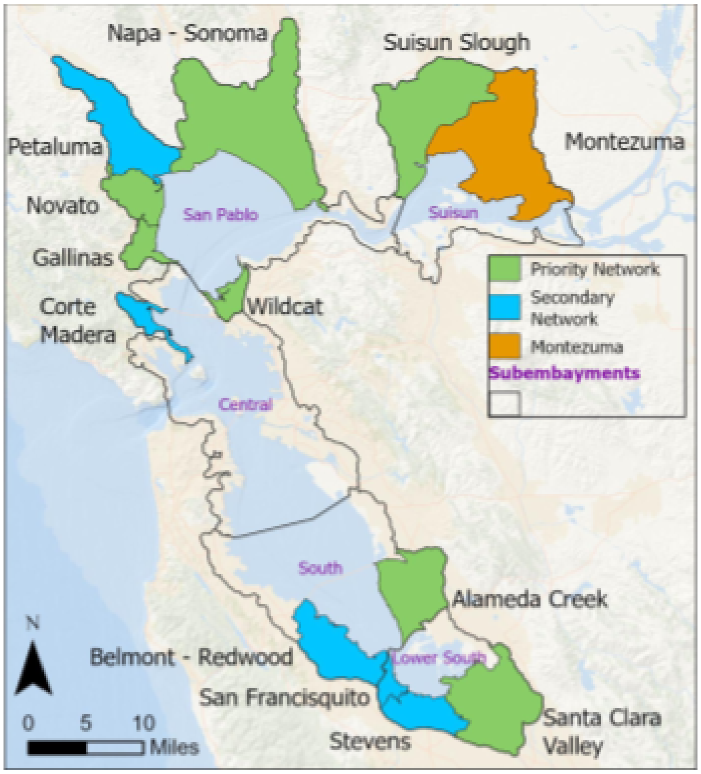

Figure 1. Map of the Operational Landscape Units, Subembayments and WRMP priority networks.

Within each network, marshes that vary in age and degree of human intervention are classified, including Benchmark Sites (relict, ancient marshes), Reference Sites (older restoration projects and centennial wetlands, fringing marshes that accreted sediment since the 19th Century), and Project Sites (recent restoration projects that reflect a variety of restoration approaches). This SOP outlines hydrogeomorphic monitoring protocols that can be applied to sites both within and outside of the Priority Monitoring Site Network.

1. Hydrogeomorphic Variables

Tidal marsh ecosystems are biogeomorphic habitats strongly influenced by the extreme physical environments that drive and define these systems. SFE's tidal marsh ecosystems are characterized by a Mediterranean climate, mixed semi-diurnal tidal influence, and freshwater influence from the Sacramento and San Joaquin rivers. The South Bay receives freshwater from much smaller watersheds and is more dependent on ocean water and water entering from the Central Bay. Over time, sediment inputs to the Estuary have decreased for several reasons: an increase in reservoirs that trap sediment, a decrease in sediment washing in from the Gold Rush era, and urbanization along creeks and rivers.

Hydrogeomorphic variables, such as inundation regime, accretion, salinity, and marsh morphology play a significant role in influencing vegetation growth and distribution, which subsequently affects invertebrate, fish, bird, and mammal habitats. Moreover, these variables affect ecosystem services to humans, such as flood attenuation and water quality.

1.1. Conceptual models

As illustrated in the conceptual models compiled in the WRMP Program Plan, hydrogeomorphic variables are fundamental drivers of tidal marsh ecosystems and their resulting habitat, biology, and functions. Due to their foundational nature, a number of these variables have been identified as metrics of importance to the WRMP for answering Guiding and Management Questions identified by the WRMP Steering Committee (see section 3 below) and for monitoring the health and function of SFE wetlands.

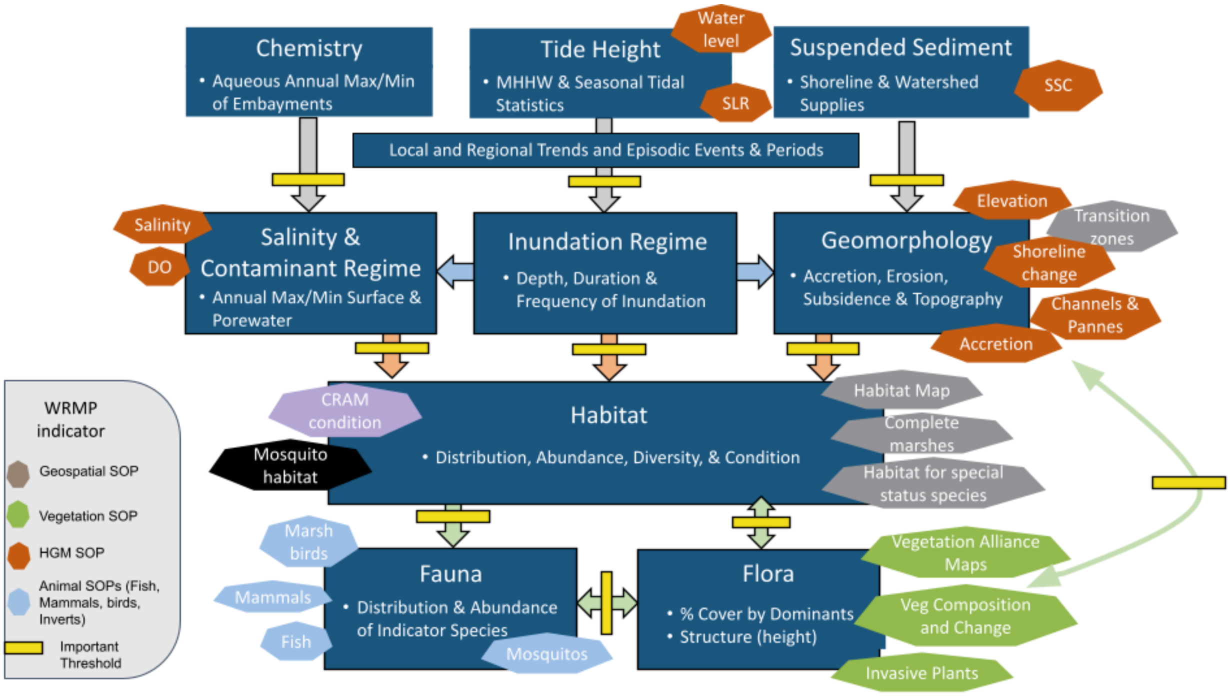

Figure 2. Conceptual model highlighting important relationships and key drivers of tidal marsh systems from the WRMP Program plan (WRMP 2020). The figure has been modified here to highlight the subset of WRMP indicators covered in this SOP in orange (HGM indicators). WRMP indicators represent factors and processes driving tidal marsh habitat conditions (upper row of diagram), the response of the system to the drivers (second row), and the response of habitat change to resident flora and fauna (third and fourth rows of diagram). The arrows between rows, and between boxes within the rows, represent causal and correlative relationships including thresholds (indicated by yellow bars). The external factors and processes are not shown in this diagram, and the noted indicators are not exhaustive. The interrelationships among all the indicators is much more complex than suggested in this simplified schematic explanation of thresholds and triggers.

1.2. Integration across WRMP SOPs

While monitoring elements of the WRMP are outlined individually in separate SOPs, they are interrelated and will be integrated in the WRMP Monitoring Plan. For instance, monitoring for indicators such as elevation, salinity, and tidal inundation should be co-located with field surveys for vegetation to answer questions about how vegetation species or alliances are distributed in regards to the tidal frame and how this changes over time. Accretion controls the ability of restored marshes to reach quasi-equilibrium elevations. Factors controlling accretion include sediment supply and above-ground plant matter accumulation. Plant matter also helps trap sediment in place, while tidal action and inundation helps transport sediment throughout the SFE. Fish are similarly influenced by hydrogeomorphic indicators; fish need adequate dissolved oxygen to survive, the transport of material can support resident nekton and macroinvertebrates, which can be foraged on by fish, and the tidal inundation regime can help dictate what fish species may be present within a marsh. These are examples of the interrelated factors that can be monitored jointly to evaluate relationships between drivers and responses of tidal marsh function, as illustrated in the conceptual model (Figure 2).

2. Hydrogeomorphic monitoring for the WRMP

Regional monitoring of hydrogeomorphic variables is needed to answer the WRMP monitoring questions as well as provide the region with robust and consistent monitoring data that increases knowledge of tidal marsh ecosystems, their current status, changes due to climatic shifts, and underlying drivers that can inform restoration projects and adaptive management.

2.1. SOP Development

A workgroup of regional experts in various aspects of tidal marsh hydrogeomorphology were invited to participate and contribute to the development of this SOP. Because standard monitoring protocols are already in use by many regional programs and agencies for many of the identified variables, this workgroup decided to collate and adopt these existing protocols as much as possible. The workgroup grouped the important physical variables into topic categories and section leaders with expertise in different elements were invited to lead subgroups. These subgroups convened to share experience, identify existing SOPs, consider best methods for the regional program, and discuss challenges and considerations. Section leaders then identified and organized key SOPs and proposed best monitoring methods to address WRMP questions. The whole HGM workgroup met several times to coordinate and exchange information on methods, and to work towards agreement on recommendations for monitoring variables across a regional scale and within the monitoring site networks.

2.1.1. SOP Structure

Due to the large scope of hydrogeomorphic variables and monitoring approaches, the SOP is organized as a main document with sections dedicated to each monitoring variable that reference a corresponding appendix with a more detailed and developed SOP for each topic.

The main document contains a summary of the appendix SOP including background information and rationale for monitoring, high-level recommendations of best methods for WRMP monitoring, and recommended products that can be developed from the monitoring data that will help answer the WRMP monitoring and management questions. The SOPs’ appendices include more background information, alternative monitoring approaches and considerations, and recommendations for the WRMP, including how monitoring can vary by site type and how to integrate different scales of monitoring (e.g., remote sensing versus field survey data). The source SOPs currently in use in the region are referenced both from the main SOP document and within the appendices.

2. Questions to be answered by monitoring

2.1. WRMP Management Questions, Monitoring Questions, and indicators

The WRMP science framework is built around a sequence of Guiding and Management Questions, which have been approved by the Steering Committee and are described at length in the WRMP Program Plan (WRMP 2020). Monitoring hydrogeomorphic variables is critical for informing all of the Guiding and Management Questions, but directly relevant and essential to answering Guiding and Management Questions 1 through 3.

Guiding Question 1: Where are the region’s tidal marsh ecosystems, including tidal marsh restoration projects, and what net landscape changes in area and condition are occurring?
- *Management Question 1A: What is the distribution, abundance, diversity, and condition of tidal marsh ecosystems, and how are they changing over time?*
- *Management Question 1B: Are changes in tidal marsh ecosystems impacting water quality?*

Guiding Question 2: How are external drivers, such as accelerated sea level rise, development pressure, and changes in runoff and sediment supply, impacting tidal marsh ecosystems?
- *Management Question 2A: How are tidal marshes and tidal flats, including restoration projects, changing in elevation and extent relative to local tidal datums?*
- *Management Question 2B: What are the regional differences in the sources and amounts of sediment available to support accretion in tidal marsh ecosystems?*

Guiding Question 3: What new information do we need to better understand regional lessons from tidal marsh restoration projects, advance tidal marsh science, and ensure the continued success of restoration projects?
- *Management Question 3A: Where and when can interventions, such as placement of dredged sediment, reconnection of restoration projects to watersheds, and construction of living shorelines, help to sustain or increase the quantity and quality of tidal marsh ecosystems?*

To answer the Management and Guiding Questions, Monitoring Questions and associated indicators were developed and approved by the TAC and Steering Committee and listed in the Program Plan’s Master Matrix (WRMP 2020 Appendix A2). The Monitoring Questions and indicators relevant to hydrogeomorphic monitoring and described in this document are listed below and within table 1:

- What are the elevations of the estuary's existing and restoring tidal marshes? What is their elevation capital?
- Where are shorelines eroding landward and/or prograding bayward?
- Where are unvegetated areas such as channels, ponds, and pannes expanding and deepening?
- How are the elevations of marsh plains (including high tide refugia) changing over time, and where in the estuary are tidal marsh accretion rates keeping up with rates of sea level rise?
- Where is there adequate suspended sediment to support rates of accretion that are equal to or greater than sea level rise (SLR), and monitoring data are needed to develop and calibrate numerical models that forecast the variations in suspended sediment supply?
- How do tidal inundation regimes differ throughout the estuary's tidal marshes, and are they muted, choked, or otherwise different from source tides?
- How are the primary and secondary salinity gradients in the estuary's tidal marshes changing over time?

2.2. Regulatory interest in hydrogeomorphology - impact analysis, permit requirements

Current efforts are underway through the Regulatory Roadmap, discussions with the BRRIT, and individual regulator agencies to understand how hydrogeomorphic monitoring can support permit required monitoring. **This section will be updated** over time as progress is made toward understanding how overall regional monitoring can support typical permit-required monitoring of projects.

Table 1. Matrix of monitoring questions, metrics, recommended methods and recommended products. Note, some products are recommended at an Operational Landscape Unit (OLU) scale, an area that is topographically delineated around common watershed features, thus sharing water and sediment properties and are more meaningful for wetlands than jurisdictional boundaries.

Monitoring Questions	Indicator #	Spatial Scale	Metrics	Recommended Method	Recommended Products	
What are the elevations and elevation capital of the estuary's tidal wetlands?	2	Regional	Elevations (ft NAVD88) and elevation capital (Z*); relative to local MHHW)	Bias-corrected LiDAR	Maps of bayland elevations and elevation capital, hypsometric curves for tidal bayland units	Site-scale analyses of elevation distributions of vegetated marsh (% below MHW, lowest 1/3 of plant distribution, skewness)
Where are shorelines eroding landward and/or growing seaward?	6	Regional	Shoreline location and typology	Baylands change basemap	Maps of changes in shoreline location and typology over time	
How are the elevations of key tidal bayland geomorphic gradients (e.g. channels, marsh plains, upland/alluvial edges, mudflats) changing over time?		Site-based	Elevations (ft NAVD88) and positions (XY)	RTK surveys	Graphs of vertical and horizontal change of key tidal bayland gradients over time	
Where are unvegetated areas such as channels, ponds, and pannes expanding?	9	Regional & site-based	Drainage network length, channel density/width, panne area, unvegetated tidal marsh area	Baylands change basemap and channel cross sections	OLU/site-scale maps of pond/panne expansion and UVVR changes in tidal marshes	Site scale metrics of channel diversity and complexity
What are the rates of accretion and elevation change in the region's tidal baylands, and how are they changing over time?	12	Site-based	Rates of accretion	MHs and sediment pins	Graphs of accretion rates at MHs and sediment pins	
			Rates of net elevation change	SET-MHs and RTK	Graphs of elevation change at SETs	Regional comparison of change in wetland surface elevations (Indicator 12) in relation to local rates of sea level rise (Indicator 15)
How does suspended-sediment concentration (SSC) vary across wetland systems in the estuary?	13	Subregional & site-based	Suspended sediment concentrations	Turbidity sensors	Graphs of trends in seasonal and intraannual SSC in tidal baylands	Regional comparison of change in wetland surface elevations (Indicator 12) in relation to turbidity/SSC

					(Indicator 13)
How do tidal inundation regimes differ throughout the estuary's tidal baylands (marshes + channels),	14	Subregional & site-based	Tidal inundation regime	Long-term tide gauges and pressure transducers	Tabular water surface elevation data and derived statistics (e.g. tidal datums, inundation distribution curves)
How does the tidal inundation regime of a marsh differ from a source tide (are they muted, choked, or otherwise different)					
What are the regional rates of sea level rise and how do they vary throughout the estuary?	15	Subregional & site-based	Relative rate of SLR	Long-term tide gauges	Graphs and tabular data of calculated rates of SLR over time
What are the surface water salinity fields in the estuary's tidal baylands, and how do they change over time?	16 a,b	Subregional & site-based	Surface water salinity	Electrical conductance	Graphs of trends in seasonal and intraannual surface salinity in tidal baylands
What are the porewater salinity fields in the estuary's tidal baylands and how do they change over time?		Site-based	Porewater or groundwater salinity (see SOP)	Electrical conductance	Graphs of trends in seasonal and intraannual porewater salinity in tidal baylands

3. Monitoring Approaches

Table 1 highlights monitoring approaches for each of the monitoring questions and their corresponding indicators. The table also provides a summary of the recommended method and products associated with each metric. In each subsection below, the information found within table 1 is spelled out in greater detail.

3.1. Horizontal and Vertical Control

3.1.1. Background

Horizontal and vertical control are essential components of geodetic and surveying systems used to establish accurate and consistent reference frameworks for mapping and various geospatial applications. Horizontal control refers to the horizontal position on the Earth's surface (longitude and latitude, relative to a defined horizontal datum) and associated accuracy. Vertical control refers to the vertical height or elevation of a location relative to specified reference surface (usually a defined vertical datum) and associated accuracy of the reported elevation. Horizontal and vertical control exists for the purpose of providing an accurate position from which to reference future surveys, and supporting application of other SOPs, particularly marsh elevation and water levels which then tie into interpretative analysis such as for vegetation change.

Implementation of horizontal and vertical control occurs within or near the area of study and involves the placement of physical markers with known positions relative to established datums (called control points or monuments). The longevity of control points can range from highly durable to fairly temporary and the cost of establishing and maintaining horizontal and vertical control points relates directly with the selected level of durability. Thus, deciding as much as possible and as early as possible what use needs will be (and recognizing that they may change over time) is the core input information to select appropriate methods.

3.1.2. Methods

See Appendix 3 for additional information on methods for implementing horizontal and vertical control.

3.1.3. Recommendation for Horizontal and Vertical Control

- Establish and document horizontal and vertical control for Benchmark and Reference sites within the Priority Site Network initially and then add horizontal and vertical control points for additional Benchmark and Reference sites as funding allows.

3.1.4. Products

- Report providing a written and visual description of horizontal and vertical control points for Benchmark and Reference sites including, at the minimum:
    - Control point (horizontal and vertical) monument names
    - Elevation and associated vertical datum (e.g., North American Vertical Datum of 1988, NAVD 88)
    - Horizontal coordinates and associated horizontal datum (e.g., North American Datum of 1983, NAD 83)
    - Date established
    - General description
    - Survey methods used (instruments, software, etc) and crew names
    - Accuracy based on methods used
    - Any adjustments made to control point or adjustments required for data usage
    - Site photos and relevant comments for future access

3.2. Topography

Background understanding and recommended approaches to monitoring Topography is summarized from the Topography SOP (Appendix 4) which describes in more detail the considerations and recommendations for the WRMP.

3.2.1. Background

Owing to their location at the interface of land and water, the study of coastal ecosystems requires an understanding of the elevation of the earth's surface both above and below the water surface. Topography, used in this document to mean the elevation of the surface of the earth, is essential for a comprehensive assessment of estuarine ecosystems and their responses to changing environmental conditions, including sea-level rise.

Elevation relative to tidal flooding exerts strong control on many tidal marsh ecosystem processes. For example, marsh plant species have unique tolerances to flooding and tend to organize into zones characterized by relative elevation and salinity (Pennings et al. 2005; Janousek et al. 2019). Generally, rates of sediment deposition decrease as relative elevation increases (i.e., sediment deposition rate is inversely correlated with relative elevation). For example, areas relatively high compared to tidal fluctuations (higher in the "tide frame") are flooded for shorter durations, to shallower depths, and at lower frequency than areas relatively low compared to tidal fluctuations (lower in the "tide frame"). The concept of elevation "capital" is also key for understanding vulnerability of marshes to sea-level rise; the higher a marsh is in the tidal frame, the longer it will take to transition or "drown", while marshes with less elevation capital are low in the tide frame and more susceptible to sea-level rise (Cahoon et al. 2019).

Bathymetry, or the below-water topography in aquatic environments, plays a crucial role in understanding tidal marsh ecosystems. Bathymetry data provide spatial variation of water depth and is important to understand wave and tidal flow patterns, the resuspension of fine sediment, and the extent of subtidal habitats.

Elevation of the land surface can be measured in several ways, each suited to specific accuracy requirements, spatial scales, and resolution needs. The choice of method depends on the project's objectives and conditions. For larger spatial scales and broader topographic assessments, remote sensing technologies like InSAR (Interferometric Synthetic Aperture Radar), LiDAR (Light Detection and Ranging), and Unoccupied Aerial Vehicles (UAVs) equipped with LiDAR or photogrammetry capabilities (e.g., SfM, "Structure from Motion") are often the preferred choice. These methods provide efficient coverage over large areas, making them suitable for regional mapping.

On the other hand, when more precise, field survey elevation measurements are required, terrestrial sensors such as Total Stations or Real-Time Kinematic-Global Navigation Satellite System (RTK-GNSS) systems are more appropriate. These instruments offer higher levels of accuracy, but since they are ground based, they are infeasible over large spatial scales (see section on site, scale, elevation change/accretion in Appendix 4).

For bathymetry, single and multi-beam echo sounders are standard methods for measuring water depth. Single-beam echo sounders emit a single sonar pulse vertically downward from a boat or ship, making them a cost-effective solution for shallow water surveys (although they tend to produce lower-quality datasets and cannot be used in very-shallow waters). Multi-beam systems, on the other hand, are widely used for detailed mapping and hydrographic surveys. They emit multiple sonar beams to measure the return time from the seafloor, enabling the simultaneous mapping of a wide swath of the seafloor with high resolution. Additional bathymetric measurement methods include side-scan sonar, which primarily images underwater objects, but can provide depth information when used in combination with other sensors.

3.2.2. Recommended Method for Monitoring Tidal Marsh Elevations

Airborne LiDAR provides broad spatial coverage of elevation data with reasonable accuracy (centimeter-scale on bare-earth; Hodgson and Bresnahan 2004) and is therefore the recommended tool for tracking elevation and elevation change over time at the regional scale. Regular remapping (e.g., every 5 years) would help facilitate updating the habitat classification in the WRMP Baylands Change Basemap[4]. A LiDAR system (sensor, inertial motion unit, GNSS) is mounted to a small aircraft (e.g., Cessna), and is flown in a crisscrossing pattern across the study area. Surveys need to be flown at low tide since LiDAR typically does not penetrate the water. While green wavelength LiDAR is able to collect data in clear water, the waters in the San Francisco Estuary are generally too turbid for this approach to be successful. Vendors provide a bare-earth Digital Elevation Model (DEM), generated with last return points, and which undergoes substantial post-processing (e.g., hydro-flattening water features, removal of bridges, etc). The accuracy of the bare earth DEM is assessed by the vendor using RTKGNSS surveys on hard surfaces [e.g., parking lots] or in sparse vegetation, but not in marshes.

See Appendix 4 for more details on LiDAR and specifications for sampling or (Schmid et al. 2011) available online directly for SOP.

3.2.3. Products

A map of bayland elevation, elevation capital, and hypsometric curves for tidal bayland units will help answer the monitoring question: **What are the elevations and elevation capital of the estuary's tidal wetlands?** To produce this, both a bias-corrected LiDAR DEM, and the relative tidal elevation are needed. Z*, also known as relative tidal elevation or dimensionless depth, is calculated by:

$$Z* = (marsh\ elevation - MSL) \div (MHHW - MSL)$$

where MSL is mean sea level and MHHW is mean higher high water, both found using local tidal datums (Swanson et al. 2014).

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[4] Name subject to change

3.3. Accretion, Erosion, and Elevation Change

Background understanding and recommended approaches to monitoring accretion and erosion is summarized from the Accretion and Erosion SOP (Appendix 5) which describes in more detail the considerations and recommendations for the WRMP.

3.3.1. Background

A key goal from long-term monitoring is to understand how rates of tidal marsh elevation change vary around San Francisco Bay and whether they are keeping pace with accelerating rates of sea-level rise. With the decrease in sediment delivery from the Sacramento-San Joaquin Delta (Schoellhamer 2011) and given the extensive tidal marsh restoration efforts of subsided baylands (Williams and Orr 2002; Callaway et al. 2011), questions arise about the availability of sufficient sediment to support the development of restored lands and natural tidal marsh accretion in the face of rising sea levels. Data on rates of marsh elevation change will help support regional decision making and adaptive management.

Tidal marsh elevation or topographic change is driven by two primary processes: *accretion*, the accumulation of sediment and organic matter at the surface; and *subsurface elevation change* driven by belowground processes such as decomposition, subsidence, and compaction.

Within tidal marshes, there are several considerations when deciding the best method for measuring marsh topographic evolution. The best method can vary based on age of the site, available funding and desired accuracy (Table 2).

Table 2. Field methods for assessing marsh topographic evolution. Site types and networks are described in the WRMP Priority Monitoring Site Networks memo, January 2023 (link).

Method	Measurement	Appropriate Site*	Accuracy	Spatial Coverage (ha)	Cost
Total station/ differential leveling	Elevation change	Benchmark, Reference, Project (engineered or developed)	0.001-0.005 m (@100-300m)	1	$30k+ equipment, 2 people
RTK GNSS	Elevation change	Project (subsided)	0.02-0.12 m	1-1000	$20k equipment, 1 person
Single/multi beam bathy	Elevation change	Project (subsided)	0.02-0.12 m?	1-1000	$20-50k equipment, 2 people
Marker horizon plots	Accretion	Benchmark, Reference	0.001-0.004 m	0.01 (?)	$40 for 50# feldspar bag, enough for 6 plots, 1 person
rSET-MH	Accretion &	Benchmark,	0.001-0.007 m	1x10-4	$8k installation (x4

	Elevation change	Reference			SETs) 1 day x 2 people to read
Sediment pins	Elevation change	Project (subsided, developed)	0.02-0.04 m	0.01 (?)	$50-100 for PVC, 1 person
Sediment pads/tiles	Accretion (mass)	Special study	milligrams	0.001 (?)	Pads ~$0.5 each, a lot of lab time required

* Engineered: sites that have been graded to an elevation suitable for plant establishment; substrate may be consolidated or unconsolidated. Developed: restorations that have accreted sediment naturally and are vegetated with consolidated substrate. Subsided: sites where tidal flow has been reconnected but the elevation is too low for plant establishment and the substrate is unconsolidated.

3.3.2. Recommended Methods for Measuring Accretion and Erosion

For benchmark and reference sites the recommended method is surface elevation tables with marker horizons (SET-MHs). They are capable of measuring millimeter-scale changes in marsh accretion and elevation through time and account for erosion, compaction/subsidence, and organic/mineral accretion. For project sites, sediment pins are the recommended method as they work well in unconsolidated mud and are relatively inexpensive, but lack the same precision as the SET-MHs. Both local-scale methods (SET-MH and sediment pins) can be integrated in site-wide elevation measurements using a Total Station or RTK-GNSS.

For detailed standard operating procedures including choosing best methods, deployment and data collection see Appendix 5 or (USGS 2012) available online for sediment pin methods and (Lynch et al. 2015) available online for SET-MH methods.

3.3.3. Recommended Method for Bathymetry

While the WRMP does not specifically have a monitoring question regarding bathymetry, these methods are recommended for subtidal project sites. Echo sounders are used to measure water depth using the principles of sonar. Transducers are mounted on a boat, along with RTK-GNSS to establish position relative to a datum. In multibeam systems, an inertial measurement unit is also used to account for the pitch and roll of the boat. The swath width of multibeam returns increases with water depth, while a single beam system measures depth at the nadir. Since water density affects the speed of the sonar pulse, salinity should also be measured and accounted for in post-processing. As the system relies on RTK-GNSS for absolute elevation, accuracy is at best ~2 cm, but likely lower when boat motion, water density, and bed properties are considered. Echo sounder techniques for bathymetry data can be used to understand how bed elevation is changing over time (Takekawa et al. 2010). For each survey, conducting a bar check procedure is recommended to check sensor accuracy. A bar check procedure involves lowering a medium-sized flat plate below the transducer to known depths, allowing comparison of sensor output to actual measured depth. This procedure can assess the accuracy of the echo sounder readings across the range of depths encountered in the survey (e.g., every 5 ft).

See (USACE 2013) available online for details on how to conduct a bathymetric survey.

3.3.4. Products

Change in wetland elevation is a combination of vertical erosion, compaction and accretion. These variables vary within individual wetland units and within Operational Landscape Units (OLUs), topographically delineated areas around common watershed features that share water and sediment properties. Maps of elevation capital and erosion/accretion provide insight into what areas might be more or less vulnerable to sea level rise. As sea levels continue to rise, understanding how sediment accumulation rates compare to these rising water levels is essential for predicting the fate of these ecosystems and planning adaptation strategies. Graphs of elevation change (such as in Figure 3), regional comparison of change in wetland surface elevations in relation to sea level rise, and statistics will help answer the question: **How are the elevations of marsh plains (including high tide refugia) changing over time, and where in the estuary are tidal wetland accretion rates keeping up with rates of sea level rise?**

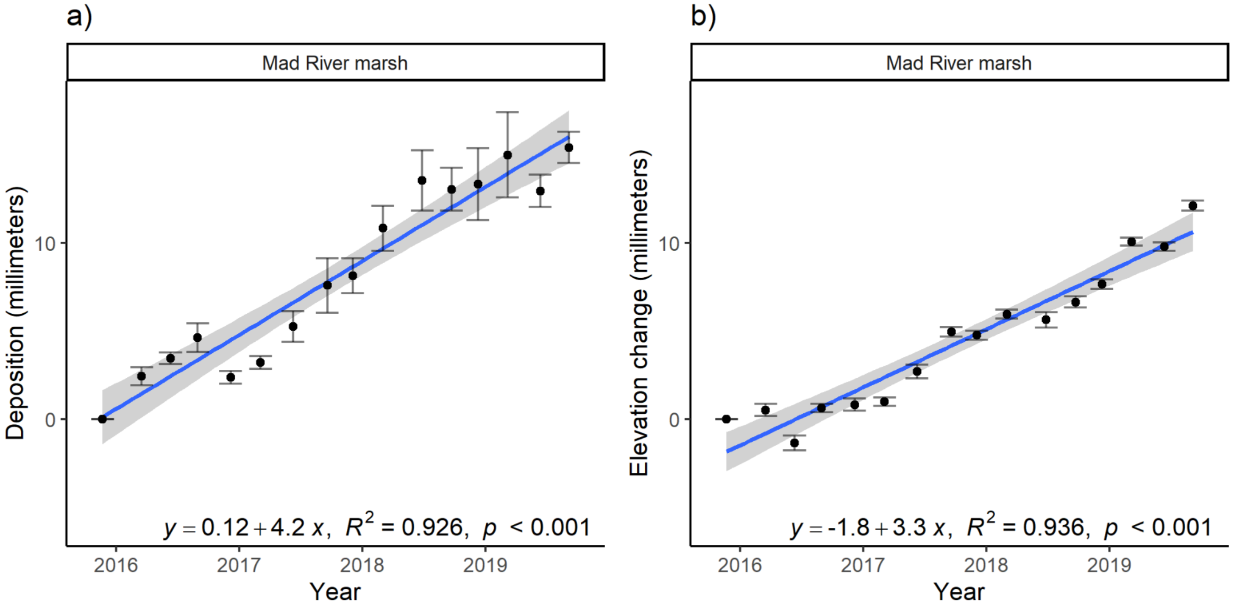


Figure 3. Example product of surface elevation table-marker horizons (SET-MH) measurements. Average (standard error) accretion from Marker Horizon plots (a) and net elevation change measured by SETs (b). Adapted from Curtis et al. (2022).

3.4. Shoreline Change

Background understanding and recommended approaches to monitoring Shoreline Change is summarized from the Shoreline Change SOP (Appendix 6) which describes in more detail the considerations and recommendations for the WRMP.

3.4.1. Background

As sea level rises, the tidal marshlands will continue to evolve in three major directions: vertically accreting or downshifting (depending on sediment supply and organic accumulation), migrating upslope and inland (depending on accommodation space), and laterally expanding or retreating at the Bay edge (Brinson et al. 1995). Lateral changes in the position of the marsh edge are extremely important because marsh retreat is thought to be the chief mechanism by which coastal wetlands worldwide are being lost (Francalanci and Solari 2011; Marani et al. 2011; Fagherazzi 2013).

Shoreline change can be monitored through field survey or remote sensing methods. The choice between these approaches depends on factors like the scale of the area being studied, the required level of accuracy, and the available resources. Remote sensing is more practical for large areas, while in the field, site-specific measurements can yield higher accuracy but are limited to smaller areas. In combination, field surveys can be used to validate remote sensing methods. Common field survey methods for tracking shoreline change include time-lapse photography to capture gradual changes over time, topographic surveys to measure elevation and substrate composition, and RTK-GNSS surveys for precise location data. Various remote sensing technologies can be employed, including LiDAR surveys for high-resolution elevation data and Structure from Motion (SfM).

3.4.2. Recommended Method for Tracking Shoreline Change

Level 1, bay-wide map of the shoreline.

Using the Baylands Change Basemap, a bay-wide map of the shoreline can be estimated. The shoreline is defined here as the vegetated edge using a combination of LiDAR and aerial imagery and object-based classification (WRMP 2021). The vegetated edge is mapped as “intertidal marsh” within the Baylands Change Basemap. This intertidal marsh will be mapped every five years when the basemap is updated (see Geospatial SOP for Indicators 1 and 3; WRMP 2021) and by comparing the updated map with the previous version, the change in the edge of intertidal marsh (or shoreline location) can be calculated. To help facilitate change detection, tools such as the Digital Shoreline Analysis System (DSAS) can be utilized. Currently this tool is only compatible with ArcMap (not ArcPro) and has an end of life date in February 2024, however a new stand-alone version is in development. The Baylands Change Basemap classifies habitat type using polygons, while DSAS uses line features. The shoreline edge within the basemap therefore needs to be converted into a line feature. This can be done by creating a new line shapefile and tracing the shoreline delineated within the basemap. Each subsequent year the basemap is produced this can be repeated. The line feature layer created from the Baylands Change Basemap can then be used within DSAS and change within the shoreline extent can be analyzed. **Details on DSAS can be found online within (Himmelstoss et al. 2021).**

Level 3, site-level monitoring
The marsh edge (shoreline) is defined as the geomorphic change in topography, slope, and soil shear strength at the scarp or ramped bayward edge of the marsh platform (Beagle et al. 2015). Either unvegetated bay mud or low cordgrass marsh occurs bayward of the marsh platform edge, while consolidated, mostly vegetated marsh plain, typically dominated by pickleweed (*Sarcocornia pacifica*), occurs landward.

- For scarp typologies, use of LiDAR or SfM data and automated shoreline detection methods are recommended
- For slopes typologies, RTK GNSS field surveys needed to accurately delineate shoreline based on bed consolidation
- Shoreline monitoring transects can also be located at the bay edge of vegetation transects. Shoreline edge transects should be relatively short (5 m) but with high point density (0.2 m spacing) to capture small features. Regular RTK GNSS measurements would provide validation of remote sensing-based estimates of shoreline change. Use of mapping feature on RTK GNSS would allow for precise revisiting of points along each transect.

For detailed standard operating procedures for shoreline change, reference Appendix 6 and SOPs therein.

3.4.3. Products

Lateral erosion and depositional expansion of the shoreline indicates where tidal marsh loss and gain is occurring. These maps and time series analysis are vital to answering: **Where are shorelines eroding landward and/or growing seaward?** Erosion and deposition themselves are natural processes and interact together to both build and degrade the shoreline. Monitoring and synthesizing the change overtime can help show where the shoreline is changing over time.

3.5. Water Surface Elevations, Inundation, and Sea-Level Rise

This section provides background and recommended approaches to monitoring water surface elevations (WSE), inundation and sea-level rise (SLR). See the Water Surface Elevations, Inundation, and Sea-Level Rise SOP (Appendix 7) for more details about the considerations and recommendations for the WRMP.

In general, NOAA has developed standardized procedures for measuring water and ground surface elevations in tidal wetlands, especially those that are monitored to understand coastal habitat responses to rising sea levels, more extreme storms, and other impacts of climate change. NOAA published the most-recent version of these procedures (*NOAA NOS Manual: Accurate Elevations for Sea Level Change Sentinel Sites,* Hensel et al. 2023) with input from its National Ocean Service (NOS), National Geodetic Survey (NGS), Center for Operational Oceanographic Products and Services (CO-OPS), and Office for Coastal Management (OCM). NOAA developed these procedures to support the NERR Sentinel Site system as well as other agencies and organizations with similar programs to monitor SLR along the nation's coasts, such as the WRMP. Since its inception, the WRMP has regularly consulted with the NOAA staff responsible for developing these procedures, to seek advice for monitoring of ground and water surface elevations. Hensel et al. (2023) describes best practices for establishing water level and geodetic infrastructure as well as connecting measurements of water surface elevations, ground surface elevations (via SETs), groundwater elevations, and vegetation plots. This publication describes a method for measuring water surface elevations consistent with relatively more exacting CO-OPS/National Water Level Observation Network (NWLON) standards, as well as a lower-cost method that utilizes more commercially available sensors. This publication also includes case studies of different methods employed by NERR sites to monitor water surface elevations and derive products such as tidal datums, SLR trends, and related information. The recommendations in Hensel et al. (2023) form the technical basis of the WSE monitoring SOP.

3.5.1. Background

Inundation is the depth of water at a given location, which can be calculated as the difference between water surface elevations and ground surface elevations at the location. The frequency, depth, and duration of inundation in tidally influenced baylands is a fundamental driver of their condition, function, and resilience. Inundation mediates the movement and net flux of salt, sediment, nutrients, food web production, and other key environmental constituents between tidal marshes and adjacent mudflats and open estuarine waters. Due to the wide, relatively flat characteristics of the region's tidal marshes and mudflats, relatively small changes in water and ground surface elevations in these systems can result in significant differences in inundation regimes and dependent physical and ecological functions. As sea-level rise continues and potentially accelerates due to climate change, the inundation regime is expected to change. If the rate sea-level rise exceeds the rate of marsh surface accretion, the marsh will begin to drown, higher elevations may see increased flooding, and the extent of inundation will increase.

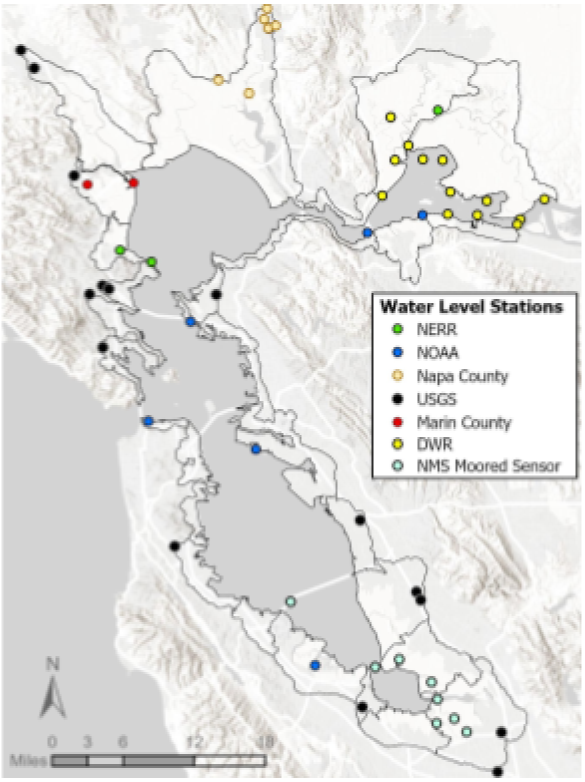


Figure 4. Map of current tidally influenced water surface elevation gauges within the WRMP study area.

Monitoring of water surface elevations and bathymetry, and therefore inundation and sea-level rise, in SFE is primarily limited to NOAA-operated and maintained stations along the main axis of the estuary, where timely and accurate data are necessary to support navigation and public safety, with minimal data collection near shorelines and intertidal baylands. As of 2023, NOAA implements real-time data collection at six tide gauges in deep shipping channels along the main axis of SFE: Port Chicago, Martinez-Amorco Pier, Richmond, San Francisco at Golden Gate, Alameda, and Redwood City (Figure 4). As of 2023, continuous, long-term WSE monitoring in shallow tidal baylands ***outside*** the main estuarine axis is currently limited to:

- A network of tide gauges in Suisun Marsh managed by DWR to support water and salinity management operations
- A network of multi-parameter (WSEs, salinity, DO) gauges in the South Bay managed by SFEI to support the Nutrient Management Strategy
- A USGS tide gauge on Coyote Creek near Alviso
- Tide gauges operated by the SF Bay National Estuarine Research Reserve at China Camp and Rush Ranch
- Tide gauges on Novato Creek and the Napa River operated by the Marin and Napa County Flood Control Districts, respectfully

Long-term gauges are typically permanently installed at fixed locations, and are designed for durability and reliability. Short-term gauges are typically used for immediate or near-real-time monitoring and are often deployed for specific projects or events. They are cheaper than long-term gauges, are often portable, and can be quickly installed and removed as needed.

Tidal datums

Tidal datums serve as critical reference points for measuring water levels in tidal marshes, playing a pivotal role in understanding and managing these ecosystems. Tidal datums provide a vertical height datum relative to tidal fluctuations at a given location and are computed via statistical analysis. Commonly reported tidal datums include Mean Higher High Water (MHHW), Mean High Water (MHW), Mean Tide Level (MTL), Mean Low Water (MLW), and Mean Lower Low Water (MLLW). Of these, MHHW and MLLW provide consistency and precision in monitoring water levels, enabling researchers and managers to track changes, assess ecosystem health, and manage habitat effectively. Tidal marsh ecosystems are highly sensitive to water level fluctuations, making accurate tidal datum information essential for studying their dynamics, supporting diverse flora and fauna, and designing strategies to protect these habitats in the face of rising sea levels and changing environmental conditions.

Inundation regimes - frequency distributions

The tidal inundation regime refers to the frequency, depth, and duration of tidal flooding. These are key metrics that also help control and influence geomorphology within tidal marshes, and can be computed at a site if WSE and bathymetry data are known. The duration and frequency of drying are both meaningful ecologically and should be monitored.

Extreme events

Extreme events are periods of very-high or very-low water surface elevation and can have significant impacts on tidal marshes. During extreme high tides or storm surges, water levels will exceed normal tidal ranges, leading to the increased inundation of tidal marshes. These events can result in saltwater intrusion, which affects vegetation that is less tolerant of salinity and may cause stress and mortality in plant species. Higher water levels can also impact wildlife by flooding their habitats and affecting nesting sites for birds and burrowing animals.

Extreme low tides can also affect the site by exposing wetland areas to prolonged periods of drying, which can stress vegetation and disrupt habitats. Furthermore, extreme fluctuations in water levels can lead to shoreline erosion and alter sediment deposition patterns.

3.5.2. Recommended Methods for Water Surface Elevation

For monitoring regional rates of SLR: **New long-term tide gauge installations** at locations which are not well-sampled by the existing gauge network is recommended. Partnership with agencies is likely needed to maintain and install long-term gauges. In addition to gathering equipment, access and permitting needs to be considered. **Methods should follow the NOAA NOS Manual (Hensel et al., 2023) available online.**

For monitoring variability in tidal inundation regimes between a tidal marsh and its connected tidal channels, between different wetlands connected to the same tidal channel, and between different locations in the same tidal marsh: **New short-term tide gauge installations at WRMP priority Benchmark, Reference, and Project sites should follow methods outline by (US Geological Survey 2012) available online.**

See Appendix 7 for more background on short-term and long-term tide gauges.

3.5.3. Products

WRMP priority products related to water surface elevation, inundation, and SLR include:

- Time series **water surface elevation data** (relative to NAVD 88 datum), accessible through an interactive map that facilitates queryable access to:
    - Graphic data
        - Full data sets
        - Zoom-in to shorter time durations to illustrate conditions, compare spring vs. neap tides, equinoxes vs. solstices, etc.
        - Include plot of computed differences on second y-axis to illustrate magnitudes and any patterns of differences which may or may not exist
    - Tabular data, including calculations of:
        - Statistics on differences – average, minimum, maximum, standard deviation

    - Statistics for full data sets and subsets reflecting spring vs. neap, equinoxes vs. solstices, etc.
    - Tidal datums
    - Inundation regimes
        - Depth, duration, frequency are key metrics
        - Flood duration and dry duration are separate and both very meaningful ecologically (esp. dry duration)
    - Extreme events
        - Focus on high and low tides only, not all tide data
        - Very relevant to NOAA National Water Level Observation Network (NWLON) stations – calculate observed vs. predicted tides – magnitudes, seasonality, relationship to heights of predicted high and low tides
        - Very useful for local stations esp. when relative to site-specific features (marsh plain elevations, roads, etc.)
- Metadata of deployments, including calibration data, barometric pressure adjusted data (if applicable), computations for conversion to NAVD88 (if applicable)

Derived products from tabular water surface elevation data to better quantify and compare water tidal inundation regimes include:

Statistics on differences – average, minimum, maximum, standard deviation

Finding the average, minimum, maximum and standard deviation of water surface elevation at sites or within OLUs facilitates the comparison of different inundation regimes. Though two sites may have similar minimum and maximum water surface elevations the standard deviations might be different. This would indicate that tidal variability differs between the sites. In addition, two sites might have the same average water surface elevation, but different minimum and maximum water surface elevations. This indicates that the tidal range at the sites are different.

Statistics for full data sets and subsets reflecting spring vs. neap, equinoxes vs. solstices, etc.

Tidal variations between spring and neap tides, as well as equinoxes and solstices, strongly influences tidal marshes. Spring tides, occurring during the new and full moon phases, bring higher high tides and lower low tides and greatly impact tidal marsh inundation patterns. In contrast, neap tides, associated with the first and third quarter moon phases, produce lower tidal fluctuations. Equinoxes, when day and night are of equal length, occur two times in a year and influence the timing and extent of tidal inundations in wetlands. Solstices, marking the extremes of daylight duration, occur two times in a year and accentuate seasonal variations in wetland hydrology. Calculating water surface elevations at these various cycles for wetland units and OLUs will help understand how these cycles influence water surface elevation.

3.6. Salinity

Background understanding and recommended approaches to monitoring salinity is summarized from the Salinity SOP (Appendix 8) which describes in more detail the considerations and recommendations for the WRMP.

3.6.1. Background

Salinity is a crucial variable that significantly influences physical and biological processes within estuaries, impacting the distribution of plants and animals. It represents a complex mixture of dissolved salts with various chemical compositions found in seawater. In an estuary, salinity is affected by the salinity of ocean water, magnitude and timing of freshwater inflow, and basin morphology. Salinity influences what plants can grow in the region as well as microbial activity and nutrient cycling. Salinity affects the dynamics of mixing for the water body; large variations in salinity in the water column can give rise to stratified conditions that inhibit mixing and can affect other water-quality parameters (e.g., dissolved oxygen).

At a given location, salinity can be measured in the water column (surface water), in sediment pore water, or in near-surface sediments (shallow groundwater). Surface-water salinity refers to measurements made within the water column, often at various depths. Porewater salinity refers to measurements made on water collected from the pore spaces between sediment particles usually within the top 20 cm of the bed. Shallow groundwater salinity refers to measurements made in the groundwater within the top 3 m of the bed.

3.6.2. Recommended Methods For Salinity Monitoring

The WRMP recommends the use of moored electrical conductivity sensors for continuous monitoring of water conductivity and salinity over extended periods. These sensors offer high temporal resolution, making them well-suited for tracking short-term variations and diurnal patterns. They are cost-effective, easy to calibrate, and widely employed in various applications throughout the estuary. **To ensure high-quality data, adherence to established procedures for the collection of continuous data is recommended (e.g., Wagner et al., 2006; USGS, 2019). For shallow groundwater salinity measurements, piezometers should be installed in accordance with Sprecher (1993) and fitted with an electrical conductivity sensor.**

Electrical conductivity (EC) sensors typically arrive off-the-shelf with a manufacturer certification of laboratory calibration. Sensor output must be periodically checked against known solutions to ensure data accuracy (“sensor check procedure”); some sensors allow for user-defined calibrations that override the factory calibration. This sensor check procedure allows for some level of interchangeability for EC sensors between sites. Biological fouling typically affects sensor output by decreasing sensor reading to levels that are much less than actual (i.e., artificially low readings). Fouling can be substantially decreased by the use of commercially available wipers, which clean the sensor cell at user-specified intervals.

Special studies comparing the three measurement methods (surface water, porewater, and shallow groundwater) would improve understanding of how these methods relate and support future guidance for monitoring programs.

3.6.3. Products

Maps of seasonal and intra-annual surface salinity within tidal baylands will answer: **How are the primary and secondary salinity gradients in the estuary's tidal wetlands changing over time?** Maps of seasonal and interannual shallow groundwater salinity within tidal baylands will help answer: **How are the primary and secondary salinity gradients in the estuary's tidal wetlands changing over time?**

A data collection report should be prepared for each new salinity gauge installation that describes methods for sensor installation and calibration procedures, instrumentation deployed including specifications sheets, deployment descriptions (install dates, download dates, retrieval dates), field methods and records for converting EC to salinity data including QA/QC, photographs of stations, and other relevant installation and deployment attributes.

3.7. Suspended-Sediment Concentration

Background understanding and recommended approaches to monitoring suspended sediment is summarized from the Suspended-Sediment Concentration SOP (Appendix 9) which describes in more detail the considerations and recommendations for the WRMP.

3.7.1. Background

Tidal marshes are dynamic ecosystems located at the interface of land and water, and they depend on the deposition of sediments for their growth and maintenance. Sediments carried by tides provide the building blocks for marshes. The sediment settles in the marsh during high tides and, along with organic material from roots and rhizomes, gradually builds up the marsh platform. Sediment deposition is crucial for marsh elevation gain, allowing marshes to keep pace with rising sea levels. Sediment can also transport nutrients (or even contaminants). Some nutrients, such as phosphorus adsorb to sediment particles, similarly contaminants such as mercury adsorb to sediment. The nutrients can help fertilize the marsh, if not in excess, while contaminants can be harmful to wildlife. High concentrations of suspended sediment can significantly impact water quality. These sediments cloud the water, reducing light penetration, which in turn hinders the growth of submerged aquatic vegetation. Furthermore, highly turbid water can be detrimental to fish as it may clog their gills, affecting their ability to respire.

Suspended-sediment concentration (SSC) and total suspended solids (TSS) are measures of the solid-phase material within a volume of water. The difference between these parameters is in the laboratory analysis, where for SSC the entire sample volume is analyzed and for TSS only a subsample is analyzed. Previous studies have determined that data produced using SSC analytical methods have greater accuracy and increased comparability between samples compared to TSS data (Gray et al. 2000). Thus, measuring SSC is considered a better approach when seeking to understand sediment transport and determine sediment budgets and SSC is the recommended metric.

Suspended-sediment concentrations can be measured in numerous ways, either directly or indirectly. Direct measurements are more labor intensive, and require collecting samples in the field then processing them in the lab. Indirect measurements using surrogates are more commonly used and involve establishing a correlation between the parameter being measured and the likely suspended-sediment concentrations. Given the interest in SSC variation over longer time periods (weeks to months), indirect measurement of SSC is conducted through continuous observations of a surrogate parameter such as turbidity, optical backscatter, or acoustic backscatter. Surrogate parameters must be related or calibrated to *in-situ* (i.e., site-specific) sediment characteristics using a robust calibration program. Turbidity meters or optical backscatter use light scattering to measure turbidity of the water, which then can be correlated with suspended-sediment concentrations. Acoustic backscatter instruments use sound waves to measure the intensity of sound reflected by suspended particles in the water. Water-quality probes, such as a multiparameter sonde, can measure turbidity. And on a larger scale, remote sensing analysis can relate multispectral imagery to surface suspended-sediment concentrations.

3.7.2. Recommended Method for Suspended Sediment

For continuous monitoring of SSC, surrogate parameters are more feasible than direct measurements. Turbidity sensors are among the most-common surrogates used to calculate SSC and are the recommended method for the WRMP.

Turbidity sensors typically arrive off-the-shelf with a manufacturer certification of laboratory calibration. Sensor output must be periodically checked against known solutions to ensure data accuracy (“sensor check procedure”); some sensors allow for user-defined calibrations that override the factory calibration. This sensor check procedure allows for some level of interchangeability for optical sensors between sites. Biological fouling typically affects sensor output by increasing sensor reading to levels that are much greater than actual (i.e., artificially high readings). Fouling can be substantially decreased by the use of commercially available wipers, which clean the sensor face at user-specified intervals. **To ensure high-quality data, adherence to established procedures from Anderson (2005) or Wagner et al., (2006) for the collection of continuous data is recommended**. **See Appendix 8 for more background and detailed methods.**

3.7.3. Products

Maps of seasonal and intra-annual suspended sediment in tidal baylands will help answer the monitoring question: **Where is there adequate suspended sediment to support rates of**

accretion that are equal to or greater than sea level rise (SLR), and monitoring data are needed to develop and calibrate numerical models that forecast the variations in suspended sediment supply?

3.8. Channels, Pannes, and Ponds

3.8.1. Background

Tidal channel order, density, and distribution are key features of least-disturbed and restored tidal marshes (Zeff 1999; Hood 2002; D’Alpaos et al. 2007; D’Alpaos et al. 2010; Bridgeland et al. 2017). Natural channel networks possess the necessary densities and sizes (stream order) to facilitate vital ecosystem functions, including hydrologic connectivity between estuaries and vegetated wetland plains. This connection supports the exchange of organisms and the transport of materials and energy, including saline water, nutrients, organic carbon, and sediments (Reed et al. 1999; Buffington et al. 2020). In-fill of tidal channels within diked areas can significantly alter the surface topography, impairing the ability of wetlands to deliver essential functions after restoration. A panne is a small depression within a marsh, not connected by channels, that experiences periodic inundation. They play a valuable role in supporting unique plant and animal communities and contribute to the overall ecological health of the marsh. However, continued expansion of a panne can indicate stress to the system and loss of habitat.

3.8.2. Recommended Methods for Change Over Time in Channels, Ponds and Pannes

Remote sensing analysis can help describe and quantify planform metrics within SFE. Using the output from the WRMP Baylands Change Basemap, important metrics can be tracked, specifically: network length, channel density, panne/pond dimensions, and total unvegetated to vegetated ratio. Within the Baylands Change Basemap, intertidal channel, marsh panne, low marsh, and intertidal marsh are relevant habitat type classifications. To measure channel density, the area of intertidal channels compared to the overall marsh unit area should be calculated. To measure network length, the intertidal channel length per marsh unit can be calculated. To assess pond/panne dimensions the area, length and width of marsh pannes in relation to the marsh unit can be calculated. For total unvegetated to vegetated ratio the area of intertidal marsh compared to the area of intertidal channel and pannes can be calculated. Using subsequent baylands change basemaps, change within these metrics can be tracked over time.

3.8.3. Recommended Methods for Channel-Cross Section

Within project sites the WRMP recommends mapping channel-cross sections at key locations. The channel-cross section should be measured using an RTK-GNSS unit; **more detailed cross-section methods are outlined in (US Geological Survey 2011) also available online. See appendix 10 for further details and in depth methods.**

3.8.4. Products

Mapping and monitoring change over time within ponds, pannes and channels with answer:
Where are unvegetated areas such as channels, ponds, and pannes expanding?

- OLU/site-scale maps of pond/panne expansion and UVVR change
- Site-scale metrics of channel diversity/complexity
- Channel networks maps, time series, and statistics

3.9 Photo-documentation

Photo-point monitoring is an easy and cost effective way to track changes in tidal wetland vegetation, morphology, and overall ecosystem health over time. It is an especially useful approach in newly restored wetlands, where it can often help satisfy regulatory (permit) requirements for post-project monitoring and performance assessment. One of the key benefits of photo-point monitoring is its non-invasive nature, as it does not require extensive transects throughout a site, and can often be implemented from relatively more accessible locations such as upland edges and levee crests. Photo-point monitoring can be used at Project, Reference, and Benchmark sites but is particularly useful for documenting early stages of morphological and vegetative development at Project sites. While remote sensing provides a landscape-scale perspective, photo-points offer the advantage of detecting finer-scale changes that may not be discernible through remote sensing alone. In addition, field-based monitoring such as transects can be time consuming, costly, and not appropriate if the site is recently restored with no or little vegetation.

Photo-point station locations should be distributed throughout a site at key areas of interest, including but not limited to: breach locations, expected locations of accretion maxima, estuarine-terrestrial transition zones, the edges of tidal creeks, locations where upstream watersheds and/or other freshwater features discharge into a site, and related locations of expected geomorphic and vegetation change. A sufficient number of stations should be established to track changes across a site over time. Stations should clearly be marked on a map so they can easily be found on the ground. Location can either be marked with a permanent marker (such as a PVC pipe or stake), or navigated to using a GPS with high accuracy (centimeter accuracy). Photo stations should be permanent, and the direction of each photo taken at a given photo-point should be constant and determined with compass bearings. Some photo-points may lend themselves to the collection of photos in multiple directions, and/or each cardinal direction, at each sampling episode. If significant and noteworthy changes occur in new locations, additional permanent photo stations can be established to capture these developments.

3.9.1 Photography Technique

This SOP incorporates by reference the detailed photography techniques described in the US Forest Service Photo Point Monitoring Handbook (Hall, 2002) and an SOP for Photo-Documentation approved by the California State Water Resources Control Board's Surface Water Ambient Monitoring Program (CARCD, 2001). In summary, photographs should be taken with a digital camera using the same settings for each re-image. Photographers should ensure the chosen camera settings provide a deep depth of field to keep both foreground and background in sharp focus (small aperture or high f-stop), and set camera resolution to at least 20 megapixels (Cox et al., 2021). Photographers should utilize the Landscape mode (full frame on a 35 mm camera or 26 mm focal length on a cellphone), and hold the camera at eye level (5 feet above the ground surface). Photographers must use a compass to ensure that the orientation and angle of the photo is the same each time. They should select the most suitable shooting conditions for capturing accurate and high-quality images, and whenever possible, consider incorporating distinctive reference points, such as rocks, trees, fencelines, or prominent hills, to facilitate accurate replication of photos or scenes in future monitoring efforts. Photos should also minimize the amount of sky and place the horizon towards the top of the frame. It is beneficial to review previous photos in the field to ensure that sequential images cover the same area consistently.

In the future, photo-point monitoring could benefit from drone technology. Drones offer the advantage of capturing photos quickly while minimizing environmental disturbance, as they eliminate the need for manual site access. These unmanned aerial vehicles can be programmed to revisit specific locations, providing valuable data over time. However, it's worth noting that drone use is currently restricted from certain areas, such as within the National Estuarine Research Reserve sites like China Camp and Rush Ranch, and requires licensed operators. However, several restoration projects without those restrictions in the SFE area using drone technology to capture project conditions. Drone use is not a recommended method for photo-point monitoring but this can change in the future with technology advancements, change in access restrictions, and more people having a license to fly a drone.

3.9.2 Timing and Frequency

To accurately capture changes in geomorphology over time, and minimize the influence of tide stage on photo interpretation, photographs at photo-points should be taken during the same tide stage, preferably at low tide. Photographers should utilize predicted and observed tides from the National Oceanic and Atmospheric Administration (NOAA) to time their photographs as accurately as practicable. The time of each photograph should be recorded, and its tide level determined from the nearest tide gauge.

Wherever possible, photographs at photo-points should be captured immediately before and after a site is restored to tidal action, to establish a baseline for assessing change over time. Since Project sites often experience rapid change, photographs should be taken at photo-points least twice annually. The second set of photographs should occur in the early spring so as to capture any geomorphic changes to the system due to winter rain events.

3.9.3 Photo management

Photos should be properly documented and organized to allow for easy access and analysis. Photo numbers must be recorded to indicate which photo corresponds to which photo-point, at which orientation. Photos should be organized in a structured folder system on a computer or related digital storage system, with clear and descriptive names for each folder. Files should have a standard naming convention and should include relevant details such as site name, date, photopoint ID, and cardinal direction of the photo. Photographers/data managers should utilize metadata tagging to embed essential information directly into the photo files. This can include details like camera settings, location coordinates, date, and even keywords describing the content of the photo. Metadata makes it easier to search and sort through the photo collection. Ideally, photos will be uploaded into a WRMP data visualization platform (yet to be developed) that will allow a user to click on a photopoint and observe an annotated time series of the photographs taken at a given location. Photo annotations should include key observations, the date/times of any management actions that may be relevant to conditions observed in the photos (e.g. after a breach, after vegetation management actions, etc.), and the bearing (in degrees) of the photograph

3.9.4 Analysis

Photos should be visually analyzed each year to assess geomorphic and vegetation change throughout each site. Analysts should note significant changes such as the accretion of mudflats, the emergence of channels, other shifts in geomorphology, and the presence of any invasive species (e.g., plants with a “high” rating in the California Invasive Plant Council Inventory). Ultimately, the primary objective of this photo-point monitoring is to diligently document any new landscape changes, providing valuable insights into the evolving dynamics of the wetland ecosystem.

4. Data management

Proper data management ensures the accuracy, reliability, and accessibility of critical information. If field sheets are collected they should be scanned by field workers after data collection to make sure they are complete, that values are legible, and that there are no outstanding questions about the data. Physical field-sheets should be entered into digital spreadsheets or tables (e.g., Excel, Access, or other).

4.1. Quality Assurance/Quality Control (QA/QC)

Digital data should be QA/QC checked and archived. We recommend data validation limits (e.g., in digital spreadsheets or databases) to minimize entry errors and out-of-bound values. We also recommend the plotting of all raw data to identify and correct outliers (with data validation limits in place) and examination of known relationships (e.g., conductivity and salinity; dissolved oxygen concentration and % saturation; etc.) to control for data integrity and accuracy.

4.2. Data format and metadata

All QA/QC procedures, outcomes, and adjustments should be documented in a metadata file and respective tables associated with the project. Final, clean data sets, including metadata and QAQC history, should be uploaded to the WRMP Data Submission Portal annually for long-term monitoring or at the completion of a short-term project window, or as is otherwise specified by WRMP guidelines.

4.3. Data storage and retrieval

Raw and processed data should be submitted to and stored on the WRMP Data Portal (https://data.wrmp.org/) with accompanying metadata. The data can be subsequently retrieved from the Data Portal.

4.4. Data sharing and interpretation

Data accessibility and the interpretation and synthesis of results are critical components of a data management system. Considerations for data processing, sharing, and visualization include:

- Develop plans for hosting the visualized data, key calculations, and the source datasets;
- Leverage online platform for annual and baseline mapping and customized reporting and summary tools (e.g., EcoAtlas);
- Identify clear repeatable metrics with clear data sources to calculate metrics;
- Provide easy reference back to source data and clear metadata, e.g., data layer or suite of tools;
- Describe how we will integrate with other tools and data sources; and
- If applicable, calculate indicators on regular intervals for regional accounting strategy (e.g., annually published metrics in the State of the Estuary Report).

5. References

https://doi.org/10.3133/wri004191

Hensel, P. F., Galagher, C. M., Johnson, A., & Lerberg, S. (2023). NOAA NOS Manual: Accurate elevations for sea level change sentinel sites. National Ocean Service, National Oceanic and Atmospheric Administration.

https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/u43544q/487964726F67726170686963/

Anderson CW. 2005. Chapter A6. Section 6.7. Turbidity. Reston, VA. https://doi.org/10.3133/twri09A6.7

Beagle J, Salomon M, Baumgarten S, Grossinger R. 2015. Shifting shores: Marsh expansion and retreat in San Pablo Bay. Prepared for the US EPA San Francisco Bay Program and the San Francisco Estuary Partnership. Richmond, CA: San Francisco Estuary Institute. [accessed 2023 Oct 3]. Available from: https://www.sfei.org/sites/default/files/biblio_files/ShiftingShores%20SFEI%20063015_medres_final.pdf

Bridgeland ET, Brophy L, Wetering S van de, So KJ, Hoy R van, Lowe RW, Ledig DB. 2017. Ni-les'tun Tidal Wetlands Restoration Project: Planning, Implementation, and Lessons Learned. Washington, DC: U.S. Department of Interior, Fish and Wildlife Service, Region 1. [accessed 2023 Sep 28]. Available from: https://ecos.fws.gov/ServCat/Reference/Profile/95453

Brinson MM, Christian RR, Blum LK. 1995. Multiple states in the sea-level induced transition from terrestrial forest to estuary. Estuaries. 18:648–659. https://doi.org/10.2307/1352383

Buffington KJ, Goodman AC, Freeman CM, Thorne KM. 2020. Testing the interactive effects of flooding and salinity on tidal marsh plant productivity. Aquat Bot. 164:103231. https://doi.org/10.1016/j.aquabot.2020.103231

Cahoon DR, Lynch JC, Roman CT, Schmit JP, Skidds DE. 2019. Evaluating the Relationship Among Wetland Vertical Development, Elevation Capital, Sea-Level Rise, and Tidal Marsh Sustainability. Estuaries Coasts. 42:1–15. https://doi.org/10.1007/s12237-018-0448-x

Callaway JC, Parker VT, Vasey MC, Schile LM, Herbert ER. 2011. Tidal Wetland Restoration in San Francisco Bay: History and Current Issues. San Franc Estuary Watershed Sci. [accessed 2023 September 22];9:. https://doi.org/10.15447/sfews.2011v9iss3art2

Curtis JA, Thorne KM, Freeman CM, Buffington KJ, Drexler JZ. 2022. A summary of water-quality and salt marsh monitoring, Humboldt Bay, California. Reston, VA. https://doi.org/10.3133/ofr20221076

D'Alpaos A, Lanzoni S, Marani M, Rinaldo A. 2007. Landscape evolution in tidal embayments: Modeling the interplay of erosion, sedimentation, and vegetation dynamics. J Geophys Res Earth Surf. [accessed 2023 September 18];112:. https://doi.org/10.1029/2006JF000537

D'Alpaos A, Lanzoni S, Marani M, Rinaldo A. 2010. On the tidal prism–channel area relations. J

Geophys Res Earth Surf. [accessed 2023 September 18];115:. https://doi.org/10.1029/2008JF001243

Fagherazzi S. 2013. The ephemeral life of a salt marsh. Geology. 41:943–944. https://doi.org/10.1130/focus082013.1

Francalanci S, Solari L. 2011. Experimental observation on bank retreat of salt marshes. RCEM 2011. Beijing, China. p. 543–551. [accessed 2023 Sep 18]. Available from: https://www.academia.edu/24655951/Experimental_observation_on_bank_retreat_of_salt_marshes

Gray JR, Glysson GD, Turcios LM, Schwarz GE. 2000. Comparability of suspended-sediment concentration and total suspended solids data. https://doi.org/10.3133/wri004191

Himmelstoss E, Henderson RE, Kratzmann MG, Farris AS. 2021. Digital Shoreline Analysis System (DSAS) version 5.1 user guide. Reston, VA. https://doi.org/10.3133/ofr20211091

Hodgson ME, Bresnahan P. 2004. Accuracy of Airborne Lidar-Derived Elevation: Empirical Assessment and Error Budget. Photogramm Eng Remote Sens. 70:.

Hood WG. 2002. Application of Landscape Allometry to Restoration of Tidal Channels. Restor Ecol. 10:213–222. https://doi.org/10.1046/j.1526-100X.2002.02034.x

Janousek CN, Thorne KM, Takekawa JY. 2019. Vertical Zonation and Niche Breadth of Tidal Marsh Plants Along the Northeast Pacific Coast. Estuaries Coasts. 42:85–98. https://doi.org/10.1007/s12237-018-0420-9

Lynch JC, Cahoon DR, Hensel P. 2015. The surface elevation table and marker horizon technique: A protocol for monitoring wetland elevation dynamics. Available from: https://pubs.usgs.gov/publication/70160049

Marani M, D'Alpaos A, Lanzoni S, Santalucia M. 2011. Understanding and predicting wave erosion of marsh edges. Geophys Res Lett. [accessed 2023 September 18];38:. https://doi.org/10.1029/2011GL048995

Pennings SC, Grant M-B, Bertness MD. 2005. Plant zonation in low-latitude salt marshes: disentangling the roles of flooding, salinity and competition. J Ecol. 93:159–167. https://doi.org/10.1111/j.1365-2745.2004.00959.x

Reed DJ, Spencer T, Murray AL, French JR, Leonard L. 1999. Marsh surface sediment deposition and the role of tidal creeks: Implications for created and managed coastal marshes. J Coast Conserv. 5:81–90. https://doi.org/10.1007/BF02802742

Schmid KA, Hadley BC, Wijekoon N. 2011. Vertical Accuracy and Use of Topographic LIDAR Data in Coastal Marshes. J Coast Res. 275:116–132. https://doi.org/10.2112/JCOASTRES-D-10-00188.1

Schoellhamer DH. 2011. Sudden Clearing of Estuarine Waters upon Crossing the Threshold from Transport to Supply Regulation of Sediment Transport as an Erodible Sediment Pool is Depleted: San Francisco Bay, 1999. Estuaries Coasts. 34:885–899.

Sprecher SW. 1993. Installing monitoring wells/piezometers in wetlands. U.S. Army Engineer Waterways Experiment Station. [accessed 2023 Sep 21]. Available from: https://erdc-library.erdc.dren.mil/jspui/handle/11681/3599

Swanson KM, Drexler JZ, Schoellhamer DH, Thorne KM, Casazza ML, Overton CT, Callaway JC, Takekawa JY. 2014. Wetland Accretion Rate Model of Ecosystem Resilience (WARMER) and Its Application to Habitat Sustainability for Endangered Species in the San Francisco Estuary. Estuaries Coasts. 37:476–492.

https://doi.org/10.1007/s12237-013-9694-0

Takekawa JY, Woo I, Athearn ND, Demers S, Gardiner RJ, Perry WM, Ganju NK, Shellenbarger GG, Schoellhamer DH. 2010. Measuring sediment accretion in early tidal marsh restoration. Wetl Ecol Manag. 18:297–305.

US Geological Survey. 2012. Topographic Mapping RTK GPS Standard Operating Procedures. Vallejo, CA: USGS, Western Ecological Research Center, San Francisco Bay Estuary Field Station.

US Geological Survey. 2011. Channel Cross-section Standard Operating Procedures. Vallejo, CA: Western Ecological Research Center, San Francisco Bay Estuary Field Station. [accessed 2023 Sep 28]. Available from: https://www.tidalmarshmonitoring.net/pdf/USGS_WERC_ChannelCrossSection_SOP.pdf

USACE. 2013. Hydrographic surveying. Washington, DC: U.S. Army Corps of Engineers. Available from: https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/u43544q/487964726F67726170686963/

USGS. 2012. Sediment Pin Standard Operating Procedures. Vallejo, CA: USGS, Western Ecological Research Center, San Francisco Bay Estuary Field Station. [accessed 2023 Sep 22]. Available from: https://www.tidalmarshmonitoring.net/pdf/USGS-WERC-Sediment-Pin-SOP.pdf

Wagner RJ, Boulger RW, Oblinger CJ, Smith BA. 2006. Guidelines and Standard Procedures for Continuous Water-Quality Monitors: Station Operation, Record Computation, and Data Reporting. Reston, VA: U.S. Geological Survey. [accessed 2023 Oct 5]. Available from: https://pubs.usgs.gov/tm/2006/tm1D3/pdf/TM1D3.pdf

Williams PB, Orr MK. 2002. Physical Evolution of Restored Breached Levee Salt Marshes in the San Francisco Bay Estuary. Restor Ecol. 10:527–542. https://doi.org/10.1046/j.1526-100X.2002.02031.x

WRMP. 2023. Execuve Summary: WRMP Priority Monitoring Site Networks. Available from: https://www.wrmp.org/wp-content/uploads/2023/04/Exec-Summary-and-Memo_WRMP-Priority-Monitoring-Site-Networks_20230419.pdf. [accessed 2023 May 24]. Available from: https://www.wrmp.org/wp-content/uploads/2023/04/Exec-Summary-and-Memo_WRMP-Priority-Monitoring-Site-Networks_20230419.pdf

WRMP. 2020. San Francisco Estuary Wetland Regional Monitoring Program Plan prepared by the WRMP Steering Committee. San Francisco, CA. Available from: https://www.wrmp.org/wp-content/uploads/2021/04/SFE_WRMP-Program-Plan_040121_Web_ADA.pdf

WRMP. 2021. San Francisco Estuary Wetland Regional Monitoring Program: Standard Operating Procedures for Indicators 1 and 3. Richmond, CA: San Francisco Estuary Institute. [accessed 2023 May 26]. Available from: https://www.wrmp.org/wp-content/uploads/2023/01/2022-12_WRMP-SOPS-for-Indicators-1-and-3_v1_For-Posting_v2.pdf

Zeff ML. 1999. Salt Marsh Tidal Channel Morphometry: Applications for Wetland Creation and Restoration. Restor Ecol. 7:205–211. https://doi.org/10.1046/j.1526-100X.1999.72013.x

6. Appendices

Appendix 1 : Glossary

Appendix 2: Horizontal and Vertical Control Detailed Methods

This section includes a basic description of accurate control survey methods for establishing horizontal and vertical control for site monitoring. These methods will continue to be developed as the Monitoring and Implementation Plans are put into use and revised over time.

Background

Horizontal and vertical control are essential components of geodetic and surveying systems that establish accurate and consistent reference frameworks for topographic surveys and for various geospatial applications. Horizontal control refers to the accurate horizontal (longitude and latitude) positions on the Earth's surface. Vertical control refers to accuracy determination of elevations relative to a specified reference surface (usually a defined vertical datum). These are particularly important to orient and reference subsequent surveys. Vertical and horizontal control exists to support the application of other SOPs, particularly marsh elevation and water levels, which then allow interpretative analysis, such as for inundation regime and vegetation change. Simple definitions are:

- Horizontal Control: A survey point or a set of fixed survey points that can serve as a local horizontal reference for future surveys.
- Vertical Control: A point of a known elevation relative to a specific datum used to measure elevation at a site.

Purpose and Linkage to Other SOPs, Guiding, and Management Questions

Vertical and horizontal control supports the application of other SOPs, particularly marsh elevation (Appendix 5) and water levels (Appendix 7) which allow for analysis of inundation regime and vegetation change.

Establishing accurate and consistent reference frameworks to help with measuring marsh elevation can answer the following Management Question

- **Management Question 2A:** *How are tidal marshes and tidal flats, including restoration projects, changing in elevation and extent relative to local tidal datums?*

Resources for Vertical and Horizontal Control Approaches

There are numerous resources providing foundational information on methods, costs, and trade-offs for different approaches to establishing control networks and benchmarks. Some guidance and examples of its use include:

- Hensel et al. 2023. *NOAA NOS Manual: Accurate elevations for sea level change sentinel sites*. https://repository.library.noaa.gov/view/noaa/50570
- National Geodetic Survey website: https://geodesy.noaa.gov/datasheets/

Website contains useful information on different types of data and imager, tools, and survey information.

- Rydlund and Densmore. 2012. *Methods of Practice and Guidelines for Using Survey-Grade Global Navigation Satellite Systems (GNSS) to Establish Vertical Datum in the United States Geological Survey*. https://pubs.usgs.gov/tm/11d1/tm11-D1.pdf
- Weber, R.L.J. 2012. *Narragansett Bay Vertical Control Plan* http://nbnerr.org/wp-content/uploads/2017/01/2012-Weber-NBNERR-Tech-Series-2012.2.pdf

Considerations for Selecting a Preferred Approach and the Location of Control Points

Control points comprise a point or a set of fixed points that can serve as reference (or control) for future surveys. Control points can include permanent or temporary benchmarks tied into permanent benchmarks. These permanent benchmarks can include deep and shallow ROD-SET benchmarks, shallow PVC arrays, and control points established on existing infrastructure. It is important to decide the use case early on, as this will define the appropriate approach and methods.

The following considerations help determine the approach to control and the location of control points.

- Stability of the control points .
- Accuracy - ability to acquire the desired accuracy of the survey
- Ease of access - which can also help with repeatability of resurveyng the control points
- Security of the sites with regard to vandalism, weather impacts, etc
- Proximity to permanent geodetic networks to establish control points
- Frequency of surveys using the control points
- Available funds
- Anticipated satellite visibility of control points
- Ease of relocating control points

Methods

Some options for positioning systems to consider when establishing control points are:

RTK GPS (Real-Time Kinematic) GPS requires a physical base station and a roving station to measure the antennas comparable to each other and provide a relative baseline using common satellites. This method provides real-time survey ability and a high level of accuracy. Requires at least one base station at an accurately known location. There is a distance limit to establishing baselines and as the baseline increases, the precision decreases. Unobstructed sky conditions are important for good satellite visibility at both the base station and the rover. This method can provide cost savings as it can collect data in less time.

RTN GPS (Real-Time Network)((GNSS-TRN) does not need to establish a permanent base station. The user purchases a network subscription that allows access to a set of base stations in a network through a cellular provider. It's a satellite-based positioning system that uses a network of continuously operating reference stations (CORSs) characterized by highly accurate location services in real-time.

- OPUS (Online Positioning User Service) allows surveyors to upload their collected GPS data to obtain highly accurate corrected positions.
- NGS (National Geodetic Survey) website provides resources for updating geoid models and accessing CORS data which can enhance the reliability and accuracy of surveys

Leveling establishes the elevation of a location/point/benchmark relative to a datum. This can be done by measuring the elevation difference between two points. The point or benchmark can then be used as reference for other surveys.

Post-processing includes storing raw GPS base data in digital format that is later processed using post-processing software such as GPS Pathfinder or GPS Analyst against raw GPS rover files.

The following considerations help determine the choice of positioning system

- Equipment security for long GPS occupations
- RTN network choices
- Distance to known control
- Line of sight (for leveling)
- Validation of control data
- Equipment calibration

Data Collection, Analysis, and Synthesis

Field data should be recorded on a standardized geodetic data control sheet (Horizontal and Vertical Control Report) and at a minimum should include the following information

- Station name
- Monument type,
- City, county, state,
- Survey team identities and date
- Project name.
- Detailed station description and location and photo
- Coordinate plane and tidal datum information
- Instrument information (make, model, serial numbers of equipment (e.g., GPS receivers, levels, etc.)
- Field comments
- Diagram of control points
- Photos of control points

Post-field data procedures include:

- Data processing methods and solution report
- Quality Assurance/Quality Control
- Data uploaded to a secure data platform and distributed to relevant audiences

Recommendations

- Establish and document horizontal and vertical control for Benchmark and Reference sites within the Priority Site Network initially and then add horizontal and vertical control points for additional sites as funding allows.

Priority WRMP Products

- Report providing a description of the existing horizontal and vertical control points for Benchmark and Reference sites within the Priority Site Network including:
    - Control point (horizontal and vertical) monument names and elevation
    - Horizontal coordinates
    - Date established and dates surveyed
    - General description
    - Surveyors and methods used (instruments, software, etc)
    - Accuracy and adjustments
    - Field comments

References

Hensel, P.F., C.M. Gallagher, A.Johnson, and S.Lerberg. 2023. NOAA NOS Manual: Accurate elevations for sea level change sentinel sites
https://repository.library.noaa.gov/view/noaa/50570

Rydlund, P.H. and B.K. Densmore. 2012. Methods of Practice and Guidelines for Using Survey-Grade Global Navigation Satellite Systems (GNSS) to Establish Vertical Datum in the United States Geological Survey. https://pubs.usgs.gov/tm/11d1/tm11-D1.pdf

Weber, R.L.J. 2012. Narragansett Bay Vertical Control Plan. Technical Report Series 2012:2. September 2012.
http://nbnerr.org/wp-content/uploads/2017/01/2012-Weber-NBNERR-Tech-Series-2012.2.pdf

Appendix 3: Topography Detailed Methods

[Topography SOP]

Background

Elevation, relative to tidal flooding, exerts strong control on many tidal marsh ecosystem processes. For example, marsh species have unique tolerances to flooding and tend to organize into zones characterized by elevation (Pennings et al. 2005; Janousek et al. 2019). Rates of sediment deposition are inversely correlated with elevation, as areas higher in the tide frame are flooded for shorter durations and less frequently than areas lower in the tide frame (Friedrichs and Perry 2001). The concept of elevation 'capital' is also key for understanding vulnerability of marshes to sea-level rise; the higher a marsh is in the tidal frame, the longer it will take to transition or submerge, while marshes with less elevation capital are low in the tide frame and more susceptible to sea-level rise (Cahoon et al. 2019).

The WRMP is interested in these questions related to elevation:

1. What are the elevations of the estuary's existing and restoring tidal wetlands?
2. What is the elevation capital of the estuary's tidal wetlands?

Airborne LiDAR

Airborne LiDAR provides broad spatial coverage of elevation data with reasonable (centimeter-scale) accuracy and is therefore the recommended tool for tracking elevation and elevation change over time at the regional scale. Regular remapping (e.g., every 5 years) would help facilitate updating the Baylands Change basemap. A LiDAR system (sensor, inertial motion unit, GNSS) is mounted to a small aircraft (e.g. Cessna), and is flown in a lawnmower pattern across the study area. Surveys must be tide-controlled since LiDAR typically does not penetrate the water. While green wavelength LiDAR is able to collect data in clear water, the waters in SFBE are generally too turbid for this approach to be successful. Vendors provide a bare-earth DEM, generated with last return points, and which undergoes substantial post-processing (e.g., hydro-flattening water features, removal of bridges). The accuracy of the bare earth DEM is assessed by the vendor using RTK GNSS surveys on hard surfaces [e.g., parking lots] or in sparse vegetation, but not in marshes. Currently, LiDAR datasets around the estuary are a mosaic from different years and with different qualities (Figure 1).

The ability of LiDAR to capture surface elevation depends on several factors. Dense vegetation can block the ground entirely, causing a positive bias in the 'bare earth' digital elevation model. Surveying in the winter when plants are senesced may increase the chance of sampling the ground, at the expense of data on maximum plant height that is useful for estimating biomass. The density of LiDAR pulses is also key; lower altitude flights will have a greater pulse density and thus be more likely to penetrate the plant canopy, but they are also more expensive as it takes more flightlines and time to cover the same area. The USGS 3DEP program provides guidelines for LiDAR quality, based on vertical accuracy and point density (Table 1).

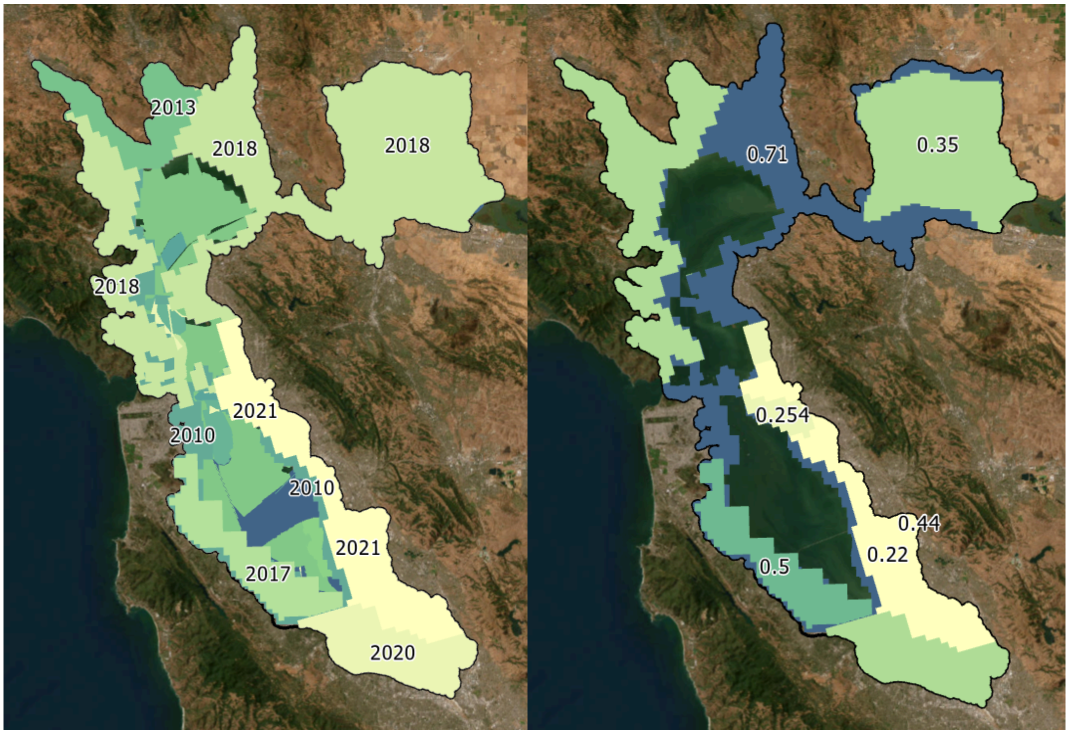


Figure 1. Map of recent LiDAR collection dates (left) and nominal point spacing (m, right).

Table 2. Lidar quality level requirements defined in the 3DEP Lidar Base Specification (from https://www.usgs.gov/3d-elevation-program/topographic-data-quality-levels-qls).

QUALITY LEVEL	DATA SOURCE	VERTICAL ACCURACY RMSEz (cm)	NOMINAL PULSE SPACING (NPS) meters	NOMINAL PULSE DENSITY (NPD) points per square meter	DIGITAL ELEVATION MODEL (DEM) cell size (meters)
QL0	Lidar	5 cm	<= 0.35 m	>= 8 pts/square meter	0.5 m

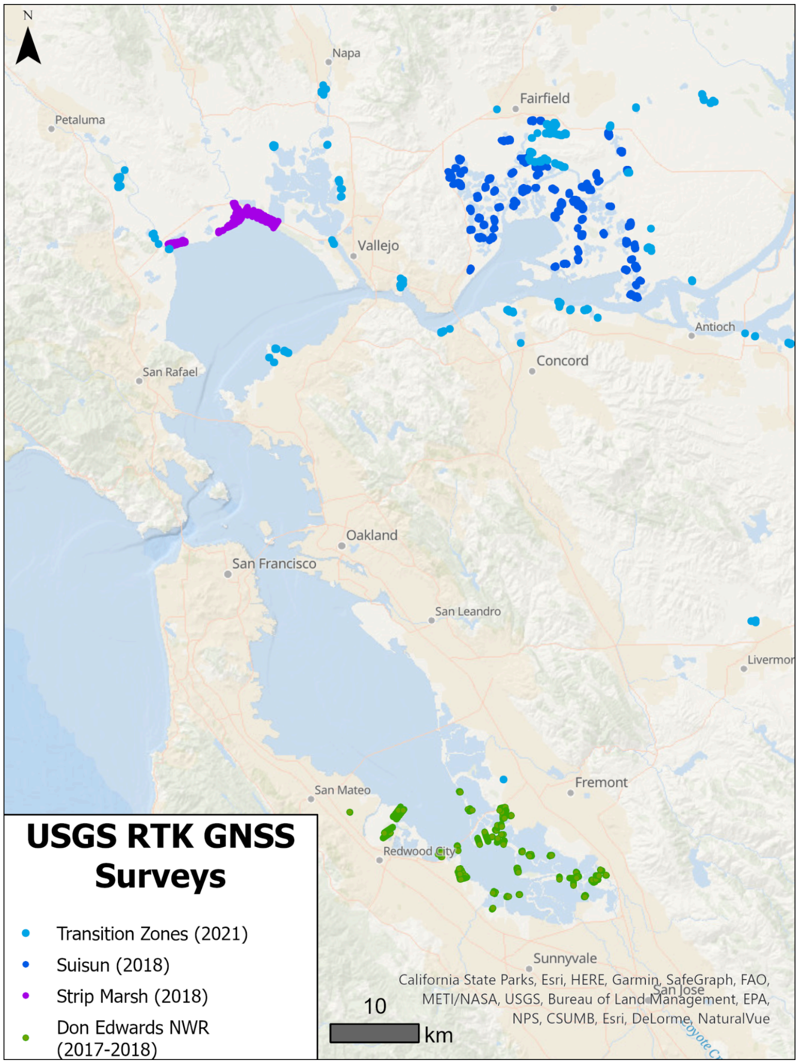
QL1	Lidar	10 cm	<= 0.35 m	>= 8 pts/square meter	0.5 m
QL2	Lidar	10 cm	<= 0.71 m	>= 2 pts/square meter	1 m
QL3	Lidar	20 cm	<= 1.41 m	>= 0.5 pts/square meter	2m

Bias correction

There are several methods available that can be used to improve the accuracy of LiDAR-derived DEMs (Schmid et al. 2011; Hladik and Alber 2012; Medeiros et al. 2015). The LEAN approach (Buffington et al. 2016) is a statistical approach that relies on ground elevation data (RTK GNSS) to train a machine learning model to remove the positive bias caused by dense vegetation. Continuous model predictors include the first and last LiDAR returns and some information on plant cover, such as the normalized difference vegetation index (NDVI) from high resolution imagery (e.g., NAIP). Intensity data from the LiDAR returns can also be used, although care should be used since those data are not typically normalized across flightlines by the vendor and variation due to flight altitude and scan angle can cause issues. The RTK GNSS surveys used to train the model should cover the full range of marsh elevation and plant communities within the study domain. Shore-normal transects are an efficient design to ensure coverage across a range of plant densities and marsh elevation. In relatively homogenous communities (e.g., pickleweed), fewer points are required to generate a correction. However if the model domain includes a salinity gradient with higher species diversity, for example, more training points are required. Since it is a statistical approach, the more points used to train the correction, the more confidence you can have that you are capturing the underlying variation creating the positive bias. Across seven San Francisco Bay marshes, Buffington et al. (2016) used a density of 7 pts/ha across relatively homogenous vegetation (203-728 points at each site). A power analysis found that about 120 points were needed to create a robust LEAN correction, provided the points are stratified across elevation and NDVI gradients.

Ideally, LiDAR, NDVI, and RTK GNSS data are all sampled within the same season. However, in practice this is unlikely to be the case. It is important for the LiDAR and other continuous predictors (NDVI) to be aligned temporally, however older RTK GNSS points can be used, especially those sampled in mature marshes. This is due to the relatively slow rate of accretion (0.002-0.004 m/yr) and the error of the RTK (0.01-0.03 m) compared to the bias that is being corrected (typically 0.1-0.5 m). As long as the marsh has a stable platform, RTK GNSS points 10 years old are likely to be within 0.03 m of the current elevation (0.003 mm/yr * 10 years) and suitable to be included in a correction model.

LEAN corrected DEMs (5 m resolution) are available across San Francisco Bay (Buffington and Thorne 2019) and Suisun Marsh (Buffington et al. 2019). The San Francisco Bay model used LiDAR from 2010 and RTK GNSS points from 2008-2018, while the Suisun Marsh model used LiDAR flown in 2017 and RTK GNSS points from 2018 (Figure 2).



California State Parks, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, CSUMB, Esri, DeLorme, NaturalVue

Figure 2. Location of recent RTK GNSS surveys conducted by the USGS that could be used in a bias-correction.

Unmanned aerial systems

Unmanned aerial systems (UAS, or drones) provide a relatively low cost option for the collection of continuous elevation data. Using the principles of photogrammetry, Structure-from-Motion techniques use overlapping photographs to generate a digital surface model (DSM). The UAS is programmed to fly in a lawnmower pattern with substantial (e.g., 70%) overlap across photos. Spatial resolution of the DSM depends on the altitude of the UAS, but is typically quite high

(5-10 cm). Traditional RGB cameras can be used, or there are multispectral options that capture the near infrared part of the spectrum and are useful for monitoring vegetation.

LiDAR sensors are now available that are small enough to be mounted on a UAS. While not appropriate for surveying large areas, UAS LiDAR would be appropriate for level 3, site-scale monitoring. UAS LiDAR has several advantages over airborne LiDAR. Because they are flown at much lower altitude, UAS LiDAR can provide a very high density of returns (800 pts/m2 vs 40 pts/m2 first returns from airborne LiDAR). As a result, there is a greater likelihood of getting ground returns in dense vegetation (Fig. 3, 4). Additionally, it would be more cost effective to conduct repeated surveys across a site, for example, to assess phenology or edge erosion, as part of a special study. Once validated, ground returns from UAS LiDAR could also be used instead of RTK GNSS to inform bias-correction efforts of aerial LiDAR across the region.

See NERRS Drone SOP for details on how to collected structure-from-motion UAS data

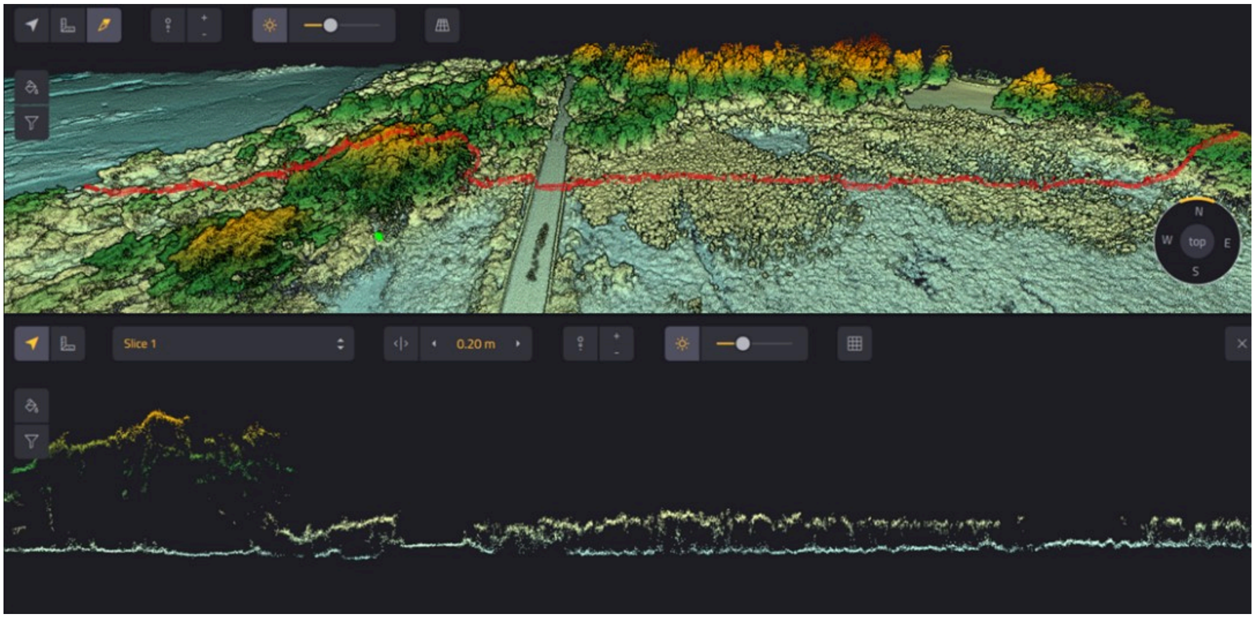


Figure 3. Example of UAS LiDAR returns from a marsh in Chesapeake Bay. The red line in the upper panel shows the location of the transect in the bottom panel, which shows first and last LiDAR returns and demonstrates the ability of UAS-mounted LiDAR to penetrate dense vegetation. The dominant vegetation across the transect is *Phragmites*.

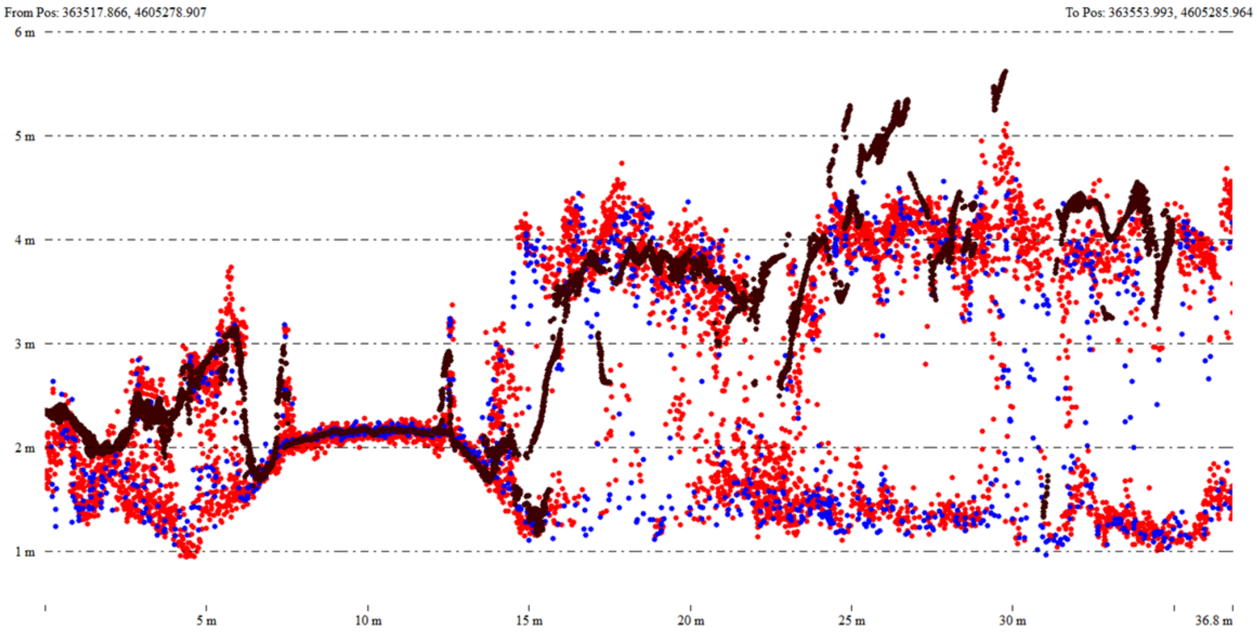


Figure 4. Comparison of UAS LiDAR and structure-from-motion photogrammetry in a *Phragmites* stand. [dark brown: SfM; red: first LiDAR returns; blue: last LiDAR returns].

Recommended Methods

Level 1 Baseline DEM

Tier 1: Bay-wide DEMs developed using available airborne LiDAR (QL2 or better) that are no more than 10 years old. Minimum-bin gridding should be used to establish bare earth elevation. Accuracy should be checked against RTK GNSS surveys in marshes with different dominant plant communities.
See Schmid et al. 2011 for SOP

Tier 2: Bay-wide DEMs should be developed from tide-controlled airborne LiDAR (QL1 or better) datasets that are no more than 5 years old. Bare earth accuracy of the DEMs should be checked against RTK GNSS surveys in marshes with different dominant plant communities and a bias-correction should be performed if a positive bias greater than 0.05 m exists. RTK GNSS surveys used to inform the correction should be no more than 10 years old. [importance: high; cost: moderate – leverage available ground elevation data wherever possible]
See Buffington et al. 2016 for SOP

References

Buffington KJ, Dugger BD, Thorne KM, Takekawa JY. 2016. Statistical correction of lidar-derived digital elevation models with multispectral airborne imagery in tidal marshes. Remote Sens Environ. 186:616–625. https://doi.org/10.1016/j.rse.2016.09.020

Buffington KJ, Thorne KM. 2019. LEAN-corrected San Francisco Bay Digital Elevation Model. https://doi.org/10.5066/P97J9GU8

Buffington KJ, Thorne KM, Takekawa JY, Chappell S, Swift T, Feldheim C, Squellati A, Mardock DK. 2019. LEAN-Corrected DEM for Suisun Marsh. https://doi.org/10.5066/P97R4ES3

Cahoon DR, Lynch JC, Roman CT, Schmit JP, Skidds DE. 2019. Evaluating the Relationship Among Wetland Vertical Development, Elevation Capital, Sea-Level Rise, and Tidal Marsh Sustainability. Estuaries Coasts. 42:1–15. https://doi.org/10.1007/s12237-018-0448-x

Friedrichs CT, Perry JE. 2001. Tidal Salt Marsh Morphodynamics: A Synthesis. J Coast Res. 7–37.

Hladik C, Alber M. 2012. Accuracy assessment and correction of a LIDAR-derived salt marsh digital elevation model. Remote Sens Environ. 121:224–235. https://doi.org/10.1016/j.rse.2012.01.018

Janousek CN, Thorne KM, Takekawa JY. 2019. Vertical Zonation and Niche Breadth of Tidal Marsh Plants Along the Northeast Pacific Coast. Estuaries Coasts. 42:85–98. https://doi.org/10.1007/s12237-018-0420-9

Medeiros S, Hagen S, Weishampel J, Angelo J. 2015. Adjusting Lidar-Derived Digital Terrain Models in Coastal Marshes Based on Estimated Aboveground Biomass Density. Remote Sens. 7:3507–3525. https://doi.org/10.3390/rs70403507

Pennings SC, Grant M-B, Bertness MD. 2005. Plant zonation in low-latitude salt marshes: disentangling the roles of flooding, salinity and competition. J Ecol. 93:159–167. https://doi.org/10.1111/j.1365-2745.2004.00959.x

Schmid KA, Hadley BC, Wijekoon N. 2011. Vertical Accuracy and Use of Topographic LIDAR Data in Coastal Marshes. J Coast Res. 275:116–132. https://doi.org/10.2112/JCOASTRES-D-10-00188.1

Appendix 4: Accretion and Erosion

Accretion & Erosion SOP

Appendix 4. Monitoring Accretion and Erosion Across WRMP Level 3 Sites

Background

A key product from long-term monitoring is to understand how rates of tidal marsh elevation change vary around San Francisco Bay and whether they are keeping pace with accelerating rates of sea-level rise. With the decrease in sediment delivery from the Sacramento-San Joaquin Delta (Schoellhamer 2011) and extensive efforts to restore subsided lands to tidal marsh, there is concern about whether there is enough sediment available to support both the development of restored lands and natural tidal marsh accretion with sea-level rise. Within a cohesive monitoring framework, data on rates of marsh elevation change will help support regional decision making and adaptive management.

The WRMP is interested in these questions regarding marsh elevation change at network sites:

WRMP Benchmark and Reference Marsh Site Questions

1. Where in the estuary are rates of tidal wetland elevation change keeping up with rates of sea level rise?
2. How are the elevations of high and low marsh (including high tide refugia) changing over time?

Project sites

3. How does the rate of elevation change compare to the rate of sea-level rise?
4. How does the rate of elevation change compare across similar aged restoration sites in comparable landscape settings?

Methods

Measurements of marsh topographic evolution over time can be grouped into two categories: accretion and elevation change. Accretion is the amount of material, primarily inorganic sediment but also some organic sediments, that is deposited on the marsh surface, measured in reference to a marker horizon. Elevation change is the net increase or decrease in surface elevation relative to a fixed datum that accounts for surface deposition and erosion as well as belowground processes, including, but not limited to, root growth, decomposition, and soil consolidation. Rates of deep subsidence or gain, due to plate tectonics, isostatic rebound, or fluid extraction, are also important to understand for the region of interest (Shirzaei and Bürgmann 2018). It is important to decide which metric is of interest and the level of accuracy that is required when selecting the appropriate monitoring technique. Common field methods and their use are listed in Table 1 and described in the subsequent sections.

Table 1. Field methods for assessing marsh topographic evolution. Site types and networks are described in the WRMP Priority Monitoring Site Networks memo, January 2023 (link).

Method	**Measurement**	**Appropriate Site***	**Accuracy**	**Spatial Coverage (ha)**	**Cost**
Total station/ differential leveling	Elevation change	Benchmark, Reference, Project (engineered or developed)	0.001-0.005 m (@100-300m)	1	$30k+ equipment, 2 people
RTK GNSS	Elevation change	Project (subsided)	0.02-0.12 m	1-1000	$20k equipment, 1 person
Single/multi beam bathy	Elevation change	Project (subsided)	0.02-0.12 m?	1-1000	$20-50k equipment, 2 people
Marker horizon plots	Accretion	Benchmark, Reference	0.001-0.004 m	0.01 (?)	$40 for 50# feldspar bag, enough for 6 plots, 1 person
rSET-MH	Accretion & Elevation change	Benchmark, Reference	0.001-0.007 m	1x10-4	$8k installation (x4 SETs) 1 day x 2 people to read
Sediment pins	Elevation change	Project (subsided, developed)	0.02-0.04 m	0.01 (?)	$50-100 for PVC, 1 person
Sediment pads/tiles	Accretion (mass)	Special study	milligrams	0.001 (?)	Pads ~$0.5 each, a lot of lab time required

* Engineered: sites that have been graded to an elevation suitable for plant establishment; substrate may be consolidated or unconsolidated.. Developed: restorations that have accreted sediment naturally and are vegetated with consolidated substrate. Subsided: sites where tidal flow has been reconnected but the elevation is too low for plant establishment and the substrate is unconsolidated.

Traditional Surveying

Total station or differential leveling can provide millimeter vertical accuracy elevation surveys across time (Cain and Hensel 2018). A total station records measurements in three dimensions

relative to the receiver; accuracy declines with increasing distances over 1-300 m. A robotic total station can automatically follow the rod, potentially allowing a single person to conduct a survey. Differential leveling techniques provide elevation data only and require a two-person team to survey. Relative measurements of elevation can be tied to a vertical datum (usually NAVD 88) by including an established benchmark in the leveling circuit, or by installing a temporary benchmark near the marsh that is measured using global navigation satellite system (GNSS) methods (described below). Achieving repeated measurements at the exact same location over time is a challenge with this method and increases uncertainty.
See Hensel et al. (2023) pg. 146 for details on how to run a differential leveling survey.

Real-time Kinematic GNSS Surveying

Real-time kinematic (RTK) GNSS survey methods offer a convenient solution for rapid collections of elevation data. A GNSS rover collects positional data from GPS satellites while receiving real-time corrections from a network of continuously operating reference stations (CORS) via a 4G or 5G signal (Fig. 1). Vertical accuracy tends to be between 1-2 cm, and depends on many factors, including the number and relative position of GPS satellites the rover is receiving data from, atmospheric conditions, and the distance to the CORS station. The error associated with each measurement can make it difficult to detect small changes in elevation (Fig. 2), requiring more rover points to detect significant changes in elevation. Across longer (5+ year; RTK error/SLR rate) timescales, RTK GNSS surveys could be used to detect elevation change in developed marshes, as the accumulated changes in elevation are more likely to be greater than instrument uncertainty (Thorne et al. 2014).
See Hensel et al. (2023) pg. 155 for details on how to run a RTK GNSS survey campaign.

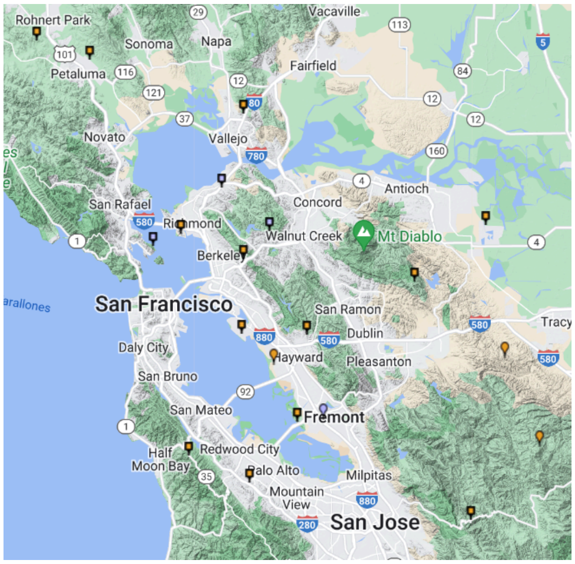
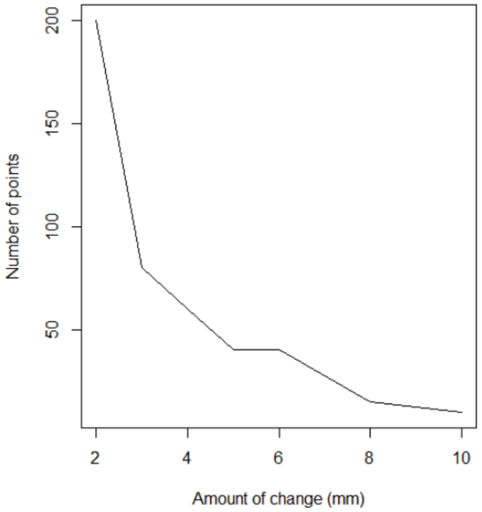


Figure 1. Locations of NGS CORS.
From https://www.ngs.noaa.gov/CORS_Map/

Figure 2. Number of RTK GNSS points needed to detect a given amount of elevation change (average across a site) using repeated measurements. Based on the error associated with elevation data across Don Edwards San Francisco Bay National Wildlife Refuge marshes (average RMSE=0.0149 m; SD RMSE=0.00487 m) and a 0.4 m range in elevation.



Single or Multi-beam Echo Sounder

Echo sounders are used to measure water depth using the principles of sonar. Transducers are mounted on a boat, along with RTK GNSS to establish position relative to a datum. In multibeam systems, an inertial measurement unit is also used to account for the pitch and roll of the boat. The swath width of multibeam returns increases with water depth, while a single beam system measures depth at the nadir. Since water density affects the speed of the sonar pulse, salinity should also be measured and accounted for in post-processing. As the system relies on RTK GNSS for absolute elevation, accuracy is at best ~2 cm, but likely lower when boat motion, water density, and bed properties are considered. Echo sounder techniques for bathymetry data can be used to understand how bed elevation is changing over time (Takekawa et al 2010). Bar checks should be used to assess the accuracy of the echo sounder readings across the range of depths encountered in the survey (e.g., every 5 ft).
See USACE (2013) for details on how to conduct a bathymetric survey.

Marker Horizon Plots

Marker horizon plots measure the amount of accretion on the marsh surface. Feldspar clay is a commonly used horizon in marsh soils, as it is fine-grained and bright white, making it easy to detect against dark marsh mud in the soil profile, and can be spread in densely vegetated plots. Feldspar plots are typically 0.25 m2 in area and can be coupled with an rSET or deployed alone in transects or a randomized design. A serrated knife is used to extract a small soil plug and the depth of accretion is measured on three sides of the plug. After measurement, the plug is put back in the original location. Careful note taking (diagrams) can be used to avoid resampling the same location in subsequent visits. In high energy or unvegetated areas feldspar can erode away, and areas with high burrowing activity (e.g. crabs) are also problematic. In unconsolidated mud, liquid nitrogen can be used to quickly freeze the ground (cryocore), allowing a measurement of the feldspar layer. Landscape cloth or plastic grids pinned to the soil surface can be used in areas where feldspar may erode away; a ruler is used to measure accretion instead of a soil plug.

See Callaway et al. (2013) for details on deploying marker horizons and cryocore methods, and Turner et al., (2012) for an example of non-feldspar marker horizons.

Rod Surface Elevation Tables with Marker Horizons (rSET-MH)

Rod surface elevation tables with marker horizons (rSET-MH) provide the most robust method for measuring accretion and changes in elevation, with millimeter-scale accuracy (Cahoon 2015). Each rSET station consists of a stainless steel rod driven into bedrock or the point of refusal and cemented as a permanent monument in the marsh. To measure the relative changes in elevation, a SET arm is attached to the rod, leveled, and nine pins are carefully lowered to the soil surface. The measurements are repeated in four different directions, resulting in 36 measurements per SET (covering ~1 m^2). Elevation changes are determined from repeated measurements of the exact same place over time, averaging the readings first by direction, then by SET station. Measurements can then be aggregated across replicate SETs and by site or region.

When installing SETs, careful consideration of the site is needed in order to minimize the influence of confounding factors. For example, distance to sediment source is known to exert strong influence over sediment deposition patterns. To minimize this effect, rSET stations should be located at least 10 m from the nearest channel or bay edge. Paired rSET-MHs at low and high marsh elevations (or edge and interior, depending on available marsh elevation gradient) provide a balance of replication and cost. If funds are available, three replicates per elevation or distance could be used to improve statistical power. See Lynch et al. (2015) for additional considerations when selecting rSET-MH locations.

rSET-MHs must be surveyed to an elevation datum to analyze measurements relative to tidal flooding. All SETs at a site should be surveyed via differential leveling or total station to determine their elevation relative to each other. GNSS measurements can then be conducted at one rSET to determine absolute elevation of all the rSETs. A special adapter is used that attaches a RTK GNSS receiver directly to the SET rod. A continuous occupation of a minimum 4 hours needs to be completed, although longer occupations (12-24 hrs) should be done if possible. To achieve higher accuracy, the occupation should be repeated under a unique GPS satellite constellation. Since California is tectonically active, GNSS measurements should be repeated after nearby earthquakes. Some parts of the bay also experience deep subsidence; for example, parts of south San Francisco Bay are subsiding at >4 mm/year (Shirzaei and Burgmann 2018, Fig. 3). Regular (e.g., every 2-3 years) re-occupation of SET rods is one way to measure this subsidence. CORS stations can also be used but typically are not located close to marshes and may not be representative of conditions in the marsh.

See Lynch et al. (2015) for details on rSET-MH installation and study design considerations.

See Hensel et al. (2023) pg 121 for more details on how to run a static GNSS survey.

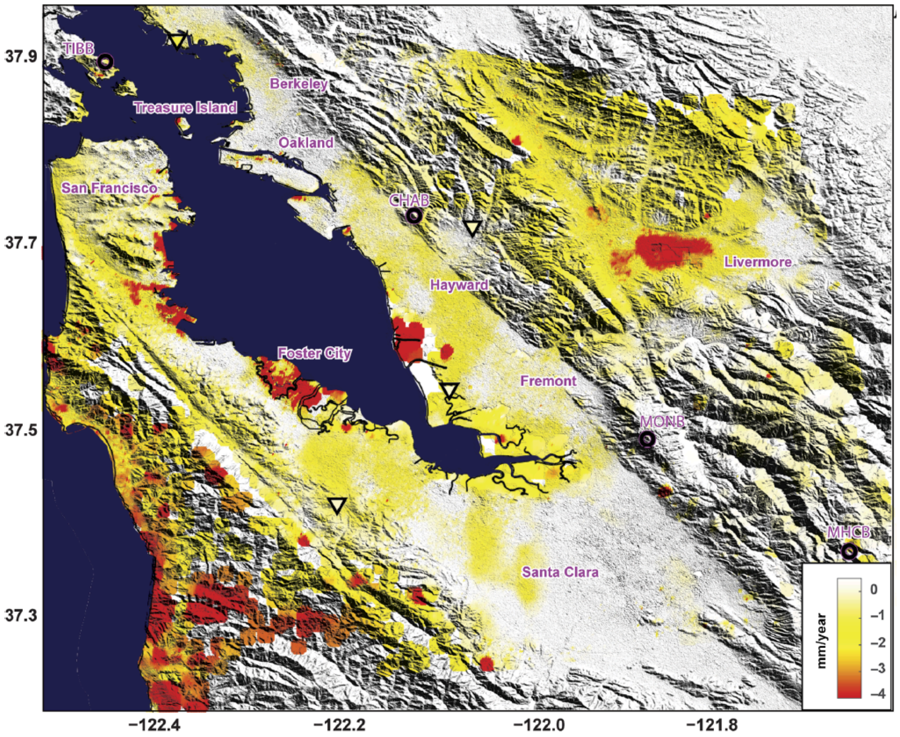


Figure 3. Map of vertical land movement from 2007-2010 using synthetic aperture radar interferometric measurements. From Shirzaei and Burgmann 2018 (fig 2D).

Sediment pins

Sediment pins are used to measure elevation change over time. Pins can also be surveyed with RTK GNSS to provide an absolute measure of elevation change. The distance from the top of the pin, typically a PVC pipe driven into the sediment with a post-pounder, and the distance to the ground is measured with a ruler. Sediment pins are typically used at restoring sites to track elevation change, because high rates of accretion make rSET investment unnecessary. Sediment pins are relatively inexpensive to deploy, they are best suited for newly restored sites with rapid rates of accretion, however they do not offer the same accuracy as SETs since they are subject to consolidation processes. Localized erosion at the base of the pin is also possible in high-energy areas, such as close to breaches in restoration sites; alternative methods should be used in these areas, such as RTK GNSS or bathymetry.

See USGS (2012) for details on deploying sediment pins.

Special Studies

Sediment deposition pads or tiles are used to generate mass-based measurements of accretion (Buffington et al. 2020). Deposition pads redeployed after a short time (2-4 weeks) are useful for understanding temporal trends in deposition. Deployed in transects perpendicular to the marsh edge or channel, pads can also capture the spatial gradients in surface deposition that develop as vegetation interacts with the water. The accretion rate can be estimated from deposition pads by sampling short (10 cm) soil cores and using the bulk density of the surface layer to convert the mass deposited on the pads into a length scale (cm). Sediment pads are best used in special studies that are designed to better understand the physical processes that drive variation in marsh accretion.

Design Considerations

rSET-MHs are the best available method for measuring both accretion and belowground processes such as root growth and soil consolidation. However, rSET-MHs are inherently point measurements and it would be prohibitively expensive to deploy rSET-MHs in sufficient density to capture spatial patterns that may be of interest. To increase spatial coverage of elevation change monitoring, feldspar plots and high accuracy elevation surveying (total station or differential leveling) can be paired to assess both surface accretion and elevation change. Plots co-located with other monitoring activities, such as vegetation transects, would provide an efficient design to monitor important marsh characteristics. The total station measurements are not able to measure shallow subsidence and achieving repeated measurements at the same location over time may be difficult; while the overall accuracy is less than rSET measurements, the additional

Methods of elevation monitoring are different for project (restoration) sites, and may also be different between subsided and engineered restorations. At subsided project sites, unconsolidated mud is likely to be a common feature for many years, making accurate on-the-ground measurements difficult or impossible. The large gain in elevation that is possible in subsided sites make rSETs a difficult option, since the rods and receiver would need to extend to the projected elevation of the marsh, making accurate measurements impossible. Feldspar plots are also likely to erode away in unvegetated areas. Landscape fabric or plastic sheeting can provide a more reliable marker horizon in high energy environments, but will only work if the area is net depositional. Single or multi-beam bathymetric surveys are a good option for monitoring the development of subsided restorations with an unconsolidated bed.

Bathymetric surveys utilize RTK GNSS for positioning and thus have similar change detection limitations as ground survey methods.

Ground measurements in project sites are possible when walking on the bed is not overly burdensome or dangerous. Sediment pins are a useful technique for measuring elevation change in restoration sites. Repeated RTK GNSS surveys may also be considered if the elevation is low in the tide frame and the site is likely to experience rapid changes in elevation that outpace instrument error.

Recommended methods: Accretion and Erosion

Benchmark and Reference sites

The primary goal of monitoring elevation change at benchmark sites is to determine whether the marsh is keeping pace with relative sea-level rise. By monitoring several sites in each sub embayment, we can generate a better understanding of regional vulnerability and know where management intervention may be most effective.

Tier 1. Due to their permanence and relatively high cost of installation, rSET-MHs are best suited for regional monitoring of marsh evolution at benchmark sites. Marshes with high elevation (typically older) have relatively low rates of annual elevation change that cannot be resolved by RTK GNSS or sediment pins. [importance: high; installation cost: high; monitoring cost: moderate [2 people/site/day]. *As mentioned above, recommended methods for* ***rSET-MH installation and study design considerations*** *are* ***detailed in Lynch el al.*** **(2015)*.***

Tier 2. rSET-MHs, with repeated total station or differential leveling surveys, ideally coinciding with vegetation surveys to minimize impact on the marsh, are recommended to expand elevation change monitoring beyond the point measurements of rSET-MHs. [importance: moderate; installation cost: none; monitoring cost: high [2 people/site, likely 1-2 days/site]. *As mentioned above, recommended methods are detailed in (Hensel et al. 2023 pg. 146)****.***

Tier 3. rSET-MHs, with additional transects of marker horizon plots paired with the total station/leveling surveys to provide a means to differentiate the above and belowground processes that control elevation change across a broad area. [importance: moderate; installation cost: low; monitoring cost: low [can be done by the vegetation survey team]. *See Callaway et al. (2013) for details on deploying marker horizons and cryocore methods, and Turner et al. (2012) for an example of non-feldspar marker horizons.*

Project Sites

The primary goals for monitoring project sites are to:

1) Determine whether the site is accreting sediment at rates that outpace sea-level rise and will likely develop into a vegetated marsh [subsided site]. Not every restoration needs to be

monitored intensely for elevation change. Given the concern about sediment supply across the bay, more intense monitoring of 1-2 project sites in each sub embayment would provide useful information about project design and management (e.g., where dredge material is most needed to supplement natural accretion). Project sites are likely to have unique spatiotemporal patterns for sediment deposition depending on their orientation and location relative to local watersheds. Given the importance of wind-wave sediment resuspension and the general pattern for easterly winds, it is important for orientation to be considered when selecting sites to intensively monitor.

2) In sites that have received dredge material, determine rates of consolidation in addition to elevation change

3) Compare rates of elevation change to a reference site [consolidated & vegetated site]. Once plants have established and the substrate has consolidated, it is reasonable to compare rates of elevation change to a reference or benchmark site.

To achieve these goals, the WRMP recommend these actions:

a) An as-built or reference DEM is a critical dataset for monitoring elevation change through time since it provides a baseline to compare with future surveys [high importance]. If the site is dry and unvegetated before breach, UAS photogrammary surveys are a cost-effective option to create a continuous DEM [moderate cost]. If the site is vegetated and walkable, RTK GNSS transect surveys across elevation gradients can provide a baseline elevation [low cost]. UAS LiDAR may be most appropriate if the site is tidal and vegetated [high cost]. If the site is underwater, single or multibeam bathymetry surveys should be conducted [moderate-high cost].
b) Sediment pins deployed across the project site to monitor elevation change, if the substrate is reasonably accessible on foot [moderate importance; low cost].
c) Repeat single/multibeam bathymetry surveys (every 2-4 years) for low elevation areas with unconsolidated mud [moderate importance, high cost] until LiDAR is able to measure the elevation.
d) Repeated soil core sampling with bulk density and grain size analyze to assess consolidation
e) Once vegetated and consolidated, establish vegetation and elevation [total station/differential leveling] transects with marker horizon plots. Transects should be shore-normal to capture dominant elevation gradients [high importance, moderate cost].

Project site monitoring should continue until the restoration is deemed functionally ‘complete’, which depends upon the project goals. More frequent monitoring early in the project lifespan is appropriate to identify whether the project is on a trajectory towards reference site conditions. Once vegetation has established, monitoring frequency for elevation can decrease in favor of satellite or aerial imagery and vegetation cover-based metrics.

References

Buffington KJ, Janousek CN, Thorne KM, Dugger BD. 2020. Spatiotemporal patterns of mineral and organic matter deposition across two San Francisco Bay-Delta tidal marshes. Wetlands. 40:1395–1407.

Cahoon DR. 2015. Estimating relative sea-level rise and submergence potential at a coastal wetland. Estuaries Coasts. 38:1077–1084.

Cain MR, Hensel PF. 2018. Wetland elevations at sub-centimeter precision: exploring the use of digital barcode leveling for elevation monitoring. Estuaries Coasts. 41:582–591.

Callaway JC, Cahoon DR, Lynch JC. 2013. The Surface Elevation Table–Marker Horizon Method for Measuring Wetland Accretion and Elevation Dynamics. Methods in Biogeochemistry of Wetlands. John Wiley & Sons, Ltd. p. 901–917. https://doi.org/10.2136/sssabookser10.c46

Hensel PF, Gallagher C, Johnson A, Lerberg S. 2023. NOAA NOS Manual: Accurate elevations for sea level change sentinel sites. [accessed 2023 September 20]. https://doi.org/10.25923/KVBQ-JW20

Lynch JC, Cahoon DR, Hensel P. 2015. The surface elevation table and marker horizon technique: A protocol for monitoring wetland elevation dynamics. Available from: https://pubs.usgs.gov/publication/70160049

Schoellhamer DH. 2011. Sudden Clearing of Estuarine Waters upon Crossing the Threshold from Transport to Supply Regulation of Sediment Transport as an Erodible Sediment Pool is Depleted: San Francisco Bay, 1999. Estuaries Coasts. 34:885–899.

Shirzaei M, Bürgmann R. 2018. Global climate change and local land subsidence exacerbate inundation risk to the San Francisco Bay Area. Sci Adv. 4:eaap9234.

Thorne KM, Elliott-Fisk DL, Wylie GD, Perry WM, Takekawa JY. 2014. Importance of biogeomorphic and spatial properties in assessing a tidal salt marsh vulnerability to sea-level rise. Estuaries Coasts. 37:941–951.

Turner J, John TY, Woo I, Ellings C, Root B, Jean TE. 2012. Marker Horizons. In: Tidal Marsh Monit. Online Handb. Available from: https://www.tidalmarshmonitoring.net/monitoring-methods-marker-horizons.php. [accessed 2023 Oct 6]. Available from: https://www.tidalmarshmonitoring.net/monitoring-methods-marker-horizons.php

USACE. 2013. Hydrographic surveying. Washington, DC: U.S. Army Corps of Engineers.

USGS. 2012. Sediment Pin Standard Operating Procedures. Vallejo, CA: USGS, Western Ecological Research Center, San Francisco Bay Estuary Field Station. [accessed 2023 Sep 22]. Available from: https://www.tidalmarshmonitoring.net/pdf/USGS-WERC-Sediment-Pin-SOP.pdf

Appendix 5: Shoreline Change Detailed Methods

Shoreline Change SOP

Background

As sea level rises, the tidal marshlands will continue to evolve in three major directions: vertically accreting or downshifting (depending on sediment supply and organic accumulation), migrating upslope and inland (depending on accommodation space), and laterally expanding or retreating at the Bay edge (Brinson et al. 1995). While vertical marsh elevation changes have been studied in San Francisco Bay (Patrick and DeLaune 1990, Goals Project 1999, Strahlberg et al. 2011, Swanson et al. 2014), less attention has been paid to the dynamics of the bayward edge of the marsh plain (the “marsh edge”). Lateral changes in the position of the marsh edge are extremely important because marsh retreat is thought to be the chief mechanism by which coastal wetlands worldwide are being lost (Francalanci et al. 2011, Marani et al. 2011, Fagherazzi 2013).

The first challenge is how to define the marsh edge. Prior efforts to map the estuarine shoreline have used mud consolidation as the defining feature (SFEI 2015). Under this definition, unconsolidated soils with sparse *Spartina* cover are considered bayward of the edge, while consolidated soils, typically dominated by pickleweed, are considered marsh. Using soil consolidation to define the edge makes it more difficult to leverage remote sensing tools for broad-scale mapping, as field surveys are required to validate the consolidation status of the soil. Alternatively, the presence of vegetation can be used to define the shoreline edge. However, this definition can prove difficult to map in prograding marshes that are sparsely vegetated. Different edge typologies (e.g., scarp, ramp) may require unique mapping techniques to determine the edge with enough accuracy for change detection over time.

This marsh edge transition can take a variety of forms. For example, in San Pablo Bay, five distinct marsh edge typologies were identified in the field and confirmed with LiDAR and aerial photos (Fig. 1). The typology was based on the presence or absence of scarps, the presence or absence of vegetation, and the inflection (rapid flattening) of the slope. The five edge types include 1) scarps with bayward vegetation (SV), 2) scarps without bayward vegetation (SN), 3) ramps with inflection points (RI), 4) ramps without inflection points (RNI), and 5) beaches fronting marshes (B).

Scarps (SV and SN), generally less than two meters high, can be identified along parts of the shoreline using oblique imagery (Google Earth, BING maps). Where scarps are present, the shoreline can be digitized at the bottom of the scarp to include the bare earth or exposed face of the scarp. Where some vegetation is visible past the bottom of the scarp extending towards the Bay (SV), the shoreline can be digitized at the bottom of the scarp. The digitized shoreline separates the bottom of the scarp on the “land side” from the presumed ephemeral or emergent vegetation on the “bay side.” Where no scarp is discernible in the oblique imagery, and the profile of the shoreline was more like a ramp, look for an inflection in slope.

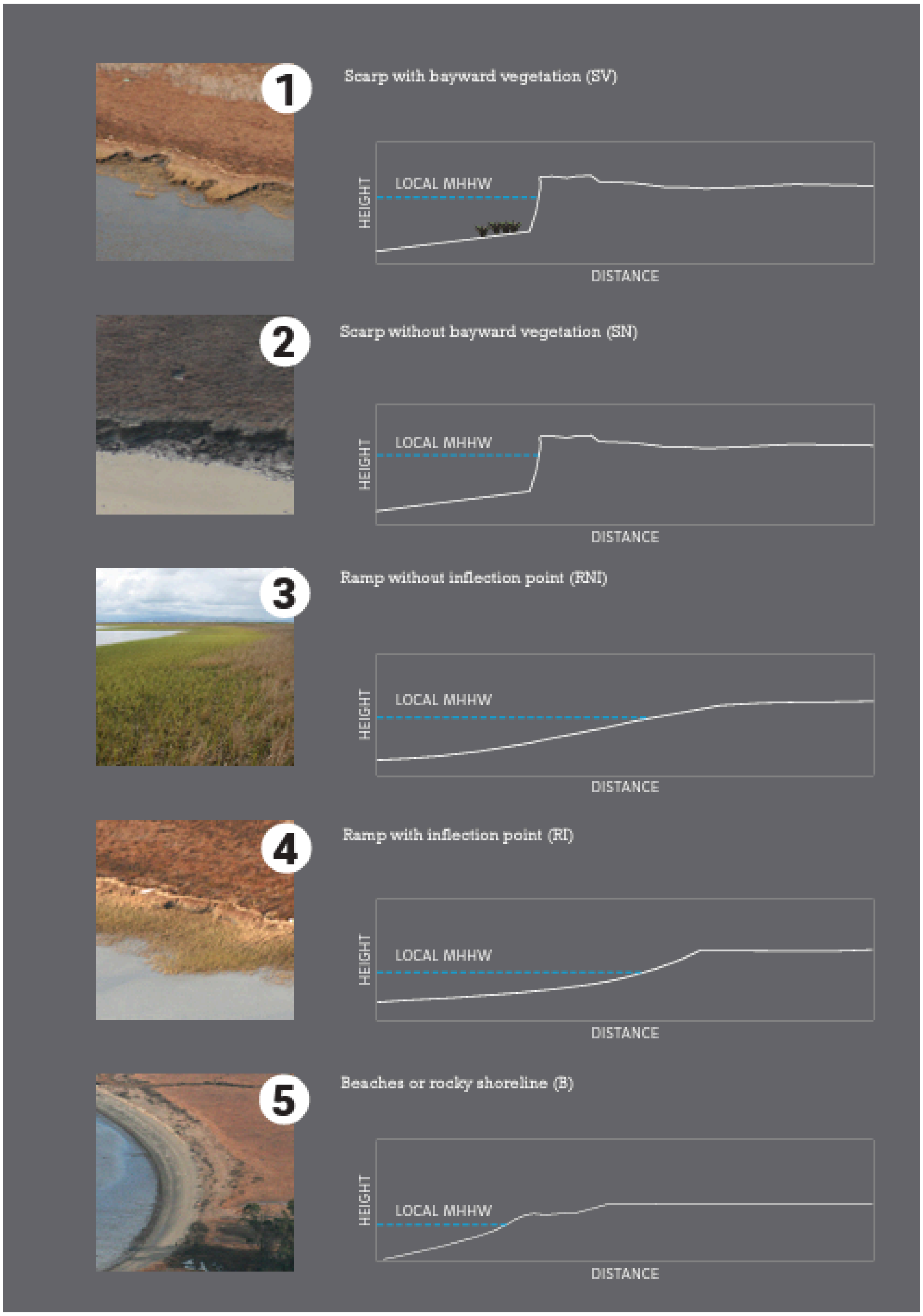


Figure 1. Example of marsh edge typologies (Shifting Shores, SFEI 2015)

The shoreline is digitized along the inflection in slope. If no inflection point is visible, the marsh edge can be digitized at a visible transition in vegetation signature. If a wrack line indicating a single-ridge marsh berm is visible, digitize the shoreline bayward of the marsh berm at the transition of the vegetation signature. Similar marsh edge types were identified in England by Moller and Spencer (2002) and Allen (1989). Prahalad et al. (2015) described slopes in

Tasmania that vary from gently sloped grassy ramps to near-vertical and even overhanging clifflets that expose sediment.

If a digital surface model (DSM) is available of the marsh site, whether from LiDAR or photogrammetry, the elevation data can be used to delineate a boundary. If the site has a scarp, it is likely that the distribution of elevations captured by the DSM is bimodal, as it includes marsh and mudflat, with some separation between the two geomorphic types. Properties of the peaks of the distribution of elevations can be used in an automated way to identify geomorphically meaningful elevations at which to draw contours on the DSM (Fig. 2, WinklerPrins et al., in prep).

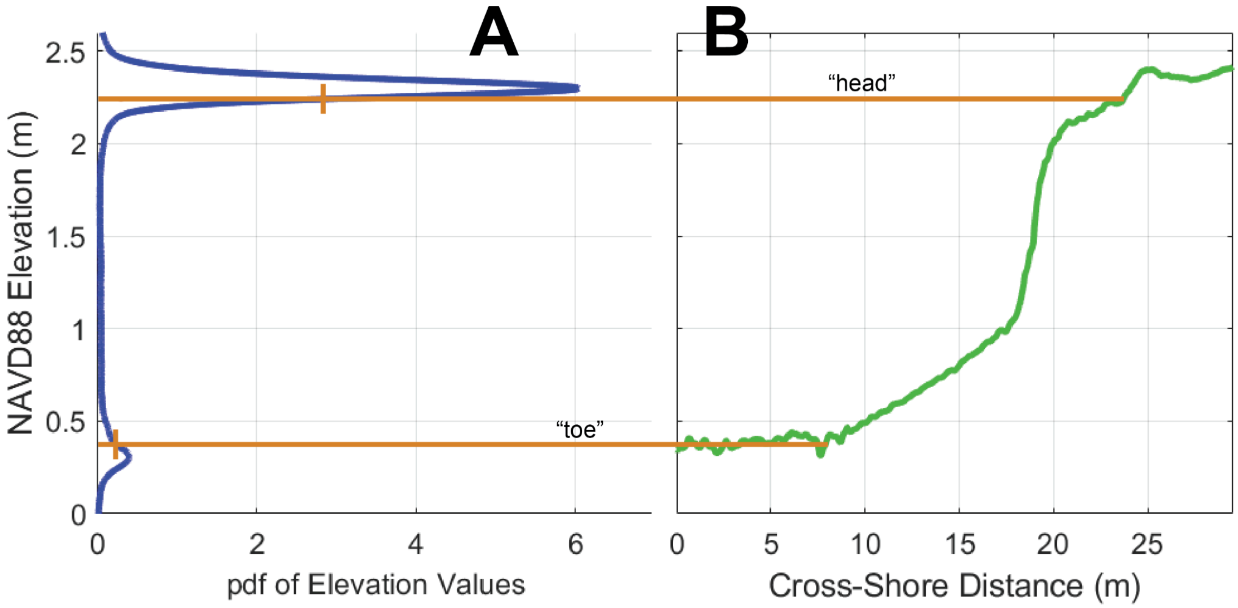


Figure 2. The "head" of the scarp is identified as the lower-elevation side of the half-prominence of the first peak in the pdf of elevation values; the "toe" of the scarp is identified as the higher-elevation side of the half-prominence of the second peak (A). Elevations are projected onto a transect (B). Example from the boundary of Whale's Tail Marsh South.

Regardless of the method used to determine the shoreline edge, the Digital Shoreline Analysis System (DSAS) can be used to calculate rates of change over time (Thieler et al. 2009). DSAS creates shore-normal transects at user-specified intervals, calculating rate of change using the points of intersection with each shoreline edge. The software is available as an ArcMap plugin.

Recommended Methods for Tracking Shoreline Change

a) Bay-wide map of the shoreline.
    i) Tier 1. Using the baylands change basemap, a bay-wide map of the shoreline can be estimated. The shoreline is defined as the vegetated edge using a combination of LiDAR and aerial imagery and object-based classification (WRMP 2021). The vegetated edge is mapped as Intertidal Marsh within the baylands change basemap. Every year the basemap is updated (on a 5 year interval) the vegetated edge is mapped, using the previous map and the current map the change in vegetated edge (or shoreline) can be calculated. Depending on results, the methods can be modified, such as generating a map of marsh edge typology (scarp, slope) to aid classification. The exact methods used should be recorded when the shoreline change is calculated. Calculate change using the USGS DSAS tool.
    ii) Tier 2. Follow Beagle et al. 2015 to map shoreline based on the consolidated edge. Field surveys needed to ground-truth edge location in ramp typologies.

b) Site-level monitoring.
    i) Tier 1.
        1) The marsh edge (shoreline) is defined as the geomorphic change in topography, slope, and soil shear strength at the scarp or ramped bayward edge of the marsh platform (Beagle et al. 2015). Either unvegetated bay mud or low cordgrass marsh occurs bayward of the marsh platform edge, while consolidated, mostly vegetated marsh plain, typically dominated by pickleweed (*Sarcocornia pacifica*), occurs landward.
        2) For scarp typologies, use of LiDAR or SfM data and automated shoreline detection methods are recommended
        3) For slopes typologies, RTK GNSS field surveys needed to accurately delineate shoreline based on bed consolidation
    ii) Tier 2
        1) Shoreline monitoring transects can also be located at the bay edge of vegetation transects. Shoreline edge transects should be relatively short (5 m) but with high point density (0.2 m spacing) to capture small features. Regular RTK GNSS measurements would provide validation of remote sensing-based estimates of shoreline change. Use of mapping feature on RTK GNSS would allow for precise revisiting of points along each transect.

References

Allen JRL. 1989. Evolution of salt-marsh cliffs in muddy and sandy systems: a qualitative comparison of British west-coast estuaries. Earth Surface Processes and Landforms 14, 1: 85-92.

Beagle J, Salomon M, Grossinger RM, Baumgarten S, Askevold RA. 2015. Shifting Shores: Marsh Expansion and Retreat in San Pablo Bay. SFEI Contribution No. 751.

Brinson MM, Christian RR, Blum, LK. 1995. Multiple states in the sea-level induced transition from terrestrial forest to estuary. Estuaries, 18(4), 648-659.

Fagherazzi S. 2013. The ephemeral life of a salt marsh. Geology 41, no. 8 (2013): 943-944.

Francalanci S, Solari L, Cappietti L, Rinaldi M, Federici GV. 2011. Experimental observation on bank retreat of salt marshes. Proc. River, Coastal and Estuarine Morphodynamics, RCEM 2011, 543-551.

Goals Project. 1999. The baylands ecosystem habitat goals: A report of habitat recommendations Prepared by the San Francisco Bay Area Wetlands Ecosystem Goals Project, U.S. Environmental Protection Agency, San Francisco, California, and San Francisco Bay Regional Water Quality Control Board, Oakland, CA.

Marani M, d’Alpaos A, Lanzoni S, Santalucia M. 2011. Understanding and predicting wave erosion of marsh edges. Geophysical Research Letters,38(21)

Möller I, Spencer T. 2002. Wave dissipation over macro-tidal saltmarshes: Effects of marsh edge typology and vegetation change. Journal of Coastal Research, 36(1), 506-521.

Patrick WH, DeLaune RD. 1990. Subsidence, accretion, and sea level rise in south San Francisco Bay marshes. Limnology and Oceanography, 35(6), 1389-1395.

Prahalad V, Sharples C, Kirkpatrick J, Mount R. 2015. Is wind-wave fetch exposure related to soft shoreline change in swell-sheltered situations with low terrestrial sediment input? Journal of Coastal Conservation, 19(1), 23-33.

Stralberg D, Brennan M, Callaway JC, Wood JK, Schile LM, Jongsomjit D, Kelly M, Parker VT, Crooks S. 2011. Evaluating tidal marsh sustainability in the face of sea-level rise: a hybrid modeling approach applied to San Francisco Bay. PloS one, 6(11), e27388.

Swanson KM, Drexler JZ, Schoellhamer DH, Thorne, KM, Casazza, ML, Overton CT, Takekawa, JY. 2014. Wetland accretion rate model of ecosystem resilience (WARMER) and its application to habitat sustainability for endangered species in the San Francisco Estuary. Estuaries and coasts, 37(2), 476-492

Thieler ER, Himmelstoss, EA, Zichichi JL, Ergul A. 2009. Digital Shoreline Analysis System (DSAS) version 4.0— An ArcGIS extension for calculating shoreline change: U.S. Geological Survey Open-File Report 2008-1278.

SOP: Water Surface Elevation, Inundation, Sea Level Rise

Appendix 6. SOP: Water Surface Elevation, Inundation, and Sea Level Rise Detailed Methods

Introduction

Inundation is the flooding of land on a periodic or permanent basis. The depth of inundation can be estimated as the difference between instantaneous water surface elevations (WSE) and ground surface elevations at a given location. The frequency, depth, and duration of inundation (or inundation regime) in tidally-influenced baylands is a fundamental driver of their condition, function, and resilience. The inundation regime mediates the movement and net flux of salt, sediment, nutrients, food web production, and other key environmental constituents between tidal wetlands, adjacent mudflats, and open estuarine waters. It serves as a primary control of habitat access and availability for aquatic and terrestrial organisms and, together with salinity and substrate, governs the distribution and composition of vegetation communities. Inundation regime therefore drives multiple key outcomes of interest to the WRMP, including the evolution of tidal wetland restoration projects, the ability of tidal wetlands to keep pace with rising sea levels, changes in the distribution, abundance, and health of wetland biota, and where management and restoration activities can support tidal wetland resilience and ecosystem services. In the 2020 Phase 1 Program Plan, the WRMP articulated two monitoring questions directly relevant to water surface elevations, inundation, and sea-level rise (SLR):

- *How do tidal inundation regimes differ throughout the estuary's tidal wetlands, and are they muted, choked, or otherwise different from source tides?*
- *What are regional rates of sea level rise, and how do they vary throughout the estuary?*

Background

Water Surface Elevations, Inundation, and Sea Level Rise

Water surface elevations in the deep water channels of the San Francisco Estuary (SFE) are broadly governed by three main forces: astronomic tides at the Golden Gate, outflow from the Sacramento-San Joaquin Delta, and outflows from local tributaries that drain directly into the SFE downstream of the Delta. The relative influence of these forces in the SFE vary across multiple scales of space and time, and of these three, only Delta outflows are subject to landscape-scale anthropogenic management via the Central Valley and State Water Projects. All three forces are influenced by climate change through mechanisms such as SLR, more extreme drought and flood conditions, and rapid shifts between drought and flood conditions (i.e. “climate whiplash,” see Swain et al. 2018). These influences are summarized briefly below.

Relative SLR, the difference between SLR and vertical land motion, are influenced by global, regional, and episodic mechanisms. Climate change drives global (eustatic) SLR largely through thermal expansion of the ocean and the addition of meltwater from glaciers, ice caps, and ice sheets. In coastal California, regional contributions to SLR include gravitational and rotational effects of polar ice sheet retreat. Vertical land motion is due to plate tectonics and land subsidence from groundwater extraction and fill compaction. Recent research indicates that while much of the SFE shoreline experiences local subsidence of less than 2 mm/yr, areas of artificial fill on top of Young Bay Mud deposits (e.g. portions of San Francisco, San Francisco International Airport, Treasure Island, and Foster City) are subsiding at rates of over 10 mm/yr (Shirzaei and Bürgmann 2018).

In SFE, episodic contributions to elevated water levels include short- to moderate-term events such as El Nino-Southern Oscillation (ENSO) or Pacific Decadal Oscillation (PDO) events (months, years), storm surges and “king” tides (hours), and periods of high Delta outflows (days). There is a growing body of evidence that sea levels in the eastern portions of the North Pacific are linked to PDO and related North Pacific wind patterns, and that these patterns may have suppressed SLR along the U.S. Pacific coast from roughly 1980 through the late 2000s, causing observed SLR in California to lag behind global SLR and well behind SLR in the western North Pacific (Bromirski et al. 2011). Research since then indicates that this pattern is potentially reversing and that sea level rise along the U.S. West Coast could be shifting into a mode of rapid acceleration that will allow it to “catch up” with global SLR (ibid, Hamlington et. al 2016).

In the absence of adequate sediment supplies, rising sea levels can drown tidal wetlands and mudflats, and prevent tidal wetland restoration sites from achieving their desired ecosystem functions (Stralberg et al. 2011, Swanson et al. 2013, Schile et al. 2014, Buffington et al. 2021). Changes in the frequency, intensity, and duration of drought or flood conditions influence the delivery of freshwater and sediment to the estuary, impacting aquatic biota as well as the availability of sediment to support accretion in tidal wetlands and mudflats.

Water Surface Elevation Monitoring in San Francisco Estuary

Due to the relatively flat topography of tidal wetlands and mudflats, relatively small changes in water and ground surface elevations in these systems can result in significant differences in inundation regimes and dependent physical and ecological functions. For these reasons, knowledge of local hydrology (including tidal datums and inundation patterns) is fundamental to tidal wetland restoration projects' design and adaptive management. Projects that are designed using inaccurate or old hydrologic information can take longer to develop their intended functions, may result in unintended hydrologic and hydraulic consequences (such as erosion and flooding) within and outside the project site, and in some cases drive costly design retrofits or adaptive management actions. Accurate water level data are also necessary to develop, calibrate, and validate hydrologic and hydraulic models that support flood management activities that help protect public health and safety.

Despite the importance of this information, monitoring of water surface elevations (and therefore inundation and rates of SLR) in SFE is primarily limited to NOAA-operated and maintained stations along the main axis of the estuary, where timely and accurate data is necessary to support commercial shipping operations and public safety, with minimal data collection near shorelines and intertidal baylands. As of 2023, NOAA implements real-time data collection at six tide gauges in deep shipping channels along the main axis of SFE: Port Chicago, Martinez-Amorco Pier, Richmond, San Francisco at Golden Gate, Alameda, and Redwood City (Figure 4, main text). These stations are part of the National Water Level Observation Network (NWLON) managed by NOAA's Center for Operational Oceanographic Products and Services (CO-OPS, tidesandcurrents.noaa.gov). Data from these stations is QAQC'd, processed, and stored by NOAA, and is made available to the public through CO-OPS. CO-OPS also calculates and publishes tidal datums, SLR trends, and other key hydrologic parameters for these stations. Though these six stations provide adequate geographic coverage of the estuary's deeper waters, they do not necessarily reflect conditions within shallower baylands that support the region's tidal wetlands and mudflats.

Water surface elevations in shallower SFE baylands, including tidal wetlands, are strongly influenced by the size and shape of local tidal channels, hydrologic inputs from local watersheds, local winds, vegetation roughness, channel/marsh plain morphology, and the operation of water management infrastructure such as tide gates. Due to these factors, measured WSEs can vary between a tidal wetland and its connected tidal channels, between different wetlands connected to the same tidal channel, and between different locations in the same tidal wetland. To date, NOAA has historically operated numerous stations throughout the baylands, mostly through short-term (on the order of months to years) deployments to aid in the prediction of local tides (Malamud-Roam in-progress). Some projects, such as the Integrated Regional Wetland Monitoring (IRWM) Pilot Project, the South Bay Salt Ponds Restoration Project, and various USGS efforts, have all at some time deployed multiple tide gauges in a tidal wetland or wetland complex to assess inundation regimes across multiple spatial scales.

Multiple tidal wetland restoration projects have tide gauges installed, but for the most part these deployments are intended to be temporary, with planned gauge removal once their permit-required monitoring periods are complete. As of 2023, continuous, long-term water surface elevation (WSE) monitoring in shallow tidal baylands outside the main estuarine axis is currently limited to a USGS tide gauge on Coyote Creek near Alviso, tide gauges operated by the SF Bay National Estuarine Research Reserve and USGS at China Camp and Rush Ranch, and tide gauges on Novato Creek and the Napa River operated by the Marin and Napa County Flood Control Districts, respectfully. [] With the exception of the USGS gauge at Coyote Creek, all of these bayland gauges are relatively recent (post-2017), and utilize different procedures for data QAQC, management, processing, and publication.

The limited geographic coverage provided by the estuary's network of existing tide gauges excludes many regions with significant acreage of existing tidal baylands and restoration projects, such as Suisun Marsh, the Napa-Sonoma baylands, eastern South Bay, and Lower South Bay. The absence of reliable WSE, inundation, and SLR data in these areas creates challenges for tidal wetland restoration projects by obscuring one of the fundamental drivers of tidal wetland condition and function. Data gaps in the baylands can also create challenges for the region's flood management agencies, who must increasingly anticipate and respond to flood events driven by the confluence of extreme creek flows on top of rising sea levels.

Therefore, the overall goal of WRMP monitoring of WSEs, inundation, and SLR is to expand the spatial and temporal coverage of monitoring throughout the region's baylands, and generate more accurate information for use by tidal wetland stakeholders.

To answer the WRMP questions related to WSE, inundation, and SLR, this SOP proposes procedures for how the WRMP will (1) collect new data, (2) synthesize new data with legacy/existing data, and (3) analyze data to develop priority products including calculation of inundation and rates of local relative SLR.

Methods and Considerations

Monitoring stations to measure water surface elevations generally have three main components: (1) a sensor that measures the water surface elevation relative to a fixed position, (2) mooring infrastructure for the sensor (e.g. stilling wells) that maintains it in a fixed position and protects it from movement and damage, and (3) associated geodetic benchmarks and control points that can be used to tie water surface elevation data from the sensor to established vertical and horizontal reference datums.

Establishing all three components in the baylands of the SFE can be challenging. For example, tidal habitats in the baylands are subject to tides, waves, storm surge, and other hydrologic and hydraulic forces that can make gauge installation, access, and maintenance difficult. Saline environments and sessile algae and invertebrates can foul sensors and stilling wells, and require frequent maintenance. Sensor calibration and efforts to reference data to established vertical and horizontal datums are complicated by bayland geomorphology and the often considerable distances between the sensor location and relatively more stable upland location of benchmarks and control points . Tectonic movement in the region complicates precise measurements of both ground and water surface elevations and the translation of these measurements into long-term trends.

To address these and related factors, NOAA has developed standardized procedures for measuring water and ground surface elevations in tidal wetlands, especially those monitored to understand coastal habitat responses to rising sea levels, more extreme storms, and other impacts of climate change. NOAA published the most recent version of these procedures (*Accurate Elevations for Sea Level Change Sentinel Sites,* Hensel et al. 2023) with input from its National Ocean Service (NOS), National Geodetic Survey (NGS), CO-OPS, and Office for Coastal Management (OCM). NOAA developed these procedures to support the NERR Sentinel

Site system and other agencies and organizations with similar programs to monitor SLR along the nation's coasts, such as the WRMP. Since its inception, the WRMP has regularly consulted with the NOAA staff responsible for developing these procedures to advise on monitoring of ground and water surface elevations. Hensel et al. 2023 describe best practices for establishing water level and geodetic infrastructure and connecting measurements of water surface elevations, ground surface elevations (via SETs), groundwater elevations, and vegetation plots. It describes a method for measuring water surface elevations consistent with relatively more exacting CO-OPS/NWLON standards and a lower-cost method that utilizes more commercially available sensors. The document also includes case studies of different methods employed by NERR sites to monitor water surface elevations and derive products such as tidal datums, SLR trends, and related information.

The US Geological Survey has resources that include schematics and visualizations that can also inform the design of establishing water level monitoring stations using data loggers with similar considerations. Methods to establish a continuous water level station are well described in the document, Continuous Water Level Standard Operating Procedure (USGS, 2012). In addition, the RMP Nutrient Management Strategy (NMS) team at SFEI monitors a set of moored sensors to inform nutrient management decisions in San Francisco Bay and also has a set of SOPs for installing, collecting, and analyzing data for moored sites in channels, sloughs, or the open bay that can also serve as a reference (https://www.sfei.org/programs/nutrients-san-francisco-bay).

The recommendations in Hensel et al. 2023 form the basis of the WRMP's monitoring protocols. The WRMP recommends using Hensel et al. 2023 when establishing water level stations at a site.

When setting up either a long- or short-term monitoring station in SFE, there are a number of general, technological, and equipment considerations to accompany the methods described in Hensel 2023.

General considerations

Access to deployment site: What type of access is needed (e.g., vehicle, boat, walking). Does it require crossing a marsh or channels? Is it easy walking or unconsolidated mud? Will access to equipment require coordinating with tidal cycles?

Safety of personnel and equipment. Will staff be safe accessing equipment? How secure will the equipment be? Is there potential for vandalism?

Sensor accuracy: What is the required accuracy, precision, resolution, and sensitivity of the measurements? . In addition to the type of sensor, data accuracy can be driven by the deployment setup, surveying errors during the setup, and quality of the measurements taken to convert to WSE, and proper documentation and verification of measurements.

Technology Considerations

For the WRMP, there are two main sensor types for measuring WSEin and near marshes:

Pressure transducers measure the weight of water, which can be converted to a depth, and can be deployed at any angle as long as they are stable. Vented transducers provide a direct reading of pressure, non-vented transducers require a barometric correction. Barometric data can be collected using a local logger or from an existing station nearby. It is important to match the sensor sensitivity range to the anticipated maximum depths, as sensor accuracies are always in % full scale of the sensor. Commonly, the shallower sensors are in depths of 3-4m. Sensors can be low cost (~$300 - $400) and this allows for the deployment of multiple sensors where it is critical to have a continuous record, and also allows for spares to replace malfunctioning sensors.

Contactless laser or radar measures the distance to the water surface from a fixed point above. The sensor needs to be stable and perpendicular to the water surface. The installation setup, therefore, has to be solid and durable so that the sensor does not move. Some newer technologies may have compensation algorithms for tilt. This equipment is more expensive and requires a more involved and engineered deployment setup.

Types of Deployment

The type of deployment of a water level station will depend on the ability to access the site easily, whether or not ready access to data is required, and the availability of telemetry to remotely download data:

Autonomous deployment is the most common form of deployment where data is downloaded directly from the sensor logger and when WSE calibration measurements are made. This also allows inspection and cleaning of the sensors, fix any deployment issues, and verify that good data is being collected. The size of sensor logger memory and battery life will determine the deployment period for a selected measurement frequency.

Telemetry systems allow access to data collected by remote WSE sensors which eliminates the need to travel to the monitoring site as frequently. Telemetry allows data to be sent directly from the remote field location to a computer, smartphone, or tablet. This is useful where there is a need to make timely decisions or if there is a need to have ready access to data. This is a more costly option, but as technology advances, it may become more economical and less complicated to set up.

Equipment Considerations

Sensors. There are a variety of sensors on the market and their suitability depends on monitoring requirements, the use case for a particular site, and budget.Multi-parameter sondes can be more expensive as they can monitor multiple water quality parameters including dissolved oxygen, Conductivity/Temperature, pH, chlorophyll, dissolved organic matter, turbidity, salinity, total suspended solids, and others). Some examples and example equipment providers typically used in the SFE include:

- YSI EXO Sondes and Sensors - tend to be more expensive, but can be outfitted with a number of sensors to concurrently measure other water quality parameters. https://www.ysi.com/products/multiparameter-sondes
- Submersible Pressure Transmitters https://transducersdirect.com/product-category/pressure-transducers/submersible-pressure-transducers/
- Water Level Loggers https://www.onsetcomp.com/products/sensors/mx2001-s

Stilling wells. Sensors are typically encased within a stilling well attached to a stable structure to protect the sensor and to ensure that readings are collected from a stable platform. This also keeps the sensor vertical and damps the effects of water ripples and waves. The specifics of installing a stilling well will depend on the conditions at the deployment location. Some considerations include:

- It is essential that the stilling well is mounted to a stable platform such as a post or to an existing structure. It is important to consider the intended duration of deployment with regard to materials used and the ease of attachment. Stilling wells can be very simple structures such as 2” PVC, ABS typical, or metal pipe and can be mounted vertically or angled (e.g., on the sloping bank of a channel).
- For a vented pressure transducer, it is important to install the stilling well to ensure that the sensor will vent above the peak water level so that no pressure builds up internally.

Converting sensor raw ‘depth’ measurements to geodetic water surface elevations. This step requires one of two approaches.

1. Collect independent water surface elevation measurements simultaneously with when the sensor is collecting a data point. This requires a surveyed fixed reference point from which to measure. The surveyed reference point should be easily accessible when water is present to allow multiple observations to be made.. .
2. Measure all the geometry of a stilling well configuration and survey one or more of those points. Be sure to always deploy the sensor to the same exact position on the stilling well(usually the bottom), and compute the sensor-to-geodetic elevation using the measured geometry. This method uses survey data of the deployment setup rather than direct WSE measurements. This is useful when you cannot access a sensor when it’s inundated and where it is difficult to collect the independent WSE measurements (e.g., pilings in open water).

Example Water Level Station Installations

The following sites and installation information provide examples of different types of sites in San Francisco Bay and installation considerations for each.

Point Buckler: The water level station is located at the adjacent Rich Island on an existing water control structure. This location allowed for installation of a stilling well which can be easily accessed directly using a vehicle, provided the levee is accessible, and via planks from the levee to the stilling well. When the levee is not accessible, it can be accessed using a boat. It is also a site with easy, safe access on private property with access permission. A nail pounded into the stable water control structure and surveyed is the reference when collecting all of the water surface elevation conversion measurements. Because it is a remote site, it was necessary to establish original survey control. The sensor is downloaded and maintained roughly at monthly intervals. Independent water surface conversion measurements were collected at the beginning and end of each deployment with a typical difference of ±0.03’ or less.

China Camp: Water level stations are located within the tidal and interior marshes. Marsh plain stations are only accessed during lower tides when the surface is not flooded. They are installed on solid posts, carefully measured and surveyed with WSE conversions based on those measurements. Data is downloaded as infrequently as possible to avoid excess walking across the marsh. The water level stations are reasonably near control points for surveying.

Hamilton Wetlands Restoration Project: Water level stations consisting of pressure transducers within stilling wells are sited around the project site.. Sensors have been deployed during specific periods to capture winter storm surges and tides and to monitor water levels and the functioning of water control structures.

Recommendations for the deployment of WRMP water level stations

For monitoring regional rates of SLR: **New long-term tide gauge installations** at locations which are not well-sampled by the existing gauge network is recommended. Partnership with agencies is likely needed to maintain and install long-term gauges. In addition to gathering equipment, access and permitting needs to be considered. **Methods should follow the NOAA NOS Manual (Hensel et al., 2023) available online.**

For monitoring variability in tidal inundation regimes between a tidal marsh and its connected tidal channels, between different wetlands connected to the same tidal channel, and between different locations in the same tidal marsh: **New short-term tide gauge installations at WRMP priority Benchmark, Reference, and Project sites should follow methods outline by (US Geological Survey 2012) available online.**

References

Hensel, P.F., C.M. Gallagher, A. Johnson, and S.Lerberg. 2023. Accurate Elevations for Sea Level Change Sentinel Sites. February 2023. NOAA NOS Manual. U.S. Department of Commerce.

US Geological Survey. 2012. Water level continuous standard operating procedures. Unpublished protocols. USGS, Western Ecological Research Center, San Francisco Bay Estuary Field Station, Vallejo, CA.

Salinity SOP draft

Appendix 7: Salinity: Draft HGM SOP

Background

Salinity is a critical parameter of water quality that influences physical and biological processes within estuaries, impacting the distribution of plants and animals and determining habitat type. Salinity represents a complex mixture of dissolved salts with various chemical compositions found in seawater. In an estuary, salinity is affected by the salinity of ocean water, magnitude and timing of freshwater inflow, and basin morphology. Salinity affects the dynamics of mixing for the water body; large variations in salinity in the water column can give rise to stratified conditions that inhibit mixing and can affect other water-quality parameters (e.g., dissolved oxygen). At a given location, salinity can be measured in the water column (surface water), in sediment pore water, or in near-surface sediments (shallow groundwater). For the WRMP, understanding the salinity in a project area over time will inform vegetation types and anticipated changes in habitat.

Monitoring questions

For salinity, the associated monitoring questions are:

1. How do **surface-water** salinity fields differ throughout the estuary's tidal baylands?
2. How do **porewater** salinity fields differ throughout the estuary's tidal baylands?
3. How do **shallow groundwater** salinity fields differ throughout the estuary's tidal baylands? (easier/cheaper to measure at higher frequency, encompass entire root zone)

Approach/Methods

Early methods of measuring salinity by modern scientists included filtration, titration, relative density, and refractometry. In modern practice, the measurement of salinity is frequently simplified to a function of electrical conductance, temperature, and depth (Fofonoff and Millard Jr 1983). Electrical conductance is the capacity of the water to conduct electrical current and is related to the concentration of ions (dissolved salts). Electrical conductivity (typical units microsiemens/centimeter or uS/cm) is a normalized form of electrical conductance to account for measurement cell size. Specific conductance (typical units uS/cm at 25 degrees Celsius) is a normalized form of electrical conductivity to account for water temperature (additional details available in resources listed in the Appendix). Widely available sensors that measure electrical conductivity and temperature report these two parameters, which can then be related to salinity via various algorithms (e.g., Fofonoff and Millard Jr 1983).

Units

Salinity is frequently reported in several units depending on how it is measured. For titration-based techniques, units include parts per hundred (%) or parts per thousand (ppt). Using mass-fraction techniques, units include grams of salt per liter or kilogram of water (g/L or g/kg). For one more-common technique, in which salinity is determined using electrical conductivity sensors via the practical salinity scale of 1978, the salinity value is unitless. A common error is the misapplication of practical salinity units (psu) to salinity values determined via the practical salinity scale.

Surface-water Salinity Measurement

Measuring salinity of surface waters is commonly completed using electrical conductivity sensors as described in the previous section. Surface-water salinity can be measured in-situ using sensors that observe data at one or more fixed locations in the water column or using a profiling system that automatically raises and lowers a sensor through the water column. Measuring salinity can also occur manually during site visits via a grab sample or collecting a profile. The advantage of in-situ sensors is that they can measure salinity continuously, which is useful for estuarine environments that experience great ranges in salinity. A common deployment method entails placement of an electrical conductivity sensor that is attached to a fixed object.

Salinity in estuarine waters can vary horizontally (e.g., with distance from freshwater inflow) and vertically (i.e., near surface versus near bed). Salinity has a large effect on the density of the water and strongly influences stratification (i.e., vertical variations in water density). Water masses of similar density may or may not mix with other water masses depending on factors such as the degree of stratification or energy in the system. Because salinity stratification can strongly influence mixing, a sampling array for salinity must consider horizontal and vertical measurement locations and sampling frequency.

Electrical conductivity sensors typically arrive off-the-shelf with a manufacturer certification of laboratory calibration. Ensure the sensor range exceeds the expected range of salinity on site. Sensor output must be periodically checked against known solutions to ensure data accuracy ("sensor check procedure"); many sensors allow for user-defined calibrations that override the factory calibration. Electrical conductivity is not site specific and this sensor check procedure allows for interchangeability of sensors at or between sites. Biological fouling typically affects sensor output by altering the measurement cell volume, leading to sensor reading to levels that are much greater and noisier than actual. Calibration issues with and/or biological fouling of electrical conductivity sensors can be significant sources of data loss; redundant sampling where feasible can help increase data return.

Recommended Method for surface-water salinity measurement

The WRMP recommends the use of moored electrical conductivity sensors for continuous monitoring of water conductivity and salinity over extended periods. These sensors offer high temporal resolution, making them well-suited for tracking short-term variations and diurnal patterns. They are cost-effective, easy to calibrate, and widely employed in various applications. **To ensure high-quality data, adherence to established procedures for the collection of continuous data is recommended (Wagner et al. 2006; USGS 2019).**

Subsurface salinity measurement

Two methods of subsurface salinity measurement are described in this section: porewater and shallow groundwater.

Porewater

Porewater salinity is a dynamic parameter influenced by a variety of factors, including tides, groundwater interactions, precipitation, and evapotranspiration. Measuring subsurface salinity of porewater entails extracting water from the pores (or voids) in between sediment particles near the bed surface. Measuring salinity in porewater of mudflats and marsh plains is completed manually during site visits; there are no presently available reliable methods to measure this parameter continuously. Porewater is sampled from a site (generally within the top 20 cm) using a syringe or a diffusion equilibrator (e.g., sipper). Salinity is determined for a subsample of the porewater using a refractometer or salinometer on site. Porewater sampling requires multiple (replicate) measurements within a site to assess variability. One advantage of porewater measurements is they can help understand the subtidal variations in salinity at a site and characterize the conditions that rooted plants encounter. Characteristics of the site (e.g., tidal range, site elevation) and seasonal variations must be considered when designing the sampling program. In some parts of the estuary, site elevation and sediment type limit the amount of porewater available for sampling. For additional considerations and sampling design examples see Krask et al. (2022).

Shallow Groundwater

Measuring salinity in shallow groundwater is considered to be an alternative to porewater salinity measurements that allows for continuous data collection. Shallow groundwater salinity can be measured *in-situ* by installing a shallow well (depth less than 3 meters) and equipping it with an electrical conductivity sensor. Considerations of well characteristics—depth, diameter, screen size and placement—along with quantity and placement of wells and sensor placement within the well are required. Designing a sampling program for shallow groundwater salinity requires considerations as for surface-water salinity and porewater salinity. See Sprecher (1993) for additional details.

The above information is summarized in Table 1 and includes level of effort and relative value of the effort in the context of existing methods used in the SFE.

Table 1. Methods for measuring salinity.

Method	**Measurements**	**Appropriate Site**	**Level of Effort**	**Relative Value Ranking (1 = highest)**
Electrical conductivity (EC)	Moored EC sensors in water column	Benchmark, Reference, Project	High: Continuous EC data collection at multiple spatial locations and two depths for 1 year	1
Electrical conductivity (EC)	Moored EC sensors in water column	Reference, Project	Low: Continuous EC data collection at one location and one depth for 2 x 2-week periods, one in dry season and one in wet season	3
Porewater	Porewater samples	Reference, Project	High: Monthly porewater sampling at multiple spatial locations for 1 year	5
Shallow groundwater	EC sensors in shallow groundwater wells	Reference, Project	High: Continuous EC data collection at multiple well locations for 1 year	4
EC, porewater, shallow groundwater	Moored EC sensors in water column, porewater samples, EC sensors in shallow groundwater wells	Special study	High: Comparison of methods: -Continuous EC data collection at multiple spatial locations and two depths for 1 year -Monthly porewater sampling at multiple spatial locations for 1 year -Continuous EC data collection at multiple well locations for 1 year	2

Recommended method for Subsurface salinity

Recommended methods to monitor subsurface salinity include installing piezometers fitted with an electrical conductance sensor. **See Sprecher (1993) for additional details on piezometer installation.**

References

Fofonoff NP, Millard Jr RC. 1983. Algorithms for the computation of fundamental properties of seawater. [accessed 2023 October 13]. https://doi.org/10.25607/OBP-1450

Krask JL, Buck TL, Dunn RP, Smith EM. 2022. Increasing tidal inundation corresponds to rising porewater nutrient concentrations in a southeastern U.S. salt marsh. PLOS ONE. 17:e0278215. https://doi.org/10.1371/journal.pone.0278215

Sprecher SW. 1993. Installing monitoring wells/piezometers in wetlands. U.S. Army Engineer

Waterways Experiment Station. [accessed 2023 Sep 21]. Available from: https://erdc-library.erdc.dren.mil/jspui/handle/11681/3599

USGS. 2019. Specific conductance: U.S. Geological Survey Techniques and Methods. Reston, VA. 15 p. https://doi.org/10.3133/tm9A6.3

Wagner RJ, Boulger RW, Oblinger CJ, Smith BA. 2006. Guidelines and Standard Procedures for Continuous Water-Quality Monitors: Station Operation, Record Computation, and Data Reporting. Reston, VA: U.S. Geological Survey. [accessed 2023 Oct 5]. Available from: https://pubs.usgs.gov/tm/2006/tm1D3/pdf/TM1D3.pdf

Suspended-sediment concentration SOP draft

Appendix 8. Suspended-Sediment Concentrations

Background

Sediment is considered an important resource for an estuary and supports the maintenance of shorelines, mudflats, and wetlands. The transport of sediment through an estuary affects sediment availability, which in turn affects ecosystem primary production, contaminant transport and fate, and navigation and dredging operations. Quantifying the sources, sinks, and pathways of sediment in a region of interests is challenging and requires rigorous data collection.

Tidal marshes are dynamic ecosystems located at the interface of land and water, and they depend on the deposition of sediments for their growth and maintenance. Sediments carried by tides provide the building blocks for marshes. The sediment settles in the marsh during high tides and, along with organic material from roots and rhizomes, gradually builds up the marsh platform. Sediment deposition is crucial for marsh elevation gain, allowing marshes to keep pace with rising sea levels. Sediment can also transport nutrients (or even contaminants). Some nutrients, such as phosphorus adsorb to sediment particles, similarly contaminants such as mercury adsorb to sediment. The nutrients can help fertilize the marsh, if not in excess, while contaminants can be harmful to wildlife. High concentrations of suspended sediment can significantly impact water quality. These sediments cloud the water, reducing light penetration, which in turn hinders the growth of submerged aquatic vegetation. Furthermore, highly turbid water can be detrimental to fish as it may clog their gills, affecting their ability to respire. For the WRMP, understanding the transport and fate of sediment in a project area will inform project management and anticipated timelines of change.

Monitoring questions

For sediment, the initial associated WRMP monitoring question that was designed to address Management Question 2B (What are the regional differences in the sources and amounts of sediment available to support accretion in tidal marsh ecosystems?):

1. Where is there adequate suspended sediment to support rates of accretion that are equal to or greater than sea-level rise?

The HGM workgroup modified this question to also ask the question:

2. How does suspended-sediment concentration (SSC) vary across wetland systems in the estuary?

Approach/Methods

Suspended-sediment concentration (SSC) and total suspended solids (TSS) are measures of the solid-phase material within a volume of water. The difference between these parameters is in the laboratory analysis, where for SSC the entire sample volume is analyzed and for TSS only a subsample is analyzed. Previous studies have determined that data produced using SSC analytical methods have greater accuracy and increased comparability between samples compared to TSS data (Gray et al. 2000). Thus, measuring SSC is considered a better approach when seeking to understand sediment transport and determine sediment budgets and **SSC is the recommended parameter for WRMP activities**. Typically, the disaggregated particle size of sediment that is found in suspension in San Francisco Bay is finer than 0.63 mm (silt and clay). SSC is measured directly using water samples that are analyzed in a laboratory. Water samples are typically collected manually at a site, though it is possible to collect water samples automatically at desired intervals using automatic water samplers. Given the interest in SSC variation over longer time periods (weeks to months), SSC is typically calculated from continuous observations of a surrogate parameter such as turbidity, optical backscatter, or acoustic backscatter. Surrogate parameters must be related or calibrated to *in-situ* (i.e., site-specific) sediment characteristics using a robust calibration program.

One important reason to observe SSC in an environment is to gain understanding of **suspended-sediment flux** (SSF) for a defined region. SSF is the product of SSC and flow (velocity times cross-sectional area). For example, SSF in a creek is the product of SSC and creek flow. SSF provides a magnitude and direction of sediment transport and can be used to develop sediment budgets to understand accretion or erosion over time. SSF is an important parameter in defining the topography and long-term resilience of mud flats and marshes in the face of sea-level rise, and these in turn affect vegetation distribution. SSF can be difficult to measure in certain environments such as mud flats or marshes because observing the water flow is impeded by ill-defined boundaries or channels and because SSC can be heterogeneous. Methods have been proposed (e.g., Nowacki and Ganju (2019)) to identify simple, predictive metrics for estimating SSF in marsh environments.

Water samples for SSC

Water samples are necessary for determining SSC and for relating to surrogate parameters. There are several methods for sample collection and important considerations for analysis, presented in this section.

Water sample collection methods

Water samples to determine SSC (and required to validate/calibrate the surrogate parameters below) can be collected in several ways:

- instantaneous,
- depth-integrating, or

- time-integrating.

A common way to collect SSC samples is using a sampler that takes an instantaneous water sample at a specific depth either manually (e.g., Van Dorn-type sampler) or automatically (e.g., single-stage sampler or sipper bottle, or pumped sampler; see IACWR (1961)). Instantaneous samples are useful for point measurements of SSC in areas where no cross section is readily apparent. Another way to collect samples is using a depth-integrating sampler that samples water at an isokinetic rate to provide a measure of depth-averaged SSC (e.g., US DH-48; https://water.usgs.gov/fisp/docs/Instructions_US_DH-48_001010.pdf). A third way to collect samples is to use a time-integrating sampler that samples water at a specific depth over time to provide a measure of time-averaged SSC (e.g., US P-61-A1; https://water.usgs.gov/fisp/docs/Instructions_US_P-61-A1_030115.pdf). Depth-integrating samples are useful to relate surrogate measurements to depth-averaged SSC such as for a defined cross section. Time-integrating samples are necessary for acoustic-derived surrogate data (see acoustic surrogates below). Water samples must be collected with a level of repeatability to minimize error; considerations for collecting water samples are available (see Anderson (2005)). **The WRMP recommends instantaneous collection methods for water samples for SSC.**

Water sample analysis methods

Analyzing a water sample for SSC is an important step that requires adherence to established methods of analysis (e.g., Guy (1977); USEPA (1971); and USEPA (1993)). **The WRMP recommends water samples are analyzed for SSC by a qualified laboratory.**

Surrogate parameters and analysis

This section describes the primary types of sensors used as surrogate parameters for SSC and how the surrogate parameter is related to SSC.

Optical surrogates

SSC can be measured using optical sensors including turbidity and optical backscatter sensors. Turbidity sensors are the most-common sensor used to calculate SSC. Turbidity is an optical property of water and is a measure of its relative clarity. Optical sensors are sensitive to sensor position (e.g., sensor sampling volume cannot be impeded by obstructions) and very susceptible to biological fouling in estuarine environments. In very shallow water, direct exposure to light can produce spikes in turbidity data, so in intertidal settings data must be interpreted with care. Turbidity sensors typically arrive off-the-shelf with a manufacturer certification of laboratory calibration. Sensor output must be periodically checked against known solutions to ensure data accuracy (“sensor check procedure”); some sensors allow for user-defined calibrations that override the factory calibration. This sensor check procedure allows for some level of interchangeability for optical sensors between sites. Biological fouling typically affects sensor output by increasing sensor reading to levels that are much greater than actual (i.e., artificially high readings). Fouling can be substantially decreased by the use of commercially available wipers, which clean the sensor face at user-specified intervals. **To ensure high-quality data, adherence to established procedures for the collection of continuous data is recommended (e.g., Anderson (2005); Wagner et al. (2006)). The WRMP recommends measuring turbidity as a surrogate for SSC.**

Remotely sensed environmental data is another form of an optical (or pseudo-optical) surrogate. Satellite imagery produces multispectral datasets that can be correlated to *in situ* measurements of SSC (e.g., Ruhl et al., (2001)). This is an emerging field of research and preliminary applications of this method are limited to well-mixed water bodies or the near-surface region of the water column for unmixed water bodies such as the San Francisco Estuary. While presently limited in broad application, remotely sensed imagery can show regional surface patterns and the relative scale of SSC variability important for informing site-level monitoring design (e.g., Taylor and Kudela (2021), Nechad et al., (2010)). Furthermore, when pairing remote sensing analysis with platforms such as Google Earth Engine, one can visualize a long time-series of modeled SSC. Correlation of imagery to SSC can be confounded by chlorophyll

Acoustic surrogates

SSC can be measured using acoustic backscatter sensors (ABS). ABS instruments are sensitive to disturbance and less susceptible to biological fouling in estuarine environments. ABS instruments are available in different frequencies that are sensitive to certain ranges of sediment grain sizes. Some ABS instruments have multiple frequencies to expand the range of grain sizes that can be observed. ABS instruments cannot be calibrated and there is no guarantee that any two ABS sensors will produce similar sensor output at a given site (i.e., there is less interchangeability for ABS instruments at one site or between multiple sites). Biological fouling typically affects sensor output by decreasing sensor reading to levels that are much lower than actual. ABS instruments for SSC measurement are still in development and not as widely used as turbidity sensors. Given their experimental nature, application of ABS instruments to WRMP sites is not recommended at this time.

Relating surrogates to SSC (analysis)

Site-specific calibration of turbidity sensors is required because the relationship between optical backscatter and SSC is strongly dependent on particle size in suspension. Particle size in suspension is influenced both by disaggregated particle size and flocculation dynamics, so is difficult to predict and can change over time. When developing the relation between surrogate sensor output and SSC, all water samples must be collected from the site of interest at the time of sensor sampling (i.e., pooling samples from multiple sites is not possible). Typically, the relation between turbidity and SSC is linear; greater turbidity indicates higher SSC at a site. USGS guidelines recommend minimum numbers of discrete water samples at a site to develop a rating, but rather than target a specific number of samples, it is better to collect water samples that span the range of observed sensor output at the site as uniformly as possible. Water samples are analyzed in a laboratory to determine SSC; these data are the dependent variable. Sensor output at the time of the water sample is the explanatory variable. There are several regression models used for relating the explanatory variable to the dependent variable including linear regression, semi-log regression, log-log regression, and repeated medians. An example relationship between turbidity and SSC is shown in Fig. 1.

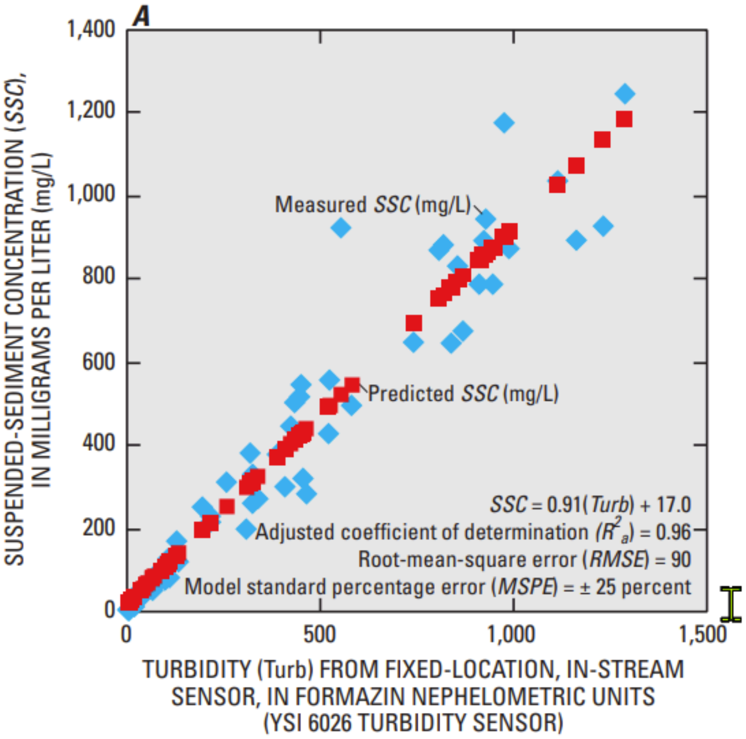


Figure 1. Example of regression model to develop relation between turbidity (surrogate) and suspended-sediment concentration (SSC, measured in situ). From Fig. 10 of Rasmussen et al. (2009).

Extensive guidance on developing regression models that relate surrogate parameters to SSC is available, for example, see the following references:

a. Helsel, D.R., and R.M. Hirsch. 1992. Statistical methods in water resources. The Netherlands: Elsevier Science Publications.

b. Rasmussen et al., 2009. Guidelines and Procedures for Computing Time-Series Suspended-Sediment Concentrations and Loads from In-Stream Turbidity-Sensor and Streamflow Data https://pubs.usgs.gov/tm/tm3c4/.

c. Landers et al. 2016. Sediment acoustic index method for computing continuous suspended-sediment concentrations https://pubs.er.usgs.gov/publication/tm3C5.

The above information is summarized in Table 1 and includes level of effort and relative value of the effort in the context of existing methods used in the SFE.

Table 1. Methods for measuring suspended-sediment concentration (SSC).

Method	**Measurements**	**Appropriate Site**	**Level of Effort**	**Relative Value Ranking (1 = highest)**
Surrogate: Optical turbidity	Turbidity, manually or automatically collected water samples for SSC	Benchmark, Reference, Project	High: Continuous turbidity data collection at multiple locations for 1 year with 36 samples for SSC per location	1
Surrogate: Optical turbidity	Turbidity, manually or automatically collected water samples for SSC	Project	Low: Continuous turbidity data collection at one location for 2 x 2-week periods, one in dry season and one in wet season, with >12 samples for SSC	2
Direct measurement	Automatically collected water samples for SSC	Project	Low: Automatic sampler deployed for 2 x 2-week periods, one in dry season and one in wet season, with >12 samples for SSC per location.	5
Surrogate: Acoustic backscatter (ABS)	ABS, water samples for SSC	Special study	High: Continuous ABS data collection at multiple locations for 1 year with 36 samples for SSC per location	3
Surrogate: Remotely sensed imagery	Water samples for SSC	Special study	High: Determine imagery collection schedule; collect samples for SSC concurrent with imagery collection	4

Recommended Methods

The WRMP recommends using turbidity sensors as a surrogate for measuring SSC. **To ensure high-quality data, adherence to established procedures from Anderson (2005) or Wagner et al., (2006) for the collection of continuous data is recommended**. Processing the turbidity data is then necessary to estimate SSC from the turbidity values, see recommended models above.

References

Anderson CW. 2005. Chapter A6. Section 6.7. Turbidity. Reston, VA. https://doi.org/10.3133/twri09A6.7

Gray JR, Glysson GD, Turcios LM, Schwarz GE. 2000. Comparability of suspended-sediment concentration and total suspended solids data. https://doi.org/10.3133/wri004191

Guy HP. 1977. Laboratory theory and methods for sediment analysis.

IACWR (Inter-agency Committee on Water Resources). 1961. The Single-stage Sampler for Suspended Sediment. Minneapolis, MN: St. Anthony Falls Hydraulic Laboratory. Available from: https://water.usgs.gov/fisp/docs/Report_13.pdf

Nechad B, Ruddick KG, Park Y. 2010. Calibration and validation of a generic multisensor algorithm for mapping of total suspended matter in turbid waters. Remote Sens Environ. 114:854–866. https://doi.org/10.1016/j.rse.2009.11.022

Nowacki DJ, Ganju NK. 2019. Simple Metrics Predict Salt-Marsh Sediment Fluxes. Geophys Res Lett. 46:12250–12257. https://doi.org/10.1029/2019GL083819

Rasmussen PP, Gray JR, Glysson GD, Ziegler AC. 2009. Guidelines and Procedures for Computing Time-Series Suspended-Sediment Concentrations and Loads from In-Stream Turbidity-Sensor and Streamflow Data. https://doi.org/10.3133/tm3C4

Ruhl CA, Schoellhamer DH, Stumpf RP, Lindsay CL. 2001. Combined Use of Remote Sensing and Continuous Monitoring to Analyse the Variability of Suspended-Sediment Concentrations in San Francisco Bay, California. Estuar Coast Shelf Sci. 53:801–812. https://doi.org/10.1006/ecss.2000.0730

Taylor NC, Kudela RM. 2021. Spatial Variability of Suspended Sediments in San Francisco Bay, California. Remote Sens. 13:4625. https://doi.org/10.3390/rs13224625

USEPA (U.S. Environmental Protection Agency). 1971. Residue, non-filterable: test method 160: 2.

USEPA (U.S. Environmental Protection Agency). 1993. Total Suspended Solids, Mass Balance, Volatile Suspended Solids. ESS Method 340.2. [accessed 2023 Oct 26]. Available from: https://www.cyanopros.com/refs/epa_TSS.pdf

Wagner RJ, Boulger RW, Oblinger CJ, Smith BA. 2006. Guidelines and Standard Procedures for Continuous Water-Quality Monitors: Station Operation, Record Computation, and Data Reporting. Reston, VA: U.S. Geological Survey. [accessed 2023 Oct 5]. Available from: https://pubs.usgs.gov/tm/2006/tm1D3/pdf/TM1D3.pdf

Appendix 9: Detailed Methods for Channels, Ponds, Pannes (Unvegetated Areas)

Channels, pannes sop

Background

Tidal channel order, density, and distribution are key features of least-disturbed and restored tidal wetlands (Zeff 1999; Hood 2002; D'Alpaos et al. 2007; D'Alpaos et al. 2010; Bridgeland et al. 2017). In-fill of tidal channels within diked areas can significantly alter the surface topography, impairing the ability of wetlands to deliver essential functions after restoration. Natural channel networks possess the necessary densities and sizes (stream order) to facilitate vital ecosystem functions, including hydrologic connectivity between estuaries and vegetated wetland plains. This connection supports the exchange of organisms and the transport of materials and energy, including saline water, nutrients, organic carbon, and sediments (Reed et al. 1999; Buffington et al. 2020). A panne is a small depression within a marsh that experiences periodic inundation. They play a valuable role in supporting unique plant and animal communities and contribute to the overall ecological health of the marsh. However, continued expansion of a panne can indicate stress to the system and loss of habitat.

Salt marsh creeks can be roughly classified as either higher-order, open-ended channels or lower-order, dead-end creeks with different tidal signatures.

- The larger, high-order creeks experience greater peak velocities (~1 m/s) occurring at mid-tide when water levels are below bank-full stage in the channel.
- Low-order (small) salt marsh creeks may exhibit a bed gradient, which enhances late ebb flow and retards early flood currents.
- Low-order channels experience relatively low flow velocities (~0.1–0.6 m/s) with velocity transients (surges) at close to bank-full conditions. Fagherazzi et al. (2008) demonstrated the importance of the frictional resistance imparted by the vegetation on channel flow.

The presence of microtopography or small capillary creeks (< 1 m wide) on the marsh platform has a significant impact on salt marsh circulation as a whole, including channel flows (Fagherazzi et al. 2008; Cea and French 2012).

Understanding channel form and function in and of itself is an important characteristic of marsh functioning and tracking metrics including network length, channel density and channel width and their change over time are important for understanding important hydrological and biological process driving marsh function such as drainage and sediment anoxia that drives productivity and vegetation patterns, fish and bird habitat and access, nutrient and productivity exchange between marine and wetland ecosystems.

Key characteristics of channels and pannes vary by typology of marsh and channel network such that establishing an understanding of marsh typology is an essential baseline for understanding important functions and expectations and for contextualizing change over time. For example, older historic wetlands tend to have a highly developed channel network with extensive branching and dendritic reaches, while younger fringing or infill wetlands have fewer and less sinuous networks. Restored wetlands can have a variety of channel typologies depending on initial design.

How channel width and density changes over time is clearly dependent on baseline marsh typology. For instance, in restoration project sites, development of the full channel network is often left to occur through the forces of tidal exchange over time and is therefore expected to include channel deepening, widening, or both, due to the increase in flow volumes after restoration of tidal exchange. In contrast, channel width in established wetlands is generally more stable over time and changes are indicative of shifts in flows, loss of sediment or other potentially degrading processes.

Monitoring the expansion of unvegetated areas in the marsh plain, both pannes/ponds and channels is an important metric of marsh loss and an indicator of marsh susceptibility to drowning. Expansion of unvegetated areas has been tracked as unvegetated to vegetated ratio (UVVR) and has been shown to indicate marsh vulnerability to SLR in some areas. As the extent of open water area within marshes increases, their ability to trap sediment is reduced, accelerating their deterioration (Ganju et al. 2017).

Monitoring Questions

The WRMP is interested in answering the Monitoring Question regarding channels, ponds and pannes:

- Where are unvegetated areas such as channels, ponds, and pannes expanding?

Approach/Methods

Planform metrics

Planform metrics in a salt marsh are typically measured to study the morphology and dynamics and refer to the physical characteristics and spatial layout of a salt marsh. These measurements are important for understanding how salt marshes change over time and how they provide ecological services. Examples of planform metrics include:

- Marsh Area:
  - Measure the total area of the salt marsh. This can be done using GPS, aerial imagery, or satellite imagery.
- Marsh Perimeter:
  - Measure the total perimeter of the salt marsh. This can be done using a GPS or by tracing the marsh boundary on a map.

- Marsh Edge Length:
    - Measure the length of the marsh edge, which is the boundary between the marsh and adjacent habitats (e.g., open water, upland).
- Marsh Width:
    - Measure the width of the marsh at various points along its length. This provides information about how wide the marsh is at different locations.
- Marsh Shape Index:
    - Calculate the shape index, which is a measure of how irregular or convoluted the marsh boundary is. A more irregular shape indicates a more complex marsh structure.
- Tidal Creek Density:
    - Count the number of tidal creeks or channels within the marsh and calculate the density (e.g., creeks per square kilometer).

Channel cross-section

An RTK-GPS can be used to measure the elevation of the channel bed at fixed intervals along the width of a channel. This can provide cm level vertical and horizontal accuracy. Measures may be needed to ensure the RTK-GPS unit does not sink into the sediment.

An automatic optical level (auto level) can be employed to measure the variations in elevation between the established benchmarks and the specific locations of interest. A stadia rod is placed onto the bed of the creek channel and using the auto level the values on the stadia rod are identified. The auto leveling operator is reading and recording the values on the stadia rod. An alternative to the stadia rod is an automatic optical barcode reading level (reading level). The use is similar to the stadia rod, however the automatic optical level reads the values itself using the barcode as well as the distance from the reading level. The values on the stadia rod or reading level need to be related to a known benchmark or geodetic control point measured with a differential GPS.

For characterizing channel morphology four metrics during the pre- and post- restoration monitoring periods are typically done:

Channel flow-path elevation (minimum elevation along an individual transect). Changes in channel flow -path elevation provide insight into the extent of scour and head cutting that occurred due to the restoration of tidal influence.Using the flow path elevations, longitudinal channel profiles can be developed to describe the relative pattern of elevation change across each monitoring reach

Channel bottom elevation (mean elevation). Difference in the base elevation of the two channel networks – a product of factors such as drainage area, channel order, the tidal prism, and sediment loading.

Channel bankfull width (width measured across the top of the channel at the point where it intersects the marsh's surface on the right and left banks). Channel bankfull width will vary with the size of the sub-basins and the size of their channel orders.

Channel width-to-depth ratio (using flow path depth rather than mean depth). Smaller drainage surface area and therefore a smaller channel order and channel width, will result in a smaller width-to-depth ratio.

Recommendations for the WRMP

Level 1 - Planform metrics

Remote sensing analysis can help describe and quantify planform metrics within SFE. Using the output from the WRMP Baylands Change Basemap, important metrics can be tracked, specifically: network length, channel density, panne/pond dimensions, and total unvegetated to vegetated ratio. Within the Baylands Change Basemap, intertidal channel, Marsh Panne, Low Marsh, and Intertidal Marsh are relevant habitat type classifications. To measure channel density, the area of intertidal channels compared to the overall marsh unit area should be calculated. To measure network length, the intertidal channel length per marsh unit can be calculated. To assess pond/panne dimensions the area, length and width of marsh pannes in relation to the marsh unit can be calculated. For total unvegetated to vegetated ratio the area of Intertidal marsh compared to the area of intertidal channel and pannes can be calculated. Using subsequent baylands change basemaps, change within these metrics can be tracked over time. Alternatively outputs from the baylands change basemap can be used as an input variable within an already existing Matlab toolbox MorphEst. MorphEst automatically measures estuarine planform geometry and is publicly available (Jung et al. 2021).

An alternative higher cost method is to use lidar to parametrize tidal creek morphology. This method may lead to higher accuracy since the purpose is directly geared towards tidal creek morphology, as opposed to the Baylands Change Basemap's main goal is to map habitat. Methods used can be similar to as Chiro et al. (2018).

Level 3 - Cross-sectional metrics

Field based geomorphic monitoring can be employed to gain insights into the evolving structure of restored tidal wetlands and channels in response to sedimentation and erosion processes occurring at the site. Channel cross-sections offer valuable information about changes in tidal channels and geomorphological shifts. These cross-sections measure depth, width and shape of tidal channels. These metrics are helpful for understanding circulation patterns within tidal marshes, and provide a habitat assessment to determine which species can access these habitats. These methods must be measured within the field, and are recommended at benchmark sites.

Within each channel, place transects from near the mouth of the channel (where channels were likely to be widest) to near their pre-restoration headwaters (Figure 3.1-3.3).

To resample identical transects after restoration, install semi-permanent monuments at both ends of each transect. Monuments consisted of 1.2 m (4 ft) long, 0.63 cm (¼ in) rebar driven into the ground and encased with 1.5 m (5 ft) of 5 cm schedule 40 PVC pipe. Set back monuments from the bank edge to allow future measurements, even if channels migrated laterally.

Measure the position and elevation of each monument with high-precision RTK GPS equipment with a 480 second occupation at 1 Hz; positions were referenced to UTM Zone 10N and NAVD88 using geoid model 12A. Vertical accuracy for these measurements was better than 5.5 cm at the 95% confidence level based on comparisons to nearby published survey control.

At each transect, establish a baseline using a CAM-Line thin-diameter graduated metal tape stretched between the transect end post monuments.

Use a laser level to measure elevation at topographic breaks along the transect relative to a known elevation benchmark (usually a transect end post monument). The number of measurements per transect varied based on channel morphology; measurements were taken at breaks in the cross section’s slope as interpreted in the field by the surveyor.

When multiple elevation benchmarks are available for a given laser level setup, perform a least-squares adjustment to assign the laser level elevation.

For each elevation measurement along a transect, record the distance along the transect and note what feature was present at each measured point (e.g., left bank, flow-path, right bank).

The elevation of each measurement represented the top of the visible sediment surface (including any soft fine sediment that was deposited).

Prior to data analysis generate elevation values at 10% intervals across the transect through interpolation of the break point values gathered in the field. Average the break point elevations immediately to the left and right of each interpolated interval, to provide the interpolated value.

See (US Geological Survey 2011) available online, for more detailed methods for measuring channel cross-section within tidal marshes.

WRMP Products

Mapping and monitoring change over time within ponds, pannes and channels with answer: **Where are unvegetated areas such as channels, ponds, and pannes expanding?**

- OLU/site-scale maps of pond/panne expansion and UVVR change
- Site-scale metrics of channel diversity/complexity

- Channel networks maps, time series, and statistics

References

Bridgeland ET, Brophy L, Wetering S van de, So KJ, Hoy R van, Lowe RW, Ledig DB. 2017. Ni-les'tun Tidal Wetlands Restoration Project: Planning, Implementation, and Lessons Learned. Washington, DC: U.S. Department of Interior, Fish and Wildlife Service, Region 1. [accessed 2023 Sep 28]. Available from: https://ecos.fws.gov/ServCat/Reference/Profile/95453

Buffington KJ, Goodman AC, Freeman CM, Thorne KM. 2020. Testing the interactive effects of flooding and salinity on tidal marsh plant productivity. Aquat Bot. 164:103231. https://doi.org/10.1016/j.aquabot.2020.103231

Cea L, French JR. 2012. Bathymetric error estimation for the calibration and validation of estuarine hydrodynamic models. Estuar Coast Shelf Sci. 100:124–132. https://doi.org/10.1016/j.ecss.2012.01.004

Chirol C, Haigh ID, Pontee N, Thompson CE, Gallop SL. 2018. Parametrizing tidal creek morphology in mature saltmarshes using semi-automated extraction from lidar. Remote Sens Environ. 209:291–311. https://doi.org/10.1016/j.rse.2017.11.012

D'Alpaos A, Lanzoni S, Marani M, Rinaldo A. 2007. Landscape evolution in tidal embayments: Modeling the interplay of erosion, sedimentation, and vegetation dynamics. J Geophys Res Earth Surf. [accessed 2023 September 18];112:. https://doi.org/10.1029/2006JF000537

D'Alpaos A, Lanzoni S, Marani M, Rinaldo A. 2010. On the tidal prism–channel area relations. J Geophys Res Earth Surf. [accessed 2023 September 18];115:. https://doi.org/10.1029/2008JF001243

Fagherazzi S, Hannion M, D'Odorico P. 2008. Geomorphic structure of tidal hydrodynamics in salt marsh creeks. Water Resour Res. [accessed 2023 October 09];44:. https://doi.org/10.1029/2007WR006289

Ganju NK, Defne Z, Kirwan ML, Fagherazzi S, D'Alpaos A, Carniello L. 2017. Spatially integrative metrics reveal hidden vulnerability of microtidal salt marshes. Nat Commun. 8:14156. https://doi.org/10.1038/ncomms14156

Hood WG. 2002. Application of Landscape Allometry to Restoration of Tidal Channels. Restor Ecol. 10:213–222. https://doi.org/10.1046/j.1526-100X.2002.02034.x

Jung NW, Lee G, Jung Y, Figueroa SM, Lagamayo KD, Jo T-C, Chang J. 2021. MorphEst: An Automated Toolbox for Measuring Estuarine Planform Geometry from Remotely Sensed Imagery and Its Application to the South Korean Coast. Remote Sens. 13:330. https://doi.org/10.3390/rs13020330

Reed DJ, Spencer T, Murray AL, French JR, Leonard L. 1999. Marsh surface sediment deposition and the role of tidal creeks: Implications for created and managed coastal marshes. J Coast Conserv. 5:81–90. https://doi.org/10.1007/BF02802742

US Geological Survey. 2011. Channel Cross-section Standard Operating Procedures. Vallejo, CA: Western Ecological Research Center, San Francisco Bay Estuary Field Station. [accessed 2023 Sep 28]. Available from:

https://www.tidalmarshmonitoring.net/pdf/USGS_WERC_ChannelCrossSection_SOP.pdf

Zeff ML. 1999. Salt Marsh Tidal Channel Morphometry: Applications for Wetland Creation and Restoration. Restor Ecol. 7:205–211. https://doi.org/10.1046/j.1526-100X.1999.72013.x