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Defining restoration targets for water depth and salinity in wind-dominated *Spartina patens* (Ait.) Muhl. coastal marshes

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SUMMARY

Coastal wetlands provide valued ecosystem functions but the sustainability of those functions often is threatened by artificial hydrologic conditions. It is widely recognized that increased flooding and salinity can stress emergent plants, but there are few measurements to guide restoration, management, and mitigation. Marsh flooding can be estimated over large areas with few data where winds have little effect on water levels, but quantifying flooding requires hourly measurements over long time periods where tides are wind-dominated such as the northern Gulf of Mexico. Estimating salinity of flood water requires direct daily measurements because coastal marshes are characterized by dynamic salinity gradients. We analyzed 399,772 hourly observations of water depth and 521,561 hourly observations of water salinity from 14 sites in Louisiana coastal marshes dominated by *Spartina patens* (Ait.) Muhl. Unlike predicted water levels, observed water levels varied monthly and annually. We attributed those observed variations to variations in river runoff and winds. In stable marshes with slow wetland loss rates, we found that marsh elevation averaged 1 cm above mean high water, 15 cm above mean water, and 32 cm above mean low water levels. Water salinity averaged 3.7 ppt during April, May, and June, and 5.4 ppt during July, August, and September. The daily, seasonal, and annual variation in water levels and salinity that were evident would support the contention that such variation be retained when designing and operating coastal wetland management and restoration projects. Our findings might be of interest to scientists, engineers, and managers involved in restoration, management, and restoration in other regions where *S. patens* or similar species are common but local data are unavailable.

Introduction

Coastal wetlands provide valued ecosystem functions and amenities worldwide (Brander et al., 2006), but the sustainability of those functions can be compromised in numerous ways. For example, the replacement of one dominant plant species, *Spartina alterniflora* Loisel, by another, *Phragmites australis* (Cav.) Trin. ex Steud., affects the functioning of some Atlantic coast marshes of North America (e.g., Buchsbaum et al., 2006). In other coastal wetlands of the United States, conversion of coastal marsh to open water, such as in Delaware Bay (Phillips, 1986), Chesapeake Bay (Kearney and Stevenon, 1991), North Carolina (Hackney and Cleary, 1987), Texas (Morton and Paine, 1990), and Louisiana (Britsch and Dunbar, 1993), results in loss of many valued ecosystem functions. Louisiana is experiencing the most rapid coastal wetland loss in the United States (Boesch et al., 1994), which has led state, federal and non-governmental agencies to implement numerous wetland restoration projects (NRC, 2006).

Restoration has been described as returning an ecosystem to a close approximation of its condition prior to disturbance; management has been described as the manipulation of an ecosystem to ensure the maintenance of one or more functions or conditions (NRC, 1992). Successful restoration, management, and creation all require accurate identification of the structure and processes in desirable ecosystems, as well as the causes of the problem (NRC, 1992). On the Atlantic coast of the US, invasion of *P. australis* into *S. alterniflora* marshes often is attributed to inadequate flooding and salinity stress caused by roadways and other structures that reduce marsh inundation by marine waters (Chambers et al.,

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2003). In Louisiana, coastal wetland loss generally is attributed to excessive flooding and/or salinity stress, caused naturally by the delta lobe cycle (see Coleman, 1988) and artificially by navigation channels and spoil banks that increase flooding and salinity (Boesch et al., 1994).

Coastal wetland restoration projects often attempt to modify flooding and salinity because those stresses regulate species composition and productivity of emergent wetland vegetation (DeLaune et al., 1987). On the Atlantic coast of the US, restoration projects often attempt to increase marsh flooding with marine water because *S. alterniflora* out-competes *P. australis* under moderate flooding and salinity but *P. australis* out-competes *S. alterniflora* under low or non-existent flooding and salinity regimes (e.g., Buchsbaum et al., 2006). In coastal Louisiana, restoration projects often attempt to reduce flooding and salinity because increases in flooding and salinity, caused by subsidence and navigation improvements, are believed to be major causes of marsh loss (Boesch et al., 1994). Restoration projects range from restoring inflow to hundreds or thousands of hectares of marshes artificially isolated from Mississippi River inflow, to hydrologic restorations using levees and water controls structures to influence water level and salinity in scores of hectares of marshes (LDNR, 2006).

It is widely recognized that flooding levels and salinity are crucial in controlling the growth and survival of coastal emergent vegetation, and there are a number of very localized or greenhouse studies documenting species responses to different salinity and flooding ranges (DeLaune et al., 1987; Flynn et al., 1999; Mendelssohn and McKee, 1988; Webb et al., 1995). However, few studies exist in which water depth and salinity have been quantified across large areas with known species abundances and with known marsh loss rates, despite the fact that such data would be useful to guide the design and operation of restoration, management and mitigation on a scale that scientists, engineers, and managers can actually use. Marsh flooding can be estimated over years with as little as three months of data where winds have little effect on water levels because flooding can be predicted from the measured elevation of the marsh and predicted water levels (e.g., Montalto et al., 2006), but quantifying flooding requires hourly measurements over many years in areas where tides are wind-dominated such as the northern Gulf of Mexico. Estimating salinity of flood water requires direct daily measurements regardless of the role of wind in water levels because coastal marshes are characterized by dynamic salinity gradients.

We obtained, compiled, and analyzed hourly water depth and water salinity data to describe hydrologic conditions in Louisiana marshes dominated by *S. patens*. We limited our analyses to a single species because we assume that the dominant species varies with flooding and salinity. We focused on *S. patens* dominated marshes because hydrological conditions in such marshes have rarely been described despite it being the most common species in coastal Louisiana (Chabreck, 1970) and common throughout the Atlantic coast of the United States. This information can be used to increase the efficiency of wetland restoration efforts by providing hydrologic restoration targets. Our study was similar to previous attempts to define flooding and salinity targets for restoration on the Atlantic coast of the United States and the eastern coast of Australia (Hughes et al., 1998; Chambers et al., 2002; Montalto et al., 2006) but differs in the extensive spatial and temporal scale of the data needed to characterize flooding and salinity in expansive coastal marshes with wind-dominated tides. Our findings might be of interest to scientists, engineers, and managers involved in restoration, management, and mitigation in other regions where *S. patens* or similar species are common but local data are unavailable. Our methods, which included a greater focus on variability in flooding and salinity than did previous studies, might be of interest to scientists, engineers, and managers in coastal wetlands worldwide.

Methods

Hourly observations of water depth and salinity were obtained from the Louisiana Department of Natural Resources (LDNR) and the Louisiana Department of Wildlife and Fisheries (LDWF). Data from LDNR are widely available via an automated website (http://dnr.louisiana.gov/crm/coastres/monitoring.asp or http://www.lacoast.gov/). The Coastal Wetland Planning Protection and Restoration Act (CWPPRA) Task Force and LDWF began collecting hourly data in the mid-1990s when coordinated coast-wide restoration efforts began and as electronic recorders became more affordable and efficient. We therefore requested data from 1 January 1995 through 1 January 2002. In addition to seasonal variation in wind speed and direction (see Walker et al. (2005) for an analyses of 10 years of wind data from coastal Louisiana), winds during this 7-year period reflected six tropical storms and three hurricanes during summer and fall (Lawrence et al., 1998, 2001; Pasch and Avila, 1999; Rappaport, 1999; Pasch et al., 2001; Franklin et al., 2001), which can affect water levels in coastal Louisiana even from as far as 400 km away (Walker, 2001), as well as numerous cold-fronts that pass every 4–5 days during winter (Walker et al., 2005). Selected stations had at least 1 year of data and the adjacent emergent vegetation was dominated by *S. patens*. Fifteen stations met those criteria; all but one of those stations clearly fell within one of two regions separated by approximately 120 km: Calcasieu Lake in the west or Acadiana Bays in the east (Fig. 1). One site (TE-10-01r), was >75 km east of Acadiana Bays and was not included in any analyses. We used the remaining 14 stations for the analyses described below; 11 of those stations had water depth data (Tables 1 and 2) but all 14 had water salinity data (Table 3). All of the sites from which we obtained data were in reference areas; i.e., not restoration project areas. Reference areas were monitored by the CWPPRA Task Force as part of "Before–After–Control–Impact" designed monitoring plans (Underwood, 1994). We did not use data from project areas because construction of the restoration projects should alter salinity and flooding during the period of record.

Ideally, we would have obtained data from 1983 through 2001 so that our data would coincide with the most recent National Tidal Datum Epoch (NTDE) but we are unaware of any source of such data. The NTDE is a specific 19-year period over which the US National Oceanic Service determines tidal datum such as mean sea level, mean lower low water, and mean high water. Nineteen-year periods are used to account for an 18.6 year astronomical cycle of significant variations in the moon and sun that cause slowly varying changes in the range of tide (Shalowitz, 1964).

We expressed water depth relative to local marsh elevation, rather than regional water level datum such as NAVD88, because marsh vegetation responds to local water depth and salinity, and because references to NAVD88 datum were not available for all stations. The elevation of the local marsh was determined from a minimum of 20 locations within approximately 60 m of each station, which generally were in small tidal channels less than 5 m wide but occasionally within 5 m of the shoreline of large ponds and lakes (e.g., Fig. 2). The proximity of the marsh to the station and the small daily tidal range (see "Results") allowed for water at each combination of marsh and water depth sensor to operate as a flat pool and prevented any gradient in water level between the marsh and sensor. Marsh elevation varies little (6 cm across 125 m of marsh; Nyman et al., 1994). Elevation was not determined on natural levees when they occurred adjacent to tidal channels, ponds, or lakes. Water salinity was expressed in parts per thousand (ppt). All stations had periods of missing data. Generally, water depth and water salinity data were missing

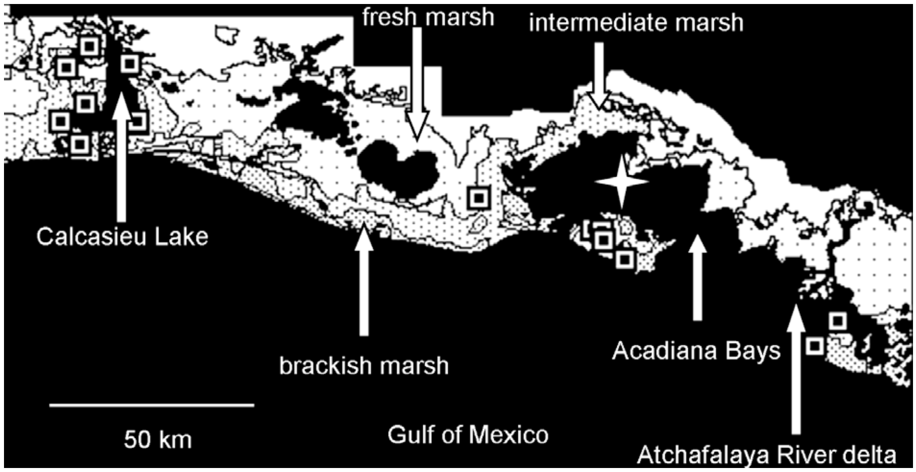

Fig. 1. Map of southwestern Louisiana, USA, showing locations of 14 locations where water depth and salinity data were analyzed for this study (square symbols) and the location of a NOAA tide gauge station from which data were used to predict water levels (star symbol). Emergent vegetation at the 14 locations where data were analyzed were either in intermediate marsh or brackish marsh, both of which are both are dominated by *Spartina patens* (Ait.) Muhl. Extensive bands of fresh marsh, dominated by *Panicum hemitomon* Schult. or *Sagittaria lancifolia* L., also occur in the region where water salinity is lower. Some saline marsh, dominated by *Spartina alterniflora* Loisel., also occurs in the region where salinity is greatest but its extent is minor at this scale. Salinity in this region of the Gulf of Mexico is dominated by the Atchafalaya River, which though a distributary of the Mississippi River, is the fifth largest river in North America.

Table 1
Water depth at stations in coastal Louisiana, USA where water depth and salinity were measured hourly. Water depths are reported relative to the elevation of the soil in the emergent marsh adjacent to the water bodies where water level and salinity were measured hourly. Station names correspond to those used by the Louisiana Department of Wildlife and Fisheries and the Louisiana Department of Natural Resources.

Station name	Days	ls mean (ls std err)		
		Daily mean (cm)	Daily min (cm)	Daily max (cm)
Acadiana Bays marshes				
MI-Jefferson	2056	−12 (<1)	−21 (<1)	−2 (<1)
MI-Lucien	1714	−13 (<1)	−23 (<1)	−3 (<1)
MI-Michael	1863	−12 (<1)	−23 (<1)	0 (<1)
MI-Oyster	1739	−9 (<1)	−31 (<1)	6 (<1)
TE-26-01r	1560	−24 (<1)	−48 (<1)	−2 (<1)
TV-06-03r	2108	−18 (<1)	−36 (<1)	0 (<1)
Regional estimate		−15 (<1)	−32 (<1)	−1 (<1)
Calcasieu Lake marshes				
CS-09-02r	927	−12 (<1)	−24 (1)	−2 (<1)
CS-17-02r	1333	−2 (<1)	−3 (<1)	0 (<1)
CS-20-14r	1420	−7 (<1)	−17 (<1)	1 (<1)
CS-20-15r	750	−15 (<1)	−28 (1)	−6 (<1
CS-21-07r	1254	−8 (<1)	−22 (<1)	4 (<1)
Regional estimate		−9 (<1)	−19 (<1)	0 (<1)

Table 2
Percent of time the marsh was flooded in coastal Louisiana, USA where water depth was measured hourly. Water depths are reported relative to the elevation of the soil in the emergent marsh adjacent to the water bodies where water level and salinity were measured hourly. Station names correspond to those used by the Louisiana Department of Wildlife and Fisheries and the Louisiana Department of Natural Resources.

Station	1994	1995	1996	1997	1998	1999	2000	2001
Acadiana Bays marshes								
MI-Jefferson		36	22	16	27	20	19	
MI-Lucien		29	16	13	25	25	5	
MI-Michael		36	20	15	29	19	28	
MI-Oyster		38	29	18	46	18	38	
TE-26-01r			0	4	16	10	9	11
TV-06r	23	23	8	17	28	22		
Calcasieu Lake marshes								
CS-09-02r				12		31	16	4
CS-17-02r					61	28		52
CS-20-14r					42	33	21	38
CS-20-15r						45	15	19
CS-21-07r				33	41	26	25	23

simultaneously except for one station that had water salinity data but lacked water-depth data because the water depth was not referenced to local marsh elevation. In coastal wetlands with highly permeable surface or subsurface sediments, water table fluctuations can extend tens of meters from creeks (Hughes et al., 1998). In such situations, flood stress on vegetation declines until the water table is below the living root zone. In most coastal marshes including coastal Louisiana, however, water table movement is restricted to within 5 or 10 m of creeks (Agosta, 1985; Nyman et al., 1994) and flood stress on vegetation in unaffected by water levels in creeks below marsh surface elevation. We therefore were very interested in the percent of time that the marsh surface was flooded. We estimated the percent of time that the marsh was flooded annually at each station from the number of hours that water depth was above local marsh elevation each year and the total number of hours in the data set for each year.

Hourly data were reduced to daily means, daily minimums, and daily maximums of water depth and salinity. For water depth, we also calculated daily tidal range as the difference between daily maximum and daily minimum water depths. Most daily estimates

Table 3
Water salinity at stations in coastal Louisiana, USA where water depth and salinity were measured hourly. Spring salinity was based on data from April, May, and June. Summer salinity was based on data from July, August, and September. Station names correspond to those used by the Louisiana Department of Wildlife and Fisheries and the Louisiana Department of Natural Resources.

Station name	Days	ls mean (ls std err)		
		Annual	Spring	Summer
Acadiana Bays marshes				
ME-04-26r	1650	4.4 (0.1)	3.6 (0.1)	4.4 (0.1)
MI-Jefferson	2056	6.3 (0.1)	4.5 (0.1)	6.9 (0.1)
MI-Lucien	1714	4.5 (0.1)	3.2 (0.1)	4.8 (0.1)
MI-Michael	1863	4.4 (0.1)	2.8 (0.1)	4.9 (0.1)
MI-Oyster	1778	5.6 (0.1)	3.8 (0.1)	6.5 (0.1)
TE-26-01r	1713	4.1 (0.1)	2.4 (0.1)	1.9 (0.1)
TV-06r	2110	4.0 (0.1)	2.4 (0.1)	5.1 (0.1)
Regional estimates		5.0 (<0.1)	3.7 (0.1)	5.4 (0.1)
Calcasieu Lake marshes				
CS-02-02r	1796	9.4 (0.2)	6.2 (0.2)	9.6 (0.2)
CS-09-02r	927	10.9 (0.2)	6.7 (0.3)	10.0 (0.3)
CS-17-02r	1551	9.4 (0.2)	8.4 (0.2)	10.1 (0.2)
CS-20-14r	1866	18.4 (0.2)	15.7 (0.2)	19.5 (0.2)
CS-20-15r	750	15.4 (0.2)	10.5 (0.3)	14.3 (0.3)
CS-21-07r	1303	13.6 (0.2)	10.4 (0.2)	16.2 (0.2)
CS-23-01r	900	18.0 (0.2)	14.4 (0.3)	22.2 (0.3)
Regional estimates		12.8 (<0.1)	10.3 (0.1)	14.6 (0.1)

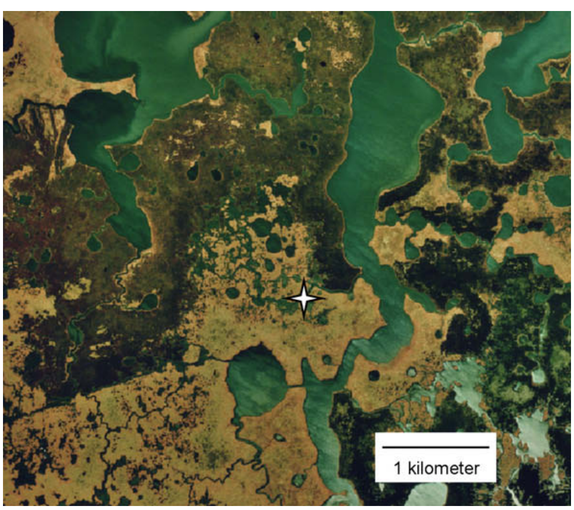

Fig. 2. Portion of a Digital Orthophoto Quarter Quadrangle from 1998 showing a wetland landscape that typifies coastal Louisiana. Topography across the area pictured varies less than 30 cm in marsh areas (i.e., supporting emergent vegetation), and less than 1 m in large open water areas. Only in small tidal channels does topography vary more than 1 m. The star near the center of the figure shows the location of one (MI-Lucien in Tables 1 and 2) of the 14 stations where a sensor recorded water level and salinity hourly. At this station, the sensor was in a small tidal channel that was approximately 10 m wide and 3 m deep. Marsh elevation was measured within 60 m of sensor at this and all other stations. The virtually flat landscape, the short distance between the sensor, and a daily tidal range averaging 26 cm prevents slopes in water surface elevation between sensor and marsh that would introduce error into estimates of flooding depth and duration.

were based on 24 observations but some days had fewer observations. Days with <24 observations generally bracketed longer periods of missing observations. Daily means were not generated for days completely lacking data. From those daily means, we calculated least-square means of means to describe central tendency. We also used those data to calculate least-square means of minimums, least-square means of maximums, least-square means of mean tidal range, and to generate frequency distributions to describe variability. We used least-square means instead of arithmetic means because there were a different numbers of observations between the regions, and among the stations, months, and years. Standard errors of least-squares means were omitted from graphs because they were too small to be displayed (<0.2 ppt and <1 cm for salinity and depth respectively). Least-square estimates have the same units as arithmetic means, are equal to arithmetic estimates when all subclasses have the same number of observations, and have the values that would be expected if all stations, months, years, and regions had the same number of observations (SAS, 2003). For salinity, we also estimated spring mean salinity and summer mean salinity because salinity goals vary seasonally in some marsh management and restoration plans. We defined spring as April, May, and June; we defined summer as July, August, and September. We did not use standard climatological definitions for the northern hemisphere (spring = March, April, and May; summer = June, July and August) because marsh management schedules in coastal Louisiana do not follow those schedules.

We also obtained predicted water level data for a station (Cypremort Point, ID number 8765251) in the Acadiana Bays from NOAA (http://tidesandcurrents.noaa.gov/index.shtml) to illustrate why hourly observations of water level are more useful than predicted water levels in wind-dominated systems. This station was located in the Acadiana Bays (Fig. 1). There was no suitable station for Lake Calcasieu for comparison. These data were obtained for the same time period (1 January 1995 through 1 January 2002) and analyzed in the same way as were the observed data except that water level data were related to MLLW (mean lower low water) datum rather than marsh elevation datum.

We did not use statistical tests to compare water level and salinity between regions, among months, among seasons, or various combinations thereof because the large number of hourly observations (water level: $n = 399{,}772$; water salinity: $n = 521{,}561$) provided enough power to detect statistically significant differences *ad nauseam*. We conducted one statistical analysis to test the hypothesis that the percent of a year that marshes were flooded at each station differed between the regions and among years. There were 59 observations for that analysis. Those data were analyzed as two way analyses of variance with blocking on year using Proc GLM of SAS release version 9.1.3 (SAS, 2003).

Ideally, we would have obtained wetland loss data over the same time period over which we analyzed water level and salinity data, but such data did not exist. We judged that the best land loss data for our purpose were those of Britsch and Dunbar (1993), who reported land loss rates in four time periods: 1935–1954/1958, 1954/1958–1974, 1974–1983, and 1983–1990. Barras et al. (2003) had a more recent estimate of land loss, 1978–1999 and 1990–2000, but reported those losses for four large regions that encompassed the entire Louisiana coast such that the two regions that included Calcasieu Lake and the Acadiana Bays also included many water bodies other than Calcasieu Lake and the Acadiana Bays. We estimated the average percent land loss in the Calcasieu Lake region from the rates reported by Britsch and Dunbar (1993) for the Cameron, Sulphur, and Sweet Lake quadrangles. All hydrologic data that we analyzed from the Calcasieu Lake region were in those three quadrangles. We estimated the average land loss rate in the Acadiana Bays region from the rates reported by Britsch and Dunbar (1993) for the Chenier Au Tigre, Marsh Island, and Point Au Fer quadrangles. The Acadiana Bays region encompasses other quadrangles, but all hydrologic data that we analyzed were in those three quadrangles.

Results

Regional wetland loss rates

Wetland loss rates from 1935 to 1990 for the three quadrangles that encompass the Acadiana Bays sites averaged 0.33%/year, whereas wetland loss rates for the three quadrangles that encompass the Calcasieu Lake sites averaged 0.48%/year. However, wetland loss rates differed between regions only during the 1955–1974 time period (Fig. 3).

Spatial variability in water depth, flooding and salinity

Water depth from both regions averaged 11 cm (std err < 1) below local marsh elevation overall, but there was considerable variation between the regions that might relate to differences in marsh loss between the regions (Table 1). Daily high water averaged near the marsh surface in both regions, but daily mean water was 6 cm lower in the Acadiana Bays marshes than in Calcasieu Lake marshes, and daily minimum water was 13 cm lower in the Acadiana Bays marshes than in Calcasieu Lake marshes (Table 1). Daily tidal range averaged 26 cm overall but there was more daily tidal range in the Acadiana Bays marshes (31 cm; std err = 0.2) than in the Calcasieu Lake marshes (19 cm; std err = 0.1). In both regions, daily tidal range varied seasonally with greatest range during July and December and least range during September and to a lesser extent around April. Despite all those differences, marsh in both regions had similar positions relative to mean daily maximum water depth (Table 1). Average daily water depth appeared to be normally distributed (Fig. 4) but not average daily water salinity (Fig. 5).

Marshes were flooded 24% of the time overall but there was considerable variation between the regions (Table 2), which might be related to the differences in marsh loss between the two regions. The percent of time marshes were flooded differed between the regions ($P = 0.0024$). On average, marshes were flooded 21% of the year near the Acadiana Bays, where marsh loss was slower, but 32% of the time near Calcasieu Lake.

Water salinity averaged 8.1 ppt overall but there was considerable variation between the regions such that water was less saline in the Acadiana Bays marshes which have experienced less marsh loss (Table 3). Mean summer salinity generally was greater than mean spring salinity in both regions (Table 3), but the difference was greater in the Calcasieu Lake marshes (Table 3). Water was less saline in the Acadiana Bays marshes, 5.0 ppt (std err < 0.1) than at the Calcasieu Lake marshes, 12.8 ppt (std err < 0.1).

Temporal variability in water depth, flooding, and salinity

There was considerable annual variation in water depth and salinity, which will complicate restoration planning based on hydrological data from a single year. Average depth varied among years, with greater range among years in average depth in Calcasieu Lake marshes (12 cm) than in Acadiana Bays marshes (8 cm) (Fig. 6). Salinity was greatest during 2000 in both regions, but the increase was less pronounced in the Acadiana Bays marshes than in the Calcasieu Lake marshes (Fig. 7). Daily minimum and daily maximum salinity rose and fell over time with mean salinity in both regions (Fig. 7). Unlike salinity, water levels did not appear unusually different in 2000 than in other years (Figs. 6 and 7).

Marshes were flooded 24% of the time overall but there was considerable variation over time (Table 2), which will complicate restoration planning based on hydrological data from a single year. The percent of time marshes were flooded differed among the years ($P = 0.0032$). Years with the most flooding were 1995 and 1998. In that statistical analyses, the interaction between region and year was not significant ($P = 0.3092$), which indicated that high flooding years occurred simultaneously in both regions, and low flooding years occurred simultaneously in both regions.

Seasonal patterns in water depth were similar in both regions but water was shallower and less saline in the Acadiana Bay marshes, where marsh loss was slower, than in the Calcasieu Lake marshes. Marshes were most likely to flood in September and October (Fig. 8) when salinity was greatest (Fig. 9). That pattern was evidently interrupted during the drought that lasted from 1998 through 2000; during those years water depth gradually declined while salinity gradually increased (Figs. 6 and 7).

Predicted water depth

Predicted water depths averaged 0.27 m above mean lower low water over the entire record, over all years, and all months and thus created a flat line when graphed annually or monthly (not shown). Predicted daily tidal range varied seasonally as would be

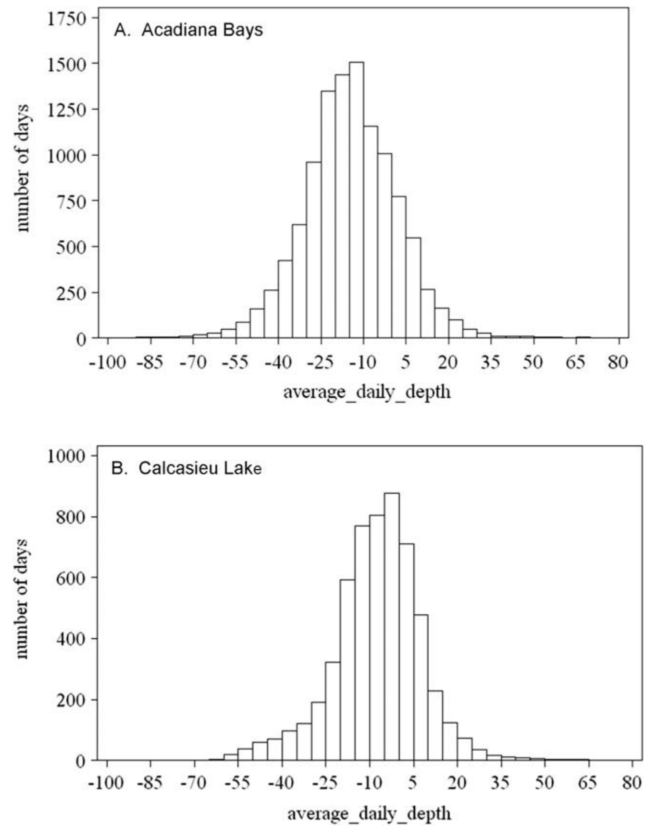

Fig. 4. Distribution of mean daily water depth in marshes of the Acadiana Bays (A) and of Calcasieu Lake (B), Louisiana, USA. Mean daily water depth was calculated from 399,772 hourly observations.

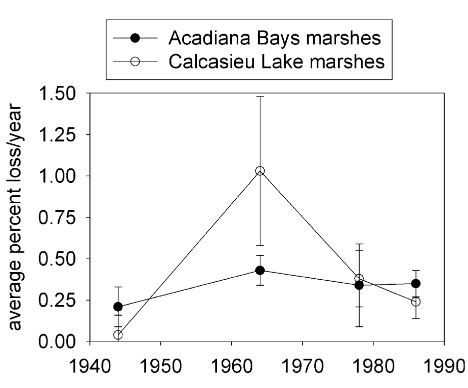

Fig. 3. Wetland loss rates reported by Britsch and Dunbar (1993) from 1935 to 1990 for the three quadrangles that encompass the Acadiana Bays sites and the three quadrangles that encompass the Calcasieu Lake sites the where water depth and salinity data that we analyzed were collected, Louisiana, USA.

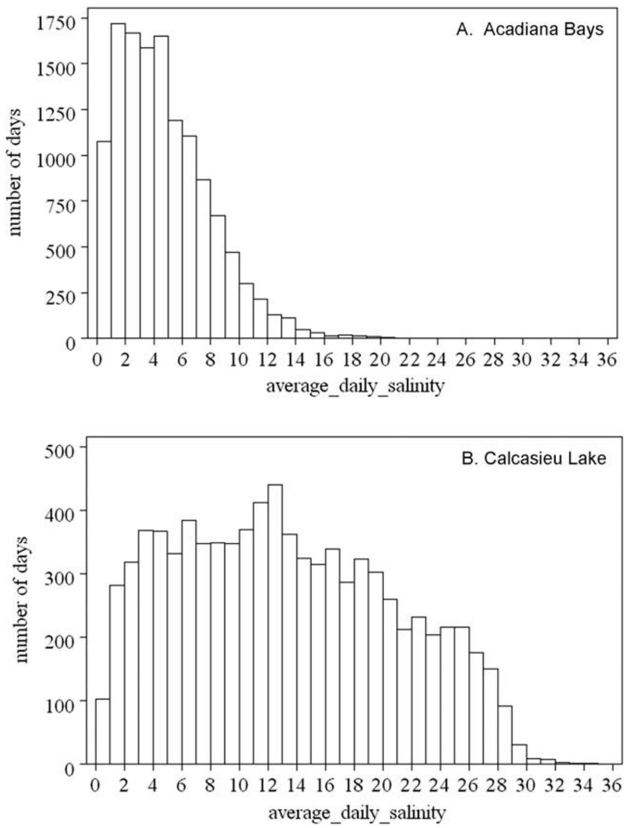

Fig. 5. Distribution of mean daily water salinity in marshes of the Acadiana Bays (A) and of Calcasieu Lake (B), Louisiana, USA. Mean daily water salinity was calculated from 521,561 hourly observations.

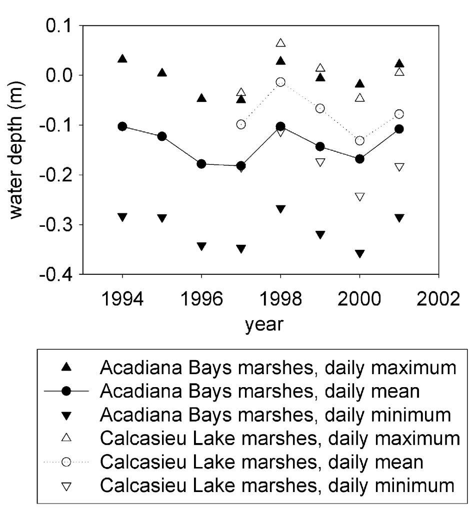

Fig. 6. Annual variability in daily maximum depth, daily mean depth, and daily minimum depth of water in marshes of the Acadiana Bays and of Calcasieu Lake, Louisiana, USA from 1994 through 2004.

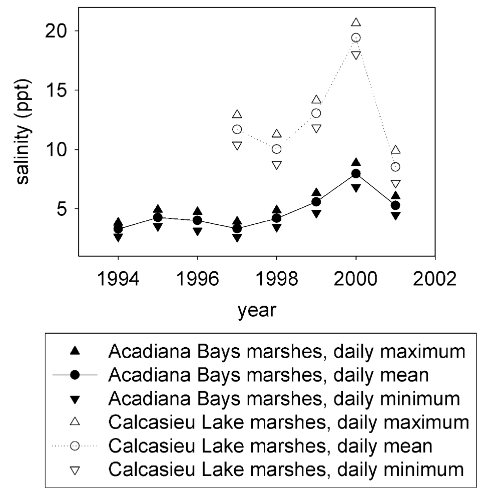

Fig. 7. Annual variability in daily maximum salinity, daily mean salinity, and daily minimum salinity of water in marshes of the Acadiana Bays and of Calcasieu Lake, Louisiana, USA from 1994 through 2004.

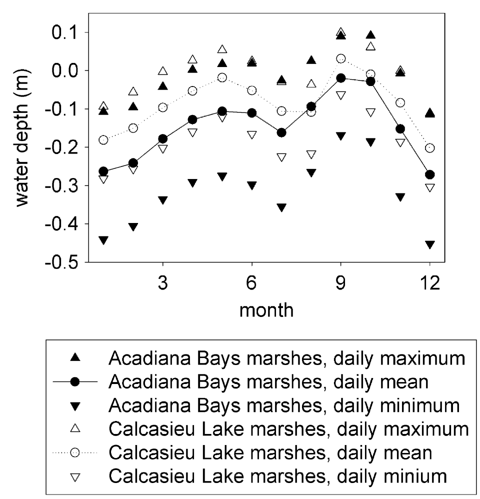

Fig. 8. Monthly variability is daily maximum depth, daily mean depth, and daily minimum depth of water in marshes of the Acadiana Bays and of Calcasieu Lake, Louisiana, USA.

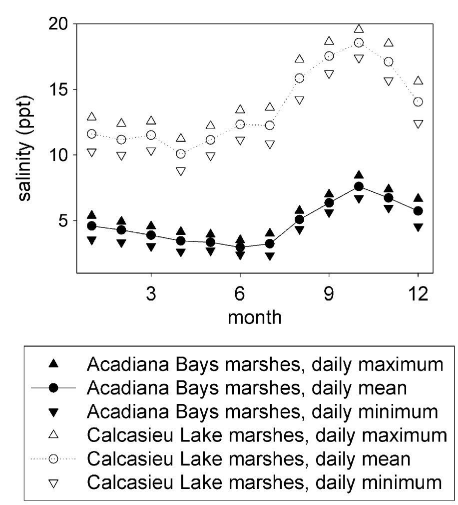

Fig. 9. Monthly variability in daily maximum salinity, daily mean salinity, and daily minimum salinity of water in marshes of the Acadiana Bays and of Calcasieu Lake, Louisiana, USA.

expected with greatest predicted daily tidal range during solstices (June and December) and least predicted daily tidal range during equinoxes (March and September) (Fig. 10). The predicted daily tidal range was greater than was observed (Fig. 10).

Discussion

Few long-term or large-scale hydrological studies of coastal marshes have documented trends in salinity and water depth over

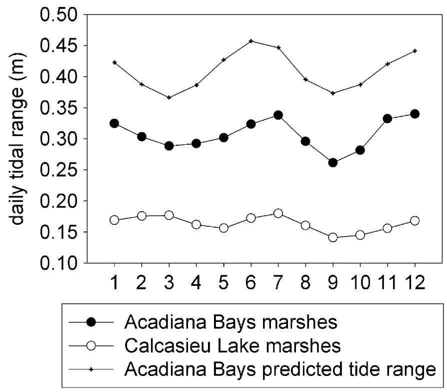

Fig. 10. Monthly variability is daily tidal range based on predicted water levels from NOAA Station number 8765251 (Cypremort Point), and based on observed water levels in marshes of the Acadiana Bays and of Calcasieu Lake, Louisiana, USA.

time. However, these data can provide critical information for scientists, engineers, and managers in setting not only target salinity and water levels, but also in defining acceptable ranges of these factors and in identifying normal seasonal and annual variation which can contribute to sustainable marsh ecosystems. Restoration and management of these coastal systems requires an understanding of key factors influencing marsh sustainability including their range and variability; while our findings are able to provide some guidance based on this analysis, clearly, the development of more extensive monitoring systems, combined with more region specific marsh loss rates would provide for better target development.

There are few long-term or large-scale hydrological estimates from other coastal marshes with which to compare the estimates reported here. Chabreck (1970) measured salinity of free soil water, rather than in surface water bodies as we did, in 302 systematically collected samples from throughout Louisiana's coastal marshes in August of 1968. Average water salinity at our sites (8.1 ppt) agreed with the average salinity that he reported for brackish marshes (8.2 ppt, $n = 110$) but was higher than the average salinity that he reported for intermediate marshes (3.3 ppt, $n = 36$), which also were dominated by *S. patens*. Chambers et al. (2002) reported flooding duration, which they measured as the percentage of 224 12-h tidal cycles that marshes were flooded, along the salinity gradient in the Housatonic River in Connecticut. Flood duration there ranged from 36% in *S. alterniflora* marshes to 19% in *P. australis* marshes. The *S. patens* marshes that we studied had intermediate flooding with water levels exceeding marsh elevation 24% of the time. Montalto et al. (2006) described water levels in a *P. australis*-dominated tidal marsh in the Hudson River estuary. In that marsh, the surface elevation was 12 cm below mean high water, and tidal range averaged 111 cm. Morris et al. (2005) working in South Carolina, USA with a tidal range of 139 cm observed that *S. alterniflora* marshes averaged 27 cm below mean high tide and *Juncus roemerianus* marshes averaged 9 cm below mean high tide. In contrast, the *S. patens* marshes that we studied experienced a smaller tidal range (31 cm) and were located within a centimeter of average daily high water. The position of the marsh surface in both regions that we studied, near the average daily high water level, is consistent with ideas regarding marsh vertical accretion being a self-regulating system controlled by flooding that stimulates mineral sedimentation or organic matter accumulation (Nyman et al., 2006).

Generally, tidal range and salinity are assumed to be correlated in coastal wetlands, but that was not the case at our sites where greater salinity was associated with less tidal range. This might largely be attributed to large-scale hydrologic alterations affecting Calcasieu Lake marshes. For example, salinity and tidal range are believed to be unnaturally high in Calcasieu Lake because of a navigation channel from the Gulf of Mexico at the south end of the lake to the city of Lake Charles at the north end of the lake (Gammill et al., 2001). Furthermore, levees and water control structures have separated Calcasieu Lake and its adjacent marshes since the mid-1990s because of attempts to reduce flooding and salinity in those marshes (Gammill et al., 2001). The flooding and salinity we thus observed in the Calcasieu Lake marshes are a product of those competing effects of the navigation channel and restoration efforts. Restoration efforts generally have reduced salinity 2–3 ppt below that found in Calcasieu Lake (e.g., Miller, 2003; Sharp and Billodeau, 2007a,b), but salinity in the Calcasieu Lake marshes none-the-less was higher than in the Acadiana Bays marshes. Attempts to reduce flooding have been successful in some Calcasieu Lake marshes (e.g., Sharp and Billodeau, 2007b), had no effect in other Calcasieu Lake marshes (Sharp and Billodeau, 2007a), and have increased water levels in other Calcasieu Lake marshes where water control structures have not been operated (Miller, 2003).

The Acadiana Bays marshes experienced slow wetland loss throughout the period of record but the Calcasieu Lake marshes experienced several decades of rapid marsh loss (Fig. 3). Rapid marsh loss in the Calcasieu marshes has been attributed to construction and occasional widening of the Calcasieu ship channel and the resulting salt water intrusion (Gammill et al., 2001). The first channel was 1.5-m deep, 24-m wide, and was dredged in 1874; the channel was deepened to 3.6 m in 1903, to 9 m in 1941, to 10.6 m in 1951, and to 12 m in 1968 when it was widened to 122 m wide (Gammill et al., 2001). The latest deepening and widening coincided with the most rapid marsh loss (Fig. 3). From 1968 to 1990 however, wetland loss rates did not appear to differ between the regions (Fig. 3). Wetland loss maps prepared by Barras et al. (2003) indicated that this trend of slower marsh loss continued into the 1990s in the Acadiana Bays and Calcasieu Lake marshes.

The temporary period of rapid marsh loss in the Calcasieu Lake marshes complicate efforts to identify relationships between marsh loss rates there during the early 1970s and hydrological conditions there during the late 1990s and early 2000s. It is likely that the flooding and salinity during the 1990s and 2000s in the Calcasieu Lake marshes were characteristic of the rapid marsh loss rates during the 1960s and 1970s, and that marsh loss slowed there because most marshes intolerant of those conditions had converted to open water by the 1980s. But it also is possible that marsh loss in the Calcasieu Lake marshes slowed because flooding and salinity decreased from the early 1970s through the early 2000s. We therefore could not determine if the flooding and salinity estimates that we reported for the Calcasieu Lake marshes characterize the period of rapid marsh loss from the 1950s to the 1970s or the slower marsh loss rates common since then, which prevent us from using observations from the Calcasieu Lake region for setting restoration targets for salinity and water levels.

The prevalence of slow marsh loss rates in the Acadiana Bays marshes throughout all periods of record support the conclusion that hydrological conditions in the Acadiana Bays marshes represent desirable conditions for management and restoration of coastal marshes dominated by *S. patens*. The estimates could be used to guide the elevation of constructed wetlands if the average elevation of water levels were known, or the estimates could be used to determine the elevation of managed water levels if the average elevation of existing wetlands were known. None-the-less, restoration planners working in areas where the tide range differs from 31 cm will need to decide whether to construct new wetlands 1 cm above average daily high water levels, 15 cm above average daily water levels, or 32 cm above average daily low water levels. The estimates might also be used to determine targets for flooding duration, water depths (low, mean, and high), and water salinity (annual and seasonal averages) for marshes that have flap-gated culverts or other structures that allow managers to influence water exchange between marshes and adjacent water bodies.

The annual and monthly differences that we observed in water levels did not agree with predicted annual and monthly water levels, which contained no variation from year to year or month to month. The failure for predicted water levels to reflect observed water levels support the contention that predicted water levels have little utility in areas with wind-dominated tides, and that managers, scientists, and engineers working in such areas should strive to obtain years of hourly water-level data related to local marsh elevation. We attributed the difference between predicted and observed water levels to a combination of the small tidal range and the seasonal variability in wind speed and direction. In spring, east and southeast winds prevail (Walker and Hammack, 2000). In summer, south winds prevail (Walker and Hammack, 2000). We attributed the increasing water levels in spring and summer (Fig. 8) to the southerly winds as other have (Walker and Hammack, 2000). Tropical storms are most likely during later summer but their effects on water levels depend on whether the hurricane passes to the east or to the west; passage on the east reduces water levels whereas passage on the west increases them (Walker and Hammack, 2000). We were unsure why there was a slight decline in water levels during July in both regions and also during August in the Calcasieu Lake marshes (Fig. 8). Perhaps the decline was related to southwest and west winds that are most common then (Walker and Hammack, 2000) and occasionally reverse the coastal current that otherwise flows from east to west in this region of the Gulf of Mexico (Walker et al., 2005). It also is possible that daily tidal range, which exhibited a peak during July (Fig. 10), also may be involved but additional research would be needed to address the anomalously low water levels during July. Northeast and north winds prevail during autumn whereas northwest and north winds prevail during winter and are stronger than in fall (Walker and Hammack, 2000); we attributed the declining water levels in autumn, and the lowest water levels in winter (Fig. 8) to these north winds as other have (Walker and Hammack, 2000). We likewise attributed annual variability in water levels to annual variability in wind speed and direction. The decreasing water levels and increasing salinity from 1998 through 2001 (LOSC, 2001) coincided with drought conditions that were attributed to La Niña; i.e., the "cold" phase of the El Niño/Southern Oscillation cycle (LOSC, 2000). By 2001, salinities were much higher than in other years, perhaps because of accumulating rainfall deficits, whereas water levels were only slightly lower than in other years, perhaps because winds that failed to bring rainfall only slightly lowered water levels in the Gulf of Mexico and because those low water levels could not accumulate.

Although productivity of emergent marsh vegetation declines with increasing flooding (DeLaune et al., 1987), it would be unnatural to continually minimize flooding and variability in flooding because water levels varied considerably as indicated by the frequency distribution (Fig. 4), annual means (Fig. 6), and monthly means (Fig. 8). Daily variability probably is most important in maintaining species composition and productivity of marshes dominated by *S. patens*. Flooding coastal marshes 21% of the time over the course of a year probably would cause extensive mortality or species replacements if the flooding occurred for 76 days early in the growing season, but probably would enhance productivity if the flooding occurred 5 h each day over a year. The greatest opportunities to promote daily flooding and draining occur when daily tidal range peaks during December and July (Fig. 10). Incorporating this information into restoration planning and management will depend upon the restoration and management goals. For example, marsh management plans focused on transient, estuarine-dependent fish and crustaceans probably would increase success if water control structures were operated during these times to allow daily tidal exchange. Alternatively, marsh management plans focused on increasing emergent plant production probably would increase success if water control structures were operated to allow daily tidal exchange during July, but not during December when plants are dormant or only slowly growing. Seasonal and annual variability also were significant in the marshes that we studied, which supports the contention that such variation should be incorporated in marsh management and restoration plans. For coastal wetland management plans focused on increasing emergent plant growth, it may be fortunate that daily tidal range peaks during the middle of the growing season because this timing creates the potential to maximize daily flooding and drainage when plant leaves most need water for photosynthesis and when plant roots most need relief from flooding stress. The availability of observed estimates of daily tidal range, as opposed to predicted estimates of daily tidal range, revealed that the greatest daily tidal ranges actually occurred in both regions during July, one month later than predicted (Fig. 3). The availability of observed water levels, as opposed to predicted water levels, also disclosed that lowest water levels occur during December and greatest water levels occur during September (Fig. 8). Coastal wetland management plans focused on increasing the productivity of emergent vegetation probably would increase success if water control structures were operated to allow gravity drainage during low tide while excluding high tides, as is possible with flap-gated culverts combined with variable crest weirs (see Chabreck and Nyman, 2005) during December and then excluding high water events during the growing season. Conversely, marsh management plans focused on increasing the growth of more flood tolerant species, such as *S. alterniflora*, at the expense of less flood tolerant species, such as *P. australis*, might be more successful if water control structures were operated to prevent gravity drainage during winter when water levels are low and then hold high water through the subsequent growing season.

Seasonal variability in flooding depths and duration also may be important for juveniles of estuarine-dependent nekton (e.g., Deegan et al., 1990), and management and restoration targeted at those species would require different seasonal variation in water level targets. Annual variability in flooding controls annual variability in wetland plant productivity, and perhaps species composition, and links estuarine fish productivity to marsh plant production (Morris et al., 1990). Unlike seasonal variability in water levels, annual variability cannot yet be predicted and therefore accounted for in planning and managing restoration projects. None-the-less, the existence of annual variability supports the contention that water level management plans vary among years.

Although productivity of emergent marsh vegetation declines with increasing salinity (DeLaune et al., 1987), it would be unnatural for managers to continually minimize mean salinity and variability in salinity because salinity did not appear to be normally distributed (Fig. 5). The lack of normal distributions (Figs. 4 and 5) was unexpected because each observation was itself the average water salinity for a single day. Those distributions illustrate the large variations in water depth and salinity that characterize hydrologic conditions in these coastal marshes, and probably are important in controlling plant species composition and productivity. Management and restoration targets should include considerable seasonal and annual variation in salinity as indicated by the frequency distribution (Fig. 5), annual means (Fig. 7), and monthly means (Fig. 9). Similarly, Thomson et al. (2002) analyzed over four decades of water level and salinity data from a station in southeastern Louisiana. Even though the adjacent wetlands were primarily a cypress-tupelo swamp (Taxodium – Nyssa), they noted seasonal patterns in water levels and salinity such that salinity was greatest in the fall when flooding was most likely (Thomson et al., 2002). These data suggest that annual variability probably is most important in maintaining species composition and productivity of marshes dominated by *S. patens*. Low salinity early in the growing season probably enhances productivity while high salinity later in the growing season probably prevents encroachment by less salt-tolerant species. Salinity in coastal waters generally follows that pattern because of the spring flood by rivers (Mossa and Roberts, 1990). The greatest opportunities to increase salinity occur during August when salinity generally increases (Fig. 9). Incorporating this information into restoration planning and management will depend upon the restoration and management goals. For example, marsh management plans focused on increasing growth of more salt-tolerant emergent plant species, such as *S. alterniflora,* at the expense of less salt-tolerant species, such as *P. australis,* would benefit from operating water control structures to maximize water exchange between managed marsh and tidal channels during August, whereas marsh management plans focused on increasing plant productivity would benefit from operating water control structures to minimize water exchange between managed marsh and tidal channels during August and instead retain fresher waters from earlier in the year. Unlike seasonal variability in water salinity, annual variability cannot yet be predicted and therefore accounted for in planning and managing restoration projects. None-the-less, the existence of annual variability supports the contention that water salinity management plans vary among years.

Summary

The annual and monthly differences that we observed in water levels did not agree with predicted annual and monthly water levels, which support the contention that predicted water levels have little utility in planning and managing coastal wetland restoration projects in areas with wind-dominated tides. We attributed the difference between predicted and monthly observed water levels to a combination of the small tidal range and the seasonal variability in wind speed and direction, but additional research may be needed to determine how seasonal variability in wind speed, wind direction, and daily tidal range interact to create seasonal patterns in water levels. We also attributed differences between predicted and annual observed water levels to La Niña; i.e., the "cold" phase of the El Niño/Southern Oscillation cycle, but additional research also is needed to verify this relationship.

The data analyzed and described support previous hypotheses and conclusions that marsh loss decreases with tidal range, and increases with flooding and salinity. If one assumes that the relatively slow marsh loss rates occurring in the Acadiana Bays represent almost ideal conditions of water depth and flooding, then hydrologic characteristics of those marshes can be used to guide planning and operation of restoration and management efforts in *S. patens* marshes. Our data thus suggest that hydrologic restoration targets within project areas dominated by *S. patens* would include (1) target water depths averaging 15 cm below marsh elevation, (2) annual flooding averaging 21% of the time, and (3) salinity averaging 5.0 ppt. Our analyses also indicated that management and restoration targets should include considerable seasonal and annual variation (Figs. 4–9). These findings and suggested targets are most applicable to coastal marshes on the northern Gulf of Mexico dominated by *S. patens* but also may be useful on the Atlantic coast of North America where hydrologic conditions have not yet been characterized in *S. patens* marshes. We described how water level targets and water salinity targets could vary seasonally with a few simplistic examples in which there was only a single management or restoration goal, but actual targets will be more complicated because actual management and restoration plans generally have multiple goals prioritized in different ways (e.g., migratory waterbirds, emergent plant species production, emergent plant species composition, and transient estuarine-dependent nekton). The methods that we used to develop these targets, including targets for seasonal variation, could also be applied to other types of coastal wetlands worldwide.

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