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Abstract

Tidal flooding of the marsh edge appears to be an important characteristic that affects the value of this habitat for juvenile nekton. We measured elevations and flooding durations of the marsh surface near the edge in 13 (10 natural and three created) *Spartina alterniflora* marshes in Galveston Bay. Benchmarks and water level recorders were installed near each marsh in 2010, and a professional surveyor measured elevations in NAVD88 by taking static GPS observations at each marsh. The elevation of the edge was variable among the 13 marshes ranging from -15.3 cm to 43.0 cm (NAVD88), with an overall mean elevation of 3.8 cm (SE = 4.1). Edge elevations appeared to be substantially higher and more variable in the three upper bay marshes with a mean of 17.9 cm NAVD88 (SE = 14.0) compared with the ten lower bay marshes (mean = - 0.5 cm NAVD88, SE = 2.7). Natural marshes in the lower bay were flooded for 83.7% of the time over the four years from 2010-2013, and the two created marshes in the lower bay had similar flooding characteristics. The Demonstration Marsh, created in 1993, in the upper bay had the highest elevation and lowest flooding duration (30.4% over 4 years) of any marsh examined. Our data support the conclusion that flooding durations in most Galveston Bay marshes are higher than in many other estuaries of the northern Gulf of Mexico, and this characteristic may be responsible for the high productivity of penaeid shrimps and blue crabs in the bay.

Introduction

Coastal wetlands in Texas and Louisiana have a large amount of edge and support high densities of juvenile fishery species such as brown shrimp *Farfantepenaeus aztecus*, white shrimp *Litopenaeus setiferus*, and blue crab *Callinectes sapidus* (Zimmerman and Minello 1984, Minello and Rozas 2002). Many marsh restoration projects are designed to replicate the geomorphology of these productive natural marshes in attempts to enhance their habitat value for fisheries (Rozas et al. 2005, Minello et al. 2012a). While the vegetation/water interface (edge) is important in providing access to the marsh surface, these habitats cannot be directly used by fishery species unless they are flooded. Thus, tidal inundation patterns (Rozas 1993, McIvor and Rozas 1996) are fundamentally important in determining marsh use and value. Where the relationship has been examined, there appears to be a correlation between use of the marsh surface and the extent of tidal inundation (Kneib and Wagner 1994, Rozas 1995, Minello et al. 2012b).

Geographic variability in estuarine hydroperiod and marsh inundation patterns can be substantial (Minello et al. 2012b), and differences in flooding patterns may be large enough to affect marsh access by fishery species and habitat value (Rozas 1995, Baker et al. 2013). Variability within estuaries also may be high, and Rozas and Zimmerman (2000) reported that marsh inundation was longer in East Bay than upper Galveston Bay. A detailed examination of flooding patterns within the Galveston Bay system will provide a more complete picture of inundation patterns within the estuary. This information also should be useful in selecting elevation targets for marsh restoration projects.

The Demonstration Marsh was created in Galveston Bay at Atkinson Island to show that valuable wetlands could be constructed using material from the widening and deepening of the Houston Ship Channel. Since its construction in 1993, various attempts have been made to increase the amount of marsh-water edge in this marsh (Turner Collie and Braden Inc. 2002). The development of edge and related fishery value in the Demonstration Marsh was examined by analyzing landscape characteristics from aerial photography taken in 1997, 1999, and 2005 with GIS and using these data in a modeling approach to estimate standing crops of selected species at the restoration site (Minello and Caldwell 2006). Based on these population models that are driven by the amount of marsh edge (Minello et al. 2008), populations of brown shrimp, white shrimp, and blue crab were estimated to be substantially higher in the marsh (12 to 154 times) than populations expected at the site before the Demonstration Marsh was constructed. Those models, however, do not incorporate any detailed information on marsh topography or marsh surface elevations. Minello and Caldwell (2006) used data from general elevation surveys and the NOAA Morgans Point tide gauge to estimate that the annual flooding duration of marsh edge at the restoration site was 41% in 2005 and was comparable to the flooding durations of nearby marsh at Atkinson Island and Hog Island. Their estimate of flooding duration at the Demonstration Marsh, however, was not based on tidal data collected onsite or on actual elevations of the marsh edge. Because the restoration site is partially surrounded by a levee, water levels in the marsh may be affected by the restricted openings into the site. Measuring water levels within the restoration site and connecting these data to edge elevations should provide a more accurate estimate of marsh flooding patterns.

Our objective in this study was to measure marsh tidal inundation patterns at a variety of natural salt marshes in Galveston Bay (Figure 1); we also measured flooding patterns at the Demonstration Marsh and two other created marshes in the bay system. These data provide information on variability in flooding patterns among natural marshes and should be useful in determining target elevations for future marsh restoration projects.

Methods

We selected 10 natural marsh shorelines and three created marshes for measurements of marsh elevation and tidal inundation patterns in the Galveston Bay system (Figure 1). The shorelines of all marshes were dominated by *Spartina alterniflora*. Our selection criteria required that marshes be in a sheltered environment (reduced wave exposure) but open to tidal exchange (not impounded). Between June 1-4, 2010, we installed instrumentation and measured sediment-surface elevations of the marsh and adjacent nonvegetated bottom. At each location, we installed a temporary benchmark, staff gauge, and HOBO water level logger (Onset Computer Corporation, 470 MacArthur Blvd., Bourne, MA 02532) to measure changes in water levels. The benchmark consisted of a 3-m long PVC pipe with an orange colored cap; the pipe was driven into the sediment until the cap was near the marsh edge surface. We calibrated measurements among the gauges by measuring the water level above the benchmark and compared that value with the reading on the staff gauge and the HOBO water level logger. We randomly selected five locations along a shoreline of approximately 1 km for measurements of elevation along transects perpendicular to the marsh edge. Transects extended 10 m into the marsh vegetation and 10 m into adjacent open water. Elevations were measured at the marsh edge (identified as the location where the lowest growing culms of vegetation occurred) and at 1-m intervals on either side of the edge. When possible, elevations were measured by comparing the water depth at locations along each transect with the water depth at the benchmark. If the marsh surface was not flooded, we used a laser level to compare the surface elevation with the benchmark.

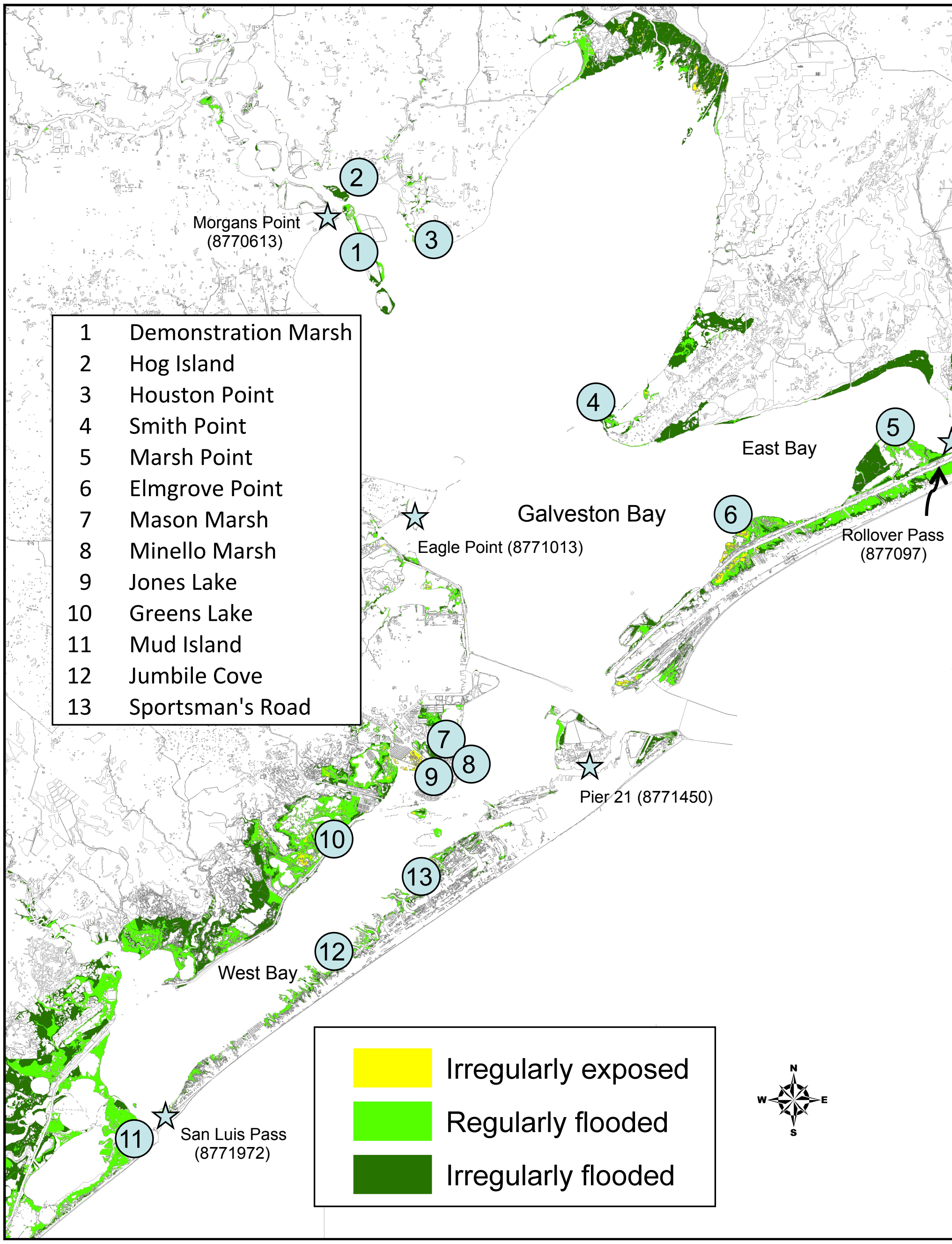

Figure 1. Location of 13 salt marshes in Galveston Bay, Texas where tidal inundation was measured. Locations of supplemental tide gauges are shown with stars and identified with NOAA tide gauge numbers. The background map was developed from USFWS National Wetland Inventory Data created from 2004-2006 sub-meter True Color USGS imagery. These updated data were unavailable for East Bay wetlands, where wetland coverage was based on imagery from 1985 to 1997. The wetland classification shown in the legend follows Cowardin *et al.* (1979).

Elevations of the benchmarks in NAVD88 (North American Vertical Datum of 1988) were measured by Delta Land Surveying (P.O. Box 368, Anna, TX 75409) from June 14-16, 2010 (Table 1). Elevations were determined by taking static GPS observations for a period of over 1 hr using Topcon Hiperlite Plus Receivers mounted on a fixed height tripod. Accuracy

Table 1. Location of benchmarks near marshes where elevations and marsh flooding was measured in the Galveston Bay system. Benchmark elevations are shown in cm NAVD88 along with the mean elevation (SE) of the marsh edge from five transects. Created marshes are in grey.

		Benchmark			Marsh Edge	
	Location	Latitude N	Longitude W	NAVD88 (cm)	Mean Elev NAVD88 (cm)	SE
1	Demonstration Marsh	29.65208	94.95856	12	43.0	3.2
2	Hog Island	29.69454	94.98007	2	16.0	3.3
3	Houston Point	29.66724	94.92654	7	-5.4	1.5
4	Smith Point	29.54328	94.77481	12	-15.3	1.9
5	Marsh Point	29.52354	94.57309	25	-6.2	1.5
6	Elmgrove Point	29.46230	94.68617	18	-11.2	2.1
7	Mason Marsh	29.32393	94.92294	5	7.2	2.8
8	Minello Marsh	29.32393	94.92294	5	-3.2	1.4
9	Jones Lake	29.31412	94.93450	8.5	-2.2	1.5
10	Greens Lake	29.27359	94.98627	16	11.8	3.5
11	Mud Island	29.08009	95.14243	8	4.1	2.7
12	Jumbile Cove	29.19742	94.98993	20	3.2	2.3
13	Sportsmans Road	29.25558	94.91544	25	7.0	2.0

standards published by NOAA on their OPUS_RS website (http://www.ngs.noaa.gov/OPUS/) indicate that a 1 hr data collection will result in 2-3 cm accuracy in the Galveston Bay area, and more specifically the accuracies should range from 1.9-2.3 cm.

Hourly measurements of water level from the HOBO loggers were used to estimate flooding of the marsh edge. HOBO pressure sensors are not vented, and values were corrected for changes in barometric pressure using additional HOBO recorders exposed to the atmosphere and NOAA gauges in the system. Because our HOBO records were incomplete due to periodic failure of the gauges, the data were supplemented with information from NOAA tide gauges in the Galveston Bay system. The locations of active tide gauges operated by NOAA's National Ocean Service (http://tidesandcurrents.noaa.gov) and used in these analyses are shown in Figure 1. Data from these gauges were compared with values from our HOBO gauges, and regression analyses were used to fill in missing water level values at our marsh sites (Table 2).

Results

Marsh elevation profiles indicated that most of the marshes examined had relatively shallow slopes (Appendix Figures 1-4). The marshes of the lower bay were generally similar with most of the marsh surface examined at elevations between 15-30 cm NAVD88. Marsh elevations at Hog Island and the Demonstration Marsh were higher, however, and the Demonstration Marsh was characterized by a high elevation flat marsh surface and a steep decline in elevation near the edge into a relatively deep channel (Appendix Figure 1).

Table 2. Regression relationships between hourly water level data from temporary HOBO water level loggers at each marsh and NOAA tide gauges in Galveston Bay. A positive lag indicates the tide reached the HOBO after reaching the NOAA gauge, and a negative lag indicates the tide reached the HOBO before the NOAA gauge. The regression y is the HOBO value in m and the x is water level in m in relation to the station datum on the NOAA gauge. HOBO data were deleted from the analysis during times when water levels were lower than the gauge. Created marshes are in grey.

	Location	Available HOBO data	NOAA Gauge used for supplementing HOBO	Lag	Regression	R^2
1	Demonstration Marsh	June, 2010 - Nov, 2011	Morgans Point	0 hrs	$y = 0.9244x - 1.4165$	97.0%
2	Hog Island	June-Dec, 2010	Morgans Point	0 hrs	$y = 0.9582x - 1.3079$	98.0%
3	Houston Point	June, 2010 - June, 2012	Morgans Point	0 hrs	$y = 0.8997x - 1.1235$	96.8%
4	Smith Point	June-Oct, 2010	Eagle Point	0 hrs	$y = 0.9629x - 1.2583$	94.7%
5	Marsh Point	June-Dec, 2010	Rollover Pass		$y = 0.1312x^2 + 0.5875x - 0.6637$	98.6%
6	Elmgrove Point	June-Nov 2010	Eagle Point	-1 hrs	$y = 0.1113x^2 + 0.4455x - 0.8126$	91.5%
7	Mason Marsh	June-July, 2010	Sportsmans Road*	+2 hrs	$y = 0.2401x^2 + 0.6122x - 0.1412$	96.1%
8	Minello Marsh	Water levels from Mason Marsh used here				
9	Jones Lake	June-Dec, 2010	Pier 21	+2 hrs	$y = 0.3798x^2 - 0.5106x$	94.1%
10	Greens Lake	June-Oct, 2010	Pier 21	+3 hrs	$y = 0.3737x^2 - 0.4929x$	92.4%
11	Mud Island	June-Dec, 2010	San Luis Pass#	0 hrs	$y = 0.9451x - 0.9793$	98.5%
12	Sportsmans Road	June, 2010 - Dec 2012	Pier 21	+3 hrs	$y = 0.3291x^2 - 0.3328x$	89.7%
13	Jumbile Cove	June 2010 - Feb 2011	Sportsmans Road*	0 hrs	$y = 0.1562x^2 + 0.8503x - 0.0492$	99.0%

* Water level data from the Sportsmans Road HOBO recorder was used to predict values
\# Water levels in 2013 were predicted from Pier 21 (R^2= 94%)

The elevation of the marsh edge was variable among the 13 marshes examined in Galveston Bay ranging from -15.3 cm to 43.0 cm (NAVD88), with an overall mean elevation of 3.8 cm (SE = 4.1) (Table 3). Marsh edge elevations appeared to be substantially higher and more variable in the upper bay (Demonstration Marsh, Hog Island, and Houston Point) with a mean of 17.9 cm NAVD88 (SE = 14.0) compared with the remaining lower bay marshes (mean = - 0.5 cm NAVD88, SE = 2.7).

When we measured edge elevations in 2010, our estimate of marsh edge flooding ranged from 31.5% at the Demonstration Marsh to 98.9% at Minello Marsh, another created marsh in West Bay (Table 3). Over the four years from 2010-2013, the mean values ranged from 30.4% at the Demonstration Marsh to 99.2% at Minello Marsh. Natural marshes in the lower bay were flooded for 83.7% of the time over the four years examined, ranging from 62.6% at Mud Island to 93.1% at Elmgrove Point. Only two natural marshes were examined in the upper bay, and the 4-year mean flooding of these two marshes was quite different; 36.6% at Hog Island and 93.5% at Houston Point.

Our flooding values estimated over the years 2010-2013 are all based on edge elevations measured in 2010, and these values should be most accurate in 2010. If we included all 13 marshes, annual flooding over the 4 years ranged from 73.9% (SE = 6.7%) in 2011 to 82.7% (SE = 6.0%) in 2012 (Table 3). Among the natural marshes of the lower bay, these values ranged from 78.6% in 2011 to 88.4% in 2012. There is some evidence that edge elevations varied over this 4-year period, particularly at Hog Island, and flooding estimates in later years of the series would be most affected by such changes. We made repeated measurements of the marsh edge in

Table 3. Percentage of time that the marsh edge was flooded for 13 Galveston Bay marshes over the years from 2010 - 2013. Based on marsh edge elevations measured in June 2010 and HOBO water level recorders. Created marshes are in grey.

	Location	Mean Edge Elev in NAVD88 (cm)	Year 2010	2011	2012	2013	Mean
1	Demonstration Marsh	43.0	31.5%	23.1%	33.6%	33.4%	30.4%
2	Hog Island	16.0	38.0%	27.8%	41.2%	39.5%	36.6%
3	Houston Point	-5.4	92.1%	91.2%	97.0%	93.7%	93.5%
4	Smith Point	-15.3	84.1%	83.4%	91.8%	90.4%	87.4%
5	Marsh Point	-6.2	86.5%	84.5%	92.5%	90.3%	88.4%
6	Elmgrove Point	-11.2	92.0%	91.3%	96.9%	92.0%	93.1%
7	Mason Marsh	7.2	90.3%	90.8%	96.7%	87.0%	91.2%
8	Minello Marsh	-3.2	98.9%	99.2%	99.2%	99.5%	99.2%
9	Jones Lake	-2.2	91.3%	89.7%	94.1%	92.9%	92.0%
10	Greens Lake	11.8	74.6%	69.0%	80.4%	78.4%	75.6%
11	Mud Island	4.1	60.6%	54.1%	70.7%	64.9%	62.6%
12	Jumbile Cove	3.2	82.2%	76.1%	88.8%	85.5%	83.2%
13	Sportsmans Road	7.0	87.8%	81.1%	91.7%	89.3%	87.5%

relation to our benchmarks in 2013, under the important assumption that our temporary benchmarks were vertically stable over this period. At Hog Island, these measurements indicated that the marsh edge had migrated down in the tidal frame 30 cm over this period. In 2010, the marsh edge at this site consisted of mixed vegetation including *S. alterniflora* and *Schoenoplectus*. In 2013 and again in 2015, when we revisited the site, the original marsh edge with *Schoenoplectus* was several meters inland from the new marsh edge; a robust monotypic stand of *S. alterniflora* occupied the area between the old and new edge. Our estimate of marsh edge flooding over the years 2010-2013 based on the edge elevation in 2013 was 82.2%, substantially higher than our earlier estimate of 36.6%, and very similar to the other natural marshes. While we consider these as anecdotal estimates, because the temporary benchmarks may have shifted, estimates of edge elevation change from 2010 to 2013 at the other natural marshes in the bay were substantially lower with a mean increase in elevation of 4.4 cm, ranging from a 15 cm increase at Elmgrove Point to a 1.3 cm decrease at Mud Island.

The relationship between marsh edge elevation and tidal flooding did not appear linear (Figure 2). However, all marshes with edge elevations below 0 NAVD88 had flooding values over 80%, and flooding generally decreased with increasing elevations above 0.

There also was a seasonal component to flooding, and mean flooding over the four years for all of the marshes was lowest during winter months at 65.8% (SE = 7.2%) of the time (Table 4). Mean flooding was 79.9% (SE = 5.7%) in spring, 83.1% (SE = 6.3%) in summer, and 84.1% (SE = 5.5%) in the fall.

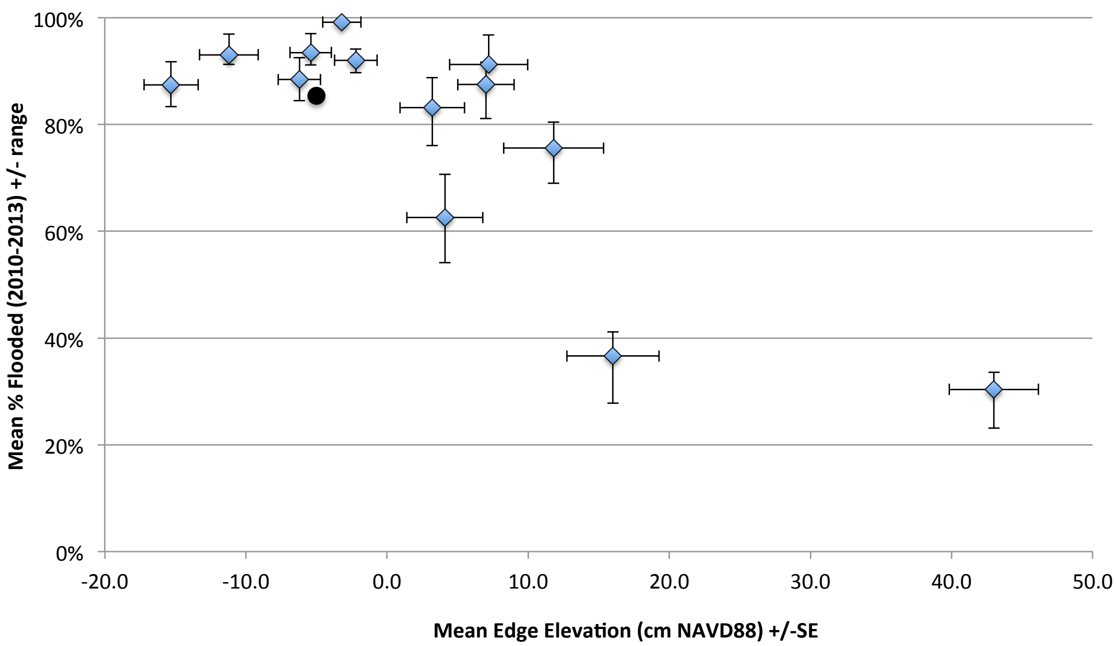

Figure 2. Relationship between marsh edge elevation and annual flooding of the marsh edge in Galveston Bay. Black circle represents mean flooding % reported in Minello et al. (2012b) for Galveston Bay in 2006-2008.

Discussion

We measured marsh edge elevations in Galveston Bay in 2010, and the estimates were variable among the natural marshes examined, ranging from -15 cm to +16 cm NAVD88. Nine of the 10 natural marshes had edge elevations below 11.8 cm NAVD88. The overall mean annual flooding duration for these marshes was 84.8% (range 62.6-93.5%) from 2010-2013; comparable to the 85.4% reported by Minello et al. (2012b) for Galveston Bay marshes in 2006-2008. The Hog Island marsh in the upper bay appeared different from most other natural marshes, with an edge elevation of 16 cm NAVD88 and a four-year mean flooding duration of only 36.6%. There was evidence that the marsh at Hog Island had expanded between 2010 and 2013, with the edge moving down and out towards the open bay; flooding of the edge in 2013 appeared to be substantially higher than in 2010. While many factors can apparently affect the elevation of the marsh edge (see Mendelssohn and Morris 2000 and Minello et al. 2012b for reviews), high flooding durations and waterlogging of *S. alterniflora* generally prevent this species from growing under constantly submerged conditions. Shoreline erosion, sediment availability, and salinity also are important, and these factors may have been responsible for the conditions at Hog Island. Hog Island is located in a high energy area of upper Galveston Bay influenced by a narrowing of the bay and the wakes of large ships in the Houston Ship Channel. Active dredging of this channel also results in high suspended sediment loads in the area, and salinity in the upper bay is generally low but variable. Together, these factors make this a dynamic system, and the marsh edge at Hog Island appears to be dynamic as well, moving both vertically and horizontally. The other natural marshes examined in the lower bay appeared more stable than at Hog island.

Table 4. Percentage of time that the marsh edge was flooded during each season over the years from 2010-2013. Spring = March-May; Summer = June-August; Fall = September-November; Winter = December-February. Created marshes are in grey.

	Location	Season	Year 2010	2011	2012	2013	Mean
1	Demonstration Marsh	Spring	30%	37%	44%	35%	36.4%
		Summer	41%	17%	42%	29%	32.3%
		Fall	41%	28%	33%	55%	39.1%
		Winter	14%	10%	15%	15%	13.5%
2	Hog Island	Spring	36%	40%	51%	40%	41.8%
		Summer	51%	26%	51%	37%	41.2%
		Fall	48%	32%	41%	63%	46.1%
		Winter	17%	13%	21%	18%	17.1%
3	Houston Point	Spring	91%	94%	99%	91%	93.8%
		Summer	100%	100%	99%	99%	99.6%
		Fall	95%	91%	99%	98%	95.9%
		Winter	82%	79%	91%	86%	84.5%
4	Smith Point	Spring	81%	89%	96%	87%	88.2%
		Summer	95%	93%	97%	96%	95.1%
		Fall	92%	86%	97%	98%	93.4%
		Winter	69%	65%	77%	80%	72.7%
5	Marsh Point	Spring	85%	89%	96%	88%	89.7%
		Summer	96%	94%	98%	96%	95.9%
		Fall	94%	87%	96%	98%	93.6%
		Winter	71%	68%	79%	79%	74.3%
6	Elmgrove Point	Spring	90%	96%	99%	90%	93.6%
		Summer	100%	99%	99%	100%	99.6%
		Fall	97%	92%	99%	98%	96.5%
		Winter	80%	78%	91%	80%	82.3%
7	Mason Marsh	Spring	81%	98%	100%	85%	91.2%
		Summer	98%	85%	98%	88%	92.3%
		Fall	98%	86%	97%	98%	94.8%
		Winter	83%	94%	92%	76%	86.4%
8	Minello Marsh	Spring	98%	100%	100%	99%	99.2%
		Summer	100%	100%	100%	100%	100.0%
		Fall	100%	98%	100%	100%	99.3%
		Winter	98%	99%	97%	99%	98.1%
9	Jones Lake	Spring	89%	94%	97%	92%	92.9%
		Summer	99%	93%	96%	94%	95.6%
		Fall	97%	93%	98%	99%	96.8%
		Winter	81%	79%	85%	86%	82.6%
10	Greens Lake	Spring	68%	77%	84%	75%	76.0%
		Summer	86%	72%	88%	78%	81.2%
		Fall	85%	73%	88%	95%	85.6%
		Winter	59%	53%	61%	65%	59.3%
11	Mud Island	Spring	51%	64%	72%	62%	62.2%
		Summer	71%	53%	76%	62%	65.6%
		Fall	77%	62%	82%	88%	77.3%
		Winter	43%	38%	52%	48%	45.1%
12	Jumbile Cove	Spring	79%	83%	93%	84%	84.9%
		Summer	91%	83%	94%	86%	88.5%
		Fall	91%	84%	96%	98%	92.3%
		Winter	68%	54%	71%	74%	66.8%
13	Sportsmans Road	Spring	84%	88%	96%	88%	89.1%
		Summer	97%	89%	97%	91%	93.1%
		Fall	95%	88%	98%	98%	94.9%
		Winter	75%	59%	76%	80%	72.6%

One of our objectives was to compare marsh edge flooding at the Demonstration Marsh with other marshes in the bay. The marsh edge elevation here was the highest measured in 2010 at 43 cm above NAVD88, and the flooding duration estimate was the lowest of all marshes at 30.4% over the four years from 2010-2013. As at Hog Island, the marsh edge elevation appeared to move down from 2010 to 2013 by 21 cm, but even so, flooding estimated at this elevation was low at 52.1% over the four year period. The differences in flooding duration were especially apparent between the Demonstration Marsh and the two other created marshes in the bay. Mason Marsh and Minello Marsh had some of the highest flooding durations estimated. The combination of limited edge in the Demonstration Marsh (Minello and Caldwell 2006) and low flooding of the marsh surface make this marsh of limited value for nekton that directly use the marsh surface.

Our results confirm that natural marsh flooding in Galveston Bay is generally high, compared with other coastal marsh systems (Minello et al. 2012b), and this characteristic may be responsible for the high densities of penaeid shrimp and blue crabs using these marshes (Zimmerman and Minello 1984, Rozas et al. 2007). Access to the marsh surface can increase growth (Minello and Zimmerman 1991, Rozas and Minello 2009) and reduce mortality (Minello et al. 1989). Spatial, seasonal, and annual variability in marsh flooding has the potential to affect productivity of nekton such as shrimp and crabs that use the marsh surface, and we are currently developing models to examine the sensitivity of their production to flooding characteristics (Baker et al. 2014). There also is some evidence that flooding affects the transfer of marsh carbon to these species (Baker et al. 2014). If a goal of marsh creation in the system is to increase fishery production for shrimp and blue crabs, both the amount of edge and the elevation of that edge should be considered. Our results indicate that created marshes can vary considerably in relation to this elevation and that sustainably high flooding durations can be achieved at edge elevations near or below 0 NAVD88.

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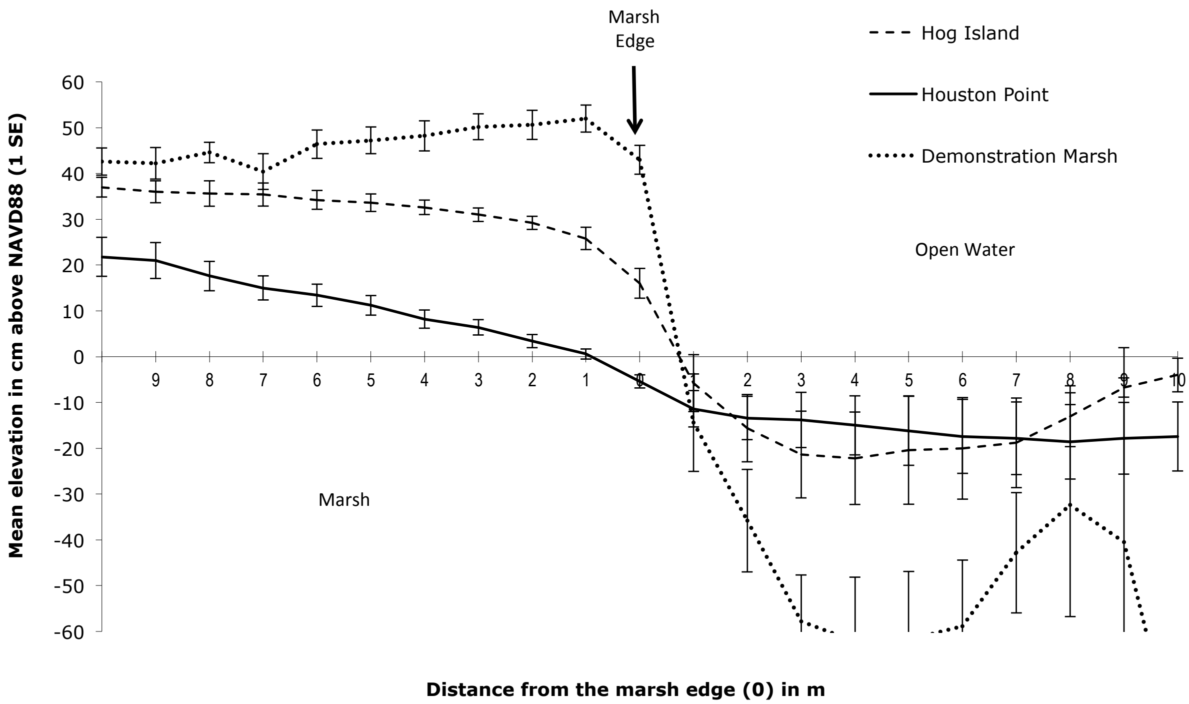
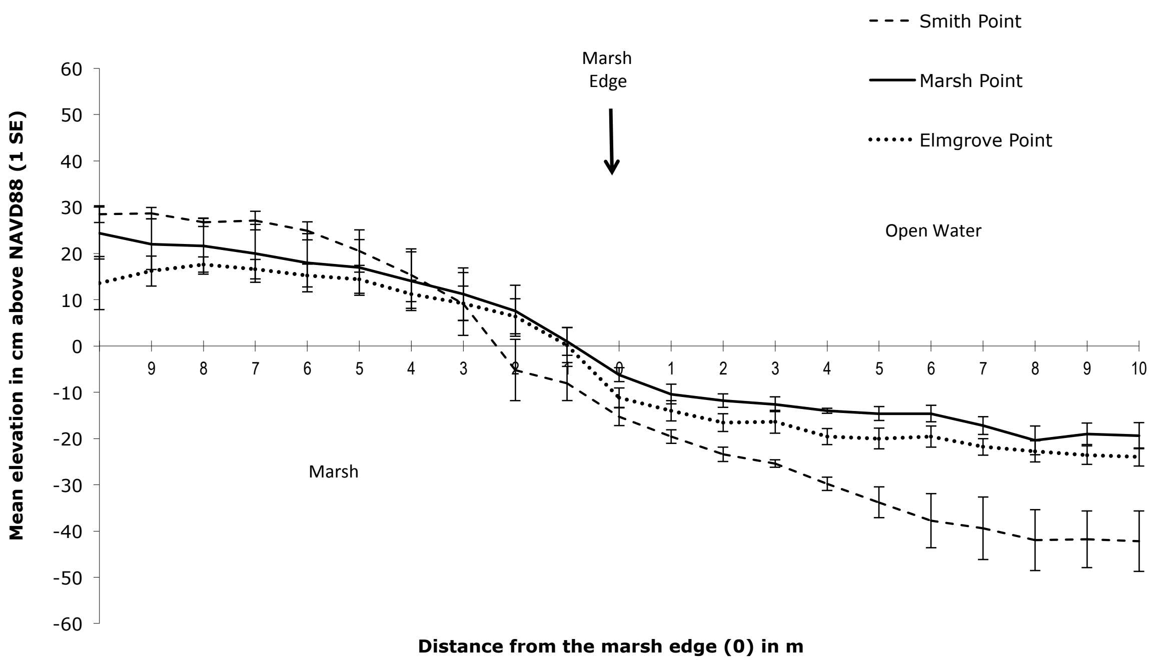
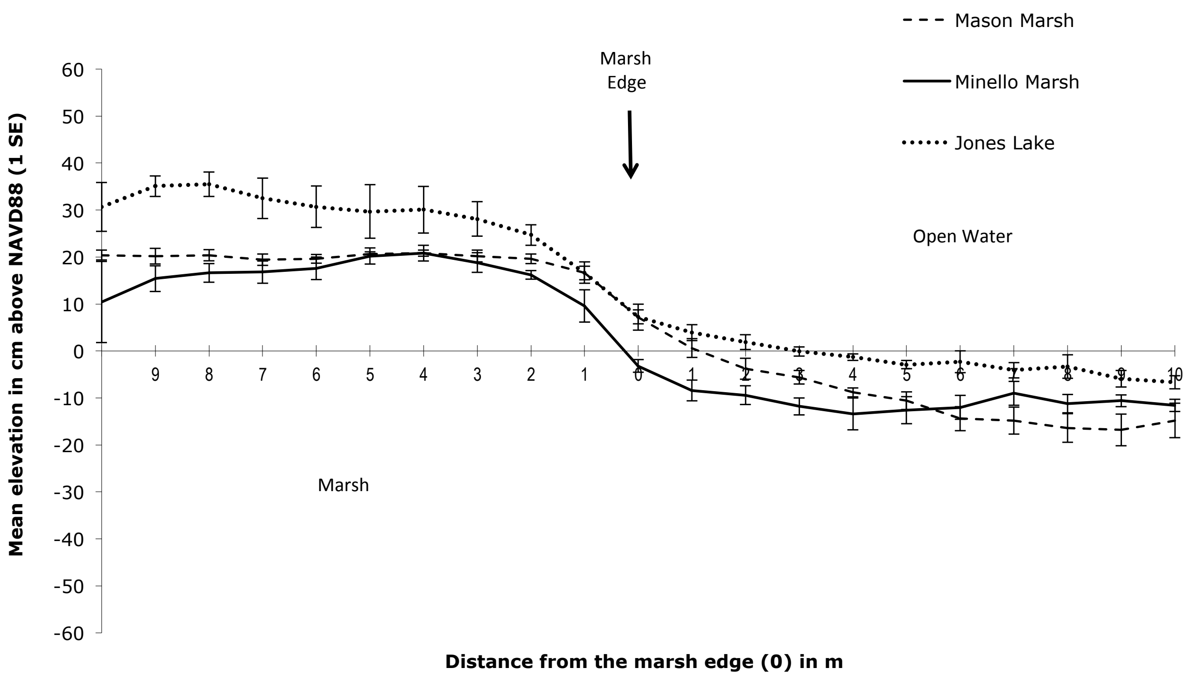
Appendix



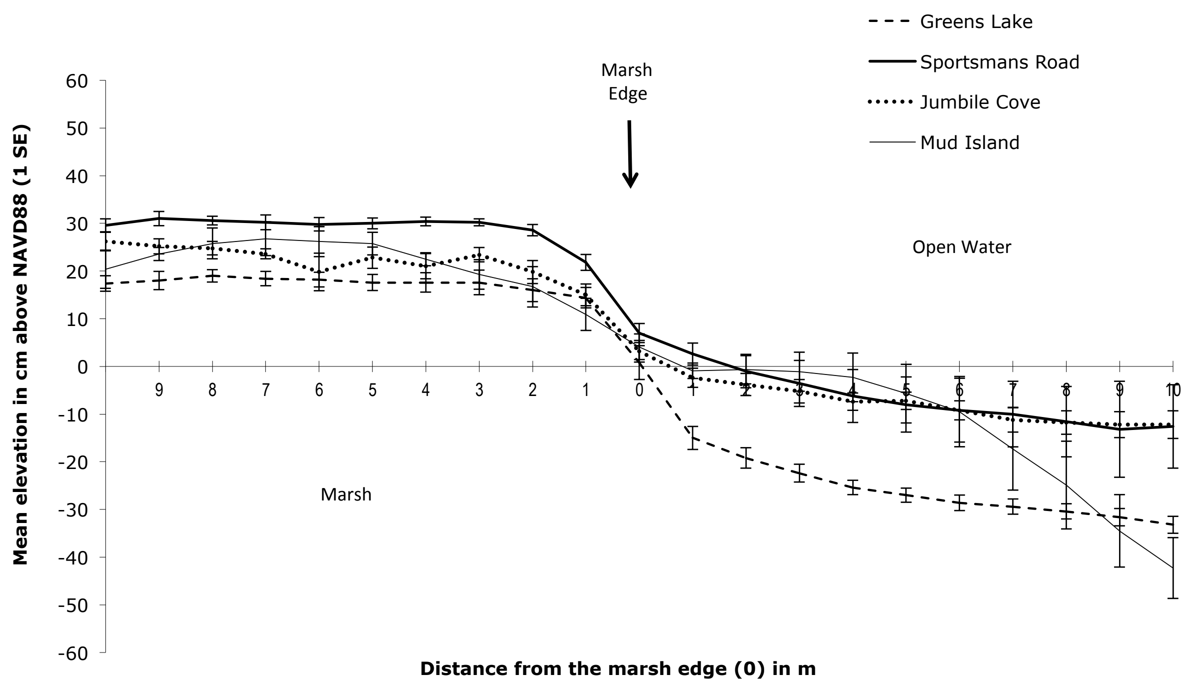
Appendix Figure 1. Elevation profiles for upper Galveston Bay marshes in NAVD88 extending 10 m into the vegetation and 10 m into open water. Mean elevations are shown, and error bars are 1 SE above and below the mean from five observations.



Appendix Figure 2. Elevation profiles for Galveston Bay marshes near East Bay in NAVD88 extending 10 m into the vegetation and 10 m into open water.



Appendix Figure 3. Elevation profiles for Galveston Bay marshes near the I-45 Causeway in NAVD88 extending 10 m into the vegetation and 10 m into open water.



Appendix Figure 4. Elevation profiles for Galveston Bay marshes in West Bay in NAVD88 extending 10 m into the vegetation and 10 m into open water.