Prepared in cooperation with the Coastal Wetlands Planning, Protection and Restoration Act

Submergence Vulnerability Index Development and Application to Coastwide Reference Monitoring System Sites and Coastal Wetlands Planning, Protection and Restoration Act Projects

Open-File Report 2013–1163

U.S. Department of the Interior
U.S. Geological Survey

Submergence Vulnerability Index Development and Application to Coastwide Reference Monitoring System Sites and Coastal Wetlands Planning, Protection and Restoration Act Projects

By Camille L. Stagg, Leigh Anne Sharp, Thomas E. McGinnis, and Gregg A. Snedden

Prepared in cooperation with the Coastal Wetlands Planning, Protection and Restoration Act

Open-File Report 2013–1163

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Stagg, C.L., Sharp, L.A., McGinnis, T.E., and Snedden, G.A., 2013, Submergence Vulnerability Index development and application to Coastwide Reference Monitoring System Sites and Coastal Wetlands Planning, Protection and Restoration Act projects: U.S. Geological Survey Open-File Report 2013–1163, 12 p., http://pubs.usgs.gov/of/2013/1163/.

Contents

Figures

Table

Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Elevation, as used in this report, refers to distance above the vertical datum.

Submergence Vulnerability Index Development and Application to Coastwide Reference Monitoring System Sites and Coastal Wetlands Planning, Protection and Restoration Act Projects

By Camille L. Stagg,[1] Leigh Anne Sharp,[2] Thomas E. McGinnis,[2] and Gregg A. Snedden[1]

Abstract

Since its implementation in 2003, the Coastwide Reference Monitoring System (CRMS) in Louisiana has facilitated the creation of a comprehensive dataset that includes, but is not limited to, vegetation, hydrologic, and soil metrics on a coastwide scale. The primary impetus for this data collection is to assess land management activities, including restoration efforts, across the coast. The aim of the CRMS analytical team is to provide a method to synthesize this data to enable multiscaled evaluations of activities in Louisiana's coastal wetlands. Several indices have been developed to facilitate data synthesis and interpretation, including a Floristic Quality Index, a Hydrologic Index, and a Landscape Index. This document details the development of the Submergence Vulnerability Index, which incorporates sediment-elevation data as well as hydrologic data to determine the vulnerability of a wetland based on its ability to keep pace with sea-level rise. The objective of this document is to provide Federal and State sponsors, project managers, planners, landowners, data users, and the rest of the coastal restoration community with the following: (1) data collection and model development methods for the sediment-elevation response variables, and (2) a description of how these response variables will be used to evaluate CWPPRA project and program effectiveness.

Introduction

In response to widespread and severe land loss along the northern Gulf of Mexico coast in Louisiana (Couvillion and others, 2011), the Coastal Wetlands Planning, Protection and Restoration Act of 1990 was passed to conserve, restore, create, or enhance coastal wetlands. In 2003, the Coastwide Reference Monitoring System (CRMS) was initiated to provide a framework for assessing the effectiveness of the restoration projects implemented through CWPPRA (fig. 1). The CRMS network provides ecological data not only from sites located within project boundaries but also from sites located across the coastal zone of Louisiana, thereby allowing for multiscale comparisons to evaluate restoration efforts on a project-specific level or an ecosystem or landscape scale (Steyer and others, 2003, 2006).

In order to synthesize the numerous ecological parameters that are measured at CRMS sites, a Floristic Quality Index (Cretini and others, 2011), a Hydrologic Index (Snedden and Swenson, 2012), and a Landscape Index (current document) were created. These indices, in conjunction with other pertinent ecological metrics, provide a mechanism to quantitatively assess the effectiveness of restoration activities and overall ecosystem health. This document describes the development and potential use of the Submergence Vulnerability Index (SVI), which incorporates ecological parameters associated with soil building, wetland elevation dynamics, and local relative water-level trends.

The SVI assesses a site's vulnerability to submergence because of sea-level rise, which results from the feedbacks among flooding regime, surface elevation, and surface accretionary processes. Wetland sustainability is maintained through regular flooding events that provide sediments and nutrients and flush phytotoxins from the soil, thereby stimulating primary production, which in turn increases sedimentation and accretion (Mendelssohn and Seneca, 1980; Nyman and others, 1993; Cahoon and others, 2006; Nyman and others, 2006). This positive feedback loop results in the maintenance of wetland elevation, which in turn influences flood regime (fig. 2). Therefore, for the purposes of this index, a site is considered vulnerable to submergence if the elevation change rate is too low to offset local sea-level rise (fig. 3).

[1]U.S. Geological Survey.

[2]State of Louisiana, Coastal Protection and Restoration Authority, Lafayette.

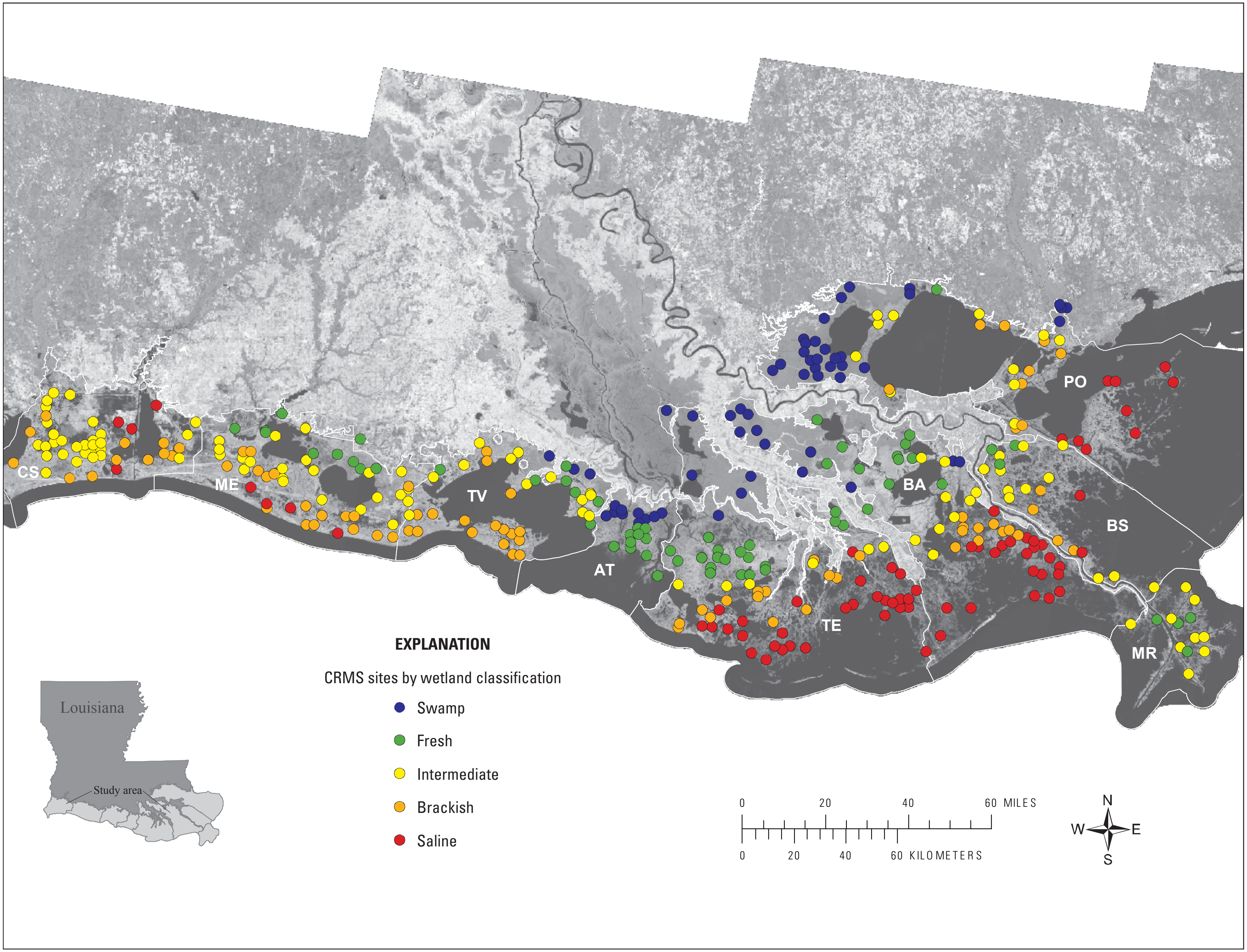

Figure 1. Louisiana coast with Coastwide Reference Monitoring System (CRMS) sites displayed according to the 2007 wetland classification (Sasser and others, 2008). (CS, Calcasieu-Sabine Basin; ME, Mermentau Basin; TV, Teche-Vermilion Basin; AT, Atchafalaya Basin; TE, Terrebonne Basin; BA, Barataria Basin; PO, Lake Pontchartrain Basin; BS, Breton Sound; MR, Mississippi River Delta)

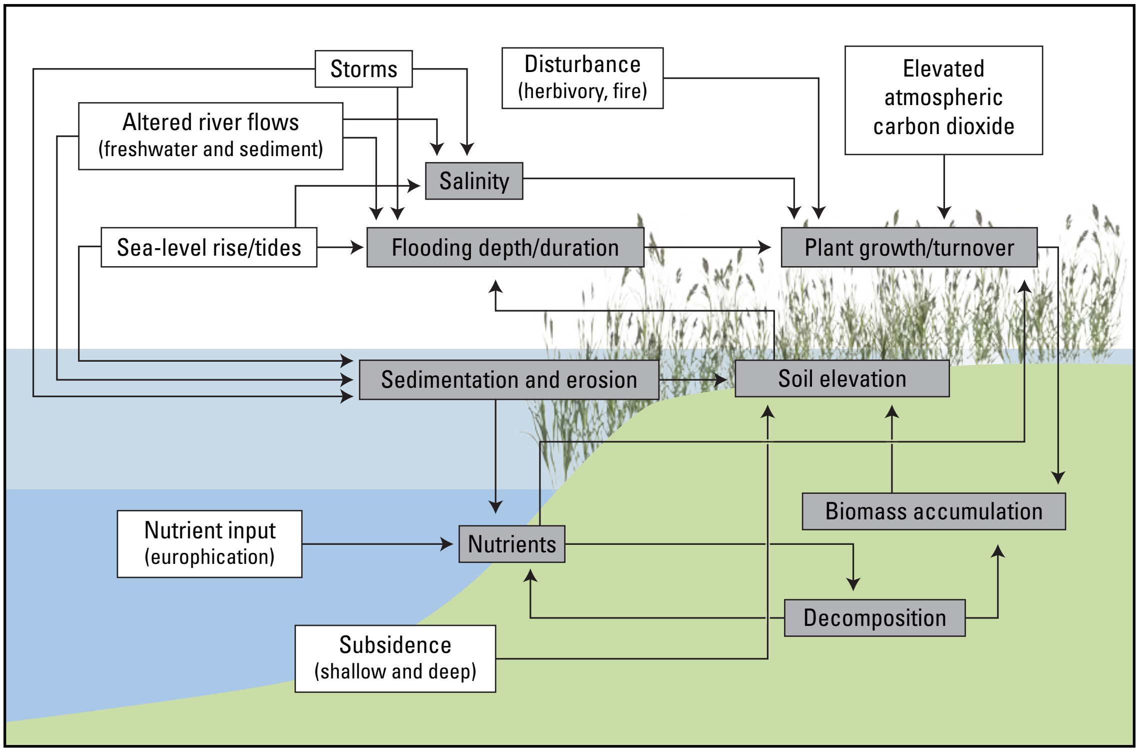

Figure 2. Conceptual model depicting how environmental processes (white boxes) and soil-development processes (grey boxes) interact to influence wetland elevation and sustainability (from Cahoon and others, 2009).

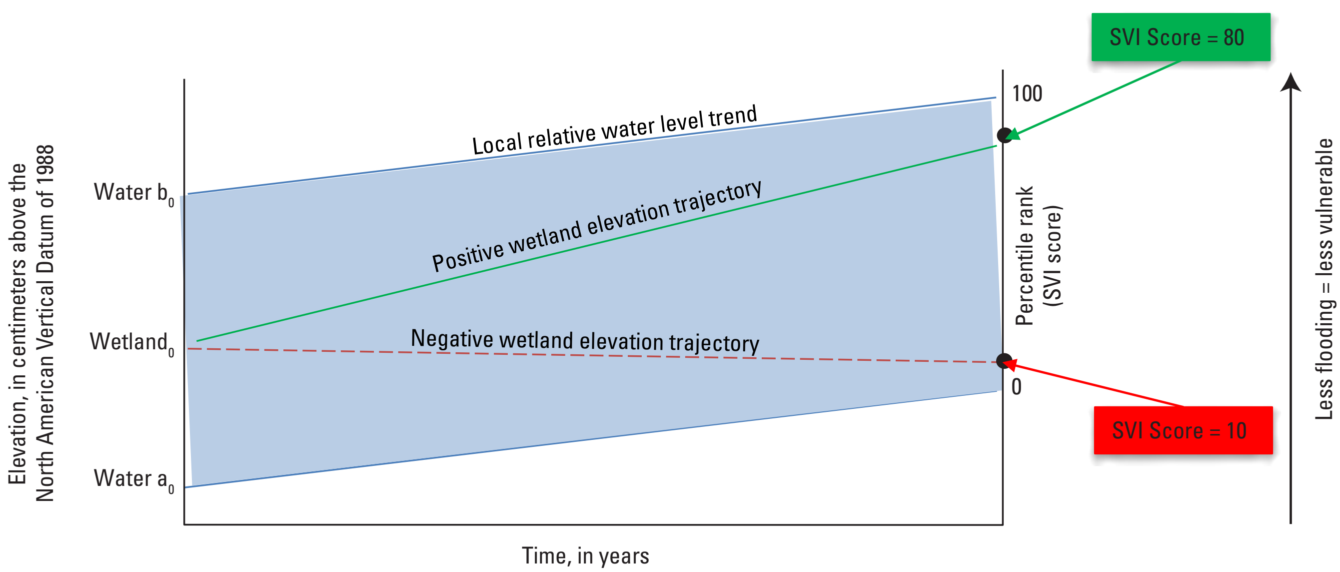

Figure 3. Conceptual model of Submergence Vulnerability Index (SVI), where wetland vulnerability is based on a projection of the relative vertical position of the wetland within the hydrologic frame. Left Y-axis represents wetland and water elevation. $Wetland_0$ represents the initial wetland elevation; Water a_0 and Water b_0 represent the upper and lower bounds of the current hydrologic frame, respectively. The right Y-axis represents the relative position of the projected wetland within the projected hydrologic frame as a percentile ranking of the wetland elevation compared to the water elevations. The x-axis represents time from the most recent wetland and water elevation measurements to 5 years in the future. The green line represents a potential scenario, where a wetland with a positive elevation trajectory is projected to have an elevation that is ranked in the 80th percentile of water-level observations. The red dashed line is an example of a potential scenario, where a wetland with a negative elevation trajectory is projected to have an elevation that is ranked among the 10th percentile of water-level observations. Higher scores represent wetlands that are flooded less often and are less vulnerable to submergence. In contrast, lower scores represent wetlands that are flooded more often and are more vulnerable to submergence.

Other coastal vulnerability assessments have been developed on global (Harrison, 1975; Gornitz, 1991) and local (Cahoon and others, 2006) scales. Because fine-scale processes such as plant production, organic matter decomposition, and sediment deposition are largely responsible for local changes in wetland elevation, site-specific assessments of wetland vulnerability are important (Cahoon and others, 2006). The SVI represents the interaction between site-specific measurements of surface-elevation dynamics and site-specific relative sea-level rise (defined in this document as local relative water-level trend) and therefore is not constrained by the differences in temporal and spatial scaling that are present when using regional, long-term historical records of sea-level rise (as in Cahoon and others, 2006).

The objective of this document is to provide Federal and State sponsors, project managers, planners, landowners, data users, and the rest of the coastal restoration community with the following: (1) data collection and model development methods for the sediment-elevation response variables, and (2) a description of how these response variables will be used to evaluate CWPPRA project and program effectiveness. New response variables may be added, or current response variables may be removed, as data become available and as our understanding of restoration success indicators develops.

Data Collection

The SVI incorporates several parameters representative of soil-building processes and elevation-change dynamics to determine the vulnerability of a site to submergence from increasing water levels (table 1). Elevation change, vertical accretion, and water elevation measured at each site are used along with regional estimates of global eustatic sea-level rise (ESLR) (Solomon and others, 2007) to make direct comparisons of wetland surface elevation to local relative water-level trends. A brief description of data collection methodology is given for each parameter included in the SVI model (table 1). Complete descriptions of the methods and sampling design for collecting elevation data in emergent wetlands at CRMS sites can be found in Folse and others (2008).

RSET Data

The Rod Surface Elevation Table method (RSET) (Cahoon and others, 2002) provides high-precision, repeatable measurements of relative sediment elevation. The RSET method, as implemented within the CRMS network, measures surface-elevation change in 6-month intervals and provides cumulative elevation change (CEC) data over time. Simultaneous measures of vertical accretion relative to an artificial soil marker horizon provide information on surficial processes. The difference between vertical accretion and CEC is shallow subsidence (Cahoon and others 1995; fig. 4). Thus, this methodology allows not only for site-specific comparisons of elevation-change trajectories to local water-level trends but also for a greater understanding of site-specific processes influencing elevation change.

One RSET benchmark is located at each CRMS site (with the exception of floating marshes and perpetually flooded, flocculent swamps). From the RSET benchmark, surface elevation is measured at nine points in four directions to calculate elevation change at 6-month intervals. CEC is defined as elevation change since station establishment. Mean elevation is calculated for each of the four directions, and an elevation-change trajectory is generated for each site by using a linear regression of CEC versus time. Five years of surface-elevation change data are required for calculation of an SVI score. Although RSET data can be interpreted sooner, extending the data completeness criterion to 5 years includes more temporal variation and also allows for a consistent comparison to the water-level record (Cahoon and others, 2006), which is defined by the most recent 5 years of data.

Table 1. Overview of soil and hydrologic data parameters included in the Submergence Vulnerability Index model.

[cm, centimeter; y, year; NAVD 88, North American Vertical Datum of 1988]

Soil and hydrologic data parameter	Units	Data source	Method
Cumulative elevation change	cm y^{-1}	Site-specific measurement	Rod Surface Elevation Table (RSET).
Vertical accretion	cm y^{-1}	Site-specific measurement	Feldspar marker horizon plots.
Shallow subsidence	cm y^{-1}	Calculation from site-specific measurements	Vertical accretion–cumulative elevation change.
Water elevation	cm NAVD 88	Site-specific measurement	Continual water-level recorder.
Eustatic sea-level rise	cm y^{-1}	Global scale data (Solomon and others, 2007)	
Local relative water-level trend	cm y^{-1}	Calculation from site-specific measurements and literature values for global scale data	Shallow subsidence + eustatic sea-level rise.

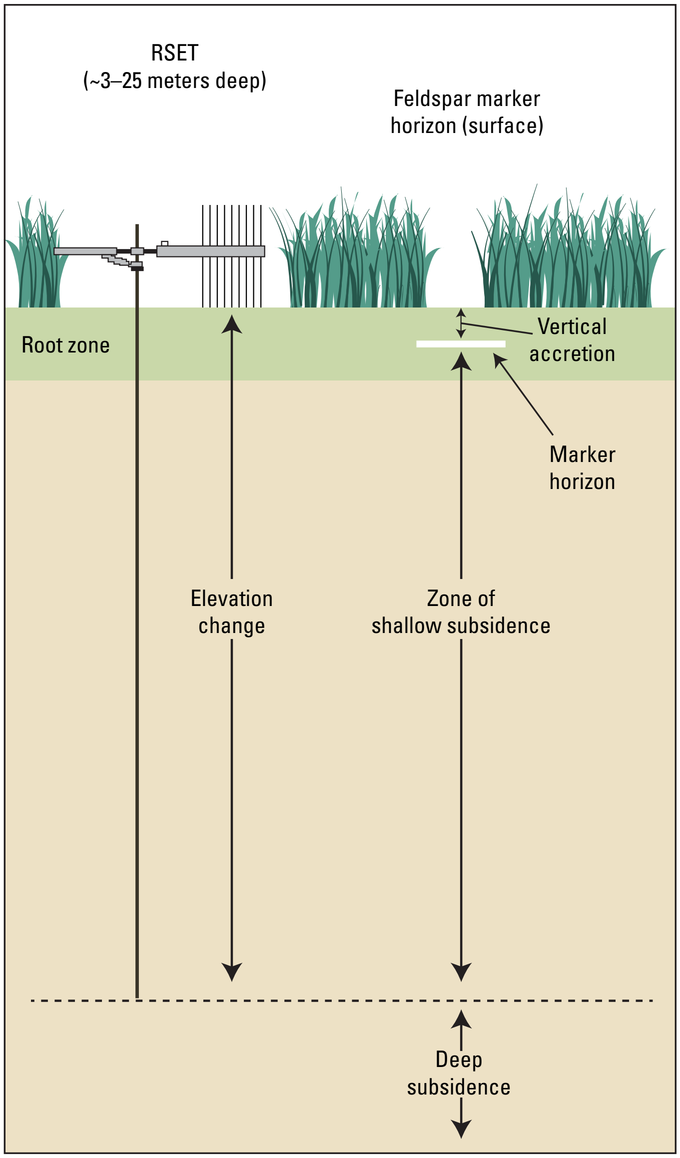

Figure 4. Conceptual diagram of the Rod Surface Elevation Table (RSET) and feldspar marker horizons (from Cahoon and Lynch, 2010).

Elevation Survey Data

The height of the RSET benchmark rod and initial wetland elevation were determined during site construction by using Real-Time Kinematic (RTK) Survey methods and tied into the North American Vertical Datum of 1988 (NAVD 88), according to the CPRA contractor's guide to minimum standards (Coastal Protection and Restoration Authority, 2011). Initial wetland elevation ($Wetland_0$), is defined as the mean of at least 20 (40 in *Spartina patens* marshes) elevation data points (6–12 meters (m) apart) from an individual CRMS site.

Vertical Accretion Data

At each RSET station, vertical accretion is measured in three replicate feldspar plots as the amount of material above the feldspar-marker horizon identified on a cryogenic core. In order to make comparisons of vertical accretion rates among sites and calculate accretion rates on scales larger than site-level (for example, basinwide or coastwide accretion rates), new marker horizons are established at 2-year intervals, to maintain the same temporal scale between sites. Marker horizons are recurrently sampled until they no longer provide accretion data; however, to maintain comparable temporal scales between sites, only short-term (3-year) accretion rates are included in the SVI model. In this model, rate calculations are limited to 3 years, because consistent data collection declines after this period of time. Accretion rates are calculated from replicate feldspar plots by using a linear regression of accretion versus time.

Hydrologic Data

Hydrologic data are collected continually at all CRMS sites. Water level, temperature, specific conductivity, and salinity data are collected hourly from surface water at permanent monitoring stations with continual recording instruments (fig. 5). The continual recording instruments are calibrated, deployed, and monitored according to specifications in Folse and others (2008). The water-level benchmark (top of continual recorder post) is surveyed by using RTK technology, and water levels are tied into the NAVD 88. The sensor rests on top of a fixed hexagonal bolt (1/4 inch (in.) x 3 in. or 5 in.), so that the elevation of the sensor relative to the benchmark can be determined by survey methods (Folse and others, 2008). Mean daily water levels are used to define the hydrologic frame for each site. The current hydrologic frame is defined as the most recent 5-year record of mean daily water levels, known as a Gulf Epoch (National Oceanic and Atmospheric Administration, 2008), and each year within the hydrologic record must meet a 70 percent data completeness criterion. The Gulf Epoch is a Modified Tidal Datum Epoch that incorporates only the most recent 5 years of hydrologic data. Modified Tidal Datum Epochs are used in anomalous areas, such as the northern Gulf of Mexico, where extreme rates of relative sea-level change occur because of localized isostatic influences, such as subsidence, glacial rebound, or tectonic activity (National Oceanic and Atmospheric Administration, 2008).

Index Description

The SVI assesses a site's susceptibility to submergence and allocates a score according to the position of the projected wetland elevation relative to the projected hydrologic frame (figs. 2, 6). Sites with more frequent flooding receive lower scores and are considered more vulnerable to submergence.

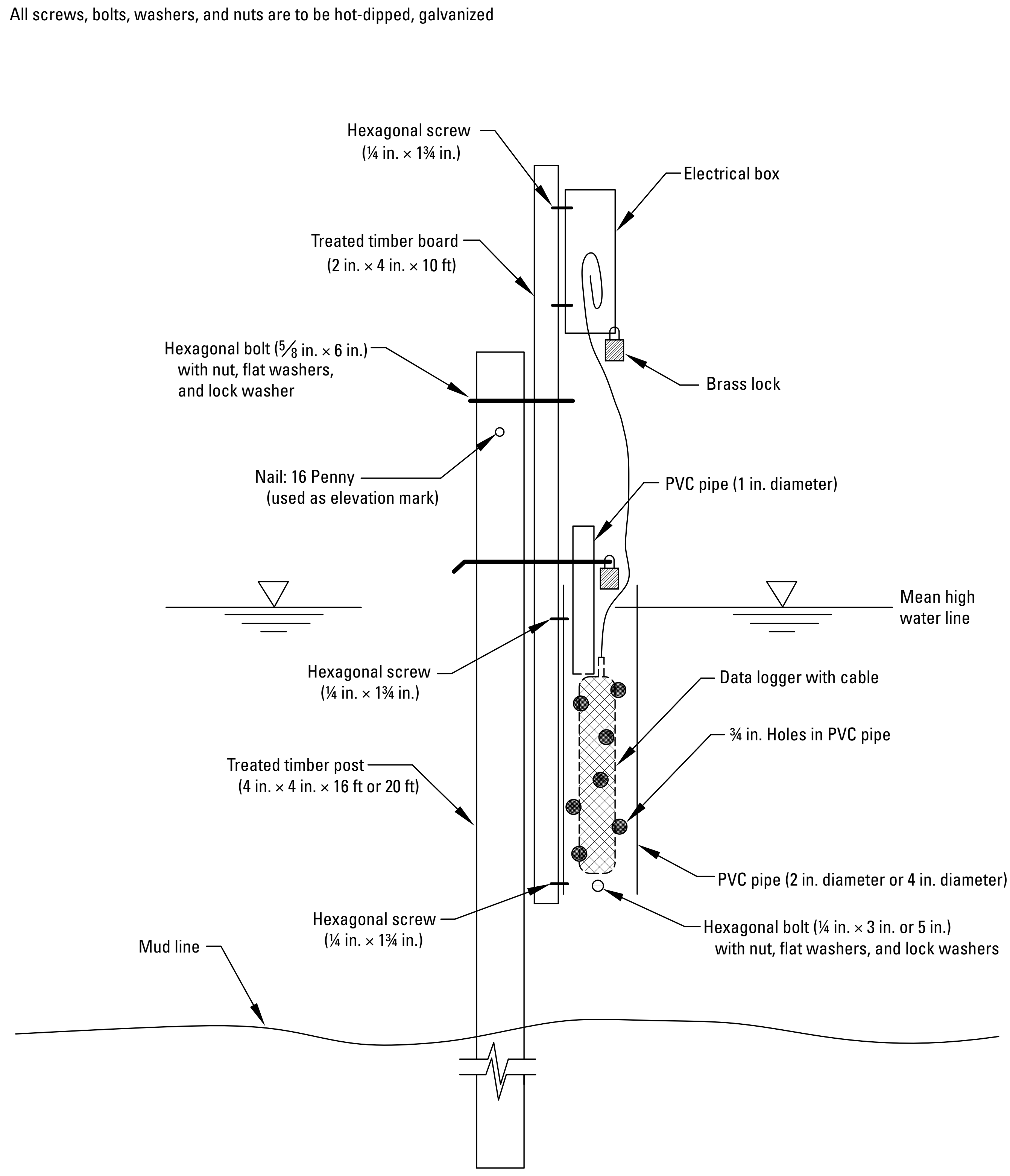

Figure 5. Schematic of the continual water-level recorder used to calculate water elevation in centimeters (cm) relative to the North American Vertical Datum of 1988 (NAVD88) (from Folse and others, 2008).

Wetland elevation is projected 5 years into the future by using the following linear model:

$$Y_{Wetland_t} = \beta_{CEC} * x + \beta_{Wetland_0} \quad (1)$$

where

$Y_{Wetland_t}$ represents the projected wetland elevation,

β_{CEC} is the slope of the wetland surface trajectory and represents the rate of annual cumulative elevation change calculated from RSET data,

x is equal to 5 years, and

$\beta_{Wetland_0}$ is the intercept and represents the initial wetland elevation.

The hydrologic frame is projected by using the following linear model, which is applied to each individual water-level observation in the current hydrologic frame:

$$_1^N Y_{water\,i_t} = \beta_{LRWLT} * x + \beta_{water\,i_0} \quad (2)$$

where

$Y_{water\,i_t}$ is an individual observation of projected mean daily water level,

β_{LRWLT} is the slope and represents the local relative water level trend,

x is equal to 5 years,

$\beta_{water\,i_0}$ is the intercept and represents the individual observation of mean daily water level in the current hydrologic frame, and

$_1^N Y_{water\,i_t}$ represents the consolidated dataset of all individual projected mean daily water levels which define the projected hydrologic frame with N total observations.

The local relative water-level trend, which may be interpreted as a temporally restricted rate of local sea-level rise, is calculated as the sum of shallow subsidence and global eustatic sea-level rise. Shallow subsidence is the difference between accretion and CEC (Cahoon and others, 1995), which are site-specific measurements. Eustatic sea-level rise is set to the global mean of 0.31 centimeters per year (Solomon and others, 2007). Eustatic sea-level rise rates will be refined as better estimates become available.

The position of the projected wetland relative to the projected hydrologic frame determines the SVI score. Specifically, the SVI score is defined in equation 3 as the percentile rank of the projected wetland elevation within the projected water-level distribution:

$$P_n = \frac{100}{N} * \left(n - \frac{1}{2}\right) \quad (3)$$

where

n is the rank of the value of the projected wetland elevation, $Y_{water\,i_t}$, within the projected hydrologic frame, $_1^N Y_{water}$, that contains N total observations.

The SVI scores are interpreted such that sites with higher scores are flooded less and are less vulnerable to submergence within the next 5 years. For example (fig. 6), a ranking in the 62d percentile represents a wetland with an elevation that is higher than 62 percent of the water level observations over a 5-year period. In other words, only 38 percent of the water-level observations are greater than the wetland elevation, indicating that the wetland will only be flooded 38 percent of the time. The underlying assumption is that wetlands situated at lower elevations within the hydrologic frame are more

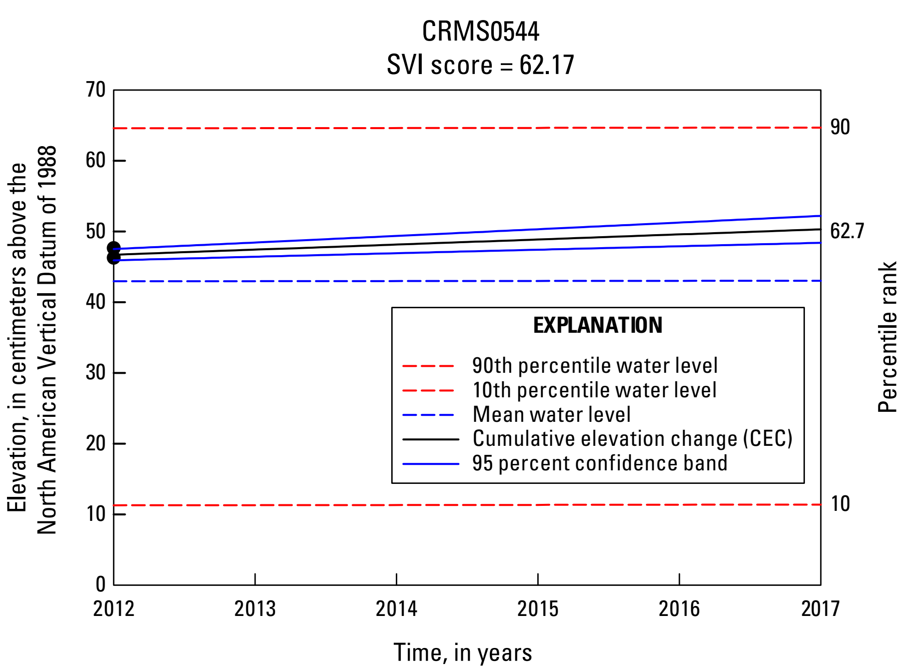

Figure 6. An example of a site-scale assessment of submergence vulnerability for site CRMS0544 by using the Submergence Vulnerability Index (SVI). Specific model parameters are provided as follows: Cumulative elevation change (CEC) = 0.73 (cm y^{-1}); accretion = 0.43 (cm $^{y-1}$); shallow subsidence = 0.29 (cm y^{-1}); eustatic sea-level rise (ESLR) = 0.31 (cm y^{-1}); site relative water level trend = 0.02 (cm y^{-1}); SVI score = 62.17.

vulnerable to future changes in sea level and submergence, than wetlands situated at higher elevations (Kirwan and others, 2012). This assumption is supported by an expansive body of research, which has demonstrated that excessive flooding adversely impacts wetland plant growth (DeLaune and others, 1983; Mendelssohn and McKee, 1988) ultimately disrupting the positive feedback between organic matter accumulation, sedimentation, and elevation sustainability (Morris and others, 2002). In contrast, increasing the elevation of the marsh surface can result in better drainage (King and others, 1982) and increased productivity (Stagg and Mendelssohn, 2010), thereby resulting in an optimal level of flooding, where the critical feedbacks between vegetation and flooding result in elevation maintenance and resilience (Odum and others 1979; Morris and others, 2002; Kirwan and Murray, 2008; Stagg and Mendelssohn, 2011).

Although the relations between vegetation production and flooding were used to develop the concept of the SVI, it is important to emphasize that the objective of this index is not to identify thresholds of collapse or productivity but to evaluate the intensity of flooding that is likely to occur based on the wetland-elevation trajectory and local water-level trends. Therefore, to achieve a complete assessment of a wetland, this index should be used in conjunction with supplemental data (for example, plant production, nutrient availability, species richness, among others) that will contribute to the understanding of the overall ecological status of the system.

Implementation and Evaluation

The primary objective of the CRMS analytical index development effort is to provide a mechanism to assess the effectiveness of CWPPRA projects. Restoration projects can be evaluated by comparing the SVI scores of CRMS sites within project boundaries to CRMS reference sites (fig. 7).

Additionally, the coastwide distribution of CRMS sites allows SVI scores to be used for multiscaled evaluations. For example, a CRMS project site can be compared to other CRMS sites across multiple scales including all sites within the basin, all sites within the same wetland classification, or all sites across the coast (fig. 8).

Similarly, a coastwide assessment can compare all restoration sites to all reference sites. This approach will allow the coastal restoration community to assess the effectiveness of particular restoration projects, regional trends, and the overall effectiveness of a coastwide restoration plan. The SVI can also be used to perform a general coastwide assessment to identify areas of vulnerability. These general assessments can be used to focus study and restoration strategy planning. In a demonstration of a coastwide assessment, the SVI was calculated by using data from 153 CRMS sites that satisfied all of the data completeness criteria (fig. 9).

The scores were distributed relatively evenly along the scale with a median score of 54, with 25 percent of the sites scoring below a score of 23 and 25 percent of sites scoring above 72 (fig. 10*A*). Spatially, however, the scores were not evenly distributed across the coast. Regions that are highly susceptible to submergence can be highlighted so that the

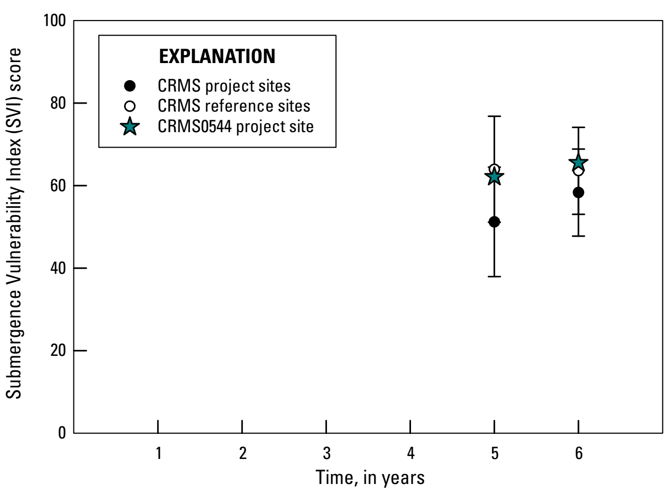

Figure 7. Submergence Vulnerability Index scores for an individual site (CRMS0544 project site) located within a restoration project. This individual site score was compared to all other Coastwide Reference Monitoring System (CRMS) sites located within in the same wetland classification and hydrologic basin within the project boundary (CRMS project sites) or outside of the project boundary (CRMS reference sites). Error bars represent standard errors.

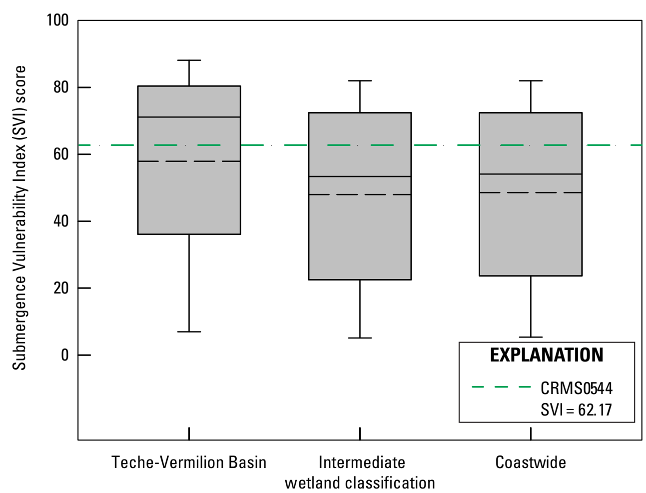

Figure 8. Multiple scale comparison of Submergence Vulnerability Index (SVI) scores between an individual site (CRMS0544) and all sites within the same basin, all sites within the same wetland classification, and all sites coastwide. The lower and upper limits of the box plot represent the first and third quartile, respectively. The solid middle line represents the median and the dashed line represents the mean. The error bars represent the 10th and 90th percentiles.

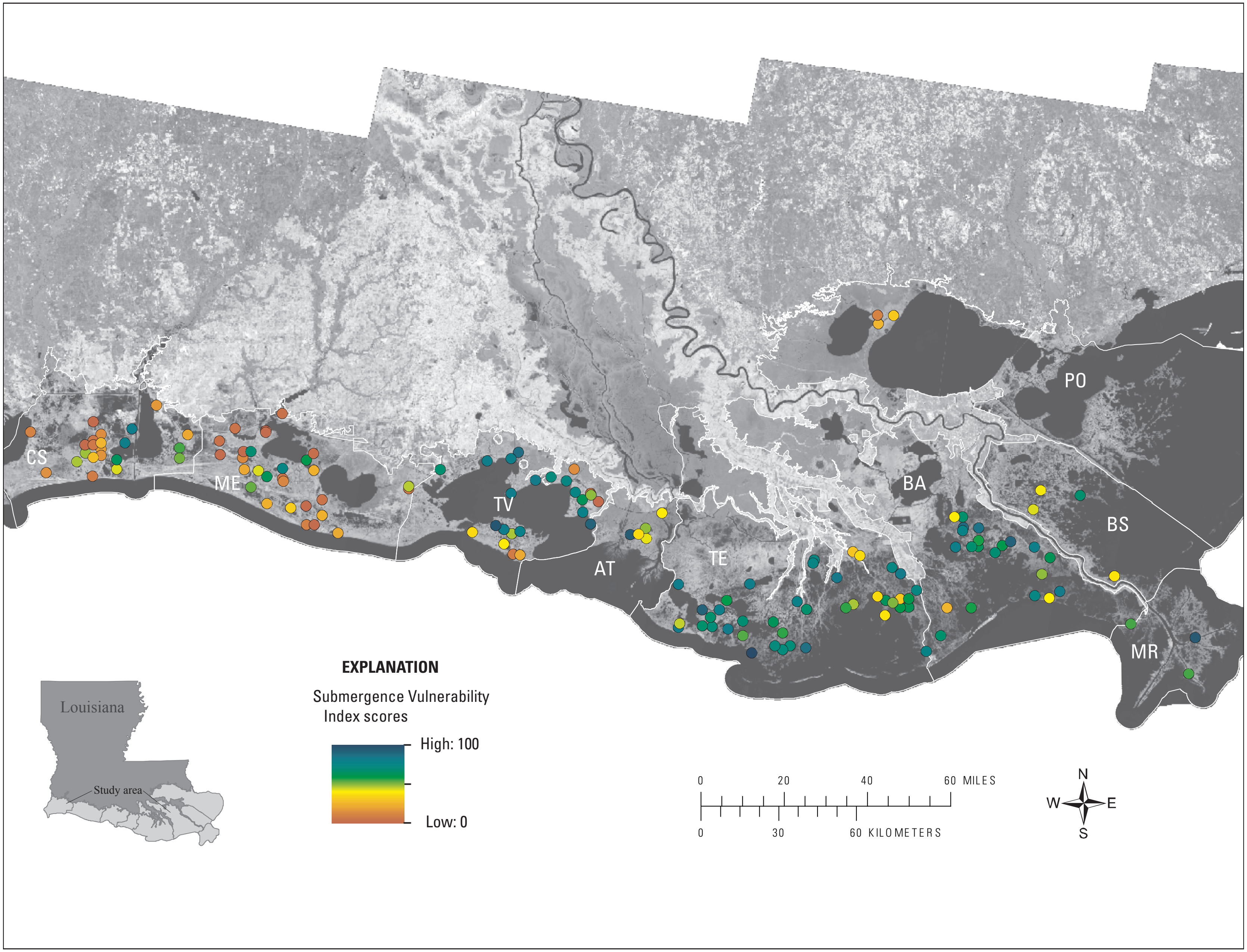

Figure 9. Coastwide spatial distribution of wetland submergence vulnerability represented by Submergence Vulnerability Index (SVI) scores for Coastwide Reference Monitoring System (CRMS) sites containing at least 5 years of elevation-change data. Sites with SVI score calculations are located in the Calcasieu Basin (CS), Mermentau Basin (ME), Teche-Vermilion Basin (TV), Atchafalaya Basin (AT), Terrebonne Basin (TE), Barataria Basin (BA), Lake Pontchartrain Basin (PO), Breton Sound (BS), and Mississippi River Delta (MR).

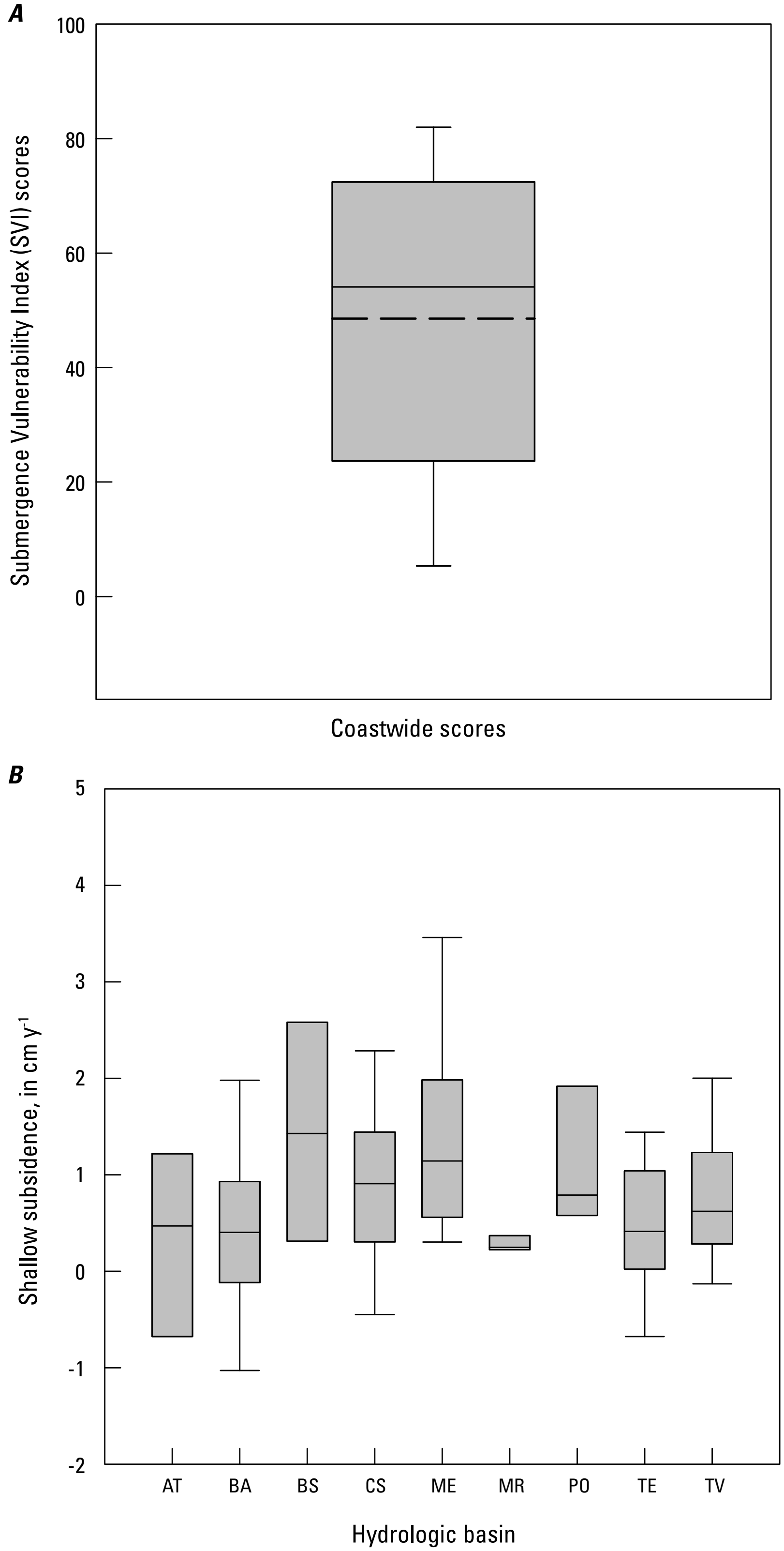

Figure 10. *A*) Distribution of coastwide Submergence Vulnerability Index (SVI) scores. The lower and upper limits of the box plot represent the first and third quartile, respectively. The solid middle line represents the median, and the dashed line represents the mean. The error bars represent the 10th and 90th percentiles. *B*) Shallow subsidence rates separated by hydrologic basin: Atchafalaya Basin (AT), Barataria Basin (BA), Breton Sound (BS), Calcasieu-Sabine Basin (CS), Mermentau Basin (ME), Mississippi River Delta (MR), Lake Pontchartrain Basin (PO), Terrebonne Basin (TE) and Teche-Vermilion Basin (TV).

causes of vulnerability may be determined. For example, the terminally impounded Mermentau (ME; fig. 10*B*) Basin on the Chenier Plain had the most sites within the lower quartile of the score distribution (scores <24). In addition to high rates of subsidence (fig. 10*B*), water levels in the Mermentau Basin area are managed for agriculture, thereby resulting in high water levels compared to wetland surface elevation. Submergence in other hydrologic basins of the coast was due to high rates of shallow subsidence (Breton Sound, Calcasieu-Sabine Basin, and Pontchartrain Basins).

Assessing a site's vulnerability to submergence can be an initial and critical step in assessing ecosystem health, project effectiveness, and planning and implementation of adaptive management. Furthermore, incorporating supplemental data describing other abiotic and biotic processes known to influence wetland elevation (Cahoon and others, 2006) can illuminate the mechanisms contributing to submergence vulnerability on a site-specific scale and inform management decisions.

References Cited

Cahoon, D.R., Hensel, P.F., Spencer, T., Reed, D.J., McKee, K.L., and Saintilan, N., 2006, Coastal wetland vulnerability to relative sea-level rise—Wetland elevation trends and process controls, *in* Verhoeven, J.T.A., Beltman, R., Bobbink, R., and Whigham, D.F., eds., Ecological studies—Wetlands and natural resource management: Berlin, Springer-Verlag, v. 190, p. 271–292.

Cahoon, D.R., and Lynch, James, 2010, Surface elevation table (SET): U.S. Geological Survey, Patuxent Wildlife Research Center, accessed March 2013, at http://www.pwrc.usgs.gov/set/.

Cahoon, D.R., Lynch, J.C., Perez, B.C., Segura, Bradley, Holland, R., Stelly, C., Stephenson, G., and Hensel, P., 2002, High precision measurement of wetland sediment elevation—II. The rod surface elevation table: Journal of Sediment Research, v. 72, p. 734–739.

Cahoon, D.R., Reed, D.J., and Day, J.W., Jr., 1995, Estimating shallow subsidence in microtidal salt marshes of the southeastern United States—Kaye and Barghoorn revisited: Marine Geology, v. 128, p. 1–9.

Cahoon, D.R., Williams, S.J., Gutierrez, B.T., Anderson, K.E., Thieler, E.R., and Gesch, D.B., 2009, Part I overview—The physical environment, chap. 4 *of* Coastal sensitivity to sea-level rise—A focus on the Mid-Atlantic Region: Washington, D.C., A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, U.S. Environmental Protection Agency, p. 191–238.

Couvillion, B.R., Barras, J.A., Steyer, G.D., Sleavin, William, Fischer, Michelle, Beck, Holly, Trahan, Nadine, Griffin, Brad, and Heckman, David, 2011, Land area change in coastal Louisiana from 1932 to 2010: U.S. Geological Survey Scientific Investigations Map 3164, scale 1:265,000, 12 p. pamphlet.

Coastal Protection and Restoration Authority [CPRA], 2011, A contractor's guide to minimum standards required by the Coastal Protection and Restoration Authority—For contractors performing GPS surveys and determining GPS derived orthometric heights within the Louisiana Coastal Zone: Baton Rouge, La., Coastal Protection and Restoration Authority, Operations Division, 40 p.

Cretini, K.F., Visser, J.M., Krauss, K.W., and Steyer, G.D., 2011, CRMS vegetation analytical team framework—Methods for collection, development, and use of vegetation response variables: U.S. Geological Survey Open-File Report 2011–1097, 60 p.

DeLaune, R.D., Smith, C.J. and Patrick, W.H., Jr., 1983, Relationship of marsh elevation, redox potential, and sulfide to *Spartina alterniflora* productivity: Soil Science Society of America, v. 47, p. 930–935.

Folse, T.M., West, J.L., Hymel, M.K., Troutman, J.P., Sharp, L.A., Weifenbach, D.K., McGinnis, T.E., Rodrigue, L.B., Boshart, W.M., Richardi, D.C., Miller, C.M., and Wood, W.B., 2008, A standard operating procedures manual for the Coast-wide Reference Monitoring System-Wetlands—Methods for site establishment, data collection, and quality assurance/quality control: Baton Rouge, La., Louisiana Coastal Protection and Restoration Authority, 207 p. (Revised 2012.)

Gornitz, V., 1991, Global coastal hazards from future sea level rise: Palaeogeography, Palaeodimatology, Palaeoecology, v. 89, p. 379–398.

Harrison, E.Z., 1975, Sedimentation rates, shoreline modification, and vegetation changes on tidal marshes along the coast of Connecticut: Ithaca, Cornell University, M.S. thesis, 107 p.

King, G.M., Klug, M.J., Wiegert, R.G., and Chalmers, A.G., 1982, Relation of soil water movement and sulfide concentration to *Spartina alterniflora* production in a Georgia salt marsh: Science, v. 218, p. 61–63.

Kirwan, M.L., Christian, R.R., Blum, L.K., and Brinson, M.M., 2012, On the relationship between sea level and *Spartina alterniflora* production: Ecosystems, v. 15, p. 140–147.

Kirwan, M.L., and Murray, A.D., 2008, Ecological and morphological response of brackish tidal marshland to the next century of sea level rise—Westham Island, British Columbia: Global and Planetary Change, v. 60, p. 471–486.

Mendelssohn, I.A., and McKee, K.L., 1988, *Spartina alterniflora* die-back in Louisiana—Time-course investigation of soil waterlogging effects: Journal of Ecology, v. 76, p. 509–521.

Mendelssohn, I.A., and Seneca, E.D., 1980, The influence of soil drainage on the growth of salt marsh cordgrass *Spartina alterniflora* in North Carolina: Estuarine and Coastal Marine Science, v. 11, p. 27–40.

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

National Oceanic and Atmospheric Administration (NOAA), 2008, Sea level variations of the United States 1854-2006: Technical Report NOS CO-OPS 053, 78 p. + variously paged appendixes.

Nyman, J.A., DeLaune, R.D., Roberts, H.H., and Patrick, W.H., Jr., 1993, Relationship between vegetation and soil formation in a rapidly submerging coastal marsh: Marine Ecology Progress Series, v. 96, p. 269–279.

Nyman, J.A., Walters, R.J., DeLaune, R.D., and Patrick, W.H., Jr., 2006, Marsh vertical accretion via vegetative growth: Estuarine, Coastal and Shelf Science, v. 69, p. 370–380.

Odum, E.P., Finn, J.T., and Franz, E.H., 1979, Perturbation theory and the subsidy-stress gradient: Bioscience, v. 29, p. 349–352.

Sasser, C.E., Visser, J.M., Mouton, E., Linscombe, J., and Hartley, S.B., 2008, Vegetation types in coastal Louisiana in 2007: U.S. Geological Survey Open-File Report 2008–1224, 1 sheet, scale 1:550,000, accessed April 2009, at http://pubs.usgs.gov/of/2008/1224/.

Snedden, G.A., and Swenson, E.M., 2012, Hydrologic index development and application to selected Coast-wide Reference Monitoring System sites and Coastal Wetlands Planning, Protection and Restoration Act projects: U.S. Geological Survey Open-File Report 2012–1122, 25 p.

Solomon, S., Qin, D., Manning, M., Marquis, M., Averyt, K., Tignor, M.M.B., Miller, H.L., Jr., and Chen, Z., eds., 2007, Climate change 2007—The physical science basis: United Kingdom, Cambridge University Press, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), 996 p.

Stagg, C.L., and Mendelssohn, I.A., 2010, Restoring ecological function to a submerged salt marsh: Restoration Ecology, v. 18, issue supplement s1, p. 10–17.

Stagg, C.L., and Mendelssohn, I.A., 2011, Controls on resilience and stability in a sediment subsidized salt marsh: Ecological Applications, v. 21, p. 1731–1744.

Steyer, G.D., Sasser, C.E., Visser, J.M., Swenson, E.M., Nyman, J.A., and Raynie, R.C., 2003, A proposed coast-wide reference monitoring system for evaluating wetland restoration trajectories in Louisiana: Environmental Monitoring and Assessment, v. 81, p. 107–117.

Steyer, G.D., Twilley, R.R., and Raynie, R.C., 2006, An integrated monitoring approach using multiple reference sites to assess sustainable restoration in coastal Louisiana: U.S. Department of Agriculture, Forest Service Proceedings RMRS-P-42CD, 8 p.

Publishing support provided by
Lafayette Publishing Service Center

USGS

Stagg and others—**Submergence Vulnerability Index Development and Application to CRMS Sites and CWPPRA Projects**—OFR 2013–1163

Printed on recycled paper