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The Surface Elevation Table and Marker Horizon Technique

A Protocol for Measuring Wetland Elevation Dynamics, Narrative (Version 2.0)



Top: National Park Service (NPS) biologists reading a deep rod SET at Assateague Island National Seashore, Maryland, USA. Lower Right: NPS biologist reading the original SET at Cape Cod National Seashore, Massachusetts, USA. Lower Left: NPS biologist with a marker horizon core from Acadia National Park, Maine, USA.

NPS / JIM LYNCH / KATIE BUTTON

The Surface Elevation Table and Marker Horizon Technique: A Protocol for Measuring Wetland Elevation Dynamics, Narrative (Version 2.0)

Science Report NPS/SR—2026/464

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Abstract

The National Park Service (NPS), in response to the growing evidence and awareness of the effects of climate change on federal lands, determined that monitoring wetland elevation change is a top priority in North Atlantic Coastal parks (Stevens et al. 2010). As a result, the NPS Northeast Coastal and Barrier Network (NCBN) in collaboration with colleagues from the U.S. Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA) have developed a protocol for monitoring wetland elevation change and other processes important for determining the viability of wetland communities. Although focused on North Atlantic Coastal parks, this document is applicable to all coastal and inland wetland regions.

Wetlands exist within a narrow range of elevation that is influenced by local hydrologic conditions. For tidally influenced coastal wetlands, local hydrologic conditions may be changing as sea levels continue to rise. As sea level rises, coastal wetland systems may either a) build elevation to maintain favorable hydrologic conditions for their survival or b) become increasingly inundated beyond their physiological tolerance resulting in an eventual conversion to open water. A better understanding of these processes will help to determine the present and future viability of coastal wetlands managed by the NPS and can help address measures to ensure these communities exist into the future.

This protocol provides the reader with instructions and guidelines on designing a monitoring plan or study to: Quantify elevation change in wetlands with the Surface Elevation Table (SET); understand the processes that influence elevation change, including vertical accretion (SET and Marker Horizon methods); survey the wetland surface and SET mark to a common reference datum to allow for comparing sample stations to each other and to local tidal datums; survey the SET mark to monitor its relative stability; and establish water level equipment to characterize the hydrology and tidal datums for a particular wetland site or sites.

The protocol is divided into two documents: The narrative (this document) presents an overview of all aspects of monitoring wetland elevation dynamics, and a document of Standard Operating Procedures (SOPs) with detailed instructions on the design, installation, data collection, and data management in support of monitoring changes in wetland elevation.

List of Terms

Accretion: The accumulation of matter, both mineral and organic, carried by a river, stream or ocean tides onto wetland and shallow water bottom surfaces. The buildup of the sediment substrate is referred to as *vertical accretion* while *lateral accretion* refers to the horizontal expansion of the sediment substrate.

Bioturbation: The reworking of soils and sediments by animals or plants.

Compaction: The process by which wetland sediments progressively lose porosity due to the effect of material loading above it.

Covariate: An observable, continuous secondary variable that may affect the response variable. Covariates are often used in a statistical model to help control variability, so that the response to the primary factors of interest can be discerned. Example: wetland elevation relative to mean high water is a secondary variable that may help determine the effect of vegetation type on elevation change.

Datum: A reference frame or surface from which positions and elevations are measured.

Elevation capital: The elevation of a wetland in relation to the growth range of the vegetation. The greater the elevation capital, the greater the wetland sustainability relative to sea-level rise.

Elevation change (wetland): Change in the height of the wetland surface relative to the base of the Surface Elevation Table (SET) mark.

Experimental unit: The smallest division of an experimental sample to which independent factor levels can be assigned.

Factors: Within an experimental design, a factor is an independent variable (e.g., tidal regime) that is hypothesized to affect the response (i.e., dependent) variable (e.g., vertical accretion or elevation change).

- **Fixed factor:** A variable whose value can be controlled (e.g., wetland type or vegetation).
- **Random factor:** A variable whose value cannot be controlled (e.g., location effects, sample effects).
- **Continuous factor:** Either a fixed or random factor that can take on a continuous range of values (e.g., temperature, water level).
- **Discrete factor:** A fixed factor that takes discrete levels (factor levels). Example: low, medium, and high inundation regimes or fertilization treatments.

Global Navigation Satellite System (GNSS): A global satellite system used to provide geo-spatial positioning. GPS, GLONASS, Galileo, and Beidou are GNSS satellite systems.

Growth range: Range of wetland elevations over which a particular species of wetland plant will grow.

Hypothesis testing: Evaluating one or more specific research questions using statistical comparisons among specific levels of independent variables. Example: comparing the wetland elevation change and vertical accretion between a restored marsh and an adjacent reference marsh.

Leveling, geodetic: The precise measurement of vertical differences among surfaces using high precision (typically <0.0001 m or better) optical or digital leveling instrumentation.

Marker horizons: An artificial soil horizon placed on a wetland surface to measure vertical accretion (i.e., the accumulation of material above the marker horizon). Feldspar is a common marker material.

Monitoring (wetland elevation and accretion): A sampling scheme designed to document overall rates (trends) of elevation change or vertical accretion within a particular sample space, which is an area of broad geographic extent. Example: evaluating wetland elevation change over time throughout an entire refuge or park.

NAD 83 - North American Datum of 1983: Official datum used for horizontal positions (latitude and longitude) and ellipsoid heights.

National Spatial Reference System (NSRS): A consistent coordinate system that defines latitude, longitude, height, scale, gravity, and orientation throughout the United States and its territories.

National Tidal Datum Epoch (NTDE): The time period used to determine tidal datums. A span of 18.7 years. At the time of this writing (2026), the current NTDE spans from 1983 to 2001. The 2002–2020 NTDE is expected to come out in 2029.

NAVD 88 - North American Vertical Datum of 1988: Official orthometric vertical datum in the National Spatial Reference System (NSRS). NAVD 88 is based on a leveling network on the North American continent constrained to a single origin point.

Orthometric height: For practical purposes, “height above sea level” based on the current NAVD 88 datum tied to a defined elevation at one point (in both location and time) rather than to local mean sea level.

Randomization: A process of assigning sample sites or sample stations such that each site or station has an equal chance of being included in the sample. Randomization is typically used to ensure a representative sample without the inclusion of bias. Note that with small sample sizes, pure randomization does not guarantee representative sampling. Restricted randomization is a variation where randomization occurs within *a priori* limits (e.g., randomly choosing sample stations within pre-determined sample sites).

Real Time Kinematic surveying (RTK): A differential GNSS surveying technique that uses multiple receivers (base and rover). A stationary base receiver set up on a known point sends real-time corrections to the rover. RTK surveys provide vertical precision in the range of several centimeters.

Real Time Network surveying (RTN): A GNSS surveying technique similar to RTK but only requires a single receiver connected to a "virtual" base that provides the corrections. Accessing this "virtual" base usually requires a connection to the internet or cell phone service.

Refusal: The point in time when the deep mark rod no longer moves (often an abrupt stop) during installation (e.g., hits bedrock or limestone). If refusal is not met, installation continues until substantial resistance occurs (refer to Resistance, substantial).

Replicate: One of several experimental units to which the same factor levels are applied or assigned (refer to Experimental unit, above).

Resistance, substantial: The point in time at which the insertion rate of rods into the ground reaches an agreed-upon minimum rate (i.e., 60 seconds per foot of rod). After reaching this threshold, insertion of the mark typically stops.

Sample site: A distinct unit within the sample space where SET sample stations may be deployed. Sample sites may be identified based on their geographic locations, their vegetation communities, elevation within the tidal frame, and other factors. Examples: a specific wetland area along a coast, or a vegetated area within one wetland.

Sample size: The number of replicates in any given factor level.

Sample space: A landscape-scale unit area that represents the study's area of interest. This is the area within which inferences will be made. Sample sites are delineated within the sample space, or individual sample stations may be distributed within the sample space. Example: a wildlife refuge, a given wetland type, an individual marsh, or an entire state or county coastline.

Sample station: The physical location within a sample site or sample space where SET and/or marker horizon measurements are collected.

Sea-level rise, eustatic: Vertical rate of increase in sea level; typically determined from long-term sea-level records and satellite altimetry.

Sea-level rise, relative: The combination of eustatic sea-level rise and local vertical land motion (i.e., subsidence or uplift).

Serial correlation: Also known as autocorrelation, this is the similarity among observations of the same sample over time. For example, repeated SET measurements for the same pin in the same position (i.e., repeatedly sampling the same point on the wetland surface) will be correlated over time.

SET and RSET mark: The permanently installed pipe (SET) or rod (RSET) infrastructure established at the sample station, from which repeated SET and RSET measurements are taken; also colloquially referred to as a SET benchmark in early SET literature. If a SET or RSET mark meets National Geodetic Survey Standards, it can be referred to as a benchmark. There are two basic types of SET marks, deep and shallow. The original SET pipe mark (6–10 m) and the deep rod SET (RSET) mark (2–40 m) are examples of deep marks. The 4-legged shallow rod SET mark (typically <1 m) is an example of a shallow mark.

Shallow subsidence: The sinking or downward movement of the wetland surface relative to the base of the SET Mark—calculated as the difference between vertical accretion as measured by a marker horizon and elevation change as measured by the SET (i.e., vertical accretion minus elevation). Shallow subsidence only applies to the portion of the substrate above the base of the SET or RSET mark, and not the portion below it.

Subsidence: The sinking or downward movement of a surface relative to a vertical datum.

Surface Elevation Table (SET): A portable mechanical device that provides high-resolution measurements of relative elevation change in wetland sediments or shallow water bottoms relative to the base of the SET mark to which it is attached. The **original SET** attaches to a deep pipe mark. The **rod SET (RSET)** attaches to a deep rod mark and a shallow four-legged mark. Refer to SET mark, above.

Surface Elevation Table-Marker Horizon (SET-MH) technique: The surface elevation table and marker horizon methods are frequently used in conjunction to understand the surface and subsurface processes controlling elevation change over the depth of the SET mark. SET marks (deep or shallow) typically integrate surface and subsurface processes. Marker horizons integrate primarily surface processes.

Surface sediment deposition: The process of suspended sediment deposition on the wetland surface, which contributes to wetland vertical accretion.

Tidal datum: The elevation of a specific phase of the tide cycle averaged over a specific time period (refer to NTDE, the National Tidal Datum Epoch, above).

Wetland: Land consisting of marshes or swamps with saturated soils where plant organic matter accumulates and soils are wet for some period of time, and plants and animals are adapted to this environment.

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Introduction

The purpose of this protocol is to provide a scientifically valid and standardized set of guidelines for measuring elevation change and vertical accretion in coastal wetland ecosystems. Knowledge and implementation of a consistent set of processes can enhance the ability to assess the vulnerability of wetland resources to changes in local hydrology.

These guidelines follow a standardized format used by the National Park Service (NPS), Inventory & Monitoring Program (Oakley et al. 2003; Stevens et al. 2005). The report is organized into two main documents: 1) A protocol narrative with background and explanation of the rationales and methodologies used for measuring wetland elevation change and vertical accretion, and 2) detailed Standard Operating Procedures (SOPs) for all phases of an inquiry-based study of wetland vertical accretion and elevation change, including experimental design, site establishment, data acquisition, and data analysis. For some SOPs, appendices are provided to give additional background and information on the technology and methods employed. All SOPs are available through the NPS DataStore (The Surface Elevation Table and Marker Horizon Technique: A Protocol for Monitoring Wetland Elevation Dynamics, Standard Operating Procedures).

Both protocol documents support the development of a consistent program of coastal elevation monitoring that is national in scope. The impetus for this effort arose within the NPS and their collaborations with the U.S. Geological Survey (USGS) in the measurement of wetland elevation change using the Surface Elevation Table (SET), and with the National Oceanic and Atmospheric Administration (NOAA) to relate SET data and other wetland datasets to local water levels within local geodetic control networks, as well as the National Spatial Reference System. These guidelines are therefore an interagency collaboration to develop a consistently applied methodology for monitoring the vulnerability of coastal wetlands to present and future sea-level rise.

Protocol Objectives

This protocol narrative document provides the reader with instructions and guidelines on designing a monitoring plan or study to:

1. Quantify elevation change in wetlands with the Surface Elevation Table (SET).
2. Understand the processes that influence elevation change, including vertical accretion (i.e., SET and marker horizon methods).
3. Survey the wetland surface, the SET mark, and water level recorders to a common vertical reference datum (NAVD 88), to allow for comparing sample stations to each other and to local tidal datums.
4. Survey the SET mark to monitor its relative stability and assess vertical land motion.
5. Establish water level recorders to characterize the local hydrology and tidal datums for a particular wetland site.

The specific information needs of a research study or monitoring program will drive the choice of what to measure and monitor, and which techniques to use. Not every objective needs to be met in any one study or monitoring program. However, including an elevation survey in a coastal vertical dynamics study will allow the elevation of the wetland surface to be related to local water levels. Elevation monitoring in general can provide managers and researchers with a feasible and valid means of quantifying processes that are essential in determining the long-term viability of these ecosystems.

Although this narrative document focuses on the specific needs for monitoring coastal wetland elevation trends with respect to local tides and sea level, the main techniques are applicable to all wetland types including non-coastal and non-tidal wetlands and shallow water ecosystems.

Background

Wetland Sensitivity to Sea-Level Rise

Tidal wetland plant communities (i.e., salt marshes, brackish marshes, mangroves, and tidal freshwater marshes and forests) exist within a narrow range of elevation that is influenced by the local tidal patterns and inundation (Figure 1). Tide ranges (from low to high) vary from area to area; thus, the vertical growth range of wetland plants will also vary according to these local conditions. If an area has a large tidal range, then there will be a large vertical growth range for the vegetation in that area. Conversely, if an area has a small tidal range, the vertical growth range will also be comparatively small (Cahoon and Guntenspergen 2010; McKee and Patrick 1988).



Figure 1. Salt marsh at Cape Cod National Seashore, Massachusetts, USA.
NPS / JAMES LYNCH

The ability of wetland plant communities to maintain their position within their vertical growth range is tied to local hydrology (McKee and Patrick 1988; Morris et al. 2002). In areas of rising sea levels

due to a combination of eustatic sea-level rise and local vertical land motion such as subsidence, a tidal wetland maintains its relative elevation within its growth range only when there is an adequate accumulation of mineral and organic matter on or in its substrate (Figure 2; Kirwan et al. 2016; Morris et al. 2002). Wetlands have existed—even flourished—during an extended period of moderate rises in sea level over the past 7,000 years through processes of vertical development (Redfield 1965, 1972). Vertical development in a wetland is the net result of several processes affecting wetland elevation both positively and negatively, including accretion (limited in part by mineral sediment supply), erosion, organic soil (peat) formation, decomposition, compaction, groundwater flux (shrink-swell of the soil), and deeper processes such as regional subsidence or uplift (Cahoon 2024).

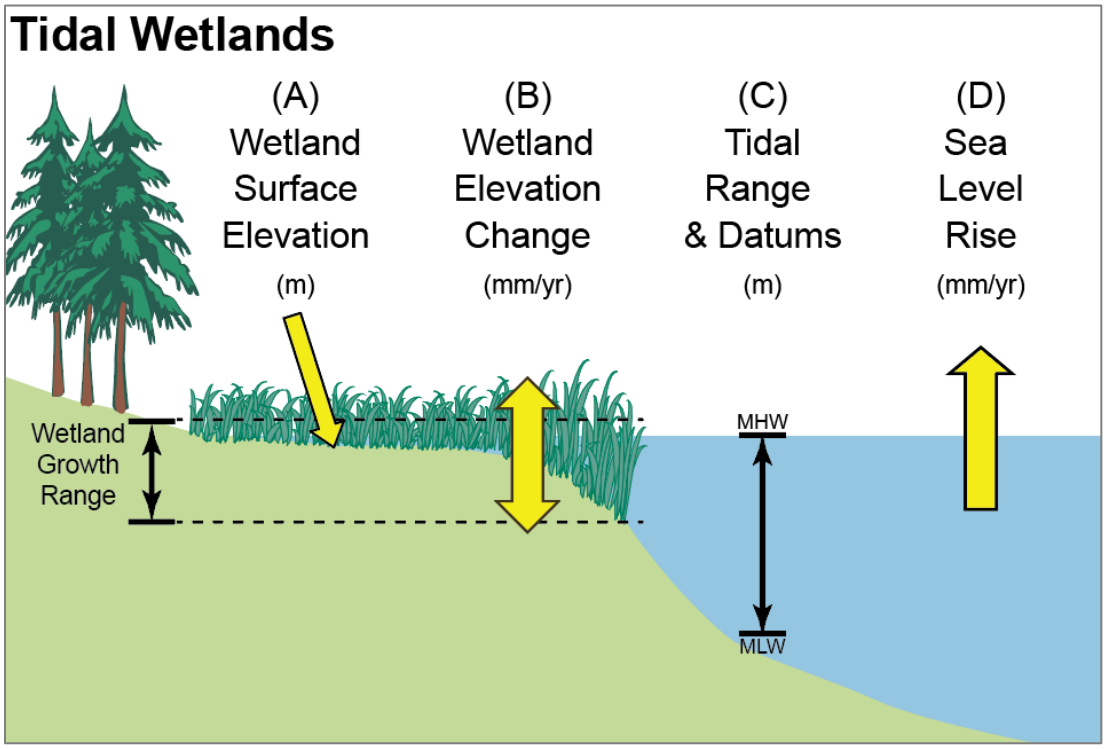


Figure 2. The relationship among wetland surface elevation (A), tidal datums (C), and their respective rates of change (B and D) in tidal wetlands. Understanding these relationships aids in evaluating the sustainability of a wetland community to sea-level rise. MHW = mean high water; MLW = mean low water. *NPS / JAMES LYNCH*

As sea level rises, only an equal or greater rate of accumulation of mineral and organic matter maintains wetland elevation at an optimal height within the growth range for plant survival (Saintilan et al. 2022). Plants existing at the lower elevation of their growth range are exposed to a higher frequency, depth and duration of flooding that may limit vegetative growth, causing a decrease in the contribution of organic matter to soil formation both above and below ground (Morris et al. 2002). Under these conditions, plant survival could be at risk, particularly in low sediment settings, and once the vegetation dies there is little chance of maintaining sufficient elevation for successful plant

recolonization to occur. The vegetated intertidal wetland eventually becomes an intertidal mud flat or a shallow submerged water bottom.

Accelerating rates of sea-level rise are the primary impact of climate change on these plant communities (Kirwan and Guntenspergen 2009; Kirwan and Temmerman 2009; Saintilan et al. 2022). If wetland elevation does not increase at a rate commensurate with the rate of sea-level rise, the wetland is said to be experiencing an "elevation deficit" (Cahoon et al. 1995, 1999). Yet, some coastal wetland plant communities are currently buffered against accelerating sea-level rise by their relatively high elevation with respect to water levels, referred to as "elevation capital" (Cahoon and Guntenspergen 2010; Cahoon et al. 2019; Reed 2002). Even if vertical processes are insufficient to counter local sea-level rise, coastal wetlands with high elevation capital (i.e., wetland elevation is high within the growth range) will survive longer than those with little elevation capital (i.e., wetland elevation is low within the growth range).

Although the national rate of wetland loss from land development has declined over the past several decades due in part to changes in regulatory enforcement in the United States (Dahl 2011), wetland loss is still occurring, and many coastal areas are increasingly vulnerable to wetland loss due to the combination of local land subsidence and sea-level rise. This is especially true in micro-tidal wetlands and areas of rapid subsidence, such as the Mississippi River Delta (e.g., Coleman and Smith 1964; Penland and Ramsey 1990; Rybczyk and Cahoon 2002; Törnqvist et al. 2006), Texas Chenier Plain (Moon et al. 2022), and the mid-Atlantic seaboard (e.g., Ohenhen et al. 2023, Hensel et al. 2024; Stevenson et al. 1985). With global rates of sea-level rise predicted to increase over the coming decades (Church et al. 2010), many more coastal wetlands may become vulnerable to increased inundation. Additionally, certain areas of the coast, such as the mid-Atlantic region, are expected to undergo even greater sea-level rise due to predicted changes in coastal ocean circulation (Sallenger et al. 2012).

Given these patterns of wetland loss and vulnerability, the coastal manager/investigator may have specific questions in mind when planning a study of wetland elevation dynamics, such as:

1. "What are the elevation characteristics of our wetlands?" (Figure 2A)
2. "Is elevation change occurring and at what rate? What is the role of surface and subsurface processes?" (Figure 2B)
3. "How do local wetland elevation dynamics relate to the local hydrology (e.g., local tidal datums, frequency of flooding, or elevation capital)?" (Figure 2C)
4. "Is elevation gain sufficient to keep pace with current and predicted sea-level rise?" (Figure 2D)

These questions relate to quantifying the wetland and hydrologic factors described in Figure 2. Leveling or GNSS surveys are used to address the elevation characteristics of a particular wetland (Question 1). The Surface Elevation Table (SET) technique is used to determine elevation change of the wetland surface (Question 2). To answer Question 3, however, the SET data will need to be expressed with respect to local water levels and local water level changes. This will normally involve

measuring and monitoring local water levels and conducting an elevation survey to connect both measurements. For Question 4, SET data are compared to local sea-level rise estimates (if available).

Coastal researchers might also be more interested in conducting manipulative experiments and testing hypotheses to understand wetland elevation responses to specific environmental variables. Such investigations will require SETs as well as other techniques (e.g., marker horizons, tide gauges, surveying techniques) and appropriate experimental designs. Again, the specific needs of the study will inform the combination of techniques required and the type of experimental design chosen.

Surface Elevation Table

The Surface Elevation Table (SET) technique measures very small changes (mm) in the elevation of the wetland surface over time. It utilizes a portable mechanical device that consists of two parts: the SET instrument and the SET mark to which it attaches.

There are two common types of SET instrument:

1. The Sedimentation-Erosion Table (SET) designed by Boumans and Day (1993) and subsequent modifications of this SET by Cahoon et al. (2002a) called the Surface Elevation Table (SET). Both designs are collectively referred to as the original SET (Figures 3, 4a).
2. The Rod Surface Elevation Table (RSET) designed by Cahoon et al. (2002b) and Callaway et al. (2013) (Figures 3, 4b).

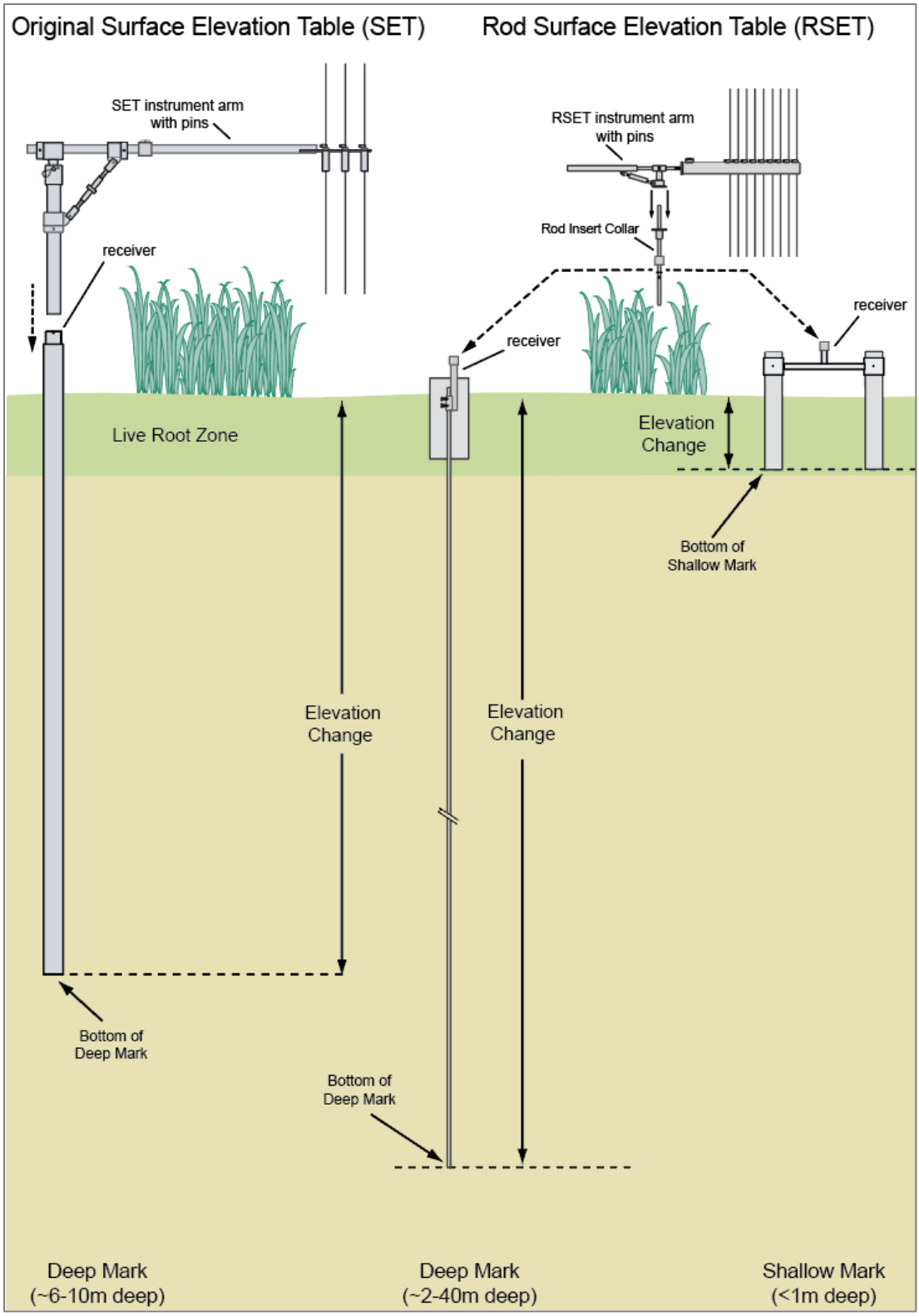


Figure 3. Conceptual diagram showing the original surface elevation table (SET), the rod surface elevation table (RSET), and the marks they couple with.

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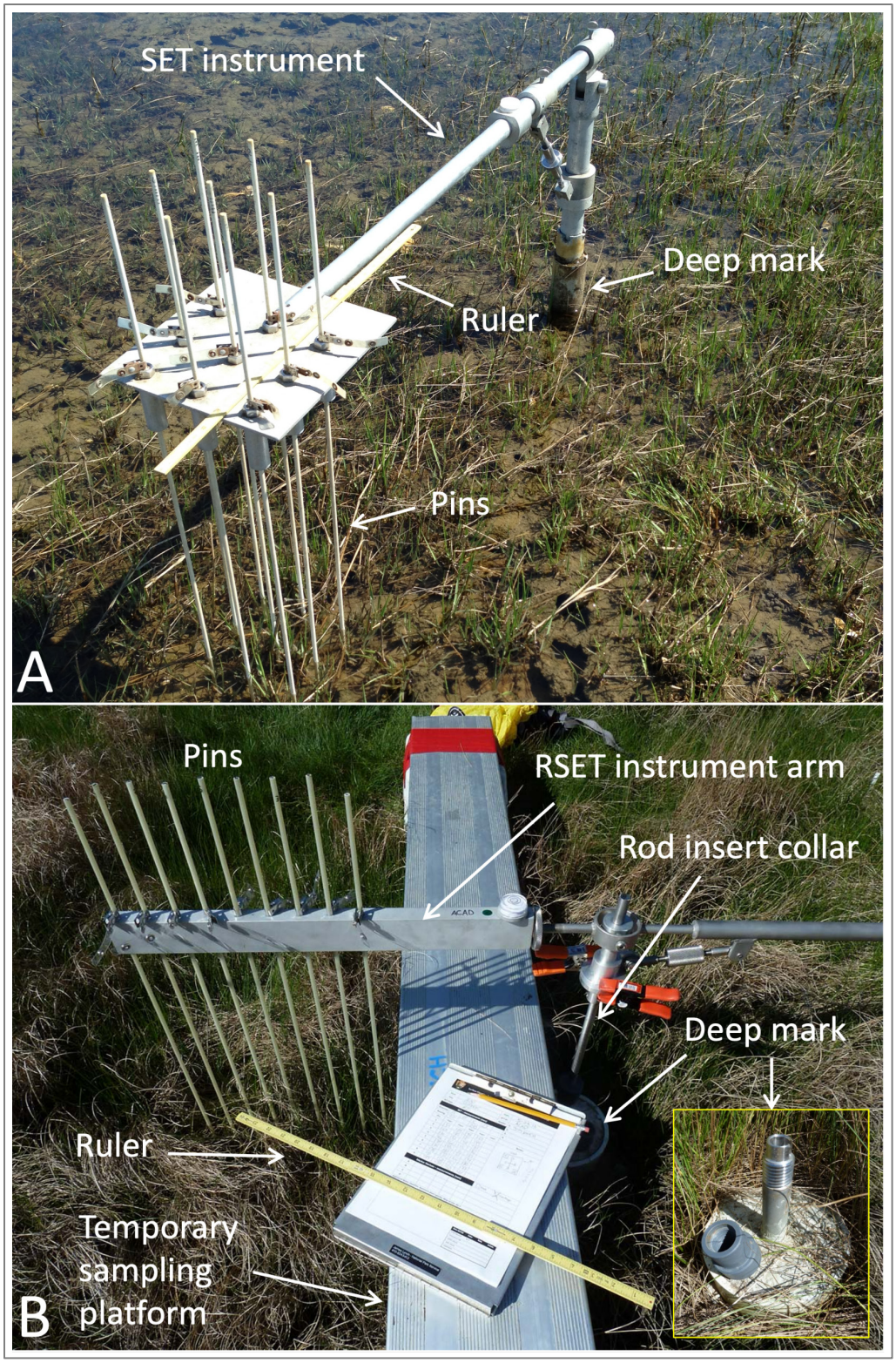


Figure 4. Photo showing the original SET and newer RSET in the field. A: Original SET instrument deployed in a tidal salt marsh (Cape Cod National Seashore, Massachusetts, USA). B: RSET instrument deployed in a tidal salt marsh (Acadia National Park, Maine, USA).

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There are two basic types of SET marks:

1. Deep Marks: The deep mark was designed to measure both surface and subsurface processes (Figure 5) in wetland sediments. It consists of an aluminum pipe for the original SET and a series of connected stainless steel rods for the RSET, both of which are driven deep into the ground to significant resistance or refusal and are therefore considered vertically stable within the soil matrix (Figures 3, 4, 6).
2. Shallow Marks (RSET only): The Shallow RSET mark was designed to measure surface and subsurface processes primarily in the live root zone (Cahoon et al. 2002b) and is typically driven less than a meter into the ground (Figures 3, 7).

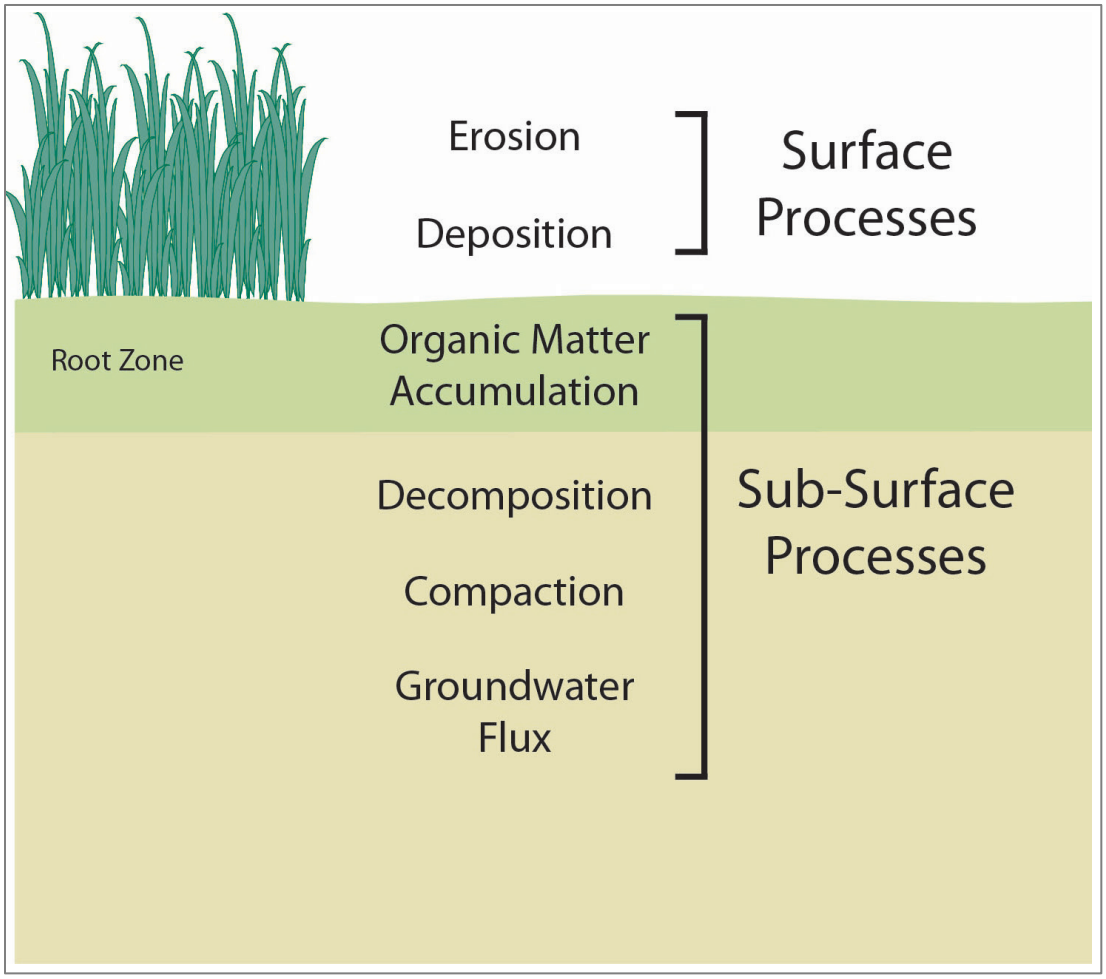


Figure 5. Elevation measures from a deep RSET mark incorporate both surface and subsurface processes influencing elevation change in a wetland. Measures from a shallow RSET mark incorporate surface and subsurface processes (primarily in the live root zone) influencing elevation change.
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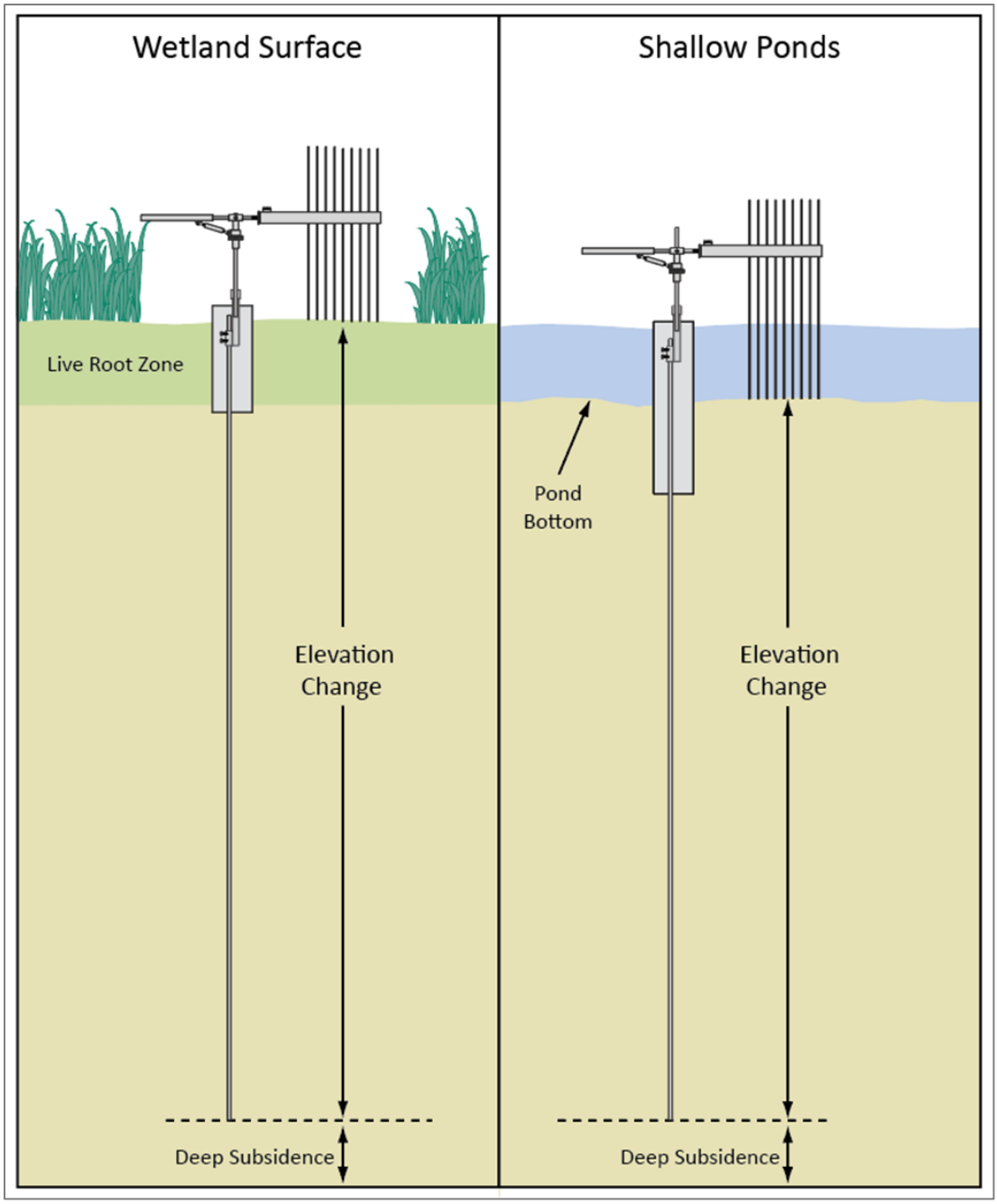


Figure 6. Conceptual diagram showing how RSETs can be used on vegetated wetlands (left panel), mud flats, and shallow ponds (right panel). In both cases, a deep RSET mark is established in the soil, and the pins are placed on the sediment surface. The RSET measures relative elevation change occurring from the base of the RSET mark up to the sediment surface.

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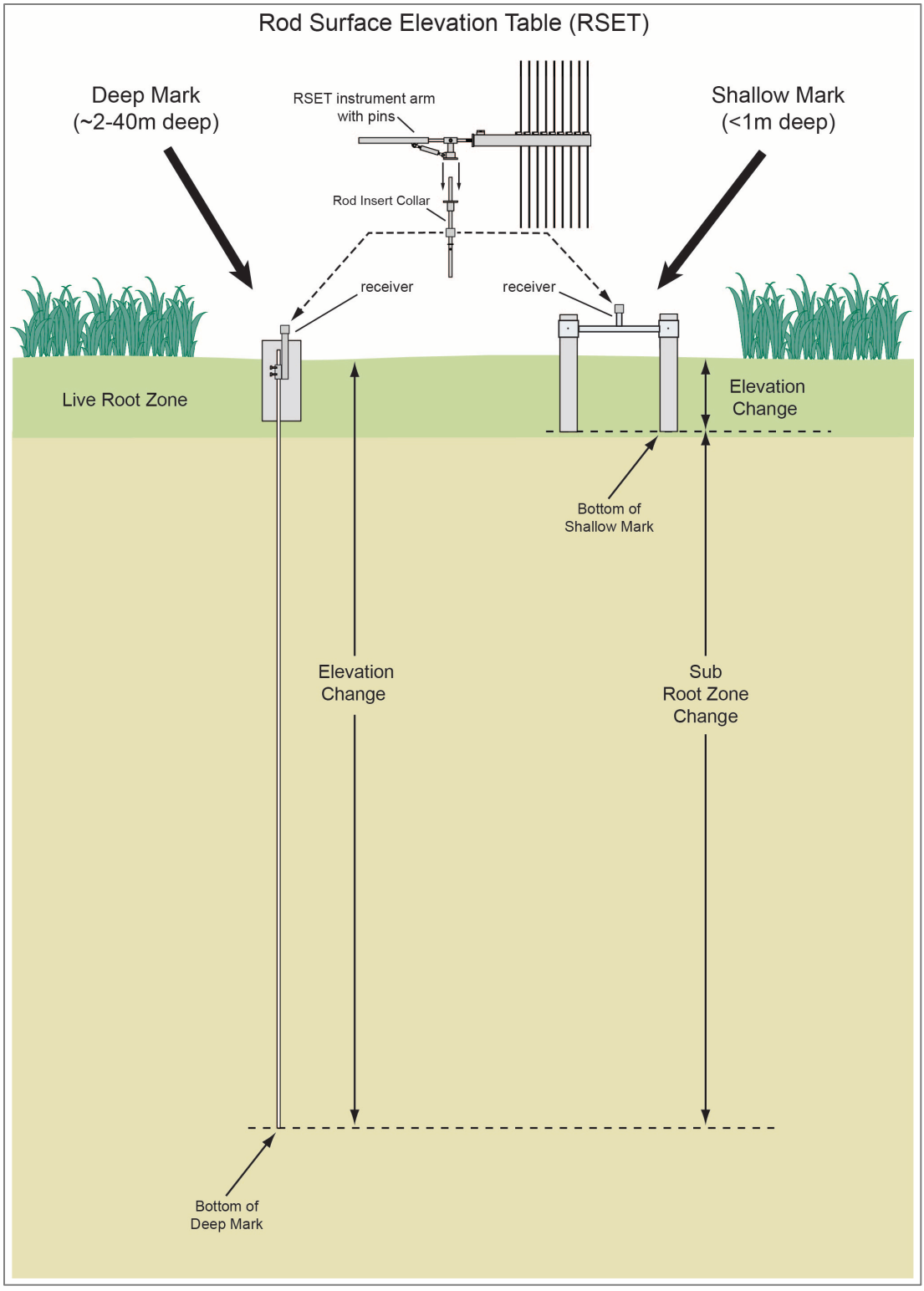


Figure 7. Conceptual diagram showing how the two RSET marks can be used together to partition vertical processes influencing wetland elevation between the live root zone and that portion of the substrate below the shallow RSET mark but above the base of the deep RSET mark (e.g., sub-root zone).

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The SET instrument is transported to the field, attached to its mark, and then leveled and positioned at four to eight fixed locations around the mark. At each fixed location, nine fiberglass pins are lowered from the instrument arm onto the marsh surface and the heights of the pins above the instrument arm are measured to the nearest millimeter, allowing for a total of 36 to 72 possible measurements per each repeated sampling event at each sampling station.

The RSET and SET sample an area of approximately 1.5 m^2 and 4.0 m^2, respectively (Cain and Hensel 2018, RSET only). Over time, the change in the height of each pin reflects the changing elevation of the sediment surface with respect to the base of the mark. Changes are typically reported as mm yr^{-1}. It may take up to five or more years of elevation change data to overcome short-term variability and obtain trends that are representative of wetland responses to sea level (Webb et al. 2013). The vertical changes at the soil surface are the net result of surface and subsurface processes occurring down to the bottom of the mark to which it is attached (Figures 5, 6, 7; Cahoon et al. 2002b). Thus, the SET and RSET methods do not measure processes occurring below the bottom of the mark such as deep subsidence (e.g., anything below the installation depth, which could be as much as 40 m deep for the RSET and 10 m deep for the original SET; Cahoon 2024).

The strengths of the SET/RSET method include:

- The ability to detect millimeter scale changes over long time periods (i.e., decadal monitoring) because the instrument and pins occupy the same position in space with respect to the mark, and measure the same point on the wetland surface, at each sampling event.
- The instrument occupies between four to eight fixed positions (36 to 72 observations) around the mark, allowing for flexibility when encountering obstructions that may limit readings in a particular direction (e.g., mangrove prop roots, branches, crab holes, rocks).
- Experimental treatments (e.g., fertilized/unfertilized) can be nested within a single sampling station (Langley et al. 2009; Morris et al. 2002).
- The measurements can be made over long periods of time and are of sufficiently high resolution to compare to long-term sea-level trends measured by tide gauges (Cahoon 2015).

The SET instrument has gone through numerous changes in design over the years and there are several current designs in use today (Cahoon 2024; Cahoon et al. 2002a, 2002b; Callaway et al. 2013). The design of the original SET, developed by Boumans and Day (1993), is derived from the Sedi-Eros Table created by Schoot and de Jong (1982). The original SET was revised several times during the 1990s to improve its precision (Cahoon et al. 2002a). The RSET instrument was developed in 2000 and attaches to marks that can be both deeper and shallower than marks used with the original SET (Cahoon et al. 2002b; Callaway et al. 2013).

The RSET is a commonly used instrument because it is more lightweight and portable than the original design and can attach to both deep and shallow marks (Figure 7). The RSET mark can attain much greater depth than previously possible with the original SET pipe mark (Cahoon et al. 2002b) that could only be anchored from 6 to 10 m in depth. The RSET mark is constructed with 1.2 m (4 foot) long, 14 mm (9/16 inch) diameter, sectional stainless steel rods that are threaded together as

they are driven into the ground to refusal or substantial resistance, often to a depth greater than 20 m. Shallow RSET marks (i.e., shallow four-legged table marks) are typically driven to the depth of the root zone (<1 m) to directly measure root zone influences on wetland elevation change.

Some developments in SET technology were also driven by the requirements of specific research projects. The shallow RSET (Figures 3, 7) was designed to measure elevation change in the live root zone of wetland plants (Cahoon et al. 2002b) or to shallow depths beneath the root zone. Changes in the heights of the pins over time reflect vertical dynamics occurring from the wetland surface down to the bottom of the mark, or about 30–50 cm. By coupling deep and shallow RSET techniques, researchers have been able to better understand where in the soil profile vertical processes that influence elevation are occurring (Figure 7, or Whelan et al. 2005). This information has led to a more complete understanding of the processes controlling coastal wetland elevation and vulnerability to local sea-level rise. Users have also developed SETs with very long arms (Refer to the section on Sampling Design), so one SET mark can support observations both inside and outside enclosures or treatment applications (Langley et al. 2009). Others have developed a "mini" SET to use in greenhouse studies (Cherry et al. 2009). Other modifications have sought to enable better vertical control, higher accuracy, or greater spatial coverage (Kargar et al. 2021; Lynch et al. 2023). A review of the evolution of SET technology can be found in Cahoon (2024) and Cahoon and Guntenspergen (2024). Throughout the remainder of the protocol, the term "SET" is used to reference any instrument used to measure elevation change, though in this document it is primarily referring to the RSET. The "Original SET" is used to reference the Boumans and Day (1993) and Cahoon et al. (2002a) instruments. "RSET" is used to reference the rod SET instrument design and any derivations from it (Cahoon et al. 2002b; Callaway et al. 2013). Refer to Cahoon (2024) for a list of alternative RSET designs.

SET and RSET: Design Features and Capabilities

The Original SET

The Sedimentation-Erosion Table (Boumans and Day 1993), with later modified versions called the Surface-Elevation Table (Cahoon et al. 2002a), is a comparatively heavy, unbalanced device with a >1-m long arm that attaches to a 6–10 m deep pipe mark. Its design, along with a remote-release mechanism for its pins, is advantageous for remotely sampling pond bottom sediments from a pond's edge, the original purpose for which it was designed (Boumans and Day 1993). When the device was used to sample vegetated wetland sediments, the long arm and remote release mechanism were no longer needed (Cahoon et al. 2002a). The heavy unbalanced design would cause a shallow (<1 m deep) pipe mark in a wetland to sink and/or lean over, making it unsuited for measuring root zone elevation dynamics. However, its long arm is an advantage when sampling both experimental treatment and control plots from the same mark in a wetland (e.g., Morris et al. 2002).

The RSET

The rod Surface-Elevation Table (Cahoon et al. 2002b) is a comparatively lightweight, balanced device with a 0.65 m long arm that originally was designed to attach directly to either a deep (10s of meters deep) or shallow (<1 m deep) mark. The collar for the RSET attached to these marks extended about 30–60 cm above the wetland surface (Cahoon et al. 2002b). However, when originally

deployed in 2001, the deep mark design proved to be vulnerable to damage and vandalism. Thus, the deep marks were redesigned in 2002 (Callaway et al. 2013) to make them more secure, and the RSET instrument was modified to consist of two pieces: the measurement arm and a rod insert collar that connects the arm to the mark (Figure 7). This version of the RSET has become the standard device for measuring wetland elevation change (Webb et al. 2013). Given its lightweight and balanced design, the RSET will not cause a shallow RSET mark to sink or lean over and is ideal for measuring wetland root zone dynamics (e.g., Whelan et al. 2005). Also, its design, when coupled to its deep mark, enables sampling a much deeper portion of the wetland substrate (>10 m) than the original SET (6–10 m).

Summary

The SET is a heavier, unbalanced device and the RSET is a lighter, balanced device, each designed with different capabilities for measuring wetland elevation dynamics. Thus, the terms SET and RSET are unique to each device. For example, when attached to a shallow mark, the RSET device is referred to as a shallow RSET, not a shallow SET. When the SET and RSET are used together, including both the shallow and deep marks of the RSET, elevation dynamics are revealed across three different depths of the wetland substrate (e.g., Whelan et al. 2005, refer to Figure 3).

Marker Horizons

Marker horizons (MH) are artificial soil layers established on the surface of the wetland or shallow water bottoms to measure vertical accretion (Baumann et al. 1984; Cahoon and Turner 1989) (Figures 8, 9). Numerous materials such as sand, feldspar, brick dust, and glitter are used as marker horizons (Cahoon 2024). Powdered white feldspar clay is commonly used. Its main advantages are that it is bright white and easily distinguishable from surrounding sediments, has a higher density than water, and forms a colloidal layer when wet so it can be deposited as a contiguous layer even in open water. Cores are taken through this layer, and the thickness of the sediment (both mineral and organic) accumulated above the layer is measured as vertical accretion. Accretion rates are typically expressed as millimeters of accretion per year.

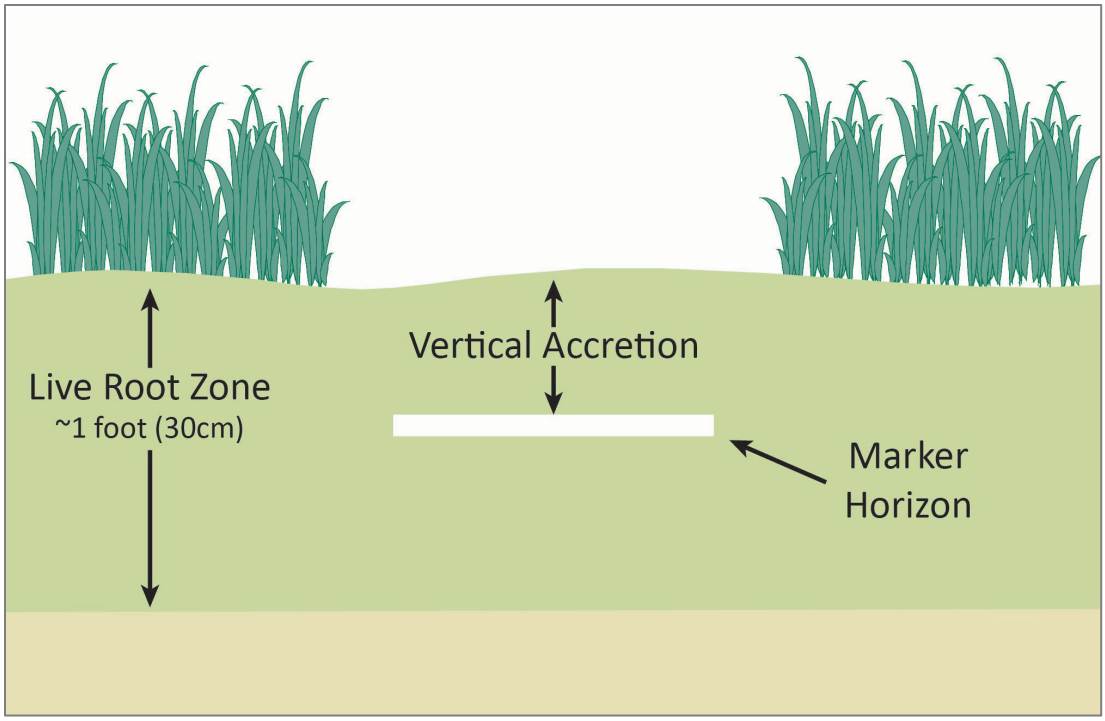


Figure 8. Conceptual diagram showing the marker horizon and the vertical accretion occurring above it.
NPS / JAMES LYNCH



Figure 9. Marker horizon sample core showing that after burial, the marker horizon technique will incorporate both surface and subsurface processes (note root material above marker layer).
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The accumulation of sediment above a marker horizon primarily provides data on surface processes of sediment deposition and erosion (Figure 5). However, it is important to note that marker horizon data are biased towards positive values. If a marker horizon is not found, no data are recorded, even though an erosion event (negative accretion) may have occurred (Cahoon and Lynch 1997). In areas of high biological activity, bioturbation may also lead to extensive losses in the integrity of the marker horizon (Cahoon and Turner 1989). In high energy areas, erosion can lead to the loss of horizons after a short period.

As a result of these issues, marker horizons have a variable and shorter lifetime than the SET. In high energy areas or areas with a lot of bioturbations, they may not persist for more than 1–2 years. Under other conditions, they may last for many years. When a marker horizon is no longer found or usable, new marker horizons can be established on the surface adjacent to the original horizon. As a marker horizon becomes buried over time, it integrates more and more subsurface processes (Figures 5, 9; Cahoon 2024).

SET-MH Technique

When the MH method is used simultaneously with the SET method (either the SET or RSET), hereafter referred to simply as the SET-MH technique, the combined methods provide information on both surface and subsurface processes that influence elevation change (Figures 5, 10; Cahoon et al. 1995). Prior to the development of the SET, most vertical accretion studies assumed the surface deposition of sediments represented an equivalent gain in elevation, followed by slow compaction over time as the accretionary layer became progressively buried. Most published SET-MH studies have shown instead that vertical accretion largely overestimates elevation gain due to subsurface processes occurring between the base of the SET mark and the soil surface (Cahoon et al. 1995). Some SET-MH studies in rapidly subsiding marshes have shown elevation loss despite very high rates of vertical accretion (Saintilan et al. 2022). This reduction in the net gain from vertical accretion, as measured by the SET-MH technique, has been termed “shallow subsidence” (Figure 10; Cahoon et al. 1995). In a few SET-MH studies (Cahoon 2024), the opposite response has been observed. The measured elevation trend is greater than the vertical accretion trend, indicating shallow expansion is occurring in the soil zone between the base of the SET mark and the soil surface. Shallow expansion has been attributed to swelling of soils by water storage (Whelan et al. 2005) and increased root volume (Langley et al. 2009; McKee et al. 2007). Thus, when used together, the SET-MH technique makes it possible to distinguish between the contributions of surface and subsurface processes to elevation change. This information can be very important in evaluating why a wetland may or may not be pacing relative sea-level rise and may therefore suggest compensatory management actions (i.e., steps that can be taken to increase surface sediment deposition to increase plant root growth and wetland elevation). Note that the combined SET-MH technique does not measure processes occurring below the RSET mark (i.e., deep subsidence or uplift, Figure 10). However, there are surveying techniques available to track vertical motion of the RSET mark, which can help estimate deep subsidence and uplift (Hensel et al. 2024).

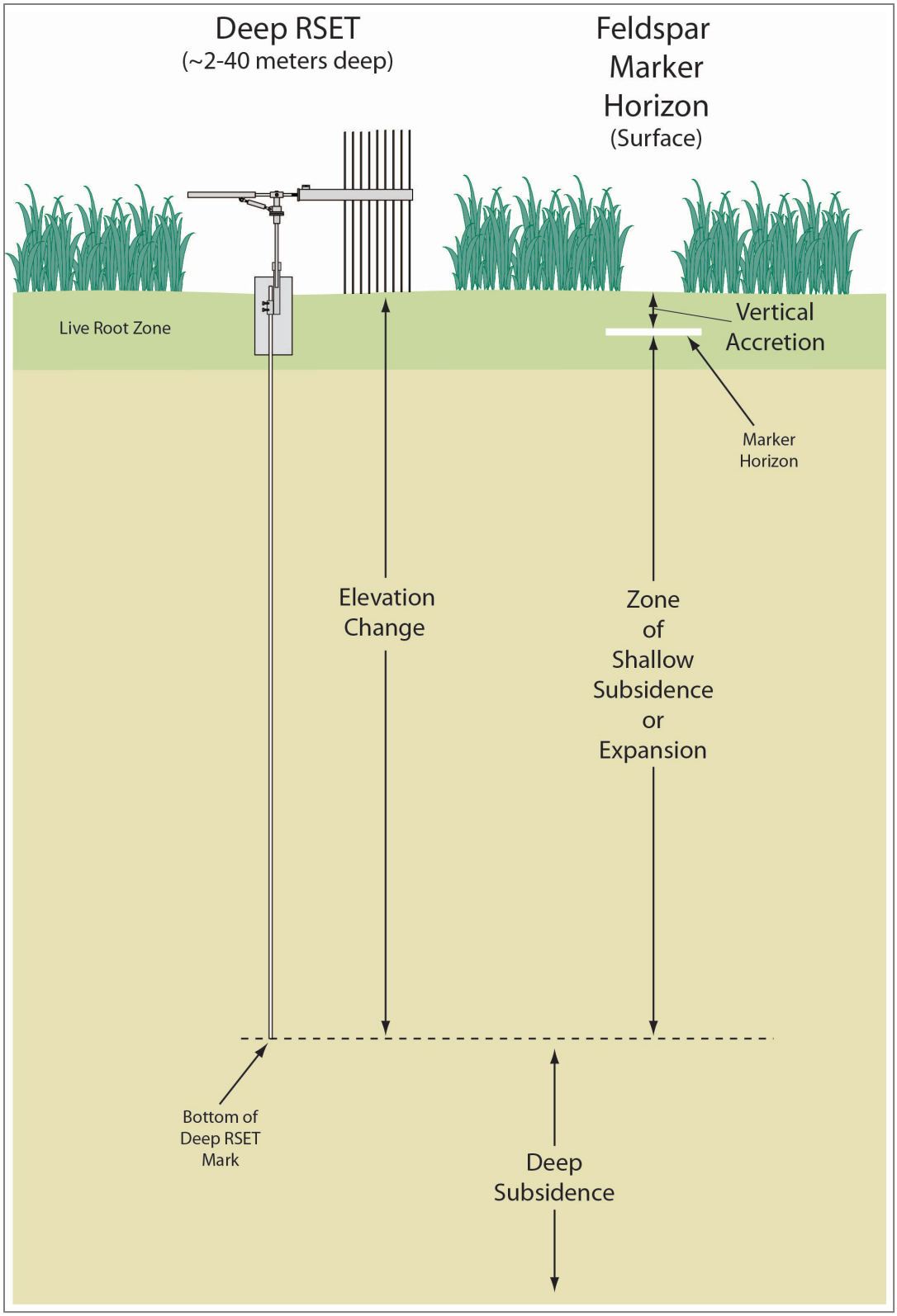


Figure 10. The combined Surface Elevation Table-Marker Horizon technique enables estimates of both surface and subsurface processes that contribute to wetland elevation change.

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Relating Wetland Elevation, Elevation Change, Local Hydrology, and Sea-Level Trends

In addition to quantifying and understanding elevation change in a wetland, the SET-MH method is also important in determining the influence of wetland elevation as well as the hydrologic processes occurring in the adjacent waters on elevation change (Figure 2). The following categories of information are helpful when evaluating the sustainability of wetland environments in the face of sea-level rise.

Wetland Elevation

By knowing the elevation of SET-MH sample stations and local water level (Figure 2A), the wetland surface elevations and elevation changes can be related to tidal datums and associated patterns of inundation. Other vertically sensitive environmental data, such as wetland vegetation plots and groundwater levels and other factors, can also be related to these datums to help understand how processes are related.

Obtaining elevations will require conducting a survey, typically a combination of Global Navigation Satellite System (GNSS) observations and/or optical measurements (leveling or total station) (Hensel et al. 2023). An added benefit of GNSS observations is that when they are repeated over time, they can be used to gauge both the stability of the SET marks, and any other vertical reference marks, such as those associated with water level recorders. GNSS measurements can also offer insights into vertical land motion occurring below the depth of the SET mark.

Local Hydrology

Wetland vegetation communities respond directly to patterns of inundation that are correlated to their height in the tidal frame (Figure 2), with vegetation at lower elevations being flooded more frequently than vegetation at higher elevations. Understanding the relationship between the elevation of the SET sites and the local hydrology is important for assessing wetland resilience (Figure 2C).

NOAA is the common source of long-term sea-level hydrology data in the U.S. Tidal datums, which are the average heights of specific stages of the tide, are collected for NOAA's National Water Level Observation Network (NWLON, https://tidesandcurrents.noaa.gov/water_level_info.html) and are referenced to a local network of tidal benchmarks, which typically include a vertical reference to NAVD 88 (Figure 11). Tidal datums from these permanent tide stations are generally not accurately transferrable to a nearby wetland site without first monitoring local water levels and using simultaneous datum comparison techniques (NOAA 2003).

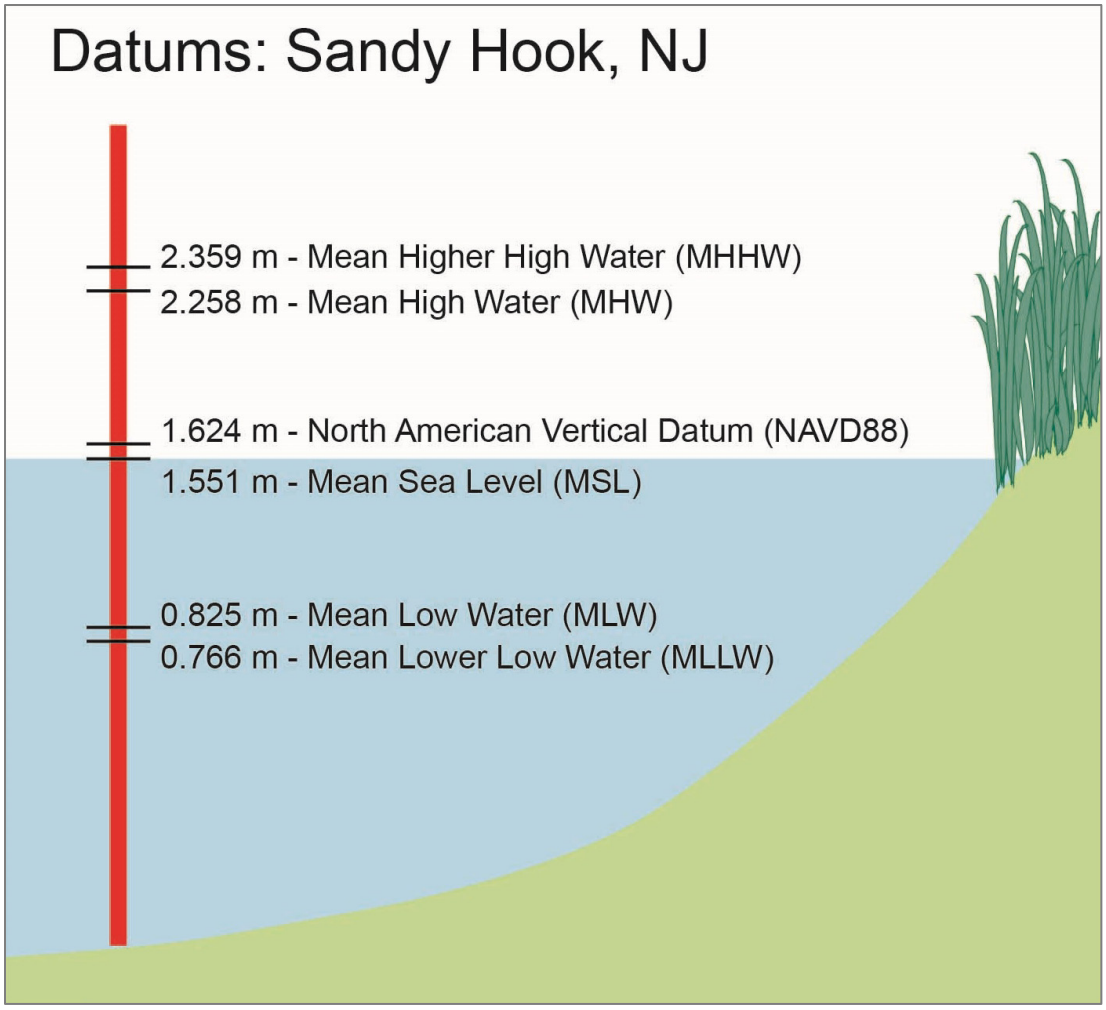


Figure 11. Schematic showing the vertical relationships among tidal datums at a tide station. All values are given with respect to the (arbitrary) local station datum. Note the reference to the orthometric datum, NAVD 88, is also given (source: NOAA Center for Operational Oceanographic Products and Services). *NPS / JAMES LYNCH*

NOAA's permanent tide stations calculate tidal datums over an 18.7-year period called the National Tidal Datum Epoch (NTDE). However, the length of the time interval (currently 1983–2001) means that, in an era of rapid sea-level rise, the tidal datum data from a nearby NOAA gauge may not be a very accurate representation of where true mean sea level, or mean high water, are today. The 2002–2020 NTDE is expected to come out in 2029.

Due to this and the fact that permanent, long-term NOAA tide gauges are not always located near SET sites, installing water-level sensors can aid in determining the short-term datums and hydrologic characteristics at the sites where you are monitoring elevation change. Local hydrologic measurements should be evaluated over a period consistent with the SET and Marker Horizon data. These hydrology data can be processed with customized tools developed for individual projects or using the tools available from NOAA (CO-OPS Datum Calculator (noaa.gov)) and elsewhere. The processing of hydrology data can be used to generate useful metrics such as:

1. Tidal datums: The average heights of specific stages of the tide, such as low and high-water levels. Commonly used tidal datums include mean sea level (MSL), mean low water (MLW) and mean high water (MHW).
2. The hydroperiod: The depth, duration, and frequency of flooding at a given site.

Sea-Level Rise

Sea-level trends (Figure 2D) are generally obtained from published, long-term rates derived from tide gauges, such as those available from the National Ocean Service. A short-term local water-level recorder can be used to transfer tidal datums to a local wetland or coastal infrastructure, however, a long-term tide gauge is needed to obtain site-specific long-term sea level trends (30–70 years; Becker et al. 2012; Church and White 2006) In addition, there are rigorous requirements for collecting long-term sea-level data from water-level records, including sensor accuracy, sensor stability, and calibration verification (Zervas 2009). Although long-term trends are very important to gauge the historical rates of sea-level rise, and provide a measure of near-term prediction, gauges only tell part of the story. With global climate change, water levels are expected to rise much faster as Earth's climate continues to warm and polar ice caps and glaciers worldwide continue to recede (O'Neill et al. 2017). In addition, SET data are typically taken over a short span of time compared to long-term sea-level trends. To compare wetland responses to synchronous changes in water levels, one should limit sea-level trends to the time coincident with SET measurements. Daily or monthly water level data in the U.S. are available from NOAA's NWLON data portal, so tidal datums and sea-level trends can be computed on a user-defined time scale. These data can be used to determine rates of sea-level rise over a similar period as the SET data record.

Sampling Design

Rationale for Selecting a Sampling Design

The sampling design will specify the locations within a wetland where SET, marker horizon, and elevation measurements will be taken, and how measurements will be taken over time. Proper quantity, selection, and distribution of sample stations over space, and sampling events over time, will ensure:

1. Conclusions can be extended over the entire geographic area of interest.
2. There is sufficient statistical power to discern real changes.
3. Temporal patterns are appropriately characterized.

The sample space (Figure 12) refers to the population that is the broad target of interest. In the case of a coastal park, the sample space might be the entire park, all wetlands in the park or a subset of wetland types found within the park. The sample site is a smaller, independent unit within the sample space. This might be an individual marsh within a coastal refuge or park. Finally, the sample station is where SET and MH measurements are made.

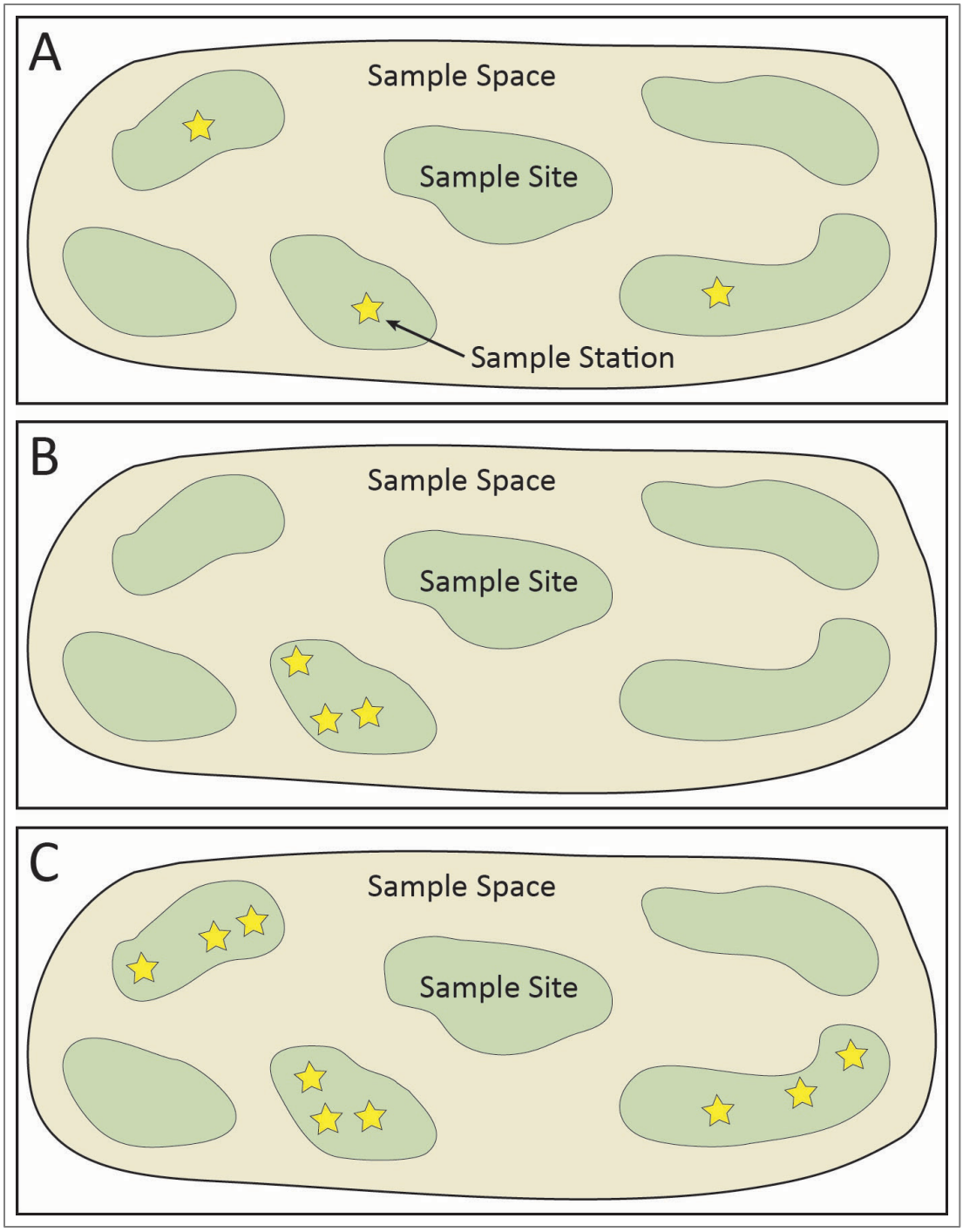


Figure 12. Conceptual diagram showing distinctions among sample space (tan), sample sites (green), and sample stations (yellow stars). In 12A, three sample sites are randomly selected from the population of all possible sites within the sample space, and one sample station is established at random within each chosen sample site. In 12B, one sample site is chosen within the sample space, and three replicate sample stations are randomly assigned within the site. Panel 12C presents a sample design that combines the designs of panels 12A and 12B, thereby providing replication both across and within sample sites.

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For the purposes of sampling design, SET studies can be divided into two types: sampling for monitoring and sampling for hypothesis testing. Sampling for monitoring will generally involve sample stations that are dispersed throughout the sample space, to ensure representation. Sample stations might also be installed in critical areas to provide an early warning of change. Hypothesis testing would involve the investigation of specific factors that affect the elevation change (e.g., restored vs. natural marsh, sediment-amended vs. sediment-restricted marshes, gradients in elevation relative to a tidal datum). Hypothesis testing focuses on specific factors of interest, and may attempt to exclude other, non-targeted factors. This often leads to clustering sample stations within a wetland or within a specific wetland plant community to reduce unwanted variability. Although we make the distinction between sampling designs for monitoring and those for hypothesis testing, it is important to note that these two approaches are never mutually exclusive. A hypothesis testing design can also inform long-term monitoring, even if its design is not ideally suited. Similarly, a long-term monitoring effort can also be used to test certain hypotheses, especially when integrated with a network of sites.

For hypothesis testing, at least three sample stations are required as replicate samples for each fixed factor level (sample size = 3). For example, if there are two treatment factors or levels (e.g., fertilized vs. unfertilized), a minimum of six sample stations would be required (three per treatment). A second factor with two levels (e.g., salinity: high and low) would double the sample size requirement. This is an absolute minimum that would provide 2 degrees of freedom per factor required for statistical analyses. Larger sample sizes would greatly increase the power of analysis, meaning that the ability to discern real differences among the experimental factors and treatments generally increases rapidly over a minimum sample size of n = 3. Researchers testing hypotheses should run power analyses to determine sample size, keeping in mind that the experimental unit is the sample station, and that the measurement precision (resolution) is at the millimeter scale.

Most SET-MH studies will have small sample sizes due to the following constraints:

- Installation: the high cost of labor and materials in establishing SET-MH sample stations.
- Sampling: recurring logistic and financial constraints involved with getting to each SET-MH station and performing all the necessary measurements on a recurring basis.

A small sample size means that the spatial distribution of sample stations is critical.

Spatial Distribution

Spatial distribution of sample stations can theoretically take several main strategies:

1. Replication across the larger sample space (e.g., multiple wetlands; Figure 12A), but no within-wetland replication.
2. Geographic restriction, with replication within a wetland plant community (Figure 12B).
3. A combination of 1 and 2, replication across and within wetland sites (Figure 12C).

The choice among these strategies may depend on the specific purpose of the study. For monitoring, the interest may be in distributing sample stations across a large extent of the coastal ecosystem. Replication here might be on the level of discrete wetlands (e.g., one sample station per wetland, Figure 12B). Hypothesis testing is typically more specific in addressing a particular question of interest—e.g., is wetland A different from wetland B; does fertilization or burning of the surface significantly alter elevation trajectories? To address these questions, one may want to replicate sample stations within a given wetland to reduce the confounding effects associated with non-target variables (e.g., different species, different locations upstream/downstream, different sediment source; Figure 12C).

Table 1 presents three sample design scenarios, including the nature of constraints involved, the requirement of prior wetland ecological knowledge, the spatial coverage, and the kinds of data and analyses supported.

Table 1. Three general scenarios for distributing sample stations within a sample space.

Sample Design	Use	Financial Constraints	Logistic Constraints	Spatial Coverage	Spatial Inference	Outcome	Data
A) Multiple sample stations randomly distributed throughout sample space	Monitoring (Sample size ≥3)	High	High	High	Moderate	Spatial monitoring & trends	• High spatial coverage. • Low site-specific knowledge. • Best variance estimate for the sample space. • No site variance.
B) One sample site chosen in sample space; multiple sample stations distributed within the site	Hypothesis testing (Sample size ≥3 per site)	High	Moderate	Moderate	Moderate	Hypothesis testing	• Moderate spatial coverage. • High site-specific knowledge. • Some variance estimate for the sample space. • Best estimate of variance for one site.
C) Multiple sample stations randomly distributed within multiple sample sites	Hypothesis testing and monitoring (Sample size ≥3 per site)	High	High	High	High	Spatial monitoring, trends & hypothesis testing	• High spatial coverage. • High site-specific knowledge. • Best variance estimate for the sample space. • Best estimate of variance for sites.

Spatial Distribution for Monitoring

The precise objectives of a monitoring program need to be made very clear, as they will influence both the number of replicate sample stations and their location. If the goal is to monitor a large coastal wetland area, sample stations will be distributed throughout the environment so that the data are representative of the larger area of interest. Note that the SET sample station covers a very small area, and the inferences from a station are limited to the vicinity of that station. This raises two sampling design considerations:

1. **To clump or not to clump?** By grouping sample stations, within-wetland variability can be modeled and tested, at the cost of spatial extent and distribution. Spatial distribution needs to balance the need for spatial extent/representation versus statistical comparisons.
2. **Transects** - Sample stations are often established using the concept of random transects, with random locations along each transect. Although this technique incorporates some elements of random sampling, it does not necessarily ensure equal probability of station selection as would occur with gridding (a requirement of pure random sampling).

Sample stations need to be representative of the target ecosystem and random sampling is a traditional approach to ensure unbiased representation. There are many ways of generating a random sample, from low-tech gridding on a map to more sophisticated techniques in geographic information system (GIS) software using specialized sampling tools. At the heart of most random sampling techniques is the concept of parcel or grid size (e.g., 100 m^2). With random sampling, all parcels or grids will have the same likelihood of being included in the sample. This also means that the sample will theoretically reflect the different proportions of plant communities in the sample space. However, this is not guaranteed, especially with very small sample sizes. As shown in Figure 13A, random sampling can easily lead to plots representing different communities or wetland zones. If the sample space is a specific type of habitat (e.g., low marsh), then all random samples chosen will need to be from that space. This is, in essence, representative sampling (Underwood 1997). Random points representing potential sample stations can be generated in the office and then visited in the field to assess how well they represent the larger area (Figure 13B). If the sample space of interest is low marsh, then a site visit of the randomly selected points can exclude all selections that fall outside the low marsh area.



Figure 13. Example of two methods for randomly selecting sample stations. In 13A, the marsh area was gridded and numbered and then three sample station locations were selected with a random number generator. In 13B, potential sample station locations were randomly generated and then visited in the field to assess how well each location represents the larger area (imagery: Esri et al. 2025).

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Another consideration is dispersion: if the goal is monitoring a broad area with a small sample size, it may be ideal to have the sample stations distributed widely. A purely random sample can, by chance, lead to stations being selected adjacent to each other. Stratified random sampling is a way to ensure broad dispersion, where a sample site is divided into sub-areas within which one or more sample stations will be located. Random or representative sampling can then be applied within each sub-area, ensuring broad dispersion throughout the target area.

Note that station three in Figure 13A may have logistical problems, given how far it is from the access point along the stream. Logistic constraints may also be considered to limit the population of potential stations prior to applying a randomization scheme. Potential sample stations might also be restricted to ensure they are out of public view and/or less likely to be vandalized. However, restrictions need to be used with care to avoid introducing biases in the study.

Monitoring Example: NPS, Assateague Island National Seashore, Maryland, USA
Problem: NPS managers at Assateague Island National Seashore need information on elevation change in the salt marsh ecosystems within the park boundaries.

Solution/Design: It was decided to install 16 SET sample stations at four marsh sites along the bay side of Assateague Island to provide long-term records of wetland elevation change. This is a monitoring design like Figure 12C with multiple sample sites and replicate sample stations within each site. Four wetland sites were randomly selected from nine marshes already being sampled for vegetation change (Figure 14). Within each site, four SET sample stations were randomly located within the dominant plant community (*Spartina alterniflora*, *Spartina patens*, *Distichlis spicata*). Each sample station is composed of an SET and three marker horizon plots. Vegetation data are collected in the same site separately from the SET sampling. An example of the resulting accretion and elevation change data from marsh 5 is presented in Figure 15.

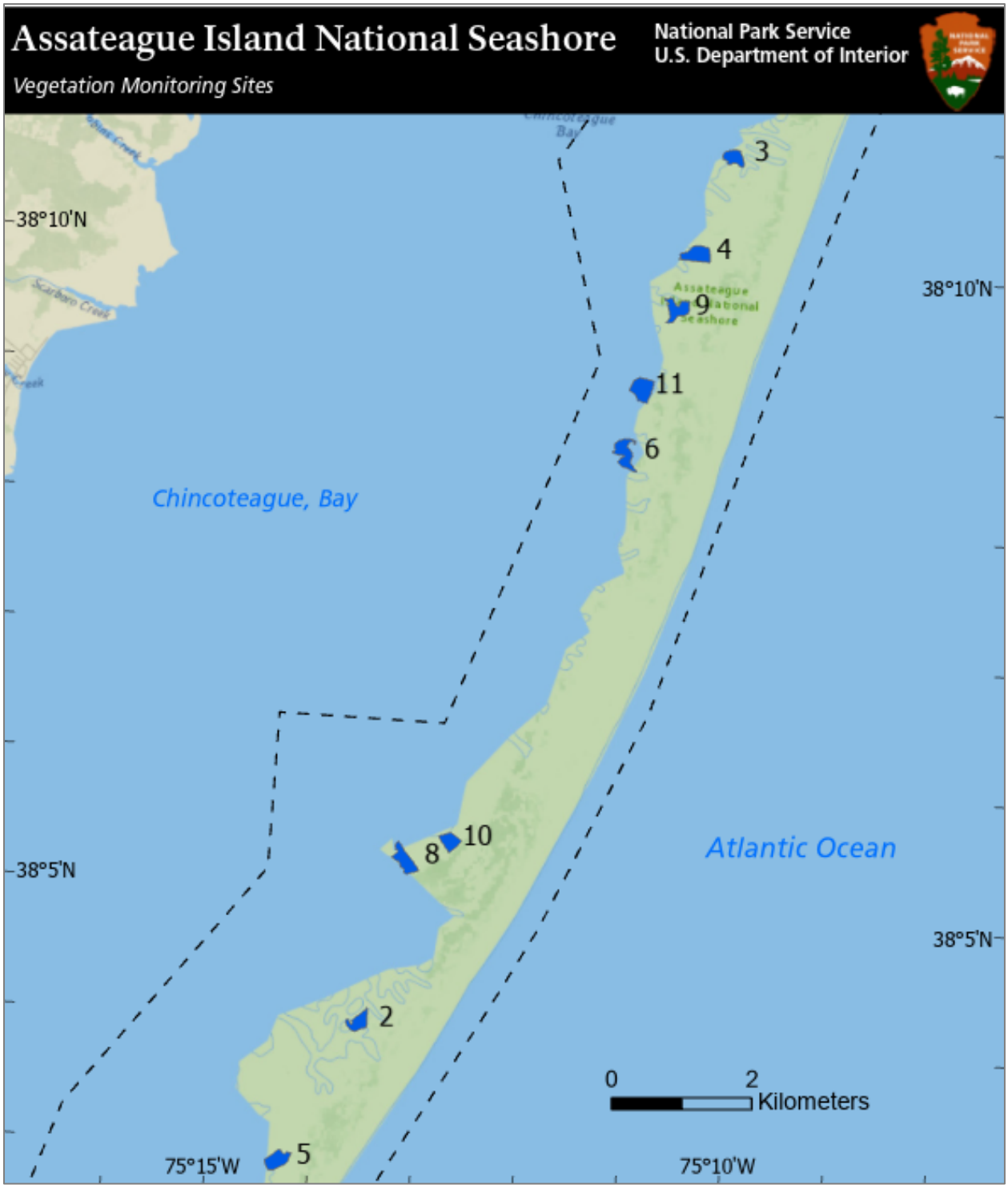


Figure 14. Map showing locations of nine randomly selected wetland sites (blue) used for long-term vegetation monitoring at Assateague Island National Seashore (Maryland, USA). Four of these sites were randomly selected for the installation of SET sampling stations (5, 6, 8, 11). Base map: Esri et al. 2025. *NPS / JAMES LYNCH*

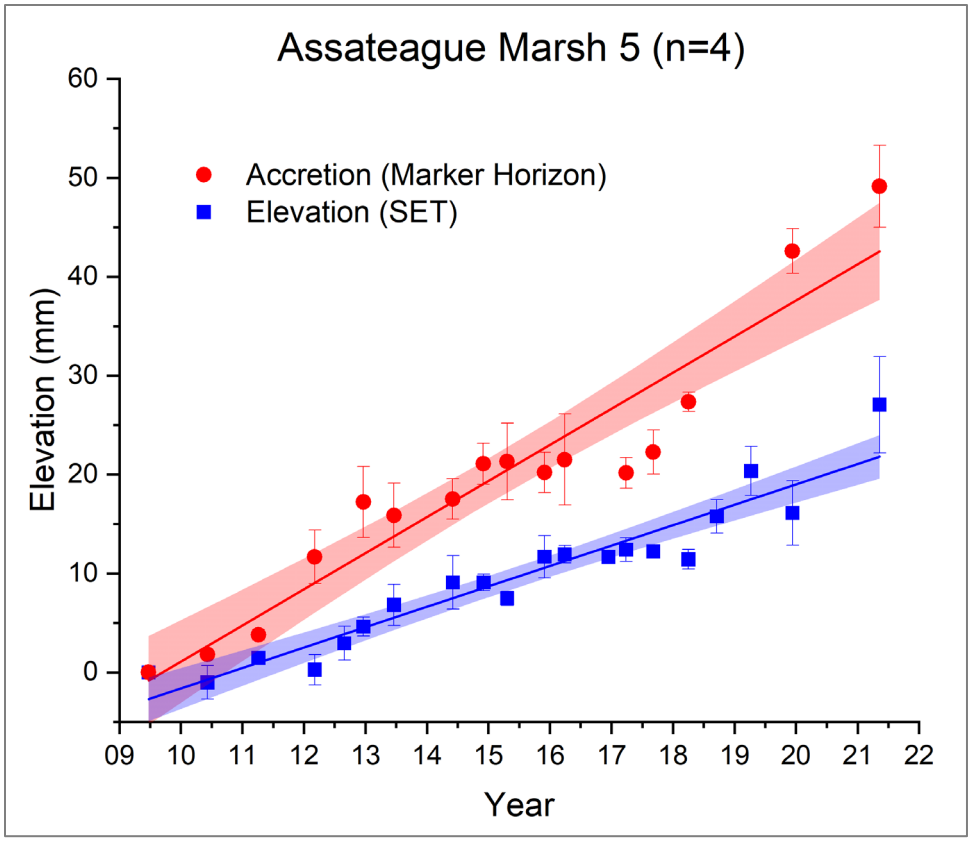


Figure 15. Example showing vertical accretion and elevation trends from one wetland site (four SETs) at Assateague Island National Seashore (Maryland, USA). Linear trend with 95% confidence bands (data source: https://irma.nps.gov/DataStore/Reference/Profile/2309427).

NPS / JAMES LYNCH

Spatial Distribution for Hypothesis Testing / Impact Analysis

The basic experimental unit is the SET-MH sample station, as this is what was randomly placed within the site or sample space. The positions and pins as defined by the placement of the SET instrument are not independent of each other and are all highly spatially correlated. Therefore, if there are three sample stations in a wetland of interest, there are three replicates, and the sample size is three, regardless of how many individual pin measurements are made around each SET mark (e.g., usually 36). The pins would be considered pseudo-replicates (Hurlbert 1984).

The selection of sample station locations for a hypothesis-driven experimental design is complicated by the typically very small sample sizes involved with SET studies (refer to the section on Rationale for Selecting a Sampling Design). Small sample sizes chosen purely at random can do a poor job of characterizing the targeted ecosystem. In addition, non-target factors (e.g., vegetation type, wetland elevation, distance from tidal channel) are more likely to influence data collected from a small sample size than from a large sample size, where the effect of multiple levels of these factors would be averaged over all the samples. Additionally, variables can be more easily confounded when there is little replication. For example:

Confounding Variables: A hypothesis compares the elevation response of two wetland vegetation communities to a storm event (vegetation community "A" vs. vegetation community "B"). The two communities chosen in the sample are situated in two different marshes: one is in an impoundment, the other has unrestricted hydrology. The SET data will therefore be reflective not only of the different vegetation communities, but also—and likely to a greater extent—of the different hydrologic regimes between the two wetlands. In other words, the vegetation community and hydrology will be confounded, and the statistical analysis will not be able to separate these two effects. If there is a statistically significant difference between the elevation responses of A compared to B, you will not know if this is due to the hydrologic effect or the vegetation community effect, or both.

Solution: Select samples such that both vegetation communities (A and B) are sampled within the same marsh. If only one marsh has both vegetation communities, then replicate sample stations will be chosen within both vegetation communities within that one marsh. However, this will limit inferences to this marsh. A better scenario would be to sample several marshes; there would be no requirement to have replicate sample stations within each marsh, if the marshes themselves are replicated in the environment. This would be a "blocked" design, with the block being the marsh.

Restricted randomized and representative sampling may help exclude some of the confounding environmental factors during analysis, reducing the underlying variability among sample stations.

Small sample sizes often suffer from low power (the ability to distinguish real differences) due to the influence of these unexplained, underlying variables. Below are some tips for maximizing analytical power.

- Replicate as much as possible within plant communities or treatments, each with $n \geq 3$ sample stations, to create as large a sample size as possible.
- Restrict sample space to a specific plant community.
- Ensure all experimental factors and levels (i.e., "treatments") are sampled at least once within the same wetland.
- Ensure that a wide range of responses can be sampled.
- Measure important covariates.

Restricted randomization helps increase power by removing confounding environmental factors from the equation. However, too much restriction can severely reduce the scope of the research questions being addressed. Another approach to dealing with the influence of non-target factors or variables is to measure them, instead of excluding them. In this way, the variables can be included in the statistical analysis and explained by the data. This is the role of covariates.

Statistical analyses typically require independent samples to guard against correlation. If there is correlation among the observations, the variance estimate will be artificially low, and the degrees of freedom used in the statistical analysis will be larger than warranted. The result may be a Type I

error, leading to claims of significant differences where they do not exist. Although unlikely, purely random sampling can result in correlation if two sample stations happen to be chosen close together. Ideally, the chosen grid size within the randomization scheme is large enough such that adjacent grid centers are far enough apart to limit correlation.

The SET mark as the experimental unit does not mean that a SET instrument samples a uniform area. Indeed, the length of the horizontal instrument arm (about 65 cm for the traditional RSET) can result in different plant communities being included within a station. For example, one side of the station may be in a mudflat, whereas the other side is vegetated. Even within a SET instrument arm position, some of the nine pins may land on vegetated hummocks (clumps), whereas other pins may land in the sediment between clumps. These different conditions may result in very different elevation change trajectories occurring within a given sample station (Osland et al. 2020). If this variability is not explained, it may reduce the power of the analysis. A corrective strategy could be to include covariates within the pin observations (e.g., is the pin on vegetation or not), or consider the station as a blocking effect (mudflat vs. marsh).

Some researchers have developed customized SET instruments that are much longer than normal: this enhances the ability of the SET instrument to encompass and measure different treatment effects (Figure 16; Langley et al. 2009). Note these adaptations result in more complex sampling designs, such as split-plot designs.



Figure 16. A Smithsonian Institution biologist reads the "Monster SET." The RSET instrument, with a 4-meter-long arm incorporating 100 pins, crosses both treatment (CO_2 enclosure = PVC structure) and control areas outside the treatment enclosure (Smithsonian Environmental Research Center, Maryland, USA).

USGS / JAMES LYNCH

Hypothesis Testing Example: Gateway National Recreation Area, New York, USA

Problem/Questions: Jamaica Bay is part of the NPS Gateway National Recreation Area in New York and New Jersey (Figure 17). Salt marshes in Jamaica Bay have been decreasing in area and many are in poor condition. Big Egg Marsh is one such area. Big Egg Marsh appears to be very low in elevation and stressed due to frequent inundation and erosion.

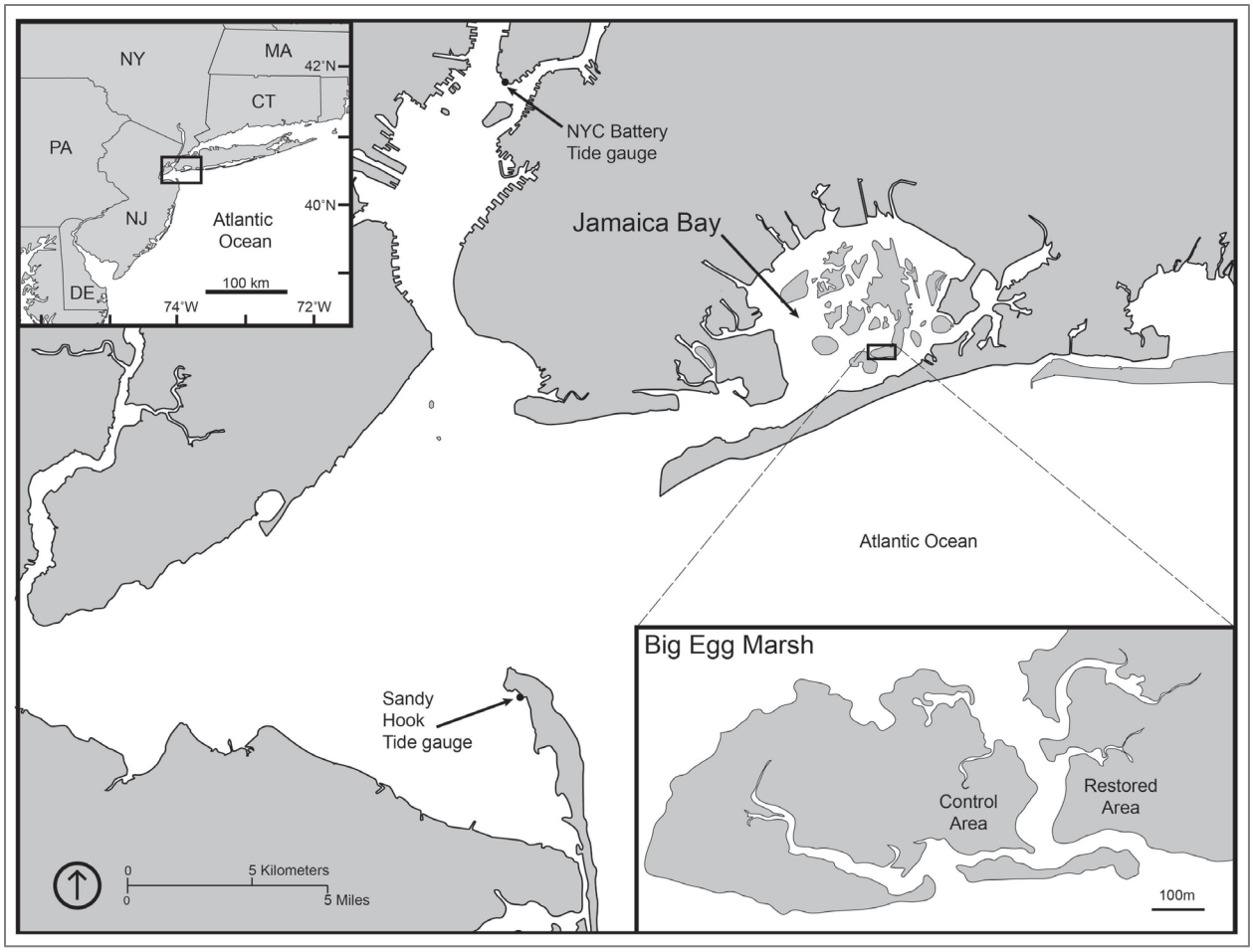


Figure 17. Map showing Big Egg Marsh, Gateway National Recreation Area, New York, USA. Base map: Esri et al. (2025).

NPS / JAMES LYNCH

Solution: It is hypothesized that increasing the elevation of the marsh surface would benefit the marsh. A pilot study was conducted at Big Egg Marsh to add sediment dredged from an adjacent channel to the marsh surface. The goal was to add approximately 45 cm of material to the treatment marsh area.

Design: Prior to dredging, six SET-MH sample stations were established in Big Egg Marsh (Figures 17, 18). Three were installed in the area that will have sediment deposited on the marsh and three in a control area across the channel. All six sample stations were restricted to areas dominated by *Spartina alterniflora*, the dominant vegetation in these marshes. The sample stations were also restricted to the interiors of the marshes, excluding both the marsh edge and the upland transition zone. The SETs were installed in the summer of 2002 and read over the following year. Dredging and sediment deposition on the marsh occurred in the fall of 2003. Sites were sampled multiple times per year (3 to 4) after restoration and are currently sampled twice per year (Figure 19; Cahoon et al. 2019).

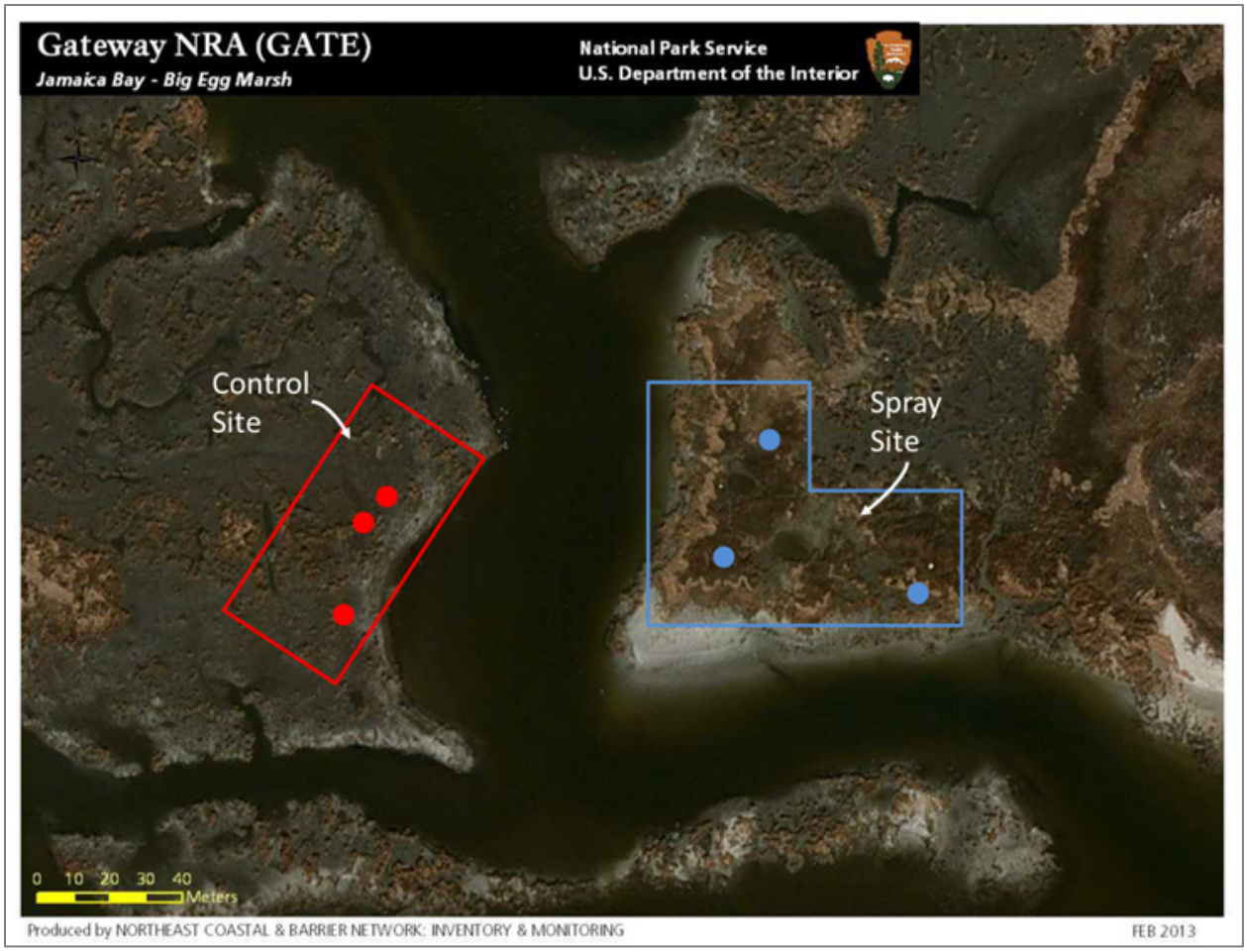


Figure 18. An aerial image showing Big Egg Marsh (sample space) with sample sites (red and blue rectangles) and sample station locations (solid circles), Gateway National Recreation Area, New York, USA. Imagery: Esri et al. (2025).

NPS / JAMES LYNCH

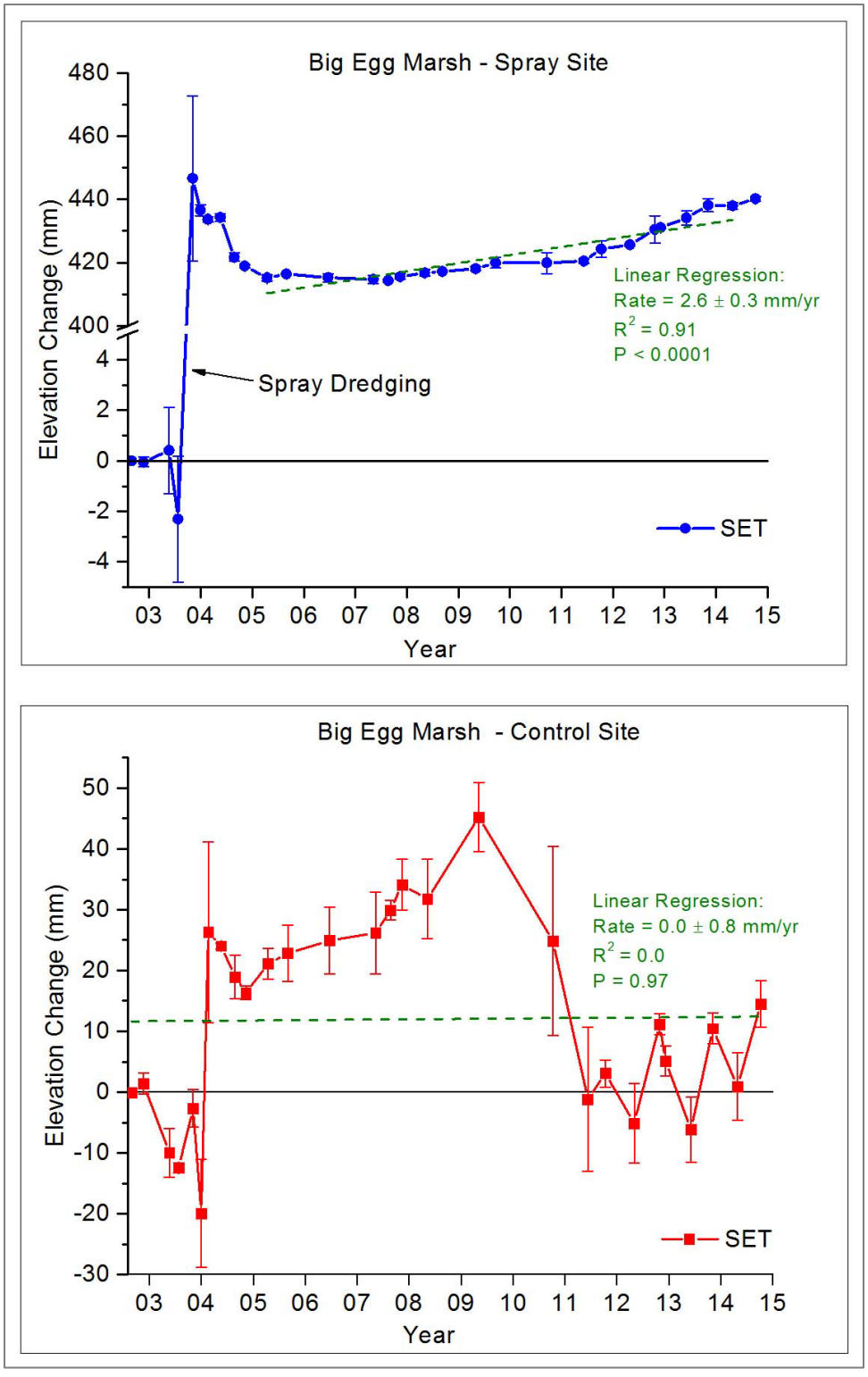


Figure 19. Elevation trends as measured by the SET method at Big Egg Marsh. Source: Cahoon et al. (2019). Linear trends for the restored site cover a subset of the record (2005–2015) whereas trends for the control site cover the entire record (2002–2015). Note the different y-axis scales.

NPS / JAMES LYNCH

Sampling over Time

One strength of the SET technique is that the same area of wetland surface is re-measured over time. This means that SET data are always a time series. A typical use of SET data is to estimate a linear trend over the entire data series, answering the question: what is the rate of wetland surface elevation change? This is a typical monitoring objective (Oakley et al. 2003). However, one may also be interested in comparing change during different periods of time (Feher et al. 2020; Moon et al. 2022, Osland et al. 2020; Whelan et al. 2009). This is especially the case in locations with pronounced seasonality, or where there has been a "before impact" period followed by an "after impact" period. The decision of whether to analyze overall cumulative trends or separate (or recurring) time periods will affect the degree to which the sampling needs to follow a rigorous schedule. One may consider a flexible, adaptive approach to sampling over time to help understand key processes.

Cumulative Trends (All Data)

When SETs are used for monitoring, it is most common to compute an overall linear trend through the entire data record or sections of it (Figures 15, 20). Hypothesis testing can also rely on long-term cumulative data. The ideal situation for cumulative data analysis is to have numerous observations distributed across the entire time series. The user should also consider spacing observations consistently through time (at least on a yearly basis). When there is a comparatively long gap between the start and end of a time series dataset, a Type I error may occur because the ends of the observation period will be overly influential in determining the slope of the linear regression, which will have an inflated R^2 and smaller than expected P-value. Continuing to collect data even after passage of substantial amounts of time can provide new insights into elevation dynamics even several years after the initial study was completed.

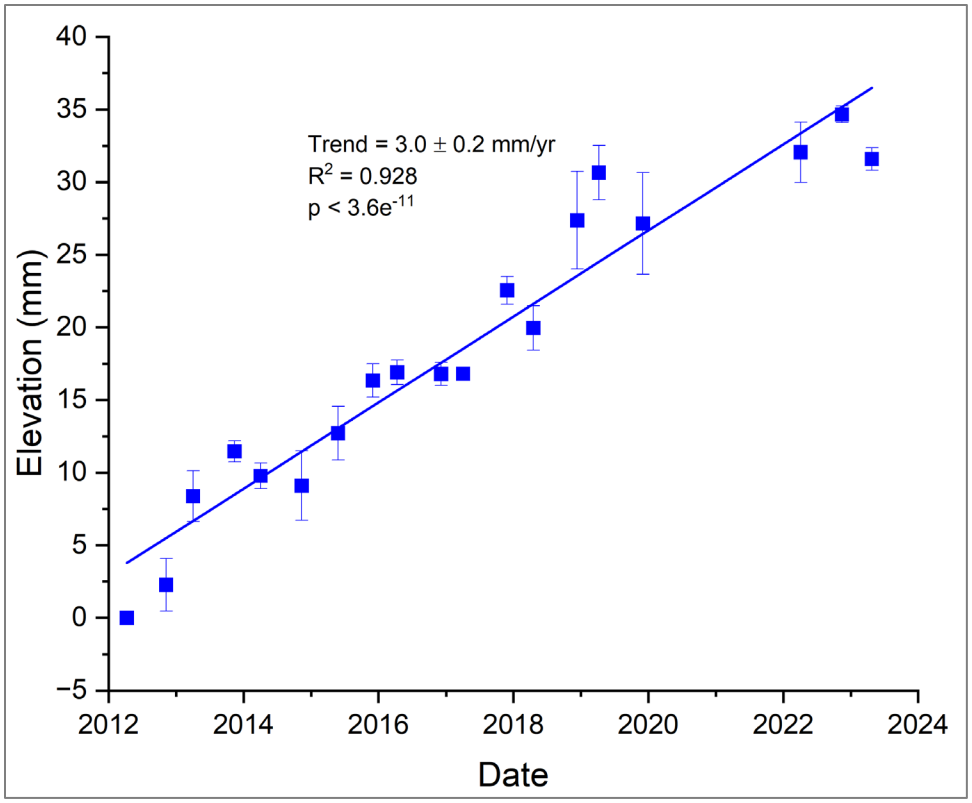


Figure 20. Example of a 13-year time series of SET data from Marsh 5 at Colonial National Historical Park (Virginia, USA) showing the average change in elevation (and standard error) from three SETs at each sampling event. A simple linear regression is used to determine the slope (linear change in elevation rate over time with standard error). Data source: https://irma.nps.gov/DataStore/Reference/Profile/2309427.
NPS / JAMES LYNCH

Cumulative Trends (Seasonal Signals)

If there are strong seasonal signals (e.g., weather, riverine discharge), one can reduce variability in the data by sampling consistently within the same season each year.

Time Period Comparisons (Splitting Data Per Period)

An analysis of incremental change data is typically used when testing for seasonal or other time-dependent effects. The temporal spacing of sampling events is very important in such situations (e.g., Whelan et al. 2005). If some intervals are larger than others (e.g., growing season >> dormant season), the longer intervals may record a larger signal than would be expected from shorter intervals. In addition, the results could be biased with the differential effect of time being confounded with the effect of season. For example, this could be the case if only one year of pre-impact change is recorded, but three years of post-impact are monitored. The post-impact interval will have had more time to estimate the elevation trajectory, which might also lead to a difference in variance, causing additional problems for statistical analysis. Therefore, with incremental data, one needs to pay careful attention to the timing of sampling and possibly correcting the data for unequal sampling intervals and variances.

Example of Incremental Data Analysis: Shark River, Florida (Whelan et al. 2005)

In this study, three groups of three sample stations were deployed in a mangrove forest along the Shark River, Florida, USA (Figure 21). Within each group, there were three SET marks: one deep RSET mark, one original pipe SET mark, and one shallow RSET mark (Cahoon et al. 2002a, 2002b). Each SET mark was inserted to a different depth in the soil. The study investigated the relationships between the depth over which vertical change was measured and changes in groundwater level or river stage. The SET data were collected regularly, once a month over the span of one year: daily elevation rates (averaged monthly) were compared to daily groundwater levels or river stage (also averaged monthly; Figure 22). For this analysis, it was critical to express all measured variables at the same frequency.

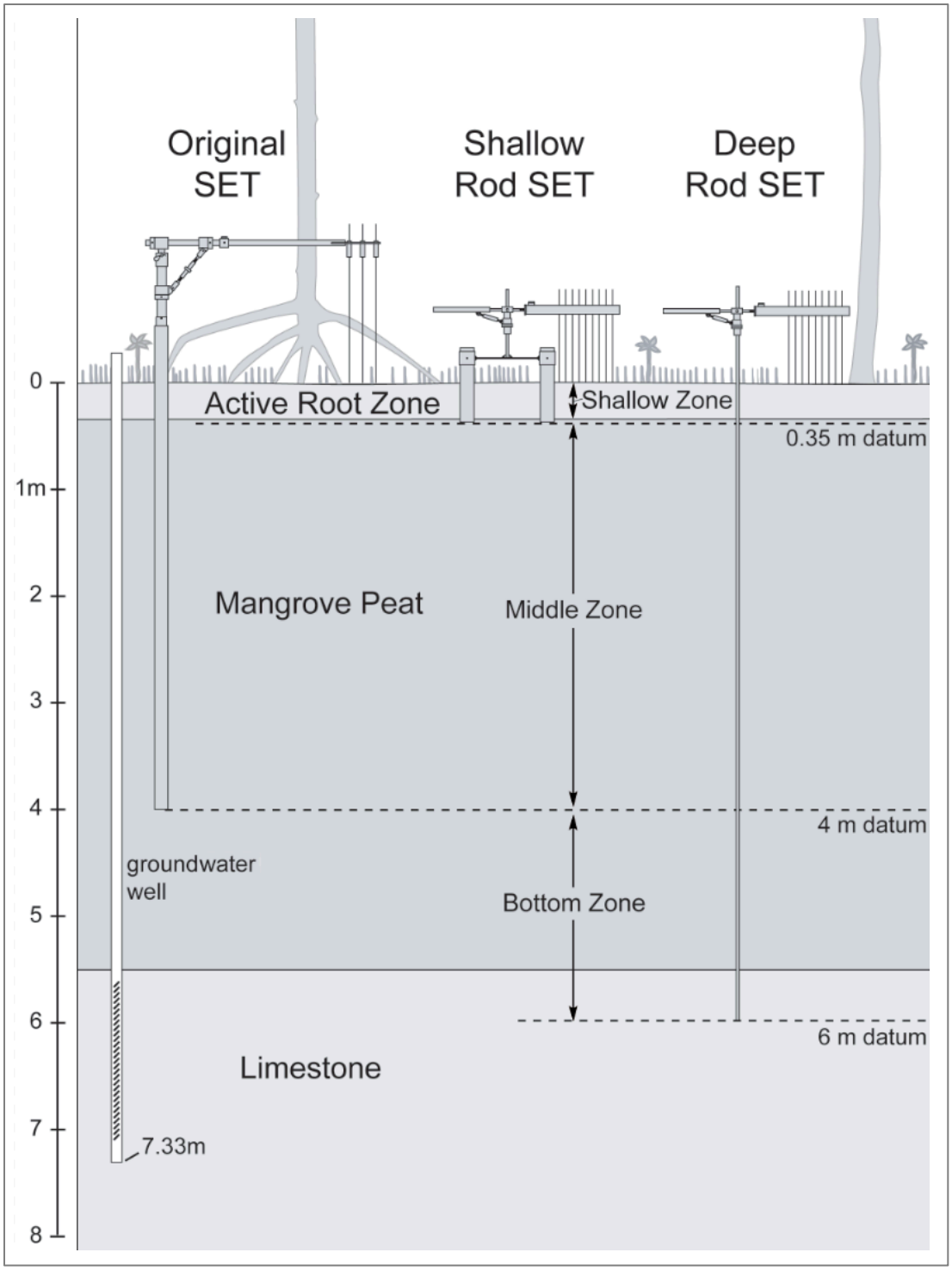


Figure 21. Conceptual diagram showing the three types of SET marks installed to partition vertical soil processes occurring in a mangrove forest. Source: Whelan et al. (2005).

NPS / JAMES LYNCH

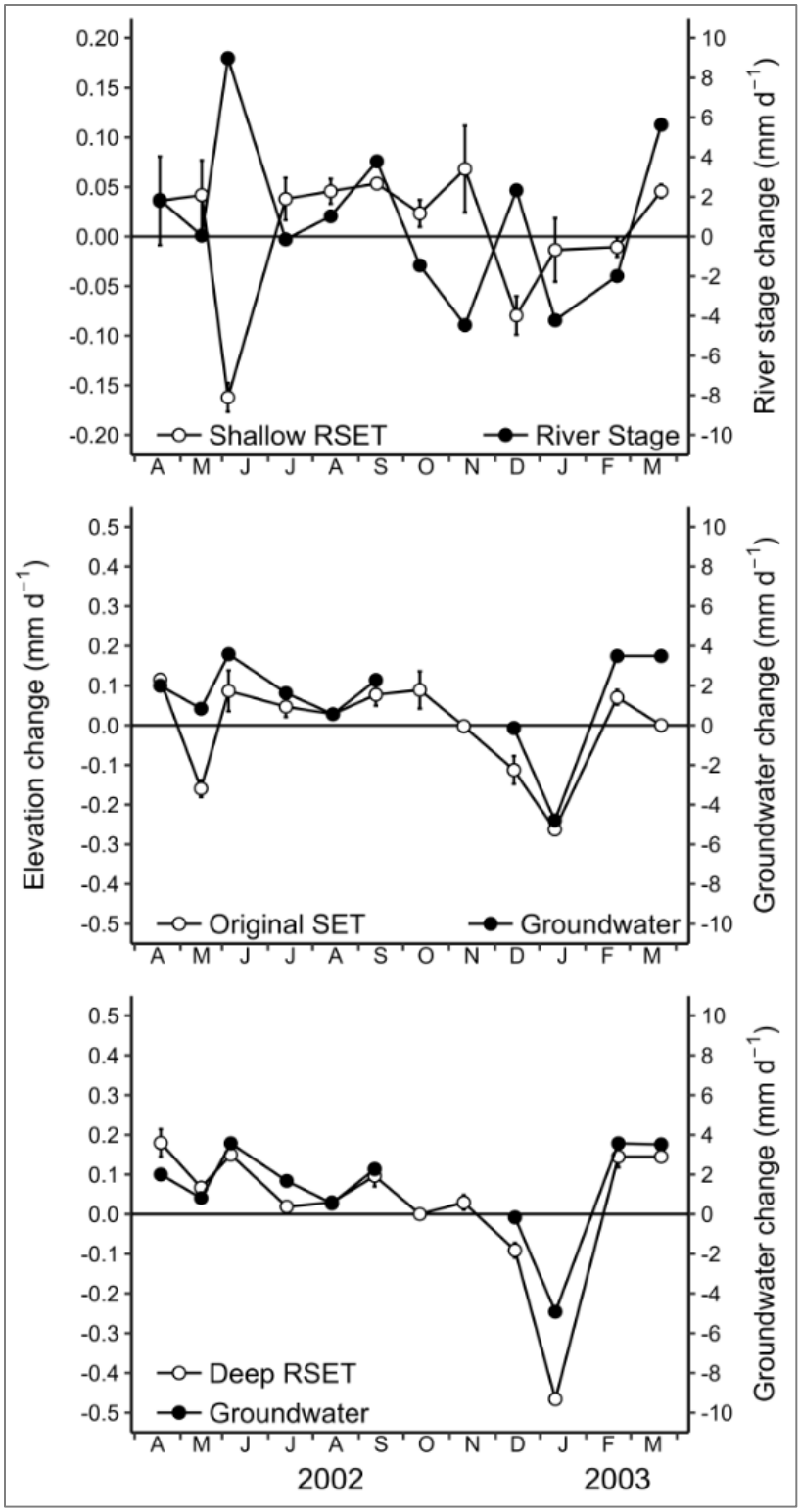


Figure 22. Example of data analysis based on incremental rates of elevation change measured by the SET method. Data expressed as incremental change rates (mm d^{-1}) and compared to groundwater level or river stage (Whelan et al. 2005).

NPS / JAMES LYNCH

Comparing SET Data with Other Datasets

SET data can be combined and compared with other data, such as marker horizon data, or even other SET data, to create new variables. These comparisons should be made at the sample station level whenever possible. For example, comparing the average depth of the feldspar marker horizon to the corresponding cumulative elevation change at the sample station level will provide an estimate of shallow subsidence (Cahoon et al. 1995):

Shallow subsidence (mm yr^{-1}) = Vertical accretion rate (mm yr^{-1}) − elevation change rate (mm yr^{-1})

Vertical accretion rates are obtained from marker horizon data, and elevation change rates from SET data, both averaged to the sample station. Note that rates must be computed over the same time intervals to match.

Similarly, as shown in Figure 21, different SET marks can be used to partition soil processes among the different sediment layers in the soil profile. In that example (Whelan et al. 2005), the following rates can be derived (in mm yr^{-1}):

1. Elevation change rate across the entire mangrove peat layer (6 m); Deep RSET rate
2. Elevation change across the top 4 m of mangrove peat; Original SET rate
3. Elevation change over the root zone depth (0.35 m, shallow zone); Shallow RSET rate
4. Elevation change of mangrove peat below the root zone (0.35 m–4 m, middle zone); Deep RSET rate − Shallow RSET rate
5. Elevation change of deep mangrove peat (4 m–6 m, bottom zone); Original SET rate − Deep RSET rate

Time to Stability

Because SET data can show an initial period of rate variability before stabilizing toward a consistent trend (Figure 23), it is important to consider the record length needed to calculate a representative elevation trend. As of this writing (2026), there are no published reports definitively addressing this point and therefore the requisite record length is likely to be site-, habitat-, or study-specific. However, because it is not possible to definitively determine the required record length *a priori*, it may be helpful to refer to previously published SET studies from similar ecosystems or with similar study designs to provide an estimated time to stability. Due to the short-term variability of SET observations, an SET study should be designed with the expectation that measurements will be taken over at least 5 years or more. Additionally, the occurrence of episodic disturbance events, such as large storm impacts, major flooding events, or other important changes in the environment may necessitate the collection of several years of post-impact data to understand the long-term effects of these events (Feher et al. 2020; Moon et al. 2022; Osland et al. 2020; Roman et al. 2024; Whelan et al. 2009).

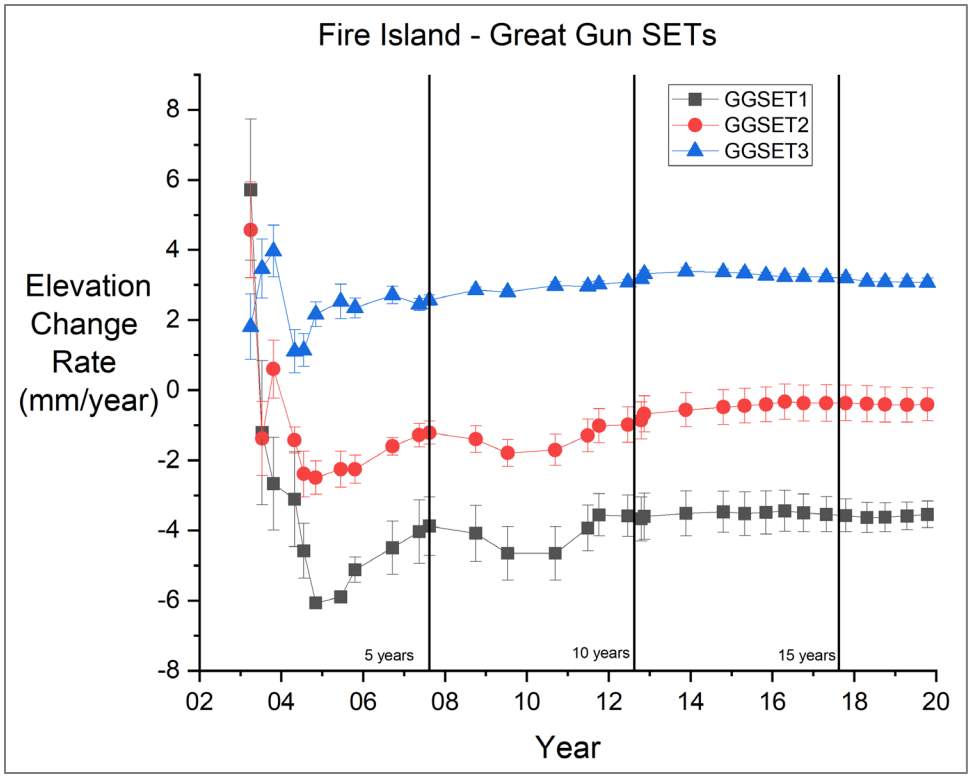


Figure 23. Elevation change rates (mm yr^{-1} ± std error) over time for three SETs at the Great Gun marsh site (Fire Island National Seashore, New York, USA). Rates may show an initial period of high variability (2003–2005) early in the data record and then stabilize over time. Data source: https://irma.nps.gov/DataStore/Reference/Profile/2309427.

NPS / JAMES LYNCH

Refer to *SOP 1: Project Planning*, which provides specific guidance on designing an SET project, including spatial and temporal data distributions, and their ramifications in data analyses.

Field Methods

Installation of SET Marks and Marker Horizons

After determining the specific design for your project, a permanent SET mark will be installed at each sample station. Installation normally involves a minimum of three people. All installation and subsequent sampling activities should take place on a platform installed above the wetland surface to minimize disturbance of the sediments around the SET mark (Figure 24). A sampling platform can be either temporary or permanent. Refer to *SOP 2: Sample Stations and Platform Options* for additional information on platform design. *SOP 3: Installing an RSET Mark* provides details on equipment and supplies needed for installing SET marks. It also provides sample datasheets that can be used to record pertinent information from a new installation.

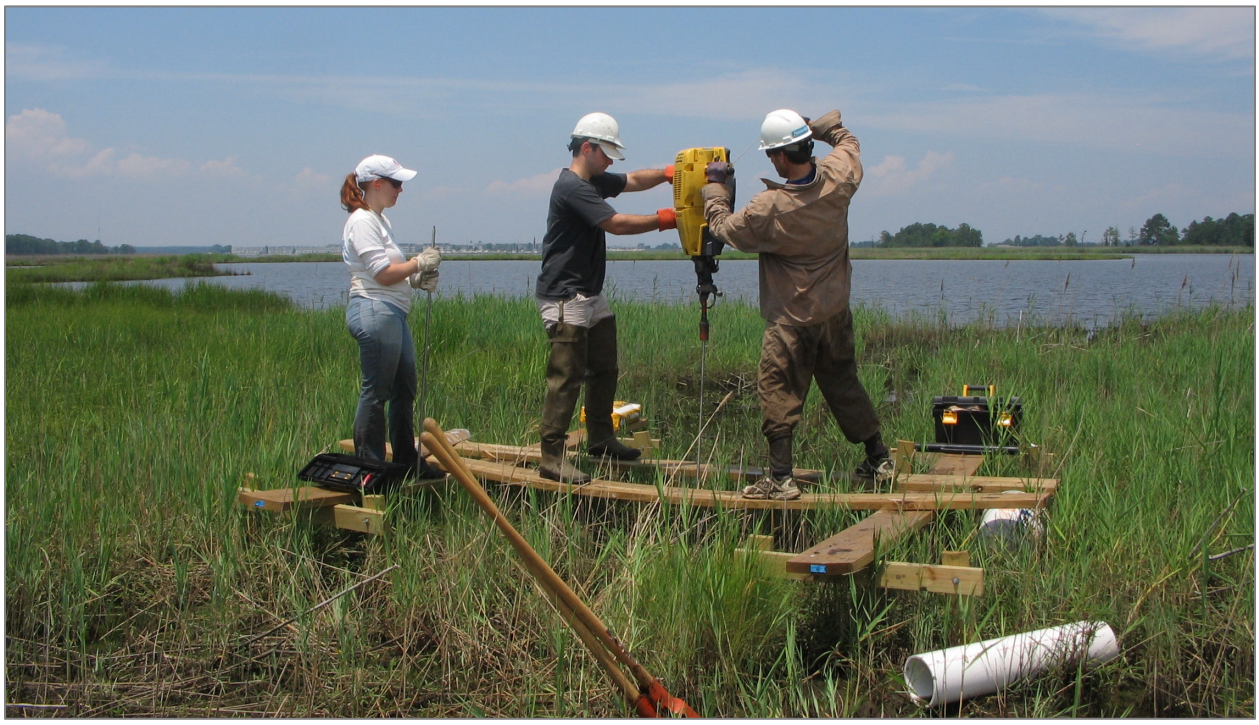


Figure 24. NOAA scientists installing a deep RSET mark in a Chesapeake Bay brackish marsh. In this example, a portable gasoline powered jackhammer is being used to drive rods. Note the permanent sampling platform installed to minimize human disturbance of the marsh surface where the readings will be taken. A removable, portable platform could also be used (Chesapeake Bay Environmental Center, Maryland, USA).
NOAA / GALEN SCOTT

This protocol focuses on the commonly used deep RSET mark, which is based on the design of deep rod survey marks (Floyd 1978). These marks consist of 1.2 m (4 foot) sections of 15 mm (9/16th inch) diameter stainless steel rod that are threaded together and driven to substantial resistance or refusal within the sediment. Depending on the underlying substrate and what equipment is used to drive the rods into the ground (jack hammers or demolition hammers), the SET mark could

incorporate anywhere from 1 to 40 m of steel rod anchoring it to the substrate. Note that we cannot presume to know the actual depth of the RSET mark itself due to the possibility of the rod mark bending in the substrate during installation. In coastal salt marshes of the eastern U.S., 2–40 m of rod is commonly used in a deep RSET mark installation (Cahoon 2024). Following rod installation, the remaining rod section is cut at the sediment surface and encased in a 60 cm to 120 cm (two to four foot) long, 15 cm (six-inch) diameter PVC pipe. A custom-built SET receiver is bolted on to the upper rod section, and the entire PVC tube is filled with concrete (Figure 25).



Figure 25. Deep RSET mark. The RSET instrument attaches to this mark via the notched and threaded receiver. The grey cap is for protecting the mark when the instrument is not attached. The brass disc is for sample station identification and is NOT used for surveying.
NPS / JAMES LYNCH

Marker horizons for measuring accretion are established at the time of the first SET readings (i.e., time zero). Refer to *SOP 5: Establishing and Sampling Markers* for detailed instructions on installing marker horizons. Typically, three marker horizon plots are established from the platform in the immediate vicinity of the SET mark. Many materials can be used for marker horizons, but feldspar

clay is commonly used. The marker horizon material is evenly sprinkled on the surface of the wetland within the MH plot, upon which sediments naturally settle and accrete.

SET-MH Sampling Methods

Field Preparation and Equipment

Below is a list of the items normally needed for collecting SET and marker horizon data on each sampling trip.

1. The SET instrument: The instrument is kept in a carrying case and brought to the site for each sampling session. Always use the same instrument at a given sampling station at each sampling event to minimize error or bias among multiple instruments. The instrument includes pins and a mechanism to restrain pins on the arm or table. A millimeter-scale ruler with true zero point is used to measure the height of each pin above the arm or table. A compass may be needed to identify SET arm directions.
2. Coring device: Examples include a soil/peat corer, cryogenic coring system, serrated knife, or other coring device.
3. Sampling platform: Platform (permanent or temporary) and associated planks needed for sampling at an established sample station.
4. Weatherproof data book or datasheets and pencils or permanent pens for recording data.
5. A field map and/or GNSS unit for locating the sample station.

Refer to *SOP 4: Taking Measurements with SET* and *SOP 5: Establishing and Sampling Markers* for detailed instructions on sampling with the SET instrument and marker horizons.

Sampling Schedule

There are numerous factors to consider when establishing your sampling schedule, including sampling frequency, funding, weather, and tides. Try to keep a consistent schedule over time to avoid unwanted noise in the data and to avoid large gaps in data collection because these can disproportionately influence the rate calculations. It is recommended that temporal gaps in the data be limited to days, not months. Any hypothesis testing for differences over time (such as investigating seasonal dynamics) should dictate the specific sampling schedule.

The number of sampling events conducted per year is a very important consideration and may change over time. Keep in mind that SETs are used for the long-term monitoring of wetland elevation, and your ability to sample them may change over time. In general, the SET-MH stations are sampled one to four times per year. Initially, try to sample two or more times per year for the first 3 or 4 years. This will provide sufficient sampling points for calculating initial elevation trends.

Sampling dates should be driven by seasonal patterns of sediment delivery, hydrology, and plant growth at the location (e.g., wet/dry seasons affecting watershed inputs, seasonal storm inputs). It may also help to illustrate seasonal fluctuations in elevation and vertical accretion that may occur over the course of the year. A common example in temperate wetlands would be to sample the SET-

MH stations twice a year; at the beginning of the growing season (spring) and then again at the end of the growing season (fall). A third or fourth sampling could be added during the growing season. Table 2 provides a summary of the recommended sampling frequencies for the SET-MH method.

Table 2. Suggested sampling frequency for different measurements involved in an SET and marker horizon study.

Measurement	Typical Sampling Frequency	Patterns to Consider
Surface Elevation Table (SET)	1 to 4 times a year (2× or more initially)	Seasons: Spring/Fall or wet/dry
Marker Horizon	1 to 4 times a year (2× or more initially)	Normally sampled when reading the SET
Water Levels	Year-round logging if possible	Winter ice could be an issue
Elevation Surveying	Initially, and then every few years	Leveling or GNSS observation
Stability of the SET Mark	Every few years, if feasible	Leveling or GNSS observation

Funding

This is the ultimate factor in determining how often to sample an SET-MH station. The costs associated with visiting the site may end up influencing the sampling schedule.

Weather

In colder climates, ensure the marsh is not frozen when reading the SET. Consequently, sampling in the winter months does not normally occur in temperate latitudes. The sampling schedule in tropical and subtropical climates may vary based on the timing of the wet and dry seasons. For this distinction, sampling should be undertaken in either the wet season or dry season always, or in both seasons always. A time series of wet season measurements should not include a dry season measurement in the series.

Tides

It is preferable to sample the SET-MH stations at similar tide levels each time because the substrate may shrink and swell with the variation in water level during a tidal cycle. Sample the SET-MH stations when the surface is free of water (i.e., low tide), if possible.

Elevation Change Measurements (SET)

The RSET instrument is attached to the deep or shallow RSET mark to directly measure the relative elevation of the wetland surface repeatedly over time to generate a trend in elevation change. *SOP 4: Taking Measurements with SET* provides details on reading the SET. A very important consideration is who will take the measurements with the SET instrument at each SET mark. It is preferable to have the same person take measurements at the same sites on successive sampling events because there are some subjective decisions that need to be made. The primary decision is determining what constitutes the wetland surface and placing the pins on this surface. In many wetlands, this is a very straightforward decision, but in some situations, it may not be clear, and the person taking the SET measurements must develop a consistent rule for determining the surface, which is effectively a bias.

This rule should be documented and followed on all subsequent sampling events. *SOP 4: Taking Measurements with SET* has details on this and other items to consider when collecting data with the SET.

Vertical Accretion Measurements (Marker Horizon)

The marker horizons are sampled at the same time as the SET measurements to determine how much vertical accretion occurred on the wetland surface since the previous sampling event. *SOP 5: Establishing and Sampling Markers* provides detailed instructions on sampling marker horizons. Coring the marker horizon needs to be accomplished without disturbing a large area of the plot. One method uses liquid nitrogen to take a small diameter frozen core from the plot that can be measured immediately in the field (Cahoon et al. 1996). Other methods for coring the marker horizons include cutting plugs with a knife or using some type of mechanical soil corer.

Water Level Recorders

To characterize the hydrology in the waters adjacent to your sampling stations, pressure transducers or similar sensors can be installed to monitor water levels. Options for sensor placement include at the edge of a wetland along a tidal creek, bay, or other waterway, or within a well in the wetland sediment (Figure 26).



Figure 26. Photo showing the deployment of a water level data logger hung from a nylon cord within a stilling well placed at the marsh edge.
NPS / JAMES LYNCH

Ideally, water level loggers would be collecting data over a similar time as the SET-MH data collection. Continuous logging would be the best option but shorter time periods throughout the year would also provide helpful information on the local hydrology. Refer to *SOP 6: Taking Water Level Measurements* for details on the installation of water level recorders, data collection, and processing of water level data.

Surveying

There are five basic steps involved with measuring high accuracy elevations of sample stations and other items of interest at a wetland site.

1. Evaluation of elevation needs: Are only local elevation connections and comparisons needed (such as within a given site), or is a connection to an official vertical datum required (e.g., NAVD 88)?
2. Development of a survey plan.
3. Installation of any additional geodetic infrastructure, if necessary (e.g., additional survey marks).
4. Connecting a local mark at your site—commonly a deep rod SET—to the U.S. National Spatial Reference System (NSRS; Hensel et al. 2023). Establishment of a high accuracy geodetic connection between this local mark, called the local control mark, and an official reference mark (Figure 27).
5. Surveying from a local control mark to additional SET marks, marker horizon plots, water level recorders, or vegetation plots at the site (Figure 28).

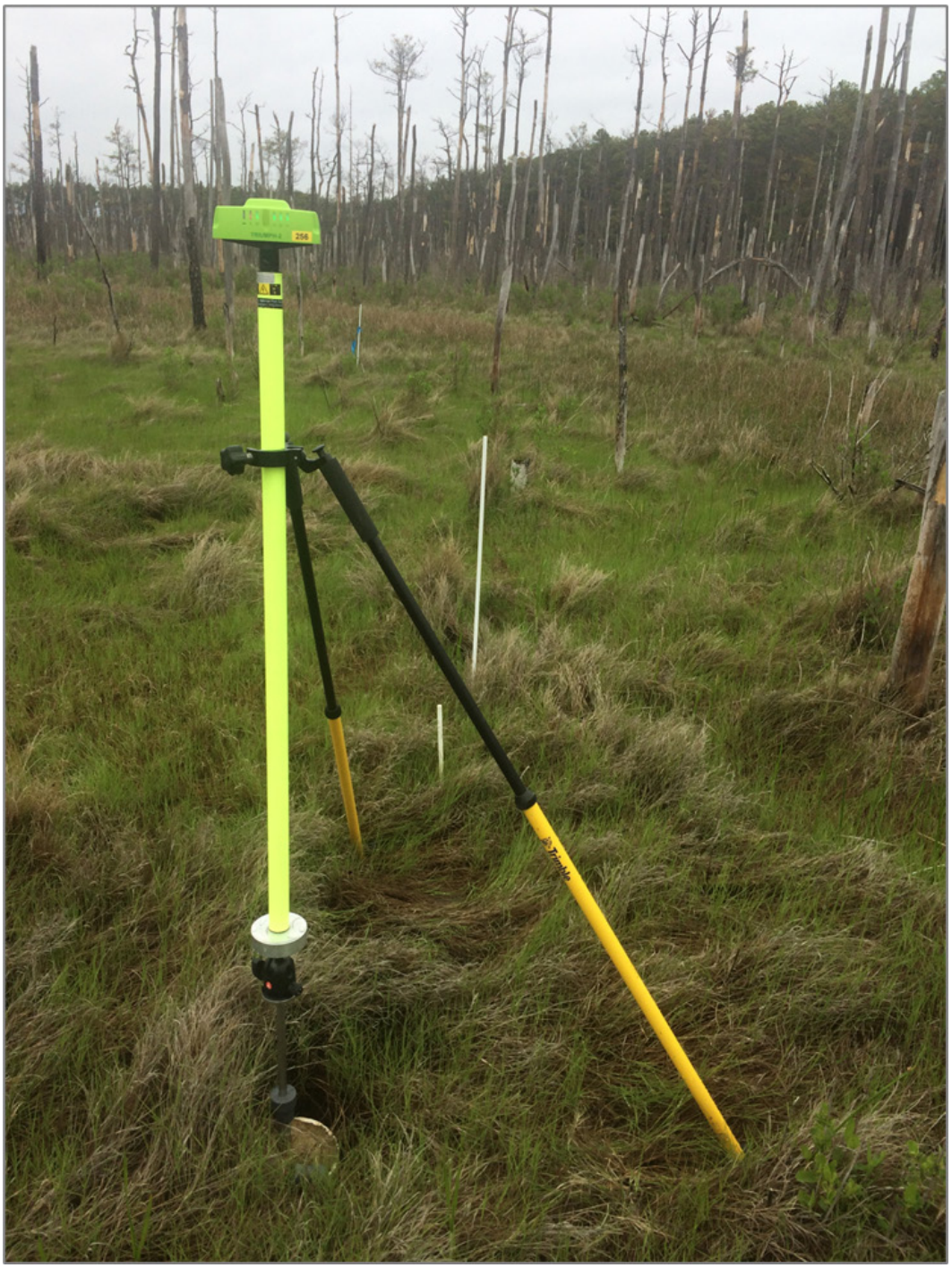


Figure 27. GNSS receiver deployed on a deep RSET mark for a static occupation (Blackwater National Wildlife Refuge, Maryland, USA). Note the “SET Adapter” that attaches the GNSS receiver directly to the SET mark for a stable occupation (see *SOP 7: Surveying the SET Mark*).

NPS / JAMES LYNCH

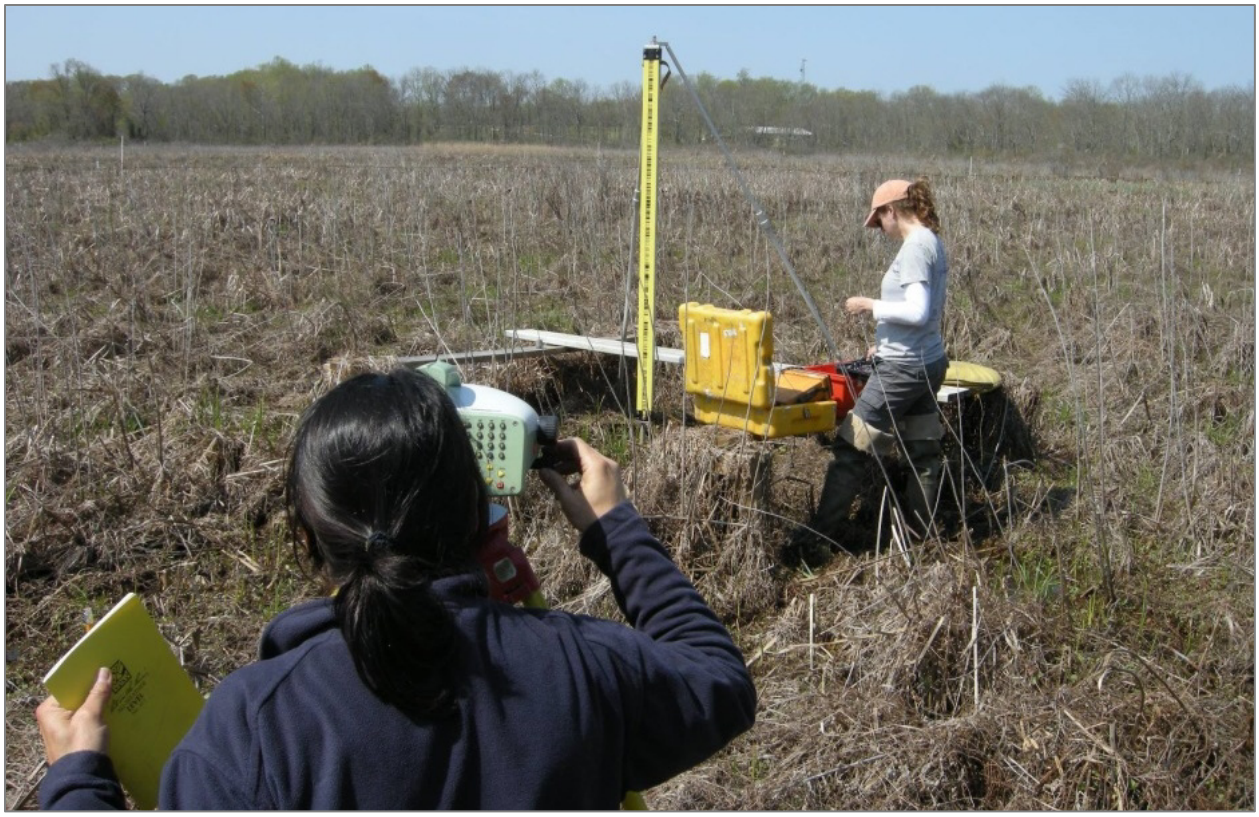


Figure 28. Maryland Department of Natural Resources biologists using a digital barcode level to compare elevations between a RSET mark and other vertical infrastructure (Jug Bay Wetlands Sanctuary, Maryland, USA).
NOAA / PHILIPPE HENSEL

Step 1 is to evaluate whether local elevation connections (such as between SET-MH stations and a local water level recorder) or elevation comparisons (including water levels) are required over a wider area. This decision will influence the type of surveying instrumentation and techniques used, as well as any requirements for additional reference marks. Note that surveying techniques can also be used to compute the vertical offset between the SET mark and the wetland sediment surface. This can be used to express SET pin measurements with respect to a vertical datum such as NAVD 88 (Figure 29). Establishing contact with a licensed, professional surveyor or your Regional Geodetic Advisor can help determine your needs, especially with regards to instrumentation. A survey plan (Step 2) should also be vetted by an experienced surveyor. Refer to *SOP 7: Surveying the SET Mark* for additional guidance.

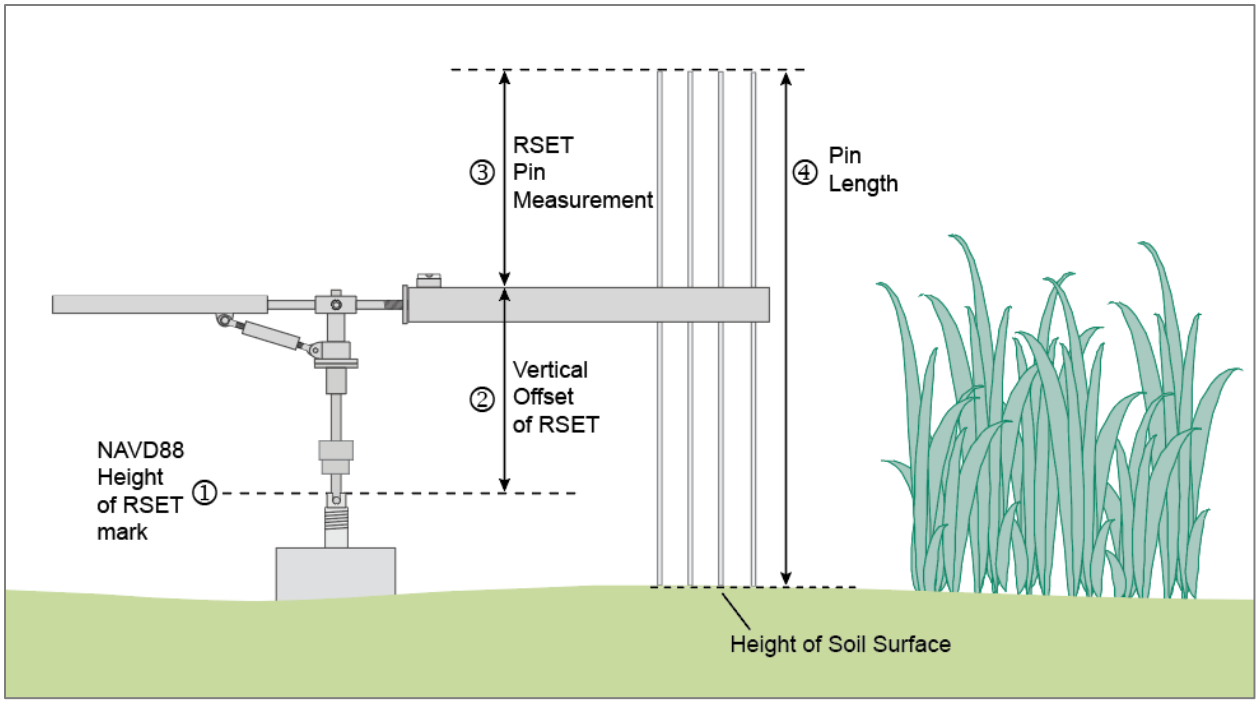


Figure 29. Diagram displaying data involved in transferring elevation of a RSET mark to individual RSET pin measurements (not all pins are shown).

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Data Collection, Entry and QA/QC

The SET and MH methods generate fundamentally different data types such that the two datasets are treated differently in collection, recording, and analyses. With SET data, elevation change of each pin is followed over time and these repeated measurements result in serial correlation that has implications for statistical analyses. With marker data, the evolution of the marker horizon plot is followed. SET data can easily be converted from cumulative to incremental change whereas marker data are inherently cumulative and must be appropriately converted at the marker horizon level if incremental changes are desired.

Metadata

For both SET and MH datasets, there are factors that can result in a bias in the data and therefore need to be documented in metadata, such as changes in observers, the nature of the sediment surface, or the phase of tide. Any dataset compiled by the NPS Inventory and Monitoring Program networks must be accompanied by Federal Geographic Data Committee (FGDC) compliant metadata. This rule applies to both spatial and non-spatial data. NPS has developed both a published, analysis-ready data package that can be accessed by the public (NPS SET data package), as well as an internal database managed by the NPS Inventory and Monitoring Program used for data entry and storage.

Specific metadata requirements can be found in the data management *SOP 8: Data Management.*

Metadata for both SET and marker horizon datasets will include the following considerations:

- Types of data taken (SET, marker horizon).
- Location of the station.
- Date and time of sampling.
- Originator of the data (observer) and other field help.
- Date that the station was established and subsequent sampling dates.

Metadata specific to SET data:

- Type of SET mark (original pipe mark, deep rod mark, or shallow rod mark), including presumed depth and date installed.
- Type of SET instrument (e.g., original SET, RSET).
- Length of SET pins used for measurements.
- SET instrument ID.
- Name of SET reader.
- Station map and direction of approach.
- Compass direction and/or other means to determine the SET positions being sampled.

Metadata specific to marker horizon data:

- Type of marker horizon and date established.
- Location of marker horizons around (SET) station and identification (e.g., numbering).
- Marker horizon sampling method (e.g., coring device, extraction with knife, cryo-coring).

Metadata should be recorded in a field notebook or datasheet that is carried to the field on future sampling dates so that the operators can cross-check original orientation, positions, and locations. Metadata are also stored and archived digitally. Waterproof datasheets are very useful for recording data; a digital voice recorder can also be used for note-taking and serve as a back-up to written notes (also can support quality control—see below).

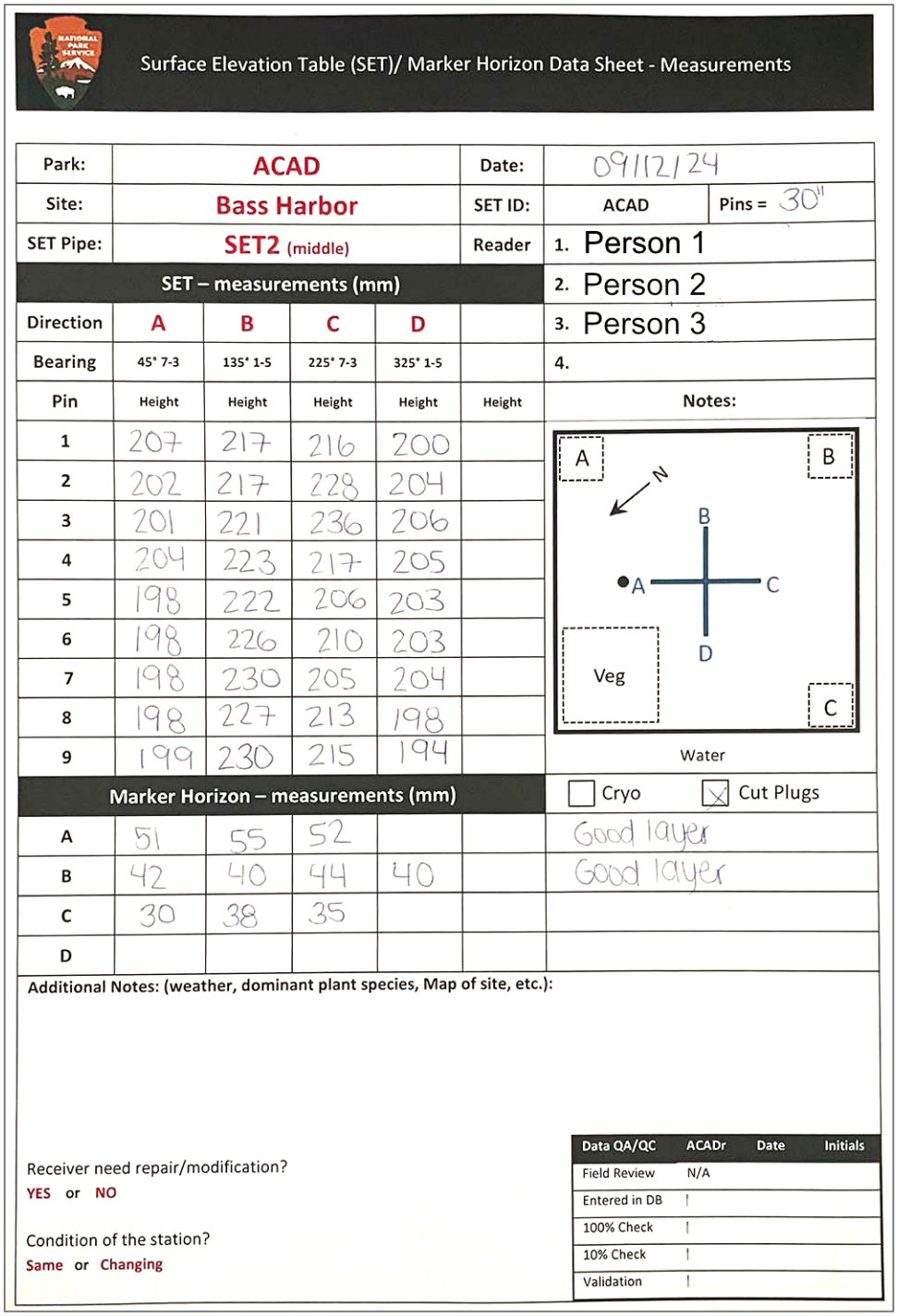
Field Documentation, Data Entry and Manipulation

Data collection, data entry, quality control and analysis represent four critical steps to data processing:

1. Field documentation: Collection of appropriate data and metadata during a sampling event in the field.
2. Data entry into a spreadsheet or database with quality assurance (QA): Entering field data into a spreadsheet or database with quality assurance checks ensuring the data are correctly entered and stored.
3. Computation of incremental changes and quality control: Making sure the data are correctly associated with earlier sampling data (QC) and contain no errors.
4. Analyses of the data and the determination of trends.

These guidelines provide a set of consistent methods to ensure that the data are accurately recorded and allow for careful quality assurance and quality control. Following this, the data can be exported for subsequent analysis.

Field documentation involves both collecting SET and marker horizon data and recording the data in a field notebook (Figures 30, 31) or by using another recording device. These are generally separate tasks involving at least two people. Specific data entry protocols and QA/QC review provide backup protection and quality checks. Data entry in a spreadsheet or database allows consistent formatting to observe changes over time, detect errors/outliers, perform quick exploratory data analysis and trend computation, as well as allow for the ability to express SET data as both incremental elevation change and total cumulative change (Figure 32). Quality control is required to evaluate whether individual SET measurements represent an actual change in the wetland sediment surface elevation, or whether there was a bias or errors due to any one of numerous factors (e.g., crab hole, footprint, detritus, mixing up SET site labels, mixing up SET arm directions). Quality control requires the use of incremental elevation change, regardless of which kind of analysis is eventually conducted on the data. Refer to *SOP 8: Data Management* for details on data management.



Surface Elevation Table (SET)/ Marker Horizon Data Sheet - Measurements

Park:	ACAD				Date:	09/12/24	
Site:	Bass Harbor				SET ID:	ACAD	Pins = 30"
SET Pipe:	SET2 (middle)				Reader	1. Person 1	
SET – measurements (mm)						2. Person 2	
Direction	A	B	C	D		3. Person 3	
Bearing	45° 7-3	135° 1-5	225° 7-3	325° 1-5		4.	
Pin	Height	Height	Height	Height	Height	Notes:	
1	207	217	216	200			
2	202	217	228	204			
3	201	221	236	206			
4	204	223	217	205			
5	198	222	206	203			
6	198	226	210	203			
7	198	230	205	204			
8	198	227	213	198			
9	199	230	215	194			
Marker Horizon – measurements (mm)						☐ Cryo ☒ Cut Plugs	
A	51	55	52			Good layer	
B	42	40	44	40		Good layer	
C	30	38	35				
D							

Additional Notes: (weather, dominant plant species, Map of site, etc.):

Receiver need repair/modification?
YES or NO

Condition of the station?
Same or Changing

Data QA/QC	ACADr	Date	Initials
Field Review	N/A		
Entered in DB	!		
100% Check	!		
10% Check	!		
Validation	!		

Figure 30. Example of an NPS datasheet as recorded during a sampling event. Note the simple map showing the general layout of the sampling area including the SET arm directions (center area—ABCD), marker horizons (dashed boxes—ABC) and a vegetation plot. “SET - measurements (mm)” contain the raw pin height data and reference measurement #3 in Figure 29. Names have been removed.
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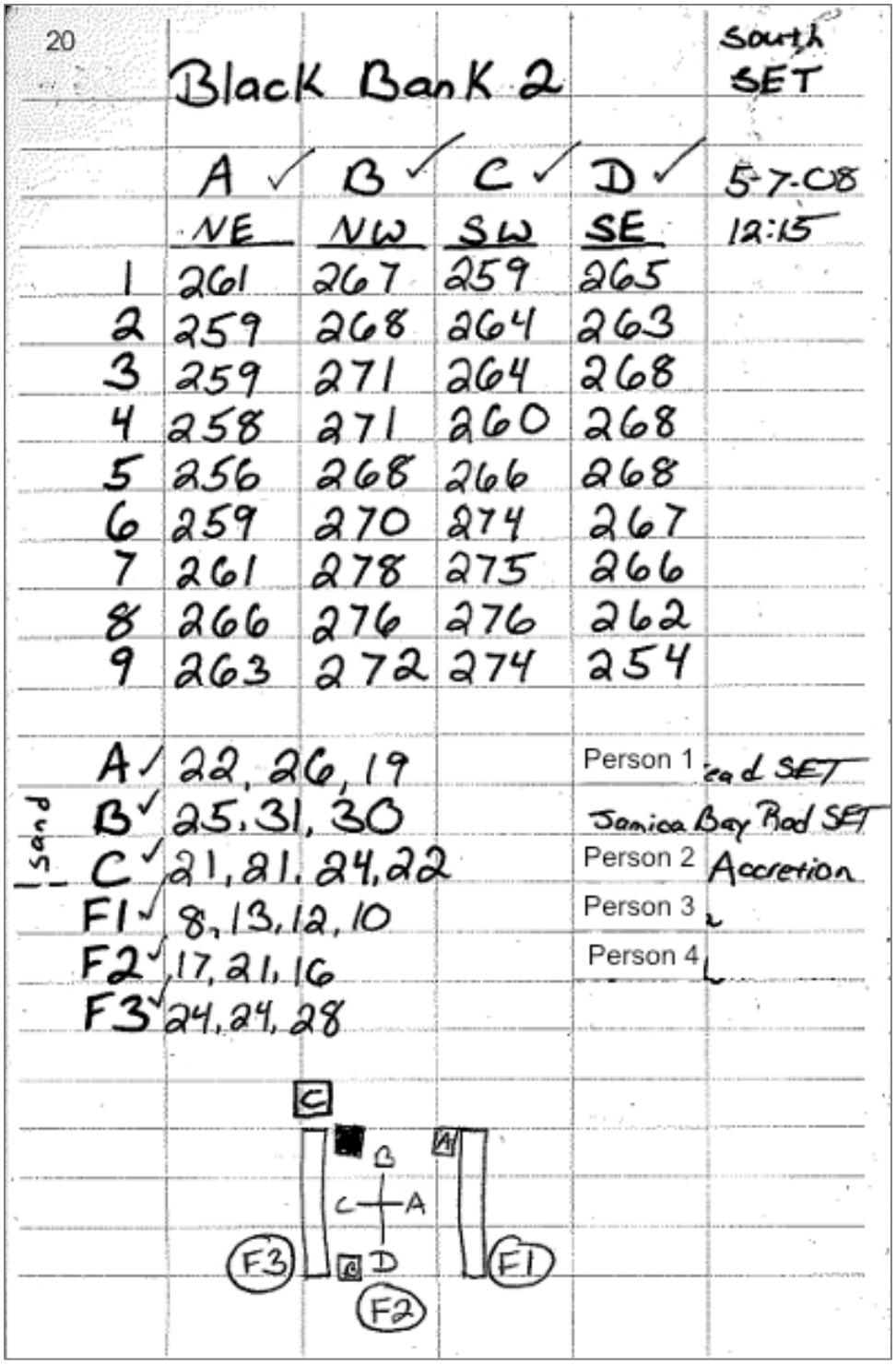


Figure 31. Typical SET-MH data book entries as recorded in the field. Note date, sample site, station ID, SET positions, pin numbers, pin heights, names (removed), and sample station sketch.

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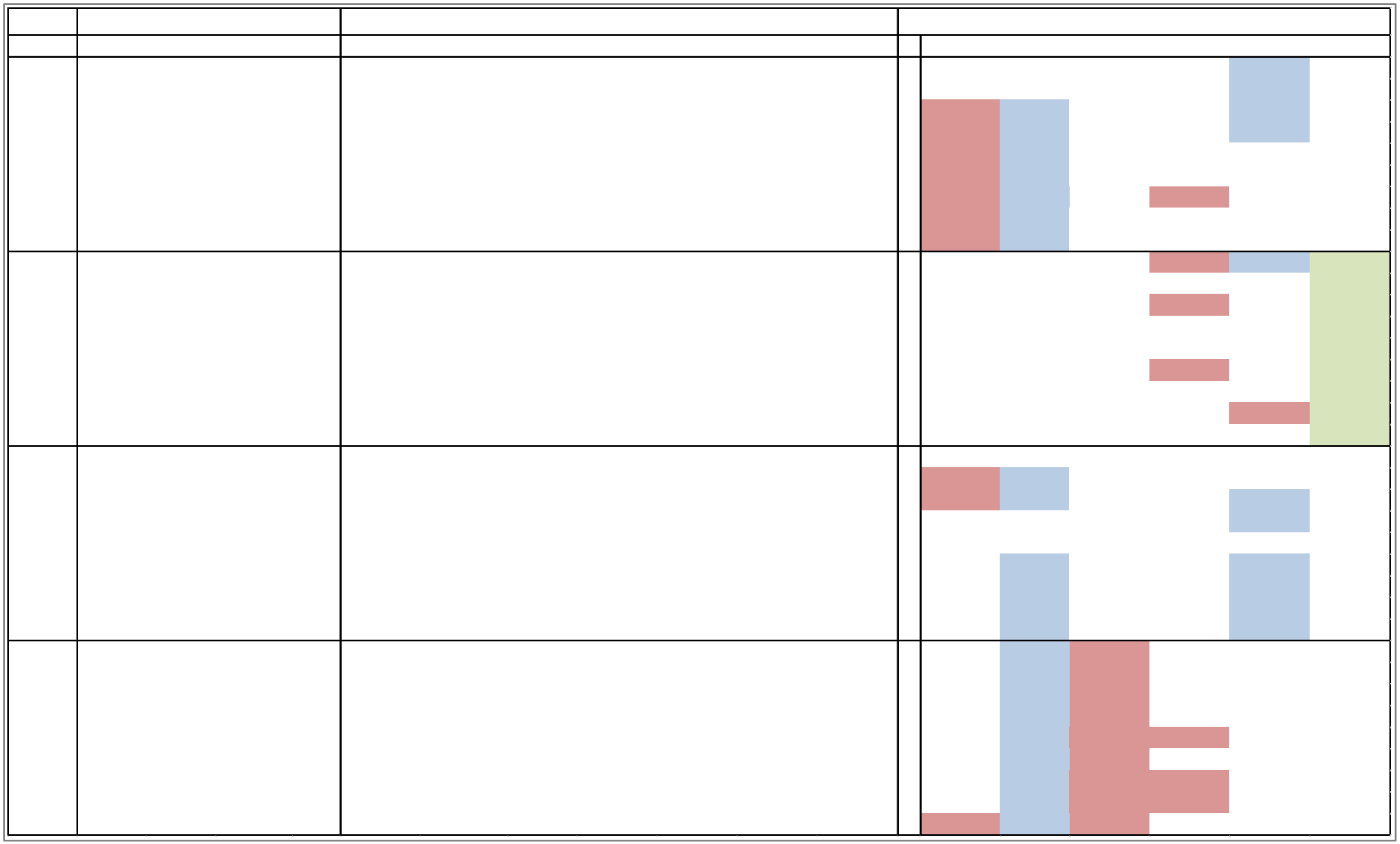


Figure 32. Example of a SET data spreadsheet produced from field measurements. Note raw pin heights collected during the sampling trips (refer to Figure 29, item number 3) and the incremental heights showing the changes between sampling trips. Note the conditional formatting that highlights large decreases (red) or increases (blue) in the pin heights. Green highlights show cells with no data.

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Data Analyses

SET and marker horizon data can be analyzed to meet a variety of objectives. Those objectives may include:

- Describing change over time in the SET and MH datasets. This change could include linear or non-linear trends.
- Comparing the patterns in SET and MH change.
- Detecting and describing sudden changes in SET and MH data where trends shift in magnitude or direction due to large storms or other disturbances.
- Comparing SET and MH data to local sea-level rise and/or water levels.
- Testing hypotheses related to the data. This could include hypotheses about change over time, spatial gradients, or other covariates.

Due to the variety of potential analyses, it is not possible to give a specific method for analyzing all data, but this section will highlight important considerations. The data may need to be analyzed a variety of ways based on the study questions and information required by a specific audience.

Considerations When Using SET Data

In selecting a method for analyzing SET data, it is important to keep in mind that SET pin heights are correlated both spatially and temporally and that changes in pin height may be non-linear over time. In general, various linear models should produce similar trends if there is not a lot of missing data. However, the choice of model can affect estimates of the standard error of the trend and care should be taken not to select a method that will produce over-confident results (Russell et al. 2022).

Considerations When Using Vertical Accretion Data

Marker horizons are used to determine cumulative sediment vertical accretion at the wetland surface. However, over time marker horizons are commonly lost due to weather events and/or bioturbation (e.g., crab activity). As a result, the likelihood of missing marker horizon data increases the longer a horizon has been deployed. The MH method tends to be biased in that it typically only quantifies positive deposition or burial and generally cannot measure erosion—unless the marker has been buried substantially enough so that a previously measured depth can erode and therefore record erosion. Furthermore, as the marker horizon is buried in the sediment, in addition to deposition, processes like root growth and sediment compaction increasingly influence the MH measurements. Finally, as marker horizons are lost, it is common to establish new ones. Therefore, though the pin data can be a single long record, the MH data are often several shorter records, and each of the marker horizons within a plot may be replaced at different times. Exploratory data analysis should be used to determine the extent to which multiple re-laying actions are impacting the data before analyzing it (Cahoon and Lynch 1997).

Describing Linear Change

The first step in any analysis should be to graph the entire data record and assess the patterns of change over time. If the data show a generally linear change over time, then standard methods using linear models are likely to be appropriate. Sometimes non-linear portions of data may occur early in the dataset during the initial period of instability or following substantial disturbance events or other large changes in the environment.

SET data can be analyzed using one of the below methods:

- Average then Regress method (ATR). Averaging all the pin height data to level of the SET, then averaging to the site level and analyzing over time to get a trend.
- Regress then Average method (RTA). Analyzing the trend for each individual pin and averaging slope coefficients to get a single overall slope for each SET. SETs are averaged to get a trend for a site.
- Using a mixed model approach where pins and/or positions and SETs are accounted for using random effects.

Russell et al. (2022) discusses the tradeoffs of the various modeling options for SET data. If there is little or no missing SET data, ATR or RTA should result in the same trend.

Marker horizon data can be analyzed using one of the below methods:

1. ATR method. Average all the marker data to the level of the plot, sampling station, and site, then regress.
2. RTA method. Determine the trend for each marker horizon plot at a sampling station and average the trends to the SET and site level. This is less common due to the increase in missing data in longer data records.
3. Mixed models where marker horizon plots are treated as a random effect.

Refer to *SOP 8: Data Management* for examples showing ATR and RTA with SET and MH data.

Describing Non-Linear Change

SET or MH data may show clear signs of non-linear change. One possible reason for this is that over time, the SET or MH data may go through distinct phases characterized by linear trends of different magnitude or direction (i.e., elevation gain vs. elevation loss). For example, there may be abrupt transitions, or change-points, between two or more periods with different slopes caused by a specific event that alters conditions at the monitoring site. Change-points may be facilitated by natural events such as a large storm or flood that alters local hydrology, or a management action, such as placing sediment on a marsh. A dataset such as this can be analyzed using change-point analysis in conjunction with a piecewise regression to calculate slopes from different time periods showing different trends (Feher et al. 2020, Osland et al. 2020). When carrying out this type of analysis, the change-points can be specified in advance based on knowledge of the system, or they can be estimated via an algorithm. This approach can allow comparisons between time periods and is also

useful if recent data show a different trend from historic data and an estimate of the current trend is desired. However, if trends are inconsistent across time, the average slope may be misleading, particularly for predicting future values. A similar approach involves the use of generalized additive models (GAMs) (Feher et al. 2022, 2024, Moon et al. 2022), which are essentially non-parametric versions of generalized linear models and are frequently used with non-linear data. Once a GAM model is fit, a single average trend could be calculated by averaging the instantaneous slopes between equally spaced, consecutive points across the fitted model (i.e., finite difference approximation). Example R code for fitting piecewise and GAM models on SET data is available (Tredennick et al. 2021).

Comparisons and Hypothesis Tests

Any analysis used for describing change could also be framed as a hypothesis test. For example, a hypothesis could be that there is a trend vs. a null model of no change over time. If a site has no change in wetland elevation or vertical accretion over time (i.e., the null hypothesis is true), this could be an important result as it indicates that there is little cumulative change in wetland elevation or little sediment accretion. Comparisons such as this can be made across the entire data record or between subsets of the record with different trends. Another hypothesis could be that the marsh elevation trend is not significantly different from local long-term sea-level rise. Similarly, additional tests could include a comparison of elevation rate changes between sites, comparisons of trends before and after a management action or major disturbance, or comparisons between sites with different spatially or temporally distributed co-variates.

For many comparisons, an alternative approach may focus on confidence intervals or credible intervals (95% or other percentile) of any trend. First, the credible interval could be assessed to determine if the analysis is precise enough to be truly informative. If the intervals are wide compared to any potential trend, then the estimates of trend may be too vague to be useful. In this situation, more data may allow for better estimates in the future.

If trend estimates are reasonably precise, the credible intervals could be compared to meaningful values, such as 0 (no trend), or mean sea-level rise to assess the status of the marsh. A precise trend that overlaps 0 would not merely be a case of not rejecting a null hypothesis, but rather an affirmative statement that there is little cumulative change in marsh elevation or little sediment accretion.

It is also possible to compare SET and MH trends to evaluate the role of surface vs. subsurface processes in affecting elevation change (Figures 5, 10). There are three potential outcomes:

1. Vertical accretion rate > Elevation rate: shallow subsidence may be occurring (Figure 15).
2. Vertical accretion rate = Elevation rate: surface accretion is driving elevation change (no subsurface influence).
3. Vertical accretion rate < Elevation rate: shallow expansion may be occurring.

Personnel Requirements and Training

Below are some of the personnel and training requirements for the NPS. Personnel requirements may vary from one organization to another. The basic principles outlined below for the NPS can apply to other groups as well and could be considered.

NPS

The Northeast Coastal and Barrier Network (NCBN) is responsible for the development and implementation of SET-MH protocols used in NPS parks in the northeast region of the U.S. and has assigned a Network staff-person as project leader (Stevens et al. 2005). The NCBN project leader is responsible for coordinating development of this document as well as an implementation plan and schedule that is suited to the needs of individual Network parks. The project leader will work closely with Network parks and their staff to develop and implement SET-MH protocols. Because the various activities associated with these protocols can be rather complex, it is best to coordinate your activities with the project leader in your network.

Network and local park staff can use this report/guideline/protocols for the collection of data on NPS property. Elevation monitoring using the SET instrument is a long-term endeavor that can occur for many years. Because reading the SET instrument involves some qualitative decisions on where the marsh surface is located, it is best to have the same person (not short-term or seasonal staff) take these measurements from year to year.

Data management will involve the NCBN project leader, the person collecting the data (if different) and Network data managers. The person reading the SET instrument and collecting the marker horizon data is responsible for backing up the data collected, initial QA/QC, and providing data essential for the metadata file. The NCBN project leader is responsible for data documentation (metadata), data summary, basic analysis, and reporting.

Training for installation and sampling of the SET-MH stations will come from the project leader in your network and/or from the SOPs contained in this report. The project leader will also work with the Network parks to ensure that local staff members are appropriately trained to meet the requirements necessary for sampling throughout the year.

Other related activities such as leveling and/or GNSS surveying should be carried out by qualified personnel as directed by the pertinent SOPs. Check with your project leader to ensure that any personnel conducting surveys are properly trained.

Operational Requirements

Annual Workload and Field Schedule

The annual workload and field schedule will vary depending on the requirements for the project. SET-MH stations are commonly sampled 2 or 3 times per year, especially in temperate climates, but actual schedules will be based on the requirements established for your design. Surveying the SET-MH stations to monitor stability of the SET mark and wetland elevation will typically happen every few years or longer. Schedules will vary depending on the needs of the design. Surveying costs are not described below. Refer to *SOP 7: Surveying the SET Mark* for details on organizing a survey for the study area.

SET-MH Installation and Sampling Costs

There are two types of costs associated with SET-MH studies described in this protocol, installation costs and sampling costs.

Installation Costs

These are upfront expenses associated with starting a new SET-MH project (Table 3). This will involve the installation of SET marks, marker horizons, water level loggers, and the associated platforms and equipment needed to install them. Be aware that some of the equipment needed for installing the SET marks (jackhammer or demolition hammer) can be expensive. This equipment can be rented or possibly borrowed from a colleague. Details on the installation of SET-MH stations can be found in *SOP 3: Installing an RSET Mark* and *SOP 5: Establishing and Sampling Markers*.

Table 3. Estimated cost for installing an SET-MH station (2026 prices in U.S. dollars).

Item	Price	Number	Total Price	Notes
Stainless Steel Receivers	$175	1 per sample station	$175	Custom built. Prices will vary depending on how many ordered.
Stainless Steel Rods (4')	$50–$60 each	10–20 per sample station	$500–$1200	Stainless Steel Rod pricing and the number needed for installation will vary considerably depending on local conditions and the equipment used to install the mark.
Hammer Drill or Demolition Hammer or Hand Pounder	$6000 or $750 or $300	1	$300–$6000	Investigate renting or borrowing the jackhammer or demolition hammer.
Miscellaneous Items (e.g., Cement, PVC pipe)	$50	–	$50	Price per sampling station.
Feldspar Clay (50 lb bag)	$15	1 bag per 2 stations	–	One 50-lb bag will provide about 6 marker horizon plots (50 cm × 50 cm).
Platform (optional)	$100	1 per station	$100	Price will depend on the size and length of the platform constructed.
Water Level Recorders	$650	1 per site	$650	Assuming the use of sealed pressure transducers.

Table 3 (continued). Estimated cost for installing an SET-MH station (2026 prices in U.S. dollars).

Item	Price	Number	Total Price	Notes
Barometric Logger	$650	1 per study space	$650	Sealed pressure transducer. Can cover multiple sites in a sample space.
Logger Housing	$50–$200	1 per site	$50–$200	–
Site Access Costs	Varies by site	–	Varies by site	Costs getting to and from the study area.

Sampling Costs

These are expenses associated with the long-term monitoring of the SET-MH sample stations (Table 4). This would include the costs associated with the logistics of accessing the sample stations and taking measurements on a particular schedule. Note that many of the measurement costs in Table 4 are one-time costs (e.g., SET instrument and cryogenic tank). The recurring costs for measuring SET-MH stations will come primarily from the travel costs of getting to and from the study area, lodging (if necessary), and the costs for liquid nitrogen, if applicable. Details on the sampling process can be found in *SOP 4: Taking Measurements with SET* and *SOP 5: Establishing and Sampling Markers*.

Table 4. Estimated cost for sampling an SET-MH station (2026 prices in U.S. dollars).

SET Sampling Costs	Price	Number	Total Price	Notes
Rod SET Instrument	$1900	1	$1900	Need only one SET instrument for most situations because it is portable. Instrument is custom built.
Cryogenic Coring System (Stainless Steel 15-liter Tank and Hoses)	$2000–$2500	1 or more	$2000–$2500	Cryogenic system will work in all substrate types. Cryogenic coring may require 2 or more liquid nitrogen tanks in areas with many marker horizons to sample.
Peat Corers	$500–$1000	1 or more	$500–$1000	Usually a custom build mini-corer.
Substrate Cutting Knife	$5–$50	1 or more	$5-$50	Using a knife to cut a core will work only in firmer substrates.
Portable Platform (optional)	$150	1 plank and stools	$150	If not using a permanent platform.
Liquid Nitrogen	$40–$60	1 tank	$40–$60	Price to fill a 15-liter cryogenic tank (if used).
Water Level Recorder Software/Cables	$150	1	$150	Price may vary depending on the vendor.
Site Access/Sampling Costs	Varies by site	–	Varies by site	Costs getting to and from the study area.

Procedures for Revising and Archiving Previous Versions of the Report

Over time, revisions to both the Report Narrative and to specific Standard Operating Procedures (SOPs) are to be expected. Complete documentation of changes to the report, and a library of previous versions, help maintain consistency in data collection and appropriate treatment of the data during data summary and analysis. The database used by NPS staff for each monitoring component contains a field that identifies which version of the protocol was being used when the data were collected. The rationale for including a narrative with supporting SOPs is based on the following:

- The Report Narrative is a general overview of the report that gives the history and justification for doing the work and an overview of the sampling methods, but it does not provide all the procedural details.
- The Report Narrative will only be revised if major changes are made to the procedures.
- The SOPs, in contrast, are very specific step-by-step instructions for performing a given task. They are expected to be revised more frequently than the Report Narrative.
- When an SOP is revised, in most cases, it is not necessary to revise the Report Narrative to reflect the specific changes made to the SOP.
- All versions of the Report Narrative and SOPs will be archived in a Report Library.

The steps for changing this report (either the Narrative or the SOPs) are outlined in *SOP 10: Revising the Protocol or SOP.* Each SOP contains a Revision History Log that should be filled out each time an SOP is modified to explain why the change was made, and to assign a new Version Number to the revised SOP. The new version of the SOP and/or Report Narrative can be found on NPS DataStore.

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