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

Open-File Report 2012–1122

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

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By Gregg A. Snedden and Erick M. Swenson

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

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

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Abstract

Hourly time-series salinity and water-level data are collected at all stations within the Coastwide Reference Monitoring System (CRMS) network across coastal Louisiana. These data, in addition to vegetation and soils data collected as part of CRMS, are used to develop a suite of metrics and indices to assess wetland condition in coastal Louisiana. This document addresses the primary objectives of the CRMS hydrologic analytical team, which were to (1) adopt standard time-series analytical techniques that could effectively assess spatial and temporal variability in hydrologic characteristics across the Louisiana coastal zone on site, project, basin, and coastwide scales and (2) develop and apply an index based on wetland hydrology that can describe the suitability of local hydrology in the context of maximizing the productivity of wetland plant communities.

Approaches to quantifying tidal variability (least squares harmonic analysis) and partitioning variability of time-series data to various time scales (spectral analysis) are presented. The relation between marsh elevation and the tidal frame of a given hydrograph is described. A hydrologic index that integrates water-level and salinity data, which are collected hourly, with vegetation data that are collected annually is developed. To demonstrate its utility, the hydrologic index is applied to 173 CRMS sites across the coast, and variability in index scores across marsh vegetation types (fresh, intermediate, brackish, and saline) is assessed. The index is also applied to 11 sites located in three Coastal Wetlands Planning, Protection and Restoration Act projects, and the ability of the index to convey temporal hydrologic variability in response to climatic stressors and restoration measures, as well as the effect that this community may have on wetland plant productivity, is illustrated.

Introduction

The Coastwide Reference Monitoring System (CRMS), a network of 392 monitoring stations across the Louisiana coast, was implemented under the Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA; Steyer and others, 2006). This network of monitoring stations enables the characterization of the Louisiana coastal wetland landscape across varying spatial and temporal scales. Because CRMS stations are located inside and outside of CWPPRA project boundaries, the stations can be used to assess CWPPRA project effectiveness. Comparisons can also be made at other spatial scales including marsh type and hydrologic basin (Steyer and others, 2003; 2006).

To evaluate the performance of CWPPRA projects with CRMS it is pertinent that existing knowledge and data are used to establish informed restoration targets. The existing knowledge includes an understanding of how vegetation communities respond to variations in local hydrology (Visser and others, 2003) and the extensive hydrologic and vegetation datasets maintained as part of the CRMS program. Individual indices for hydrology, vegetation, and soils are being developed to assess the condition of Louisiana's coastal landscapes at various scales, and these indices, along with other community indicators, can be used to assess restoration project effectiveness.

This report gives an overview of standard time-series techniques that can be applied to hydrologic time-series data collected under CRMS to quantify local hydrologic conditions at CRMS sites. This report also describes the development of a "hydrologic index" used in the analysis of data collected under CRMS in use by the U.S. Geological Survey (USGS) and Louisiana Coastal Protection and Restoration Authority (CPRA), as part of CWPPRA activities, to monitor wetland restoration projects. The term "hydrologic index" is being used in a broad sense to include water levels and salinity. This index will be used, along with vegetation and soil indices, to assess the effectiveness of projects carried out under the

CWPPRA restoration plan to create, restore, protect, and enhance the coastal wetlands of Louisiana.

Review of CWPPRA Monitoring Plans

Figure 1 presents a summary of the restoration techniques being used under CWPPRA. Of the 111 monitoring plans reviewed, 40 (36 percent) use techniques that directly involved changes in hydrology (red bars). The specific hydrologic goals for those 40 monitoring plans are presented in figure 2. Changing the water level and/or salinity regime was the specific hydrologic goal in 52 (91 percent) of the 57 hydrologic goals listed. The larger scale hydrologic questions that are of interest to these CWPPRA projects are as follows:

Question: Is CWPPRA effective in reducing the major stressors on wetlands?

Answer: As shown in figure 2, objectives for most projects include the ability to reduce flooding duration and/or decrease salinity. This question can therefore be best answered in two parts:

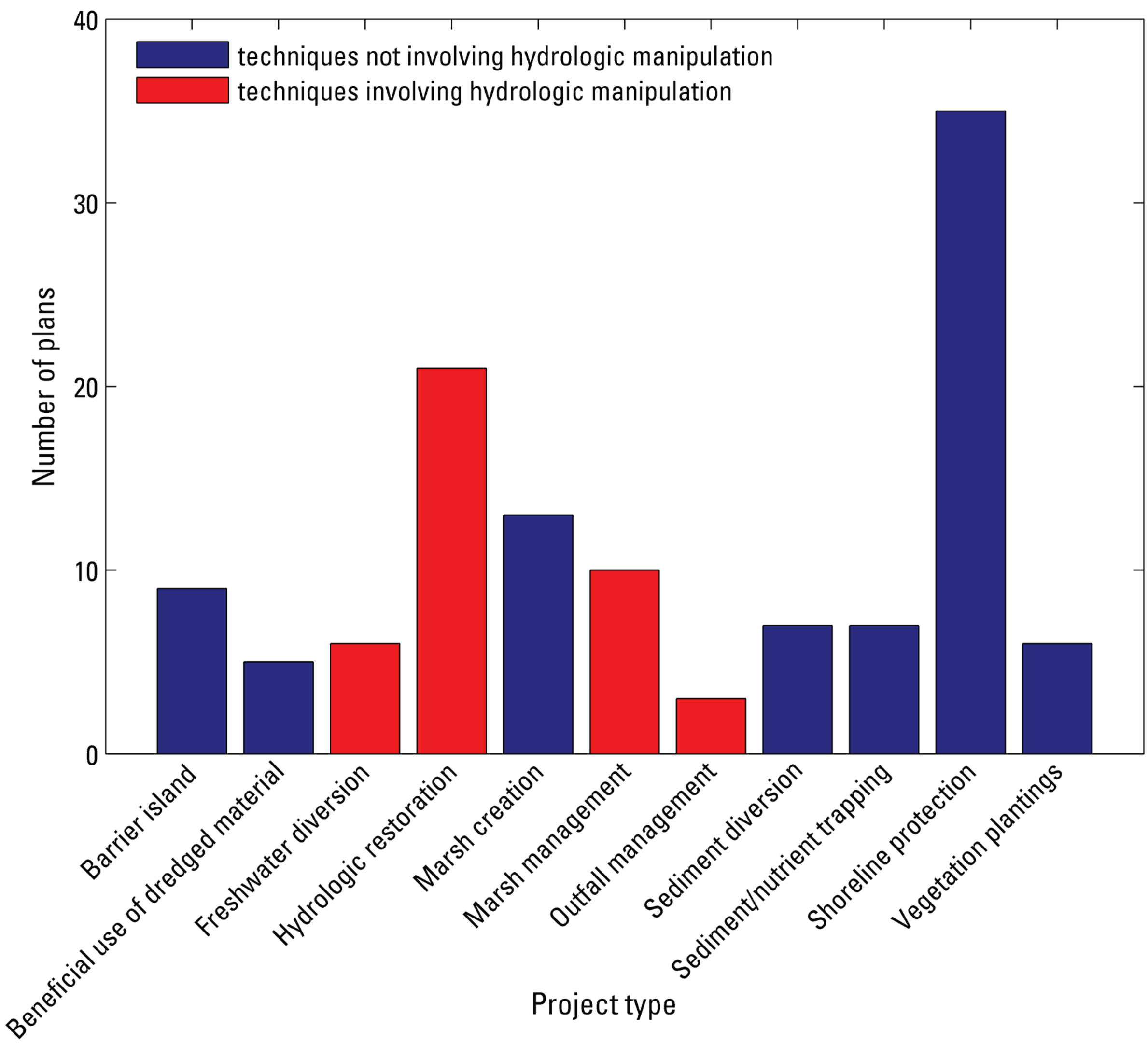


Figure 1. Summary of restoration techniques to be used on the basis of a review of 111 monitoring plans written under the Coastal Wetlands Planning, Protection and Restoration Act.

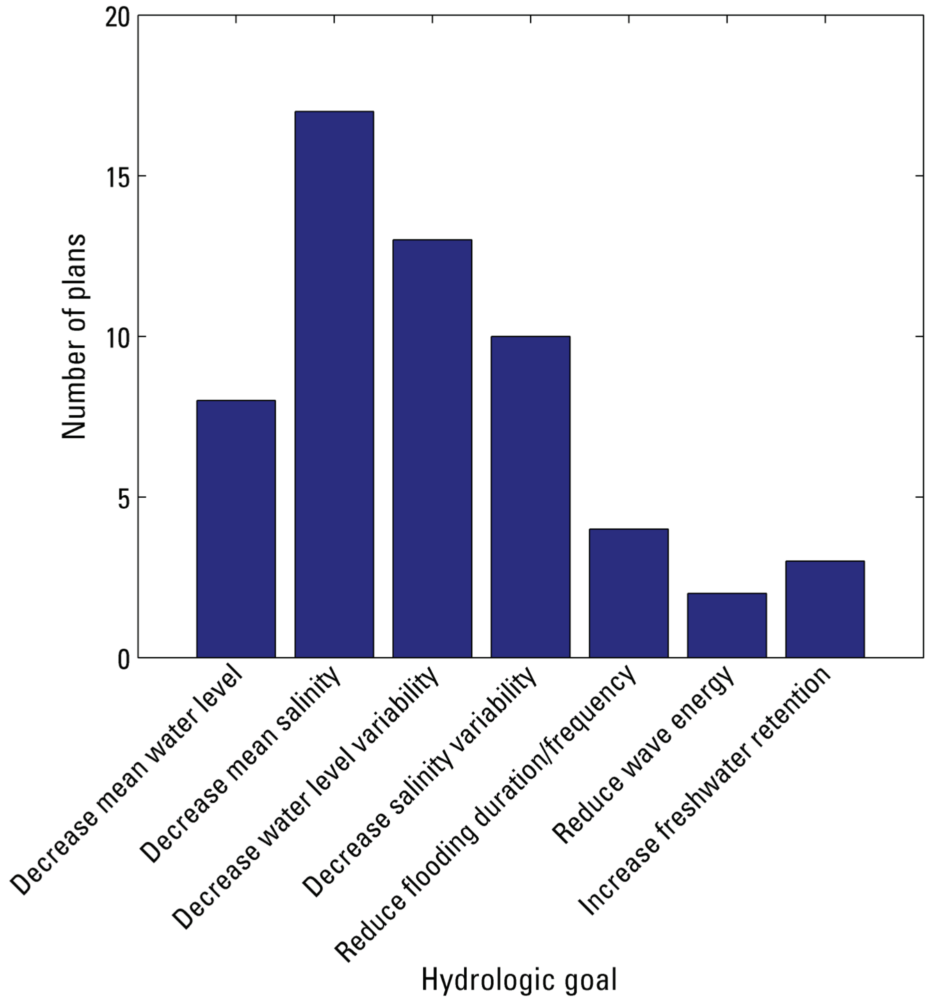


Figure 2. Summary of hydrologic goals based on a review of 40 projects funded by the Coastal Wetlands Planning, Protection and Restoration Act in which hydrologic manipulation is a project strategy.

Subquestion: Is CWPPRA effective in altering flooding in those projects that were intended to alter flooding? In other words, is the flooding reduced in the project sites relative to the flooding in the reference sites?

Answer: The comparison with the reference sites is necessary to account for changes in flooding caused by factors other than effects of CWPPRA projects, such as changes in sea level, river discharge, and rainfall. Variance components and changes in possible cycles and continuous behavior of the response will be assessed.

Subquestion: Is the CWPPRA effective in altering salinity in those projects that were intended to alter salinity?

Answer: Typically, projects are intended to reduce overall mean salinity and/or salinity spikes relative to the selected reference sites. The comparison with the selected reference sites is necessary to remove changes in salinity caused by other influences such as sea level, river discharge, and rainfall. Variance components and changes in possible cycles and continuous behavior of the response will be assessed.

Tides in the Louisiana Coastal Zone

Tides and Harmonic Analysis

The astronomical tides are the periodical rises and falls of the sea surface that result from the differences in the gravitational attraction of the sun and moon at various locations on the earth as the earth-moon system orbits the sun. The sun and the moon both generate tide-producing forces; however, the moon is 2.16 times more influential than the sun, and so the tide, in most locations, is primarily controlled by the lunar tide-generating forces and modified by the solar tide-generating forces (Hicks, 2006). The numbers of configurations of the sun, moon, and earth that are possible during the course of time are numerous, and so they are repeated only roughly during successive months (von Arx, 1974).

Excluding nontidal effects such as winds, sea level y at a given time $t_i \in \{t_1, t_2, \ldots, t_N\}$ can be resolved into M simple sinusoidal periodic forces, or tidal constituents, with angular frequency $\omega = 2\pi f$ where f is the frequency of the tidal constituent, or the inverse of the constituent's period T:

$$y(t_i) = Z_o + \sum_{j=1}^{M} \left\{ C_j \cos(\omega_j t_i) + S_j \sin(\omega_j t_i) \right\} \quad (1)$$

where Z_o is mean sea level. Obtaining C and S is achieved through harmonic analysis, where sine and cosine waves with periods corresponding to the periods of specific tidal constituents sought are fit through water-level datasets with a least squares model by finding the solution **x** to the matrix equation

$$\mathbf{x} = \mathbf{A}^{-1}\mathbf{y} \quad (2)$$

where **y** is the observation vector

$$\mathbf{y} = \begin{pmatrix} y(t_1) \\ y(t_1) \\ \cdots \\ y(t_N) \end{pmatrix} \quad (3)$$

and **A** is the design matrix

$$\mathbf{A} = \begin{pmatrix} 1 & \cos(\omega_1 t_1) & \sin(\omega_1 t_1) & \cos(\omega_2 t_1) & \sin(\omega_2 t_1) & \cdots & \cos(\omega_M t_1) & \sin(\omega_M t_1) \\ 1 & \cos(\omega_1 t_2) & \sin(\omega_1 t_2) & \cos(\omega_2 t_2) & \sin(\omega_2 t_2) & \cdots & \cos(\omega_M t_2) & \sin(\omega_M t_2) \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 1 & \cos(\omega_1 t_N) & \sin(\omega_1 t_N) & \cos(\omega_2 t_N) & \sin(\omega_2 t_N) & \cdots & \cos(\omega_M t_N) & \sin(\omega_M t_N) \end{pmatrix} \quad (4)$$

Elements from the solution vector **x**

$$\mathbf{x} = \begin{pmatrix} Z_o \\ C_1 \\ S_1 \\ C_2 \\ S_2 \\ \cdots \\ C_M \\ S_M \end{pmatrix} \quad (5)$$

can then be used to obtain amplitudes (A_j) and phases (ϕ_j) for each of the M tidal constituents according to

$$A_j = \sqrt{C_j^2 + S_j^2} \quad (6)$$

and

$$\phi_j = \arctan\left(\frac{S_j}{C_j}\right) \quad (7)$$

Amplitude describes the height of the constituent, and phase is an indicator of the timing of the constituent (fig. 3). Generally, phase becomes meaningful only when the timing of tides between two stations is examined, or when the timing of two different tidal phenomena at a single station is investigated (for example, tide height and current velocity).

Although the number of constituents can be quite large, the principal features of the tide at a given location generally can be described by using five principal constituents (table 1). The "principal lunar semidiurnal" component (M_2), which has a periodicity of 12.42 hours, and the "principal solar semidiurnal" component (S_2), which has a periodicity of 12.0 hours, together produce a semidiurnal tide which has two highs and two lows during a day. The orbit of the moon is elliptical, so the tidal-producing force varies on a 27.5 day period as the moon revolves around the earth. To account for this variation the "larger lunar elliptic semidiurnal" component (N_2), which has a period of 12.66 hours, is used. The orbit of the moon is also inclined to the plane of the equator; thus, the declinations of the sun and the moon are constantly changing. To account for this effect two other tidal components the "Lunar diurnal" component, which has a periodicity of 25.82 hours (referred to as O_1), and the "luni-solar diurnal," which has a periodicity of 23.93 hours component (referred to as K_1) are used (Marmer, 1954). These components will produce a diurnal tide which has one high and one low during a day.

If they are added together, the separate tidal constituents will reproduce the astronomically forced tidal signal at a given location, as illustrated in figure 4. This figure presents the tidal constituents for Grand Isle, Louisiana. Note, it does not include effects related to nonastronomical conditions such as winds. It can be seen that the constituents with the largest amplitude are the K_1 and O_1 diurnal tides. These constituents are typical for areas, such as the Gulf of Mexico, that are dominated by diurnal tides (Marmer, 1954).

At times of the month when the O_1 and K_1 are in phase, the two components constructively interfere, and amplitude of the tide increases. This phenomenon occurs when the moon is over the Tropic of Cancer or the Tropic of Capricorn; thus, these higher tides are referred to as "tropic tides." At times of the month when O_1 and K_1 are out of phase, the two components destructively interfere, and the amplitude of the tides decreases. This phenomenon occurs when the moon is over the Equator; thus, these lower ranges are referred to as "equatorial tides." This tropic-equatorial cycle is the diurnal

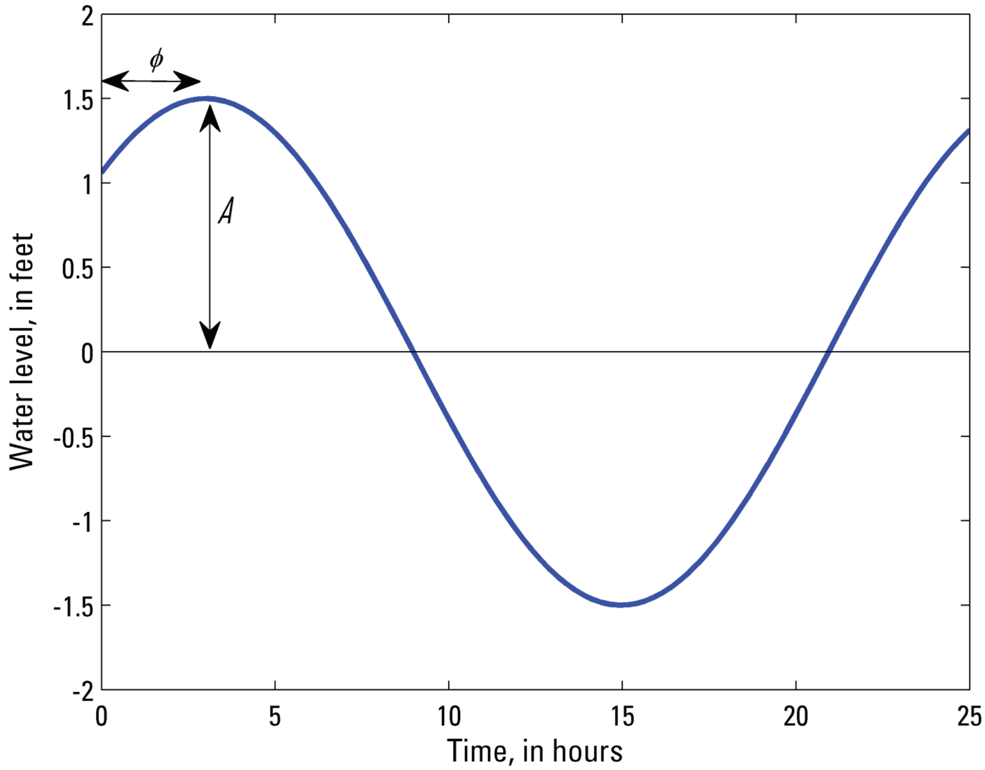


Figure 3. Graphical depiction of the amplitude (*A*) and phase (*ϕ*) components of tidal constituents.

analog of the spring-neap cycle found in coastal areas with semidiurnal tidal regimes. The variation in range between tropic and equatorial tides represents the greatest change that occurs in the astronomical tidal amplitude for tides in Louisiana. This effect can be seen at the Grand Isle location (fig. 4) and is illustrated in greater detail in figure 5.

In addition to astronomically forced variations, sea level in the northern Gulf of Mexico is also strongly influenced by wind stress, both on synoptic (3–10 day) and seasonal timescales. The synoptic-scale variations result from periodic passages of meteorological fronts and are most prominent between October and April. The seasonal fluctuations produce a semiannual sea-level cycle that exhibits highs in the spring and fall when prolonged westward wind stresses (wind blowing toward west) push water against the coast via Ekman convergence. Reduced water levels occur during late summer when wind stresses diminish. During the winter, prolonged periods of southward (toward south) and eastward (toward east) wind stress tend to push water away from the coast, producing even lower water levels (fig. 6).

The tides within the Gulf of Mexico also exhibit the effect of the 18.6-year lunar epoch. This change in tidal range is due to the change of the inclination of the Moon's orbit relative to the Earth's equator. Baumann (1987) noted that for Barataria Basin, this change is greater than the seasonal change but is much less than the biweekly change. He also noted that marsh inundation frequency is positively related to this 18.6-year cycle. The water levels in the Gulf of Mexico also exhibit longer term (30 year) trends which are due to larger scale geologic processes (such as global sea-level rise, regional subsidence). The sea-level trends for the United States were summarized by Lyles and others (1988). Their analysis of stations in the Gulf of Mexico showed relatively stable conditions at the Florida stations with long-term trends ranging from 0.007 to 0.010 ft/year (2 to 3 mm/year). The Louisiana and northern Texas stations showed long-term trends ranging from 0.020 to 0.046 ft/year (6 to 14 mm/year). The southern Texas stations (south of Rockport) again showed stable conditions with trends ranging from 0.010 to 0.013 ft/year (3 to 4 mm/year).

It is thus clear that water level can vary over a broad range of timescales including those with daily (astronomical tides), weekly (synoptic weather forcing), annual and interannual periods. Because the goal of many hydrologic restoration projects is to reduce water-level variability, it can be useful to partition the variability according to the timescale over which it occurs in order to determine what processes are driving the variability. A powerful method for partitioning time-series variability in such a manner is spectral analysis.

Table 1. Periods and frequencies of major tidal constituents.

Constituent	Name	Period (hours)	Frequency (cycles per hour)
M_2	principal lunar semidiurnal	12.42	0.0805
S_2	principal solar semidiurnal	12.00	0.0833
N_2	larger lunar elliptic semidiurnal	12.66	0.0789
O_1	lunar diurnal	25.82	0.0387
K_1	luni-solar diurnal	23.93	0.0418

Mean Sea Level

Mean sea level (MSL) is defined as the average of the hourly values of water levels measured over a 19-year tidal datum epoch (Hicks, 1989). In practice mean tide level (MTL), a plane midway between high and low water that is computed by averaging the high and low water levels over a 19-year period of observation (Swanson, 1974), is often used in place of MSL because it is easier to compute. MSL and MTL approximate each other along the open coast (Swanson, 1974). The National Geodetic Vertical Datum (NGVD), a fixed (relative to the center of the earth) datum based upon the best fit over a large area, does not take into account local variations or changing stands in sea level and should not be confused with MSL (Hicks, 1989). The relation between MTL (or MSL) and NGVD is not consistent from one location to another in either time or space (Swanson, 1974); thus, to standardize MSL estimates local tide data are tied into a specified National Tidal Datum Epoch, which is a specific 19-year time period over which observations are to be averaged to compute means (Hicks, 1989).

It is possible, however, to compute means based upon short-term datasets. This short-term mean may or may not be an accurate representation of the accepted value of MTL depending upon location. Swanson (1974) compared MSL from short-term records to MTL calculated from a 19 year record. His results indicated that for the Gulf Coast, with 1 month of observations, the accuracy of the estimate of MTL is ~0.181 ft (5.5 cm) but the accuracy improves nonlinearly to ~0.098 ft (3 cm) with 12 months of observations.

Spectral Analysis

As shown previously, periodic variability present in time series data can be represented as a sum of periodic terms involving combinations of sines and cosines. In a general sense, this principle applies not only to strictly periodic phenomena such as astronomical tides but also quasi-periodic phenomena such as meteorologically forced fluctuations that occur over longer timescales. Thus,

$$y(t_i) = Z_o + \sum_{j=1}^{M}\left\{C_j \cos(2\pi f_j t_i) + S_j \sin(2\pi f_j t_i) + \varepsilon(t_i)\right\} \quad (8)$$

still applies, though a noise term ($\varepsilon(t_i)$) is included to account for stochasticity, or noise, because the data are not strictly periodic. Unlike harmonic analysis, periods of variability are sought, rather than known *a priori*, and coefficients C_j and S_j are obtained for periods T_j that are harmonics of a fundamental period T_o such that $T_j = T_o / T_j$, where $j = 0, 1, \ldots, N/2$ and N is the total number of observations in the time series. Generally, T_o is taken equal to the length of the data series. The variance ($S_{yy}(f)$) associated with each period T_j (or frequency $f_j = \frac{1}{T_j}$) can be obtained as

$$S_{yy}(f) = N(C_f^2 + S_f^2)/2 \quad (9)$$

where $0 \le f \le f_{N/2}$.

A *variance spectrum* can then be obtained by plotting variance S_{yy} as a function of frequency f (or period T). Because water-level variability driven by different processes (for example, astronomical tides, wind-driven variations) often occur over widely disparate timescales (diurnal versus weekly), variance spectra can provide insight as to what processes are dominant in forcing water-level variability at a given site or time period.

Two contrasting sites (saline and intermediate) in Breton Sound (fig. 7) were selected to investigate water-level variability via spectral analysis. The water-level spectrum of a strongly tidal saline marsh looks considerably different from that of an intermediate marsh where the tide is strongly muted (fig. 8). Whereas variability associated with the O_1 and K_1 tidal constituents dominates the water-level spectrum from the saline marsh (upper right panel), this variability is filtered out by the frictional wetland landscape by the time the tidal wave reaches the intermediate marshes (fig. 8, upper left panel). Variability across 20-50 day timescales is more prominent in the intermediate marsh site. This marsh site is located in the outfall vicinity of the Caernarvon Diversion and its variability may result from Caernarvon operations, which tend to occur over similar timescales (Snedden and others, 2007). The bottom panels of figure 8 simply show the cumulative variance of the time series accounted for as a function of decreasing timescale. Including all timescales through the diurnal tide accounts for 0.15 ft^2 of variance at the fresh marsh site and 0.41 ft^2 of variance at the saline marsh site. These values are nearly equal to the variances of each time series indicating that intra-daily timescale variability (timescales < 1 day) is insignificant at each site. It is clear from the spectra that the saline marsh site is much more energetic from a water-level standpoint, as evidenced by its higher variance.

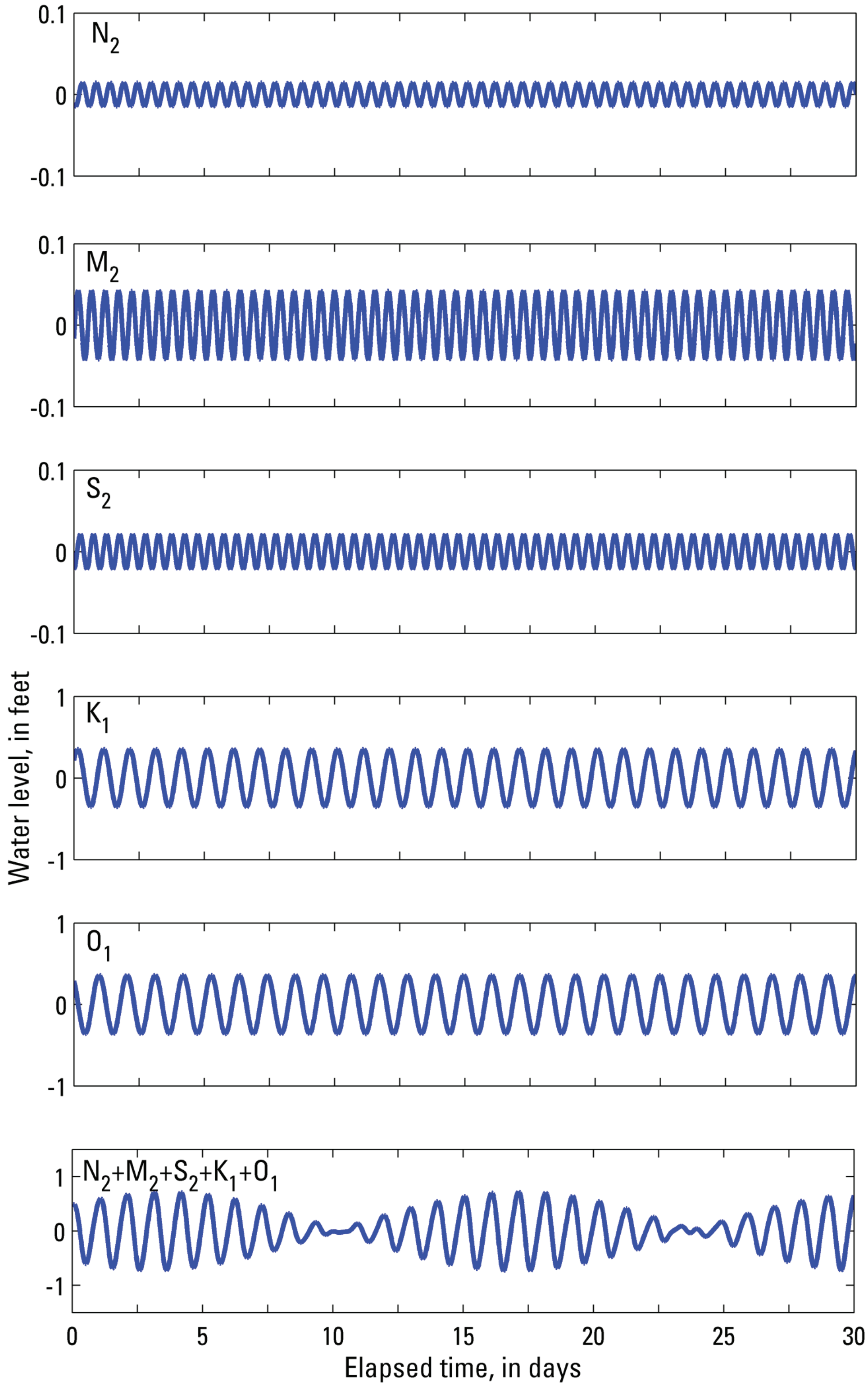


Figure 4. Tide signal resulting (bottom curve) from the addition of five separate tidal components (top five curves) obtained with harmonic analysis for the Grand Isle, Louisiana, tide station.

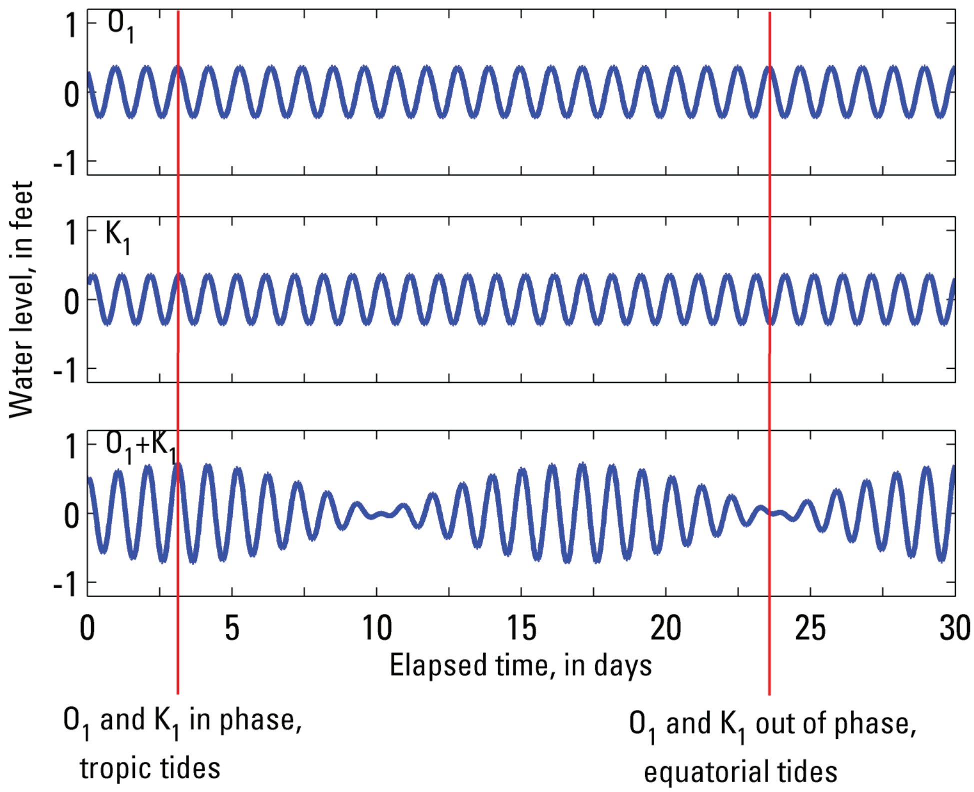


Figure 5. Interaction of the O_1 and K_1 components to produce tropic and equatorial tides.

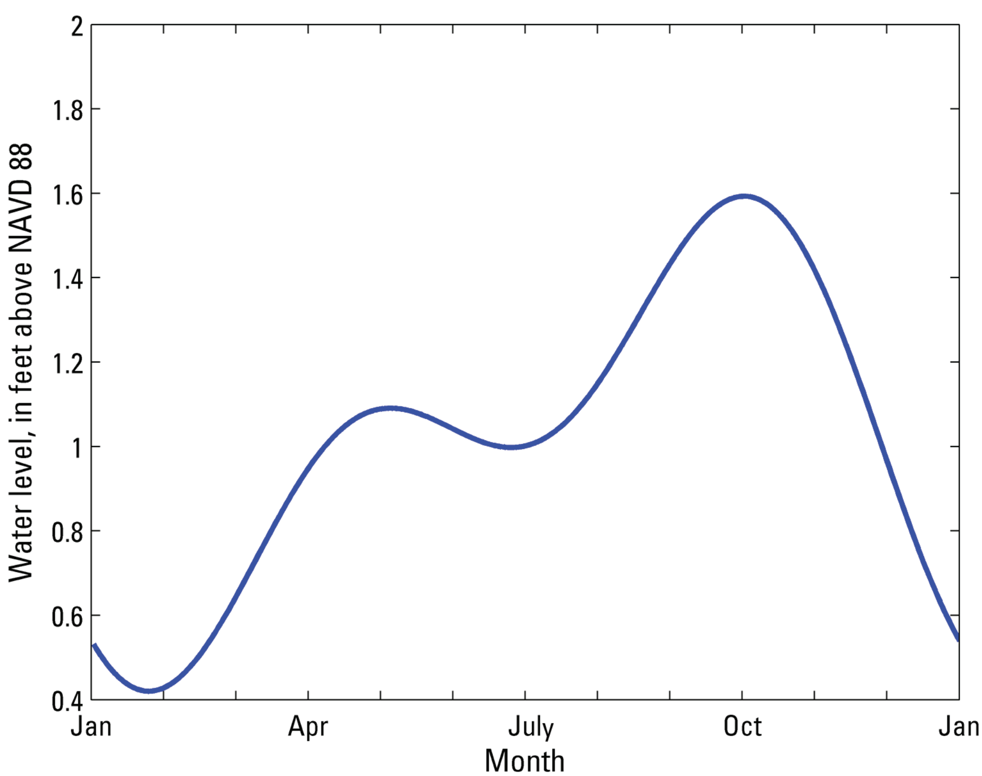


Figure 6. Semiannual and annual cycles of sea level at Grand Isle, Louisiana. The cycle was obtained by harmonic least squares regression with periods of 180 and 365 days on 11 years of data from the Grand Isle water-level gage.

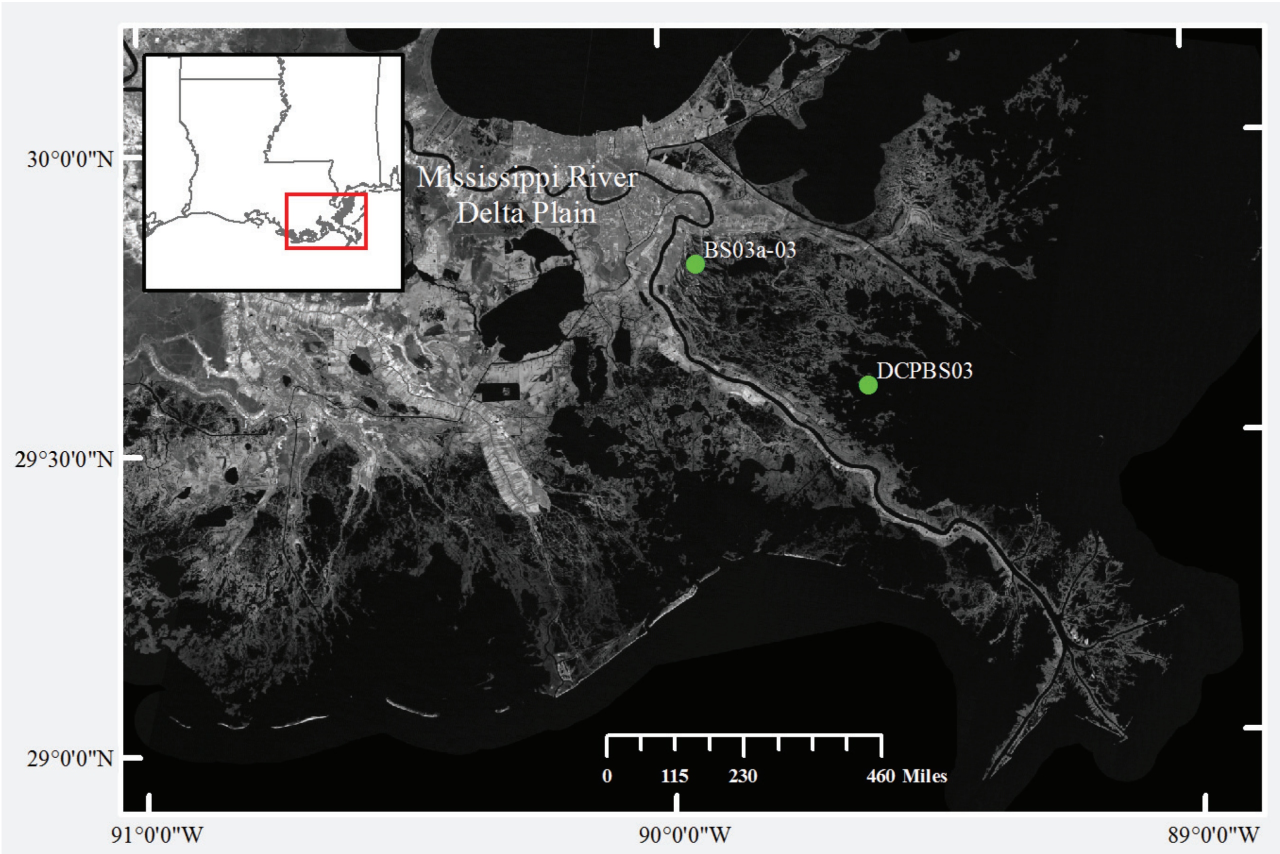


Figure 7. The sites in Breton Sound, Louisiana, used to characterize the tidal forcing.

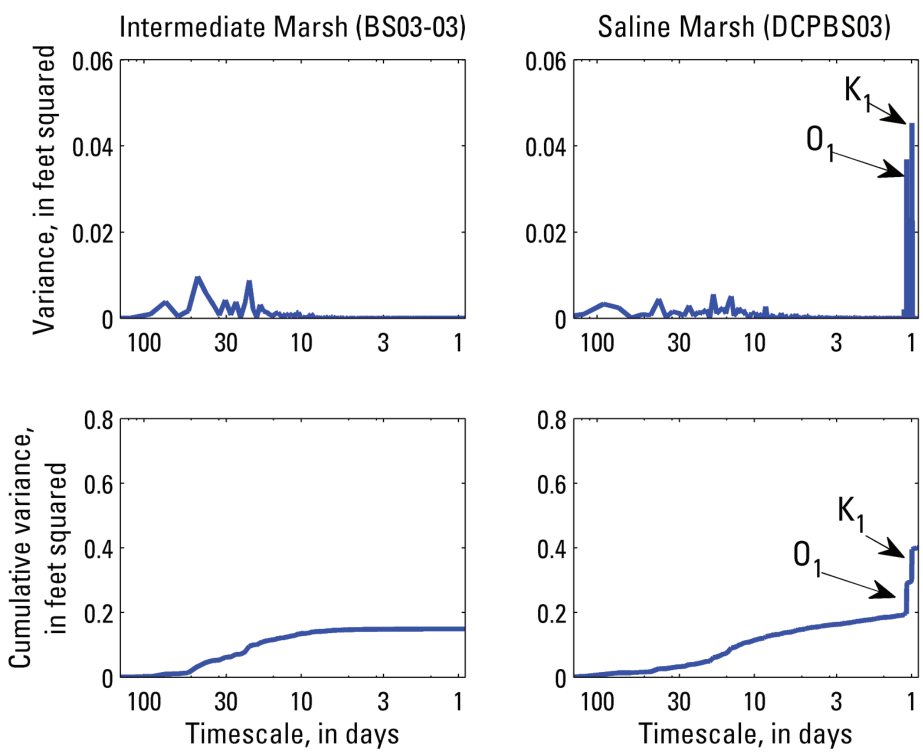


Figure 8. Variance spectra (upper) and cumulative variance spectra (lower) for intermediate (left) and saline (right) marsh sites in Breton Sound Basin, Louisiana. The intermediate site is located in the outfall vicinity of the Caernarvon Diversion.

Marsh Elevation and Tidal Forcing

The hourly water-level data from the Breton Sound stations (shown on fig. 7) were subjected to harmonic analysis to extract the tidal constituents and the mean water level. The O_1 and K_1 constituents were then used to determine the tropical and equatorial high and low tides by adding them to the means by using the following formula:

$$\text{Tropic high} = \text{mean water level} + (O_1 + K_1)$$
$$\text{Tropic low} = \text{mean water level} - (O_1 + K_1)$$
$$\text{Equatorial high} = \text{mean water level} + ([O_1 - K_1])$$
$$\text{Equatorial low} = \text{mean water level} - ([O_1 - K_1])$$

where [ ] indicates absolute value.

This analysis is limited only to the astronomical tidal forcing but is an indicator of the water levels experienced at a site on an average daily basis. The main interest is the extreme water levels, so only the tropic highs and lows were used. The results (fig. 9) show that the saline marsh exhibits about a 2.0-ft increase in water levels from tropic low to tropic high, that the marsh is inundated by over 1 ft of water at high tide, and that the mean water levels exceed the marsh elevation (suggesting that the marsh elevation is low relative to the tidal frame). On the other hand, the fresh marsh exhibits only about a 0.1-ft increase in water levels from tropic low to tropic high. The combination of the difference in marsh elevation, coupled with this difference in water levels between tropic low and tropic high tides can result in a fairly large range of tidal inundation.

Wetland Hydroperiod in the Louisiana Coastal Zone

Wetland inundation regimes, or hydroperiods, are determined by the interaction between local water levels and marsh elevations. There are three fundamental attributes of hydroperiods: frequency, duration, and depth of inundation. Frequency is simply the number of inundation events per unit time; duration is the total time a wetland is inundated for a given time period, often expressed as a percentage of the time period in question; and depth is a measure of how deep the inundation events are. In this application, we determined inundation depth by obtaining the peak depth of each inundation event over the course of a year and taking an average of all peak depths. The hydroperiods were computed for the Breton Sound stations (fig. 7).

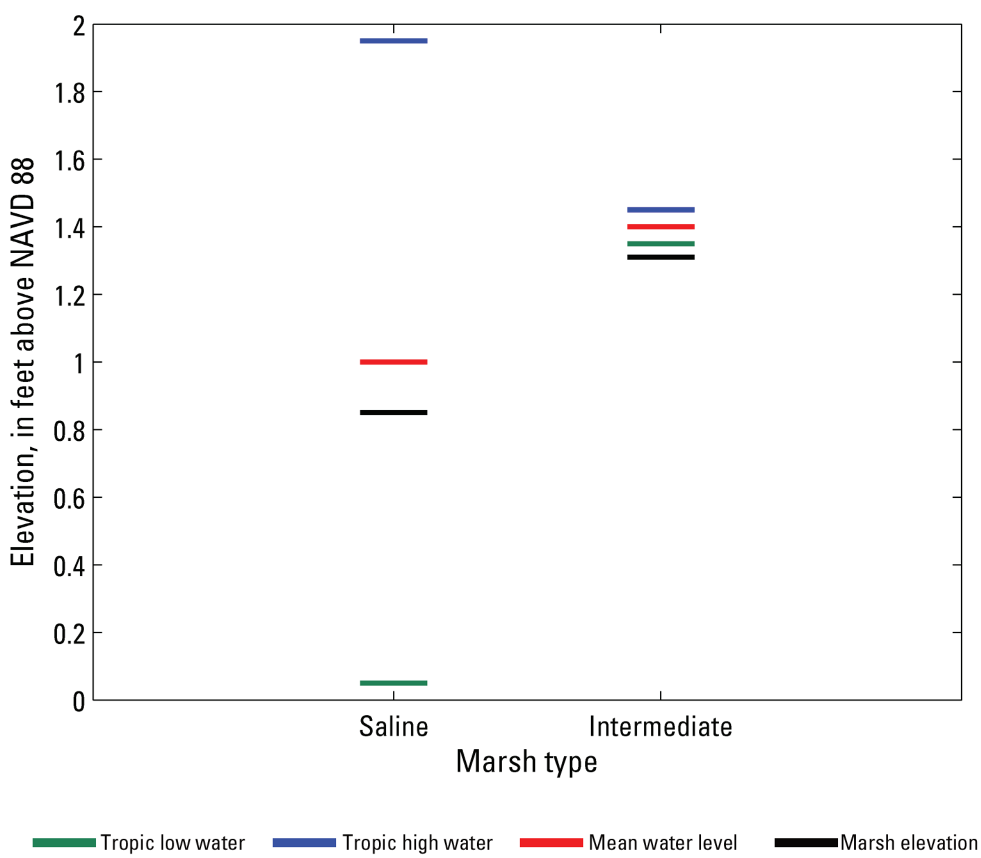


Figure 9. Elevation of the marsh surface at the Breton Sound, Louisiana, marsh sites, in relation to tidal forcing. Indicated are the marsh surface elevation in relation to the mean water level, the tropic high water levels, and the tropic low water levels.

Water-level variability is one of the drivers of wetland hydroperiods. Because high-frequency water-level variability (for example, diurnal tides) tends to be removed by frictional attenuation as one progresses inland from the coast, hydroperiods between fresh and intermediate marshes tend to be remarkably different from those in saline marshes near the coast. Relatively high diurnal tide amplitudes at saline marshes produce inundation frequencies that often exceed 200 events per year. In contrast, the diurnal tide is of minimal importance in many intermediate and most fresh marsh locations where seasonal and meteorologically driven processes produce fewer flooding events, each lasting much longer. Though the percent time flooded is very similar for both habitats (59 percent in the intermediate marsh, 54 percent in the saline marsh), how long each event lasts varies substantially. Flooding events average 8.9 days in duration at the intermediate site but only 0.9 days at the saline site.

Marsh elevation can also strongly influence wetland hydroperiods. The relations among marsh elevation and inundation frequency, inundation depth, average event duration, and percent time inundated for intermediate and saline marshes are shown in figure 10. Both habitats show similar patterns. Inundation frequency shows a Gaussian-like response to elevation, where intermediate elevations maximize the number of flooding events. Marshes that are exceedingly high rarely flood, and marshes that are low in the tidal frame rarely drain. Either extreme leads to a low number of discrete inundation events. The remaining three metrics, depth, percent time flooded, and average event duration, all show inverse relationships with elevation.

Hydrologic Index

Introduction

According to Mitsch and Gosselink (2000) salinity and water levels are the major driving forces controlling the distribution of coastal wetland types. The degree of inundation has a significant effect on plant production (Conner and Day, 1976; Broome and others, 1995; Webb and Mendelssohn, 1996; Höppner, 2002), but the level of this forcing function can differ depending on the environment. For example, much higher inundation levels are required to convert established vegetation into open water than can be tolerated by vegetation on created mudflats (Visser and others, 2003). Changes in the salinity regime may force community shifts in fresh, intermediate, brackish and saline habitats, with extreme salinities possibly leading to the conversion of fresh and intermediate marshes to open water (Flynn and others, 1995, as cited by Visser and others, 2003, Steyer and others 2010).

The challenge in developing a hydrologic index is being able to create an index that integrates the water level and salinity, which are collected continuously (hourly), with soil and vegetation data that are collected annually. Although the exact relation between salinity and water-level regime is not known, the combination of these two forcing functions is one of the critical controls on the vegetation distribution. Sasser (1977) described the broad conceptual limits of plant distribution in terms of flooding and salinity, in which species shifts such as transitions from *Spartina patens* to *Spartina alterniflora* may result from increased flooding, increased salinity, or a combination of the two.

Hydrologic Index Formulation

The hydrologic index combines the temporal behavior in water level and salinity into a single annual number that can then be related to the end of growing season vegetation data.

In the CRMS program, water level and salinity are recorded hourly, providing over 8,000 records for each site in a given year. Although any single water level or salinity data point by itself conveys very little information about the hydrology of the site, various properties of data streams (for example, percent time flooded, flooding frequency, average salinity) collected over extended time periods (for example, months, years) can be valuable in assessing abiotic stressors or subsidies to a given location. Other CRMS data related to geologic processes (for example, subsidence, erosion) or biotic structure (for example, vegetation abundance and species composition) are collected much less frequently (for example, annual sampling of emergent vegetation). The hourly water level and salinity data collected under CRMS thus need to be characterized over longer timescales in a manner that (1) characterizes important hydrologic characteristics of the hourly data, (2) provides an indication of the suitability of these hydrologic characteristics to specific wetland habitat classifications, and (3) does so over annual timescales to allow for the integration of other CRMS data collected over longer sampling intervals.

A method advancing concepts put forward by the productivity component of the Louisiana Coastal Area Habitat Switching Module (LCA HSM) (Visser and others, 2003) is proposed here. Under the LCA HSM, productivity algorithms were produced on the basis of extensive literature reviews of field and laboratory studies to obtain relationships between percent maximum emergent plant productivity of dominant species in each habitat type (*Panicum hemitomon*, *Sagittaria lancifolia*, *Spartina alterniflora*, and *Spartina patens*, *Taxodium distichum*), percent time flooded, and average annual salinity. Those relations are presented in figure 11, and parameters for those relationships are given in table 2. Here p_{sal} is proportion of maximum productivity as a function of average annual salinity, and p_{fld} is proportion of maximum productivity as a function of percent time flooded. Because salinity effects can be exacerbated by excessive flooding (Spalding and Hester, 2007), it was assumed that p_{sal} and p_{fld} interact multiplicatively. Thus, the overall proportion of maximum productivity caused by the

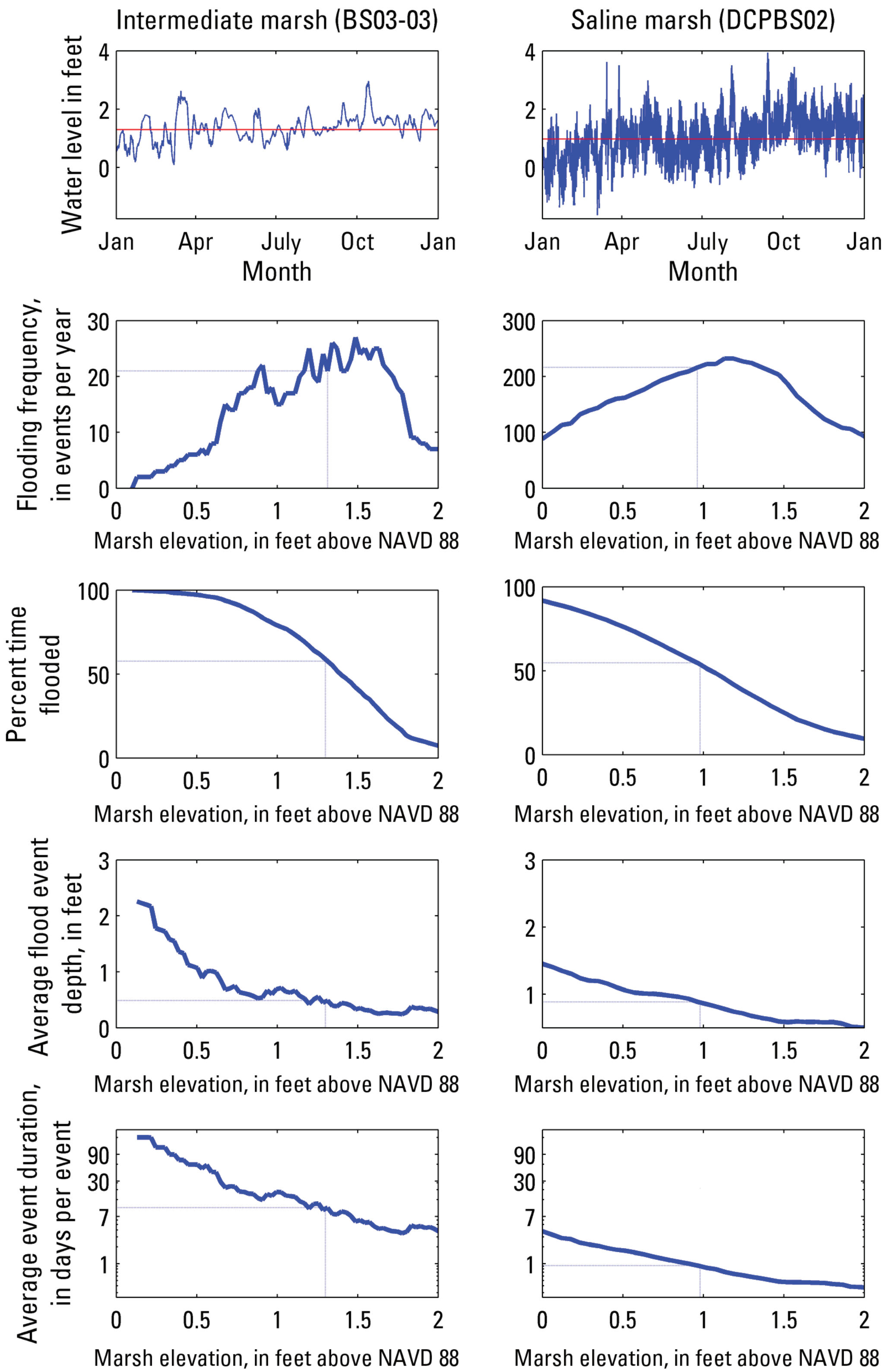


Figure 10. Hydrologic data and metrics from the intermediate marsh (left) and saline marsh (right) in Breton Sound. The top panel is the hourly water level values (NAVD 88), the next three panels present the relation between marsh elevation and flooding frequency, percent of time flooded, flood event depth, and flood event duration, respectively. The dashed vertical lines in the lower three panels indicate the actual marsh elevation at the site where the water levels were taken (also shown by the red horizontal line in the top panels). The dashed horizontal lines show the actual parameter values for the two sites.

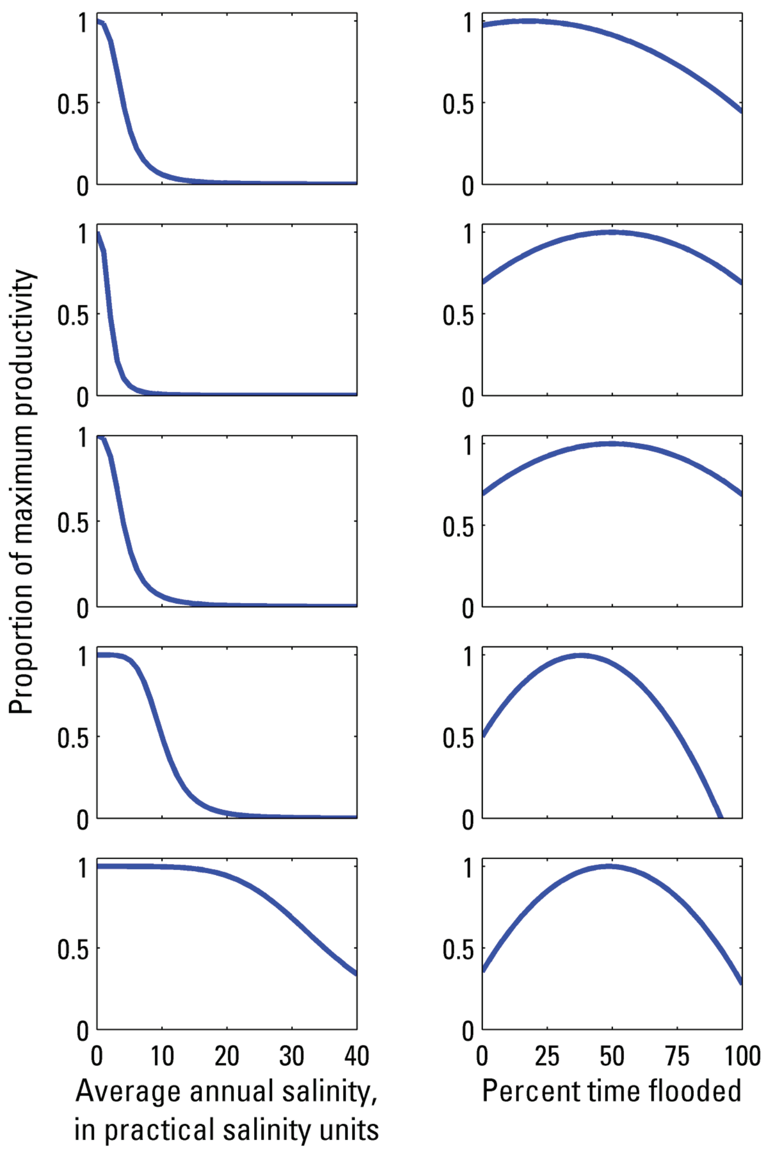


Figure 11. Proportion of maximum productivity by marsh type as a function of average annual salinity (left) and percent time flooded (right).

combined effects of salinity and flooding ($p_{overall}$) is simply $p_{sal} \times p_{fld}$. For each marsh type, $p_{overall}$ can be obtained for all combinations of average annual salinity and percent time flooded, and displayed as a surface. The swamp, fresh marsh, and intermediate marsh are quite similar with salinity exerting a stronger influence than flooding (fig. 12). The effect of prolonged flooding in lowering productivity, particularly in the swamp and intermediate marsh, is also evident. The flooding exhibits a stronger control in the brackish marsh and saline marsh resulting in a locus (circular in the brackish marsh and elongated in the saline marsh) of optimal conditions compared to the narrow band (along the flooding axis) that was evident in the swamp, fresh marsh, and intermediate marsh. The saline and brackish hydrologic index response is what one would expect based on the marsh flooding and salinity data already presented.

Because a high degree of intra-annual variation in productivity occurs in wetlands of the northern Gulf of Mexico, $p_{overall}$ is seasonally weighted according to seasonal productivity rates for each marsh type according to LCA HSM (table 3). The seasonally weighted $p_{overall}$ takes on a value between 0 and 1 and is used as the score for the hydrologic index.

Application to CRMS Sites

Hydrologic (hourly water level and salinity covering the time period covering October 01, 2007 through September 30,

Table 2. Salinity and hydroperiod productivity algorithms by marsh classification.

Marsh type	Salinity	Percent time flooded
Swamp	$p_{sal} = \dfrac{1}{1+\left(\dfrac{sal}{4}\right)^{3}}$	$p_{fld} = -0.000082\, fld^{2} + 0.0029\, fld + 0.972474$
Fresh	$p_{sal} = \dfrac{1}{1+\left(\dfrac{sal}{2}\right)^{3}}$	$p_{fld} = -0.00124\, fld^{2} + 0.012354\, fld + 0.69229$
Intermediate	$p_{sal} = \dfrac{1}{1+\left(\dfrac{sal}{4}\right)^{3}}$	$p_{fld} = -0.000124\, fld^{2} + .012354\, fld + 0.69229$
Brackish	$p_{sal} = \dfrac{1}{1+\left(\dfrac{sal}{10}\right)^{5}}$	$p_{fld} = -0.000344\, fld^{2} + 0.02613\, fld + 0.500639$
Saline	$p_{sal} = \dfrac{1}{1+\left(\dfrac{sal}{35}\right)^{5}}$	$p_{fld} = -0.000273\, fld^{2} + 0.026532\, fld + 0.35536$

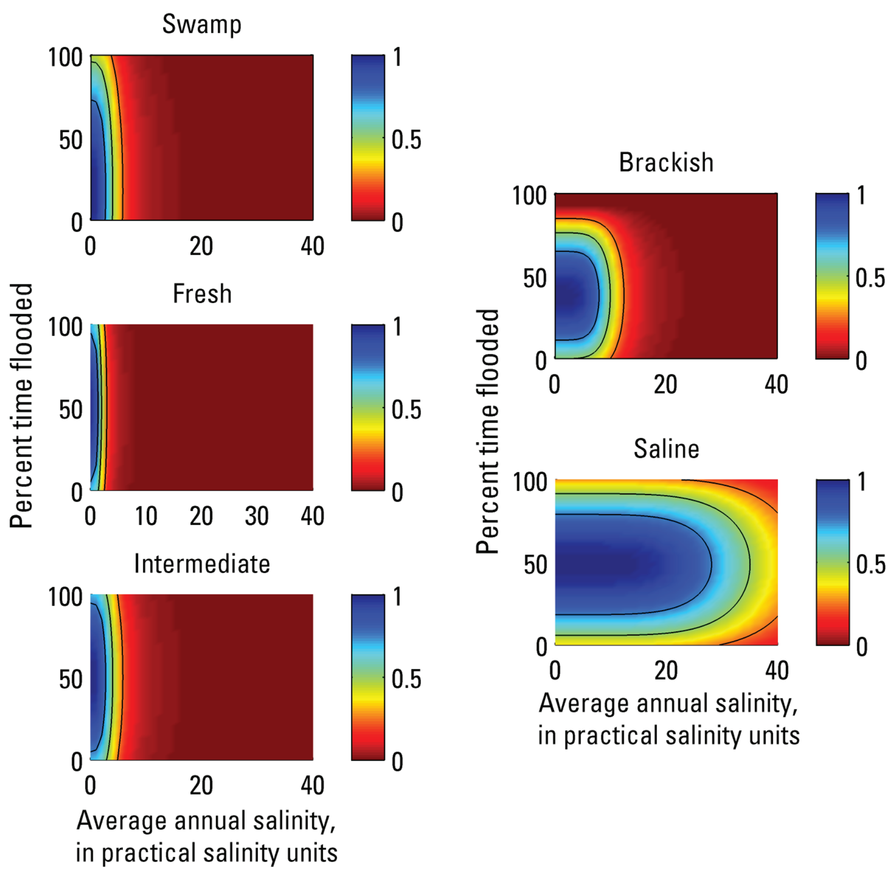


Figure 12. Proportion of maximum productivity (indicated with color axis) by marsh type as a function of the combined effects of average annual salinity and percent time flooded.

Table 3. Seasonal productivity weights for each marsh classification.

Season	Swamp	Fresh	Intermediate	Brackish	Saline
March 1–June 30	0.75	0.38	0.40	0.35	0.29
July 1–October 31	0.25	0.48	0.39	0.35	0.47
November 1–February 28	0.00	0.14	0.21	0.30	0.24

2008) and marsh elevation data from 173 CRMS sites (fig. 13) were analyzed to investigate the general hydrologic patterns at each site and compute the hydrologic indices. Because the water levels and the surveyed marsh elevations at each site were on the same datum (NAVD88), the location of the marsh surface in relation to the water level distribution can be documented. The marsh elevations for the 173 CRMS sites range from ~0.6 to ~1.8 ft NAVD88. The average elevations of the brackish marshes (1.22 ft NAVD88) and intermediate marshes (1.27 ft NAVD88) are slightly higher than the elevations of the saline marshes (1.04 ft NAVD88), although the variability is fairly high, on the order of half a foot. Figure 14d shows the percent of time flooded for each marsh type calculated from the 173 CRMS sites. The 10 percent and 90 percent quantiles for percent time flooded values are 21 and 87, respectively. This range of flooding occurs over a ~1.2 foot range in elevation across the Louisiana coastal zone, indicating how sensitive inundation regimes are to minor changes in marsh elevations. The seasonally weighted salinity for the 173 CRMS sites (fig. 14e), although variable, exhibits a coast-inland gradient, with the average salinity progressing from 13.1 practical salinity units (psu) in the saline marshes to 5.9 psu in the brackish marshes, 2.8 psu in the intermediate marshes, and 0.6 psu in the fresh marshes.

The calculated flooding index (p_{fld}), salinity index (p_{sal}) and hydrologic index ($p_{overall}$) for the 173 CRMS sites are also presented in figure 14. The saline marshes exhibit high values for all of the indices, with very little variation. This low variability is largely attributable to the high tolerance exhibited in the saline marsh salinity index curve (fig. 11, lower left panel) across a broad range of salinities. The brackish and intermediate marshes show a much greater range in all of the indices. The variability in hydrologic index scores for brackish sites is primarily driven by flooding index variability, whereas variability in hydrologic index scores for intermediate sites mainly results from salinity index variability. Overall, hydrologic index scores were greatest for saline and fresh marshes and reduced for intermediate and brackish marshes.

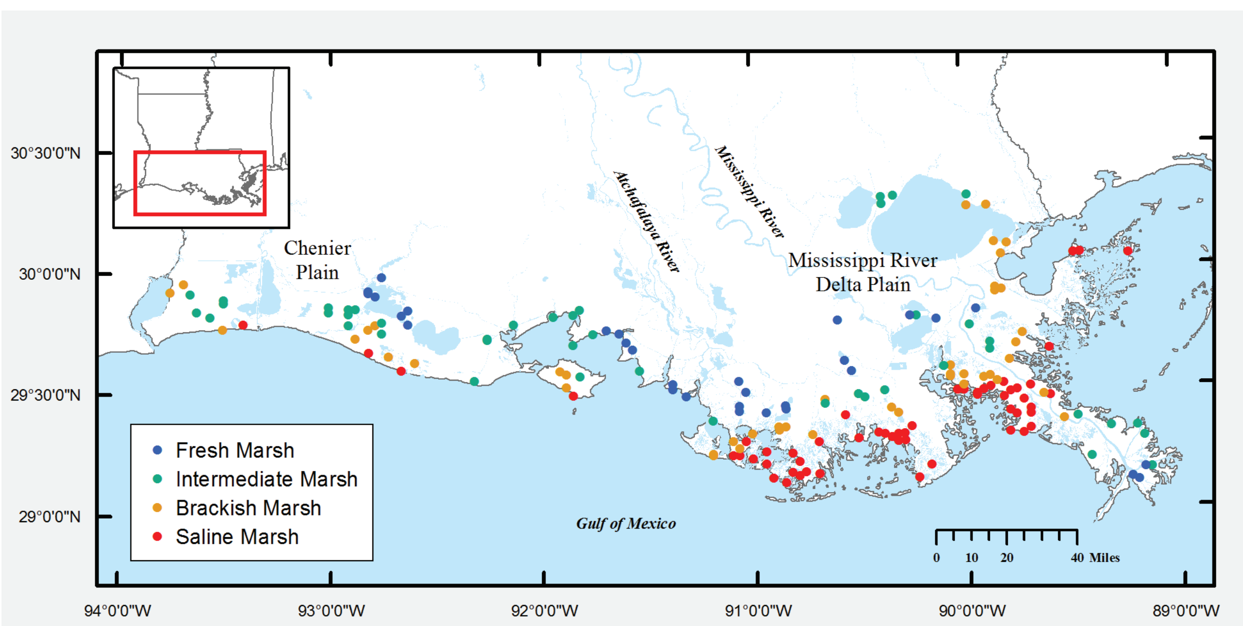


Figure 13. Location of 173 Coastwide Reference Monitoring System sites where the hydrologic index was calculated.

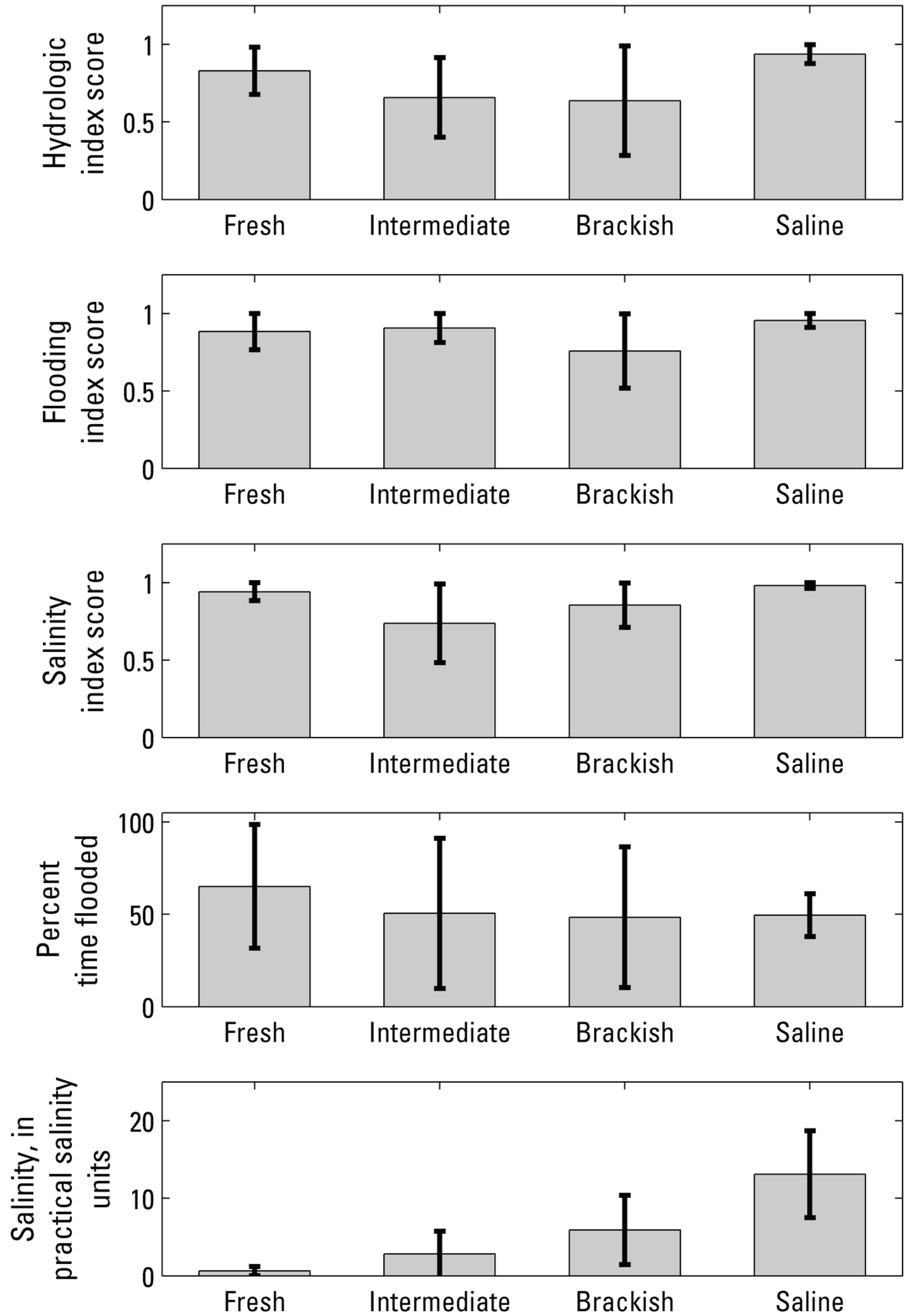


Figure 14. Mean hydrologic indices, flooding indices, salinity indices, percent time flooded, and average annual salinity by marsh type for 173 Coastwide Reference Monitoring System sites.

Examination of the spatial distribution of hydrologic index scores across the coast shows (fig. 15) that, in general, the marshes located at the lower reaches of Terrebonne, Barataria, and Breton Sound Basins exhibit high values. In contrast, many of the sites located in the Chenier Plain in southwest Louisiana exhibit much lower scores. These sites can generally be characterized by impounded hydrology, which can prolong the duration of saltwater intrusion or flooding events.

Application to CWPPRA Projects

The annual hydrologic index, average annual salinity, and percent of time flooded were calculated for CWPPRA monitoring sites in the following CWPPRA projects: East Mud Lake (CS-20; Castellanos, 2005), Naomi Siphon (BA-03; Boshart and Richard, 2008), and LaBranch Wetland Marsh Creation (PO-17; Boshart, 2008; fig. 16). CS-20 is a marsh management project designed to limit hydrologic exchange between the marshes of the project area and high saline waters that are found in nearby Calcasieu Lake. BA-03 is a freshwater diversion project designed to deliver Mississippi River water into the marshes immediately flanking the river. PO-17 is a marsh creation project on the southwest shore of Lake Pontchartrain. Detailed project descriptions and boundaries can be found at http://www.lacoast.gov.

The results are tabulated in table 4 and plotted in figure 17. The indices range from 0.01 to 0.99, and all sites show similar patterns through time in that there is a decrease from 1998 to 2000 followed by an increase in 2001. This similarity may have resulted from the coastwide drought that affected the Louisiana coastal zone during this late period which resulted in some of the highest salinities observed. The index scores for BA-03 are relatively high between 1999 and 2007, with the exception of strong minima in 2000 and 2006. The 2000 minimum likely reflects a severe drought that impacted much of the Louisiana coast, and this minimum is also present in hydrologic index scores for CS-20 and PO-17. The 2006 minimum may reflect Hurricane Katrina impacts, which resulted in prolonged elevated salinities during the 2006 water year. The indices from CS-20, which has the greatest number of sites, are presented as a time series and on the hydrologic

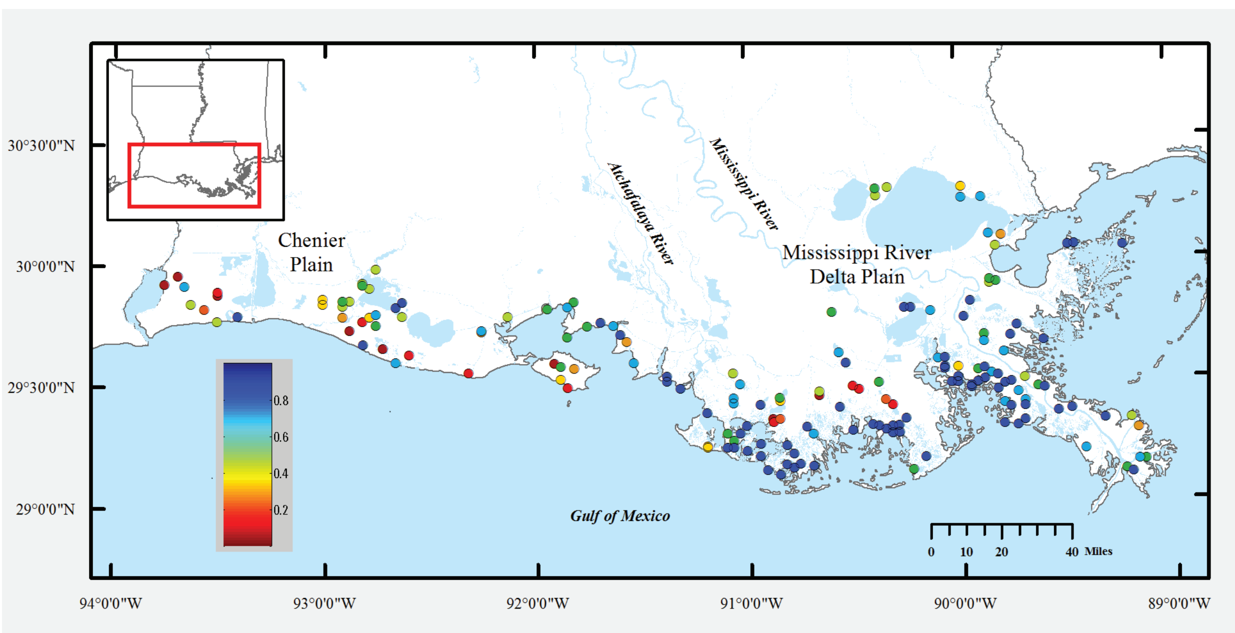


Figure 15. Hydrologic index scores for 173 Coastwide Reference Monitoring System sites during the 2007–8 water year. Blue indicates high index score; red indicates low index score.

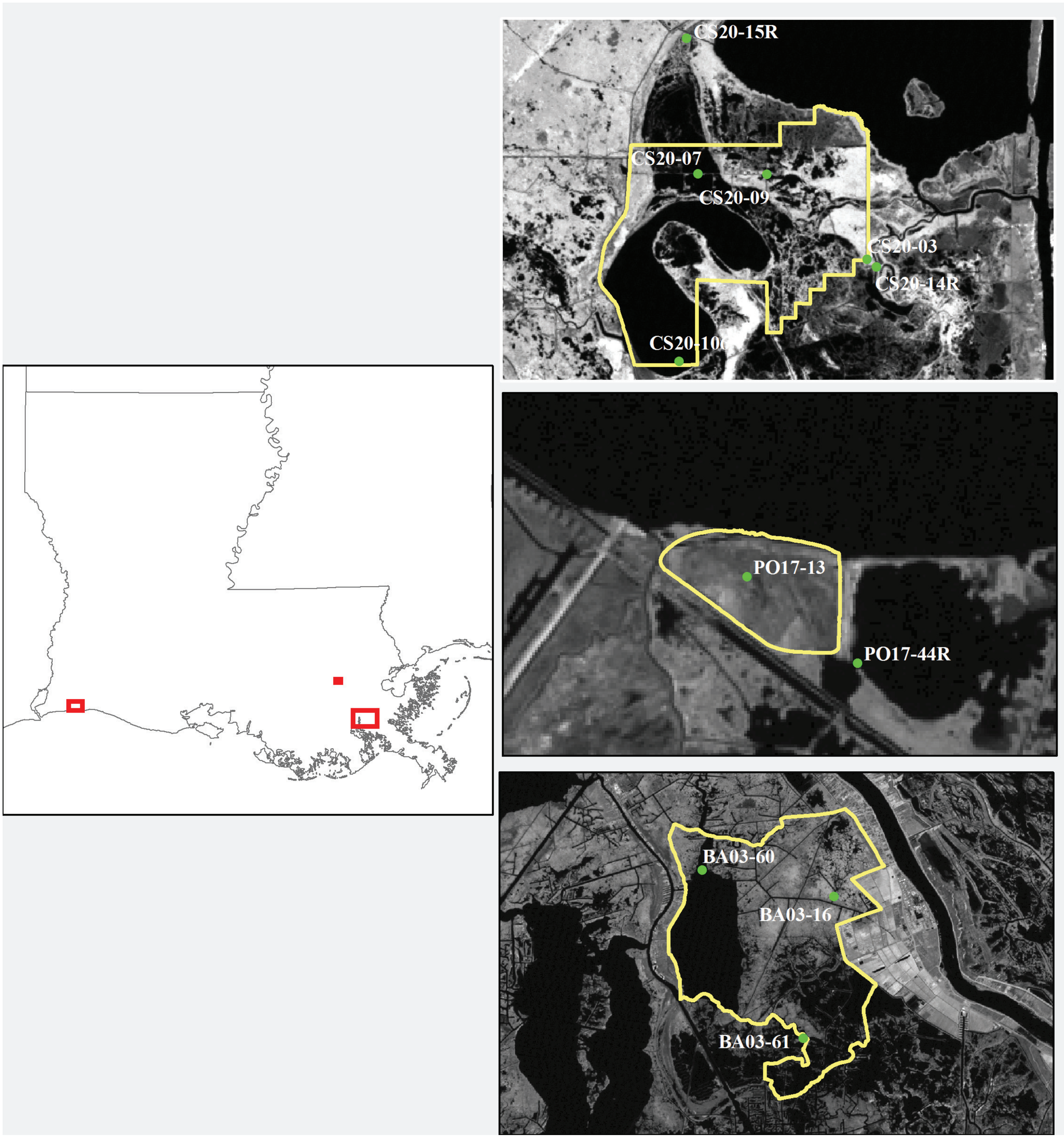


Figure 16. Locations of Coastal Wetlands Planning, Protection and Restoration Act projects and stations where hydrologic index was applied: CS-20 (top), PO-17 (middle) and BA-03 (bottom).

Table 4. Hydrologic index, average salinity, and percent of time flooded for monitoring locations at three Coastal Wetlands Planning, Protection and Restoration Act projects.

	Hydrologic index score												
	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	Mean
PO17-13	0.41	--	0.59	0.25	0.05	0.28	0.52	--	--	--	--	--	0.35
PO17-44R	0.52	0.83	0.68	0.26	0.07	0.40	0.60	--	--	--	--	--	0.48
Mean	0.45	0.83	0.63	0.25	0.07	0.34	0.56	--	--	--	--	--	0.45
CS20-03	--	--	0.24	0.05	0.01	0.40	0.40	0.24	--	--	--	--	0.22
CS20-07	--	--	0.39	0.07	0.01	0.46	0.56	0.29	--	--	--	--	0.30
CS20-17	--	--	0.53	0.12	0.02	0.37	0.52	0.59	--	--	--	--	0.35
CS20-106	--	--	0.74	0.18	0.02	0.64	0.92	0.82	--	--	--	--	0.55
CS20.14R	--	--	0.09	0.03	0.01	0.14	0.12	0.06	--	--	--	--	0.08
CS20-15R	--	--	0.54	0.45	0.03	0.64	0.77	0.50	--	--	--	--	0.49
Mean	--	--	0.42	0.15	0.02	0.44	0.55	0.41	--	--	--	--	0.33
BA03-16	--	--	--	0.79	0.26	0.88	0.88	0.88	0.98	0.98	0.54	0.99	0.8
BA03-60	--	--	--	0.85	0.19	0.91	0.99	0.98	0.91	0.94	0.64	0.99	0.82
BA03-61	--	--	--	0.23	0.03	0.4	0.61	0.58	0.69	0.61	0.09	0.70	0.44
Mean	--	--	--	0.62	0.16	0.73	0.82	0.81	0.86	0.84	0.42	0.89	0.69

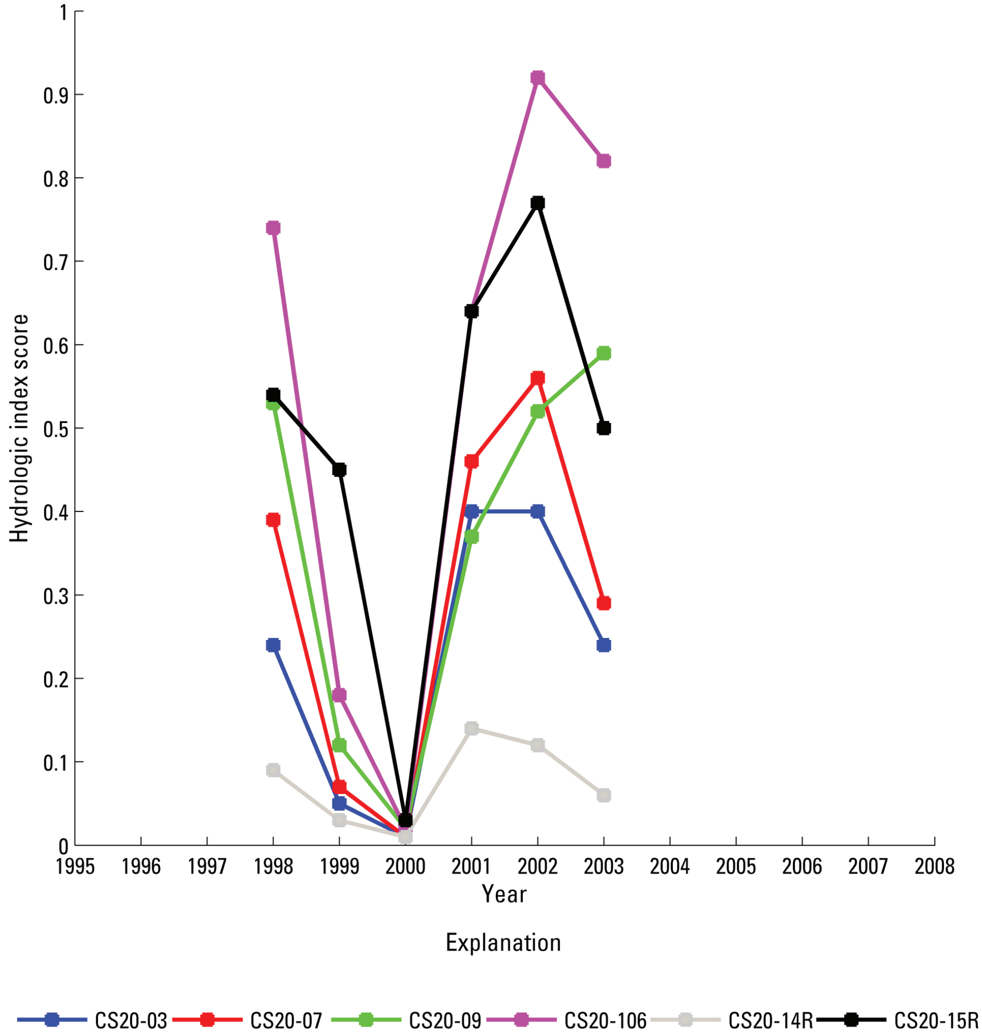
	Average annual salinity, in practical salinity units												
	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	Mean
PO17-13	4.51		3.48	5.50	9.53	5.39	3.87	--	--	--	--	--	5.38
PO17-44R	3.85	1.44	2.96	5.53	8.56	4.38	3.38	--	--	--	--	--	4.30
Mean	4.18	1.44	3.22	5.52	9.05	4.89	6.63	--	--	--	--	--	4.56
CS20-03	--	--	11.69	17.5	21.79	10.31	10.45	12.18	--	--	--	--	13.99
CS20-07	--	--	10.8	15.89	22.24	10.29	9.50	11.15	--	--	--	--	13.31
CS20-17	--	--	8.39	14.6	20.48	10.02	7.53	8.70	--	--	--	--	11.62
CS20-106	--	--	8.01	12.46	20.54	8.88	5.29	5.94	--	--	--	--	10.19
CS20.14R	--	--	15.66	19.60	24.21	14.42	14.71	17.29	--	--	--	--	17.64
CS20-15R	--	--	9.62	10.34	19.79	8.75	6.95	9.95	--	--	--	--	10.9
Mean	--	--	9.72	15.11	21.56	9.87	8.19	9.49	--	--	--	--	12.28
BA03-16	--	--	--	1.89	5.41	0.92	0.81	0.66	0.69	1.09	3.75	0.46	1.74
BA03-60	--	--	--	2.07	6.46	1.62	0.90	1.03	1.71	1.56	3.12	0.86	2.15
BA03-61	--	--	--	5.19	12.43	3.96	2.64	2.63	1.71	2.66	7.94	2.05	4.58
Mean	--	--	--	3.05	8.10	2.17	1.45	1.44	1.37	1.77	4.94	1.13	2.82

Table 4. Hydrologic index, average salinity, and percent of time flooded for monitoring locations at three Coastal Wetlands Planning, Protection and Restoration Act projects.—Continued

	Percent time flooded												
	1996	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**Mean**
PO17-13	58.79		34.84	19.24	21.03	34.39	43.75	--	--	--	--	--	35.34
PO17-44R	58.79	16.81	30.77	29.42	10.10	27.03	34.29	--	--	--	--	--	29.60
Mean	58.78	16.81	32.81	24.33	15.57	30.71	39.02	--	--	--	--	--	32.47
CS20-03	--	--	11.39	20.14	2.39	18.85	55.09	20.23	--	--	--	--	21.35
CS20-07	--	--	26.63	11.29	3.09	38.85	36.37	14.09	--	--	--	--	21.72
CS20-17	--	--	64.93	52.93	16.83	65.35	70.10	58.61	--	--	--	--	54.79
CS20-106	--	--	43.51	10.24	5.44	33.09	49.01	19.48	--	--	--	--	26.79
CS20.14R	--	--	42.92	32.83	22.33	40.17	44.70	42.97	--	--	--	--	37.65
CS20-15R	--	--	44.92	41.30	15.87	29.93	54.97	33.64	--	--	--	--	36.77
Mean	--	--	36.62	21.48	6.94	39.04	52.64	28.10	--	--	--	--	30.80
BA03-16	--	--	--	81.87	78.45	29.22	80.57	80.67	62.50	54.26	36.77	56.65	67..88
BA03-60	--	--	--	66.43	53.98	34.33	47.99	42.91	36.44	43.66	30.00	48.19	44.88
BA03-61	--	--	--	95.95	84.05	90.29	91.41	94.59	95.54	91.65	88.90	91.10	91.50
Mean	--	--	--	81.42	72.16	67.94	73.32	72.72	64.82	63.19	51.89	65.31	68.09

index response surface in figure 18. This presentation shows trajectories of movement over the response surface (from ideal to less ideal conditions) that are very similar at all stations, and indicates a large scale forcing that affects the whole project area is the dominant driver of hydrology at CS-20. In the case of a project that is improving over time, the data should begin to converge toward the more favorable conditions indicated on the response surface (blue area) with occasional movement toward less favorable conditions. The duration of the present dataset is insufficient for proper assessment of the long-term (decadal) trend.

The index can also be used to compare years in greater detail as shown in figure 19. This figure presents the clustering of all six stations in CS-20 for 2000 and 2002. It is clear that the 2000 conditions were less ideal at all stations (index value of ~0.10) in response to the coastwide drought conditions. The 2002 data show that all of the sites improved, with two of the sites having high (~0.8 or greater), three sites having moderate (0.6–0.7), and one site still having a low (~0.2) index value.



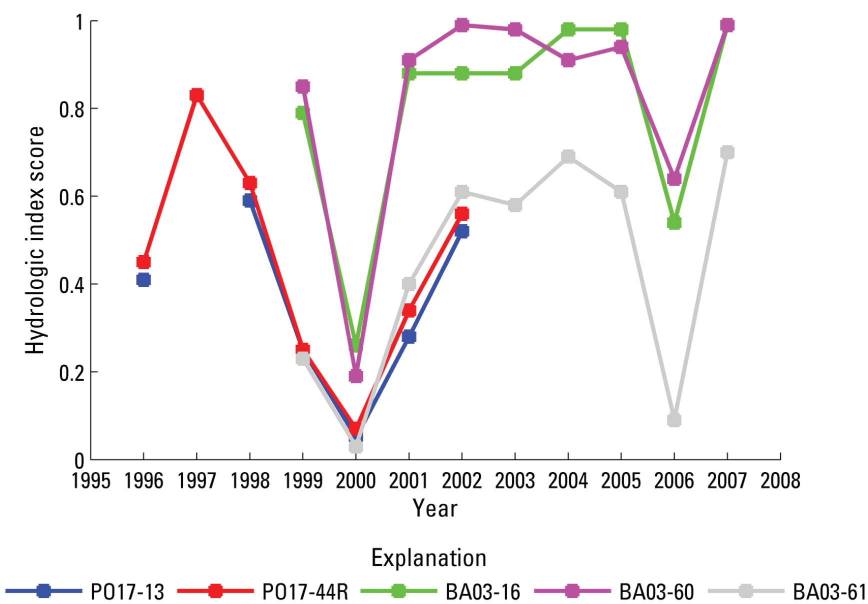


Figure 17. Time-series plots of the hydrologic indices from stations in the Coastal Wetlands Planning, Protection and Restoration Act projects CS-20 (top), PO-17 and BA-03 (bottom).

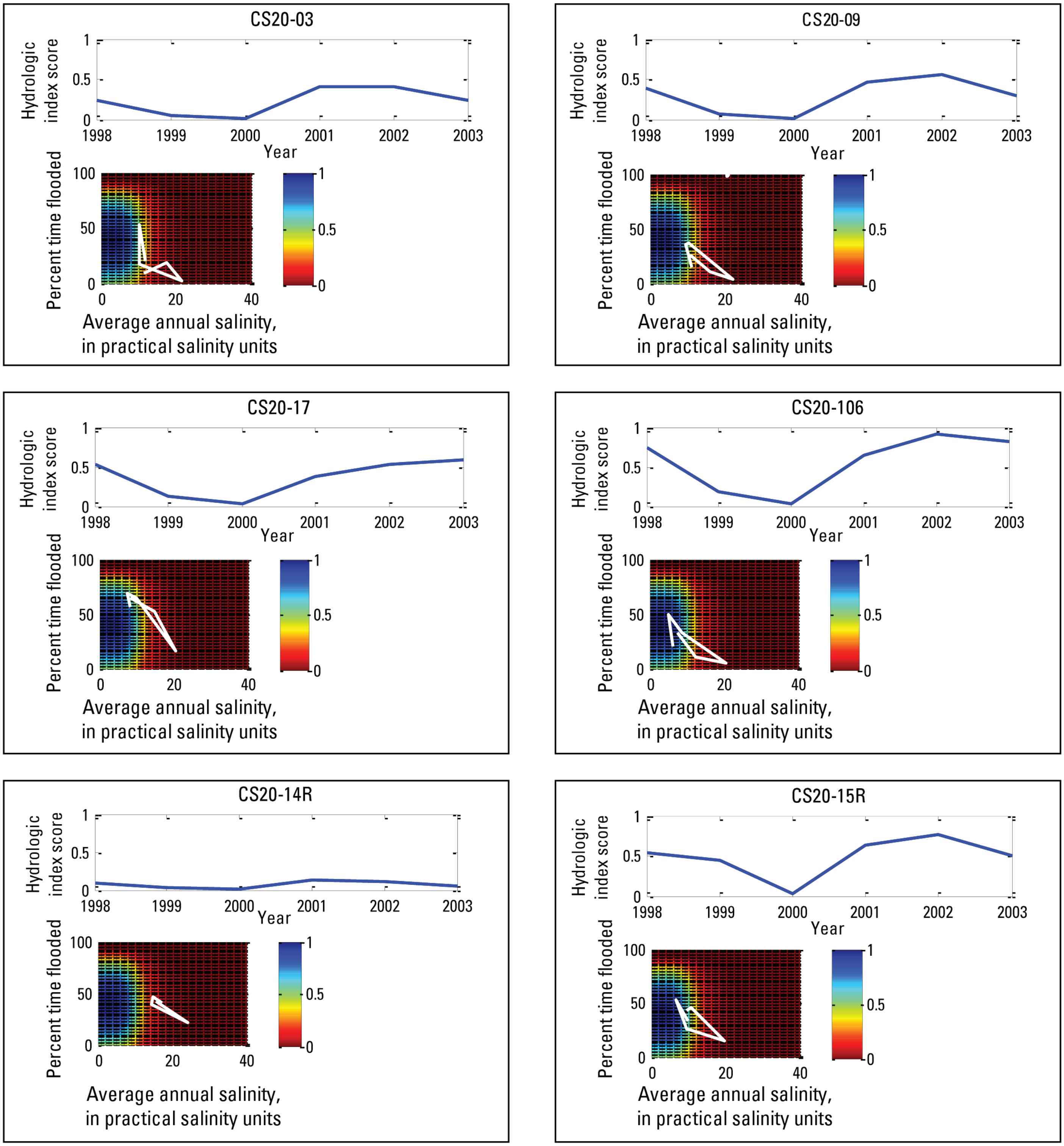


Figure 18. Hydrologic indices for six locations associated with the CS-20 Coastal Wetlands Planning, Protection and Restoration Act project. The time series of the index is presented in the line plot and on the hydrologic index response surface.

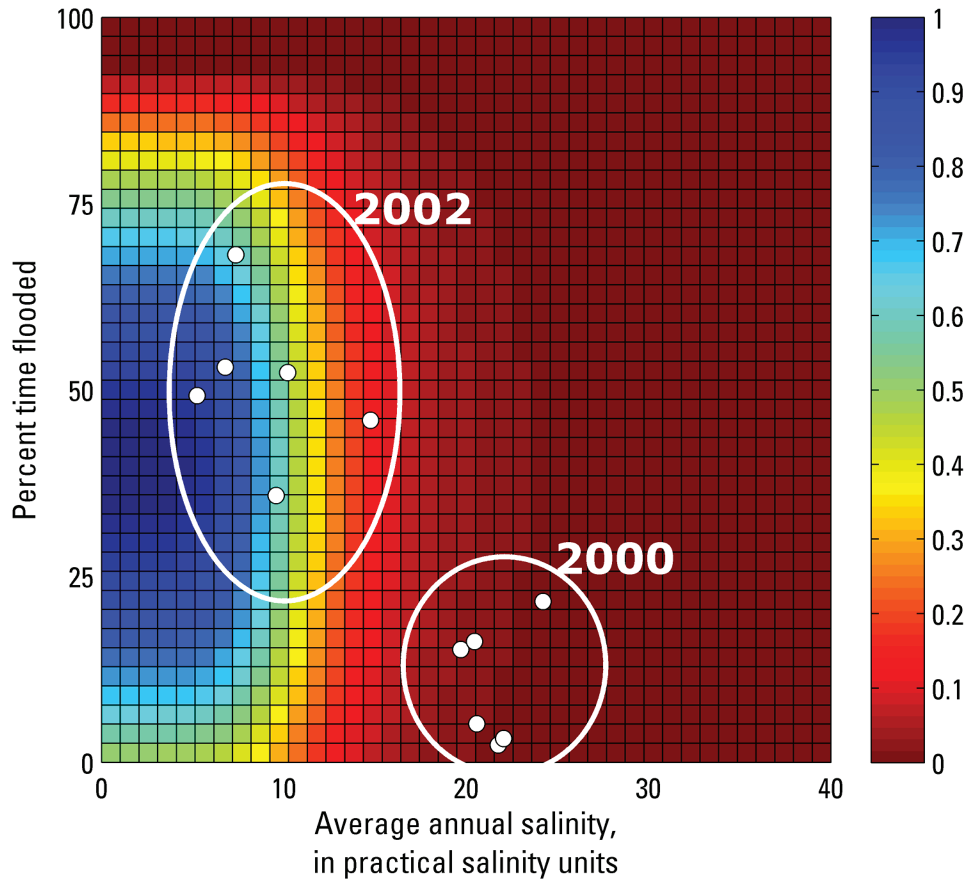


Figure 19. Comparison of hydrologic indices for six locations in the CS-20 Coastal Wetlands Planning, Protection and Restoration Act project area for different years.

Summary

Nearly 40 percent of existing Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA) projects use techniques to directly influence hydrology, and changing water level and salinity regimes are explicit goals in the majority of projects that fall under this category. Many projects, particularly marsh management and hydrologic restoration efforts, aim to reduce tidal exchange between project areas and their surroundings, and these projects are deemed successful if the overall variance in water level or salinity is significantly reduced. This approach is problematic in that there are many processes other than tidal exchange that can influence salinity or water level (for example, precipitation, seasonal variability, meteorology, river inputs) that typically occur over different time scales. This document points to several techniques such as harmonic and spectral analysis that are effective at partitioning time-series variability across different time scales. Although these techniques are commonplace in estuarine physical oceanography, to date they have rarely been applied to the assessment of coastal wetland restoration.

The hydrologic index presented in this document provides an avenue to apply the Louisiana Coastal Area Habitat Switching Model (LCA HSM) productivity component put forth by Visser and others (2003) with hourly hydrologic data collected under the Coastwide Reference Monitoring System (CRMS) program. The utility of the index rests in its ability to take all the hourly salinity and water level observations at a given CRMS site and provide an indication as to how suitable the hydrology is for emergent marsh vegetation productivity for a given marsh type. The hydrologic index can be used as a planning tool, identifying regions of the coast where index scores are low (indicating hydrology that is not conducive to high productivity) that may benefit from hydrologic restoration projects or river diversions. It can also be used to assess the effects of restoration efforts by comparing project area scores with those in nearby nonproject areas.

Though the hydrologic index provides a useful approach for assessing site hydrology, the salinity algorithms that drive it are based on relatively few studies that were performed in a laboratory setting, and the flooding algorithms were based entirely on expert opinion. Improving the index will require testing and refining these algorithms with data collected in a field setting. There is an immediate need to empirically determine the relation between productivity and percent time flooded.

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Publishing support provided by
Lafayette Publishing Service Center

Snedden and Swenson—**Hydrologic Index Development and Application to Selected CRMS Sites and CWPPRA Projects**—OFR 2012–1122

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