TEXAS WATER JOURNAL

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Freshwater inflow requirements for the Nueces Delta, Texas: *Spartina alterniflora* as an indicator of ecosystem condition

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Abstract: Estuarine wetlands and salt marshes are fundamentally driven by variations in freshwater inflow. However, many estuaries have been subject to a heavily modified hydrology due to flood protection engineering and the construction of upstream dams for municipal water supply. Assessment of the impacts of these activities on the health of estuarine wetlands has traditionally focused on tracking the abundance of economically important shellfish and finfish species. In this study, we examine fluctuations in the abundance of selected salt marsh plants and use this information to develop estimates of freshwater inflow needs. The impact of freshwater inflow events on 3 common emergent plants in the Nueces River Delta (*Spartina alterniflora*, *Borrichia frutescens*, *Salicornia virginica*) was determined from long-term monitoring of permanent census plots. Of the 3 species examined, *Spartina alterniflora* was determined to be the best indicator species because its abundance most closely tracked variations in freshwater inflow. For example, under low salinity conditions *S. alterniflora* cover approached 66%. However, when salinities exceeded 25‰, *S. alterniflora* cover declined rapidly. Our results provide clear evidence that the presence or absence of key plant indicator species (in this case *S. alterniflora*) is reflective of overall estuarine hydrological condition over time scales exceeding 6 months.

Keywords: *Spartina alterniflora*, freshwater inflow, Nueces Delta

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Terms used in paper

Short name or acronym	Descriptive name
Bayesian change point analysis	BCPA
canonical correspondence analysis	CCA
non-metric multidimensional scaling	NMDS

INTRODUCTION

Estuarine wetlands and salt marshes are fundamentally sustained by variations in freshwater inflow. The frequency, duration, and seasonal distribution of these "freshets" often determine the physiochemical characteristics of both aquatic and sedimentary wetland environments (Zedler 1983; Mitsch and Gosselink 2007). Environmental characteristics such as nutrient concentration and salinity are regulated by freshwater inflow events and ultimately restrict the distribution and abundance of estuarine organisms (Adams 1963; Alexander and Dunton 2002; Mitsch and Gosselink 2007). The relative impact of freshets within a particular estuary is dependent on the tidal regime, precipitation frequency, geomorphology, and water residence time (Solis and Powell 1999; Brock 2001). Small freshwater inflow events are capable of flushing estuaries with small water volumes and large tidal ranges. However, the waters within microtidal semi-arid estuaries exhibit long residence times and require large freshwater inflow events to effectively flush accumulated salts and nutrients from sediments (Solis and Powell 1999).

The Nueces Estuary, near Corpus Christi, Texas, represents one of the largest, driest, and least flushed estuaries along the Gulf of Mexico (Solis and Powell 1999). Although large freshwater inflow events are relatively rare in this system, their occurrence significantly impacts physiochemical characteristics and biological communities (BOR 2000; Alexander and Dunton 2002; Powell et al. 2002; Montagna et al. 2009). Freshwater inflow events in the Nueces Estuary are subject to a high degree of interannual and interdecadal variability. Increased freshwater inflow during wet years increases the abundance and physiological condition of emergent vegetation, ichthyoplankton, and benthic infauna (Montagna et al. 2002; Forbes and Dunton 2006; Tolan 2007). In contrast, salinity stress and moisture deficits common during dry years results in the decreased abundance and altered community structure of resident estuarine organisms (Forbes and Dunton 2006; Montagna et al. 2009).

The construction of upstream reservoirs, intended to increase municipal water supplies, has resulted in significant alterations to the Nueces Estuary (BOR 2000). Several environmental impact assessments followed the construction of the Lake Corpus Christi (1958) and Choke Canyon (1982) reservoirs (BOR 1975; TDWR 1982; Pulich et al. 2002). These studies were intended to document the impact of reservoir development on downstream ecosystems and estimate future freshwater inflow needs. Estimation of freshwater needs in the Nueces Estuary is confounded by extreme interannual variations in freshwater supply coupled with dramatic hydrologic changes to the watershed resulting from reservoir construction. Freshwater inflows to the Nueces Delta have decreased by approximately 99% relative to pre-reservoir conditions (BOR 2000).

The freshwater inflow management targets of particular estuaries are often determined by the physiological requirements of several "focal" or "indicator" species (TDWR 1982; Longley 1994; Doering et al. 2002; Pulich et al. 2002; Richter et al. 2003; BBEST 2011). These indicator species are selected because they are either economically important or particularly sensitive to environmental conditions (Dale and Beyeler 2001; Doering et al. 2002). Following the identification of an indicator species, field observations are used to determine its critical salinity threshold. After the salinity tolerances of a suite of indicator species have been determined, they are related to freshwater supply and used to estimate specific inflow requirements. In this study, we consider the inflow requirement in a management context. The inflow requirement is not the level below which the system is fundamentally altered and permanent loss of species occurs but rather the level below which the relative abundance of species within the vegetation community ceases to resemble that of a typical estuarine system.

It is important to note that, in this study, the term "indicator species" refers to a *condition* indicator rather than a *composition* indicator. While a composition indicator is used as a proxy for a distinct species assemblage, condition indicators are used as a proxy for a distinct set of environmental conditions (Zacharias and Roff 2001). Condition indicators are selected for their

ability to track fluctuations in environmental conditions and can be used to monitor changes in habitat quality as a result of management practices (Zacharias and Roff 2001). This is consistent with many conservation programs, which seek to limit their focus to maintaining representative habitats rather than maximizing specific productivity or biodiversity metrics (Palmer et al. 1997; Mitsch and Gosselink 2007). It should be noted that tracking the abundance of a limited number of indicator species provides only a rough measure of ecosystem health. There is little ongoing assessment of ecosystem function or species interactions (ter Braak and Prentice 1988; Palmer et al. 1997). These limitations are partially addressed through the selection of a suite of indicator species. The use of multiple condition indicators is assumed to account for unknown environmental variables as well as potential dependency among species (ter Braak and Prentice 1988).

Invertebrates, such as the blue crab (*Callinectes sapidus*) and commercially important fish species such as the Atlantic croaker (*Micropogonias undulatus*), are often used as indicators of estuarine ecosystem condition (Powell et al. 2002; BBEST 2011). The use of these species as indicators is only possible because of intensive monitoring programs (e.g. Texas Parks and Wildlife Fishery-Independent Monitoring Program, Pulich et al. 2002, Buzan et al. 2009). However, it is currently unclear whether these species provide a reliable representation of environmental conditions because they experience high population variability, incur losses due to fishing pressure, and are subject to seasonal migration (Dale and Beyeler 2001; Powell et al. 2002).

In contrast to nekton species, vascular marsh plants are immobile and are not normally subject to harvesting pressures. In estuaries, plant zonation and distribution is largely controlled by soil porewater conditions rather than tidal creek water (Bertness et al. 1992). Because porewaters have longer residence times, rooted plants reflect environmental conditions over longer time scales. Few studies have examined the utility of vascular plants as estuarine indicators. However, submerged vascular plants have been used as condition indicators to estimate freshwater inflow needs in Florida (Doering et al. 2002). Although emergent plants are infrequently used to estimate freshwater inflow needs within Texas estuaries, they satisfy established criteria for use as indicator species (Dale and Beyeler 2001) and have been developed as indicators of ecosystem condition in Georgia (White and Alber 2009).

The objective of this study was to evaluate the utility of emergent plants as indicators of ecosystem condition and freshwater inflow requirements for the Nueces River Delta, Texas. The response of the overall plant community to variations in freshwater inflow was used to determine whether the plant community exhibited a consistent response to hydroclimatic periods. Next, the response of individual plant species to freshwater inflow events was addressed by 1) determining the

salinity tolerance of potential indicator species and 2) deriving the relationship between freshwater inflow and porewater salinity. This study specifically investigated the hypothesis that smooth cordgrass (*Spartina alterniflora*) abundance reflects variations in freshwater inflow and subsequent variations in porewater salinity. We examine *S. alterniflora* individuals that were present as a result of natural processes and not the product of restoration activities. Our salinity tolerance determinations for emergent plants improves on earlier studies, which were generally limited to time periods of less than 3 years and in some cases were established from only a single survey (Penfound and Hathaway 1938; Adams 1963; Webb 1983).

METHODS

This study was conducted in the Nueces River Delta (27° 51' N, 97° 31' W) located in the Northwestern Gulf of Mexico. The delta is comprised of an expansive complex of tidal flats bisected by a tidal creek network (Figure 1). The low marsh plant assemblage is dominated by ox-eye daisy (*Borrichia frutescens*), glasswort (*Salicornia virginica*), and saltwort (*Batis maritima*). Tidal creeks are fringed with stands of smooth cordgrass (*S. alterniflora*) and high marsh areas are dominated by expansive gulf cordgrass (*Spartina spartinae*) meadows (Rasser 2009).

Hydrography

The Nueces Delta is located within a semi-arid region of low average annual precipitation (76 centimeters per day). Dry conditions persist throughout most of the year except follow-
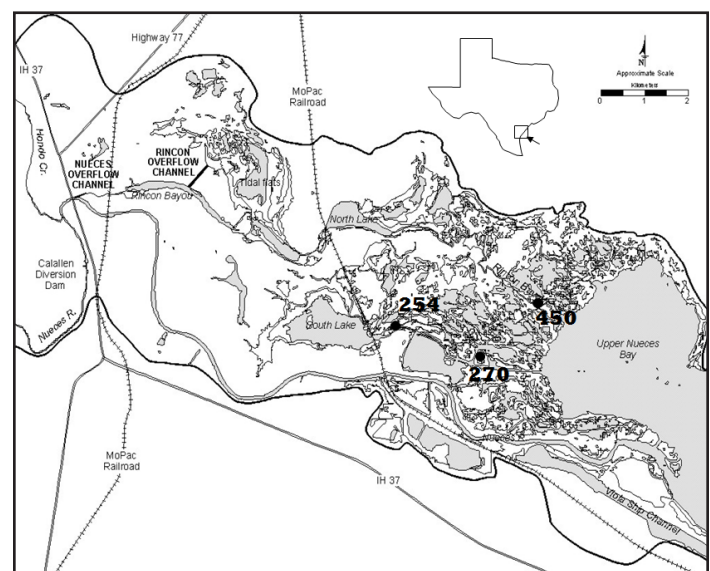

Figure 1: Location of sampling stations in the Nueces Delta.

ing rare tropical storm events that develop in late summer. The hydroclimatic regime has a marked seasonal pattern due to the pulsed nature of freshwater inflows (Figure 2) which inundate the Delta when flows in the Nueces River exceed approximately 2.16 x 10⁶ cubic meters per day (Montagna et al. 2009). When flows fail to exceed this threshold, Nueces River discharge moderates wetland salinities indirectly by lowering the salinity of Nueces Bay. Freshwater inflows to the Nueces Estuary over the past 20 years (1990–2011) exhibit highly variable patterns (Figure 2). During the study, the Delta experienced both extremely dry conditions during the period from 2008 to 2011 and extremely wet conditions during the period from 2002 to 2005. Freshwater inflows were high during the study period relative to the past 20 years, but relatively low compared to historic levels (BOR 2000). Wet and dry periods were identified using a simple statistical analysis of Nueces River flows throughout the study period (1999–2011). Dry periods were defined as years with inflows below the median (Table 1). Although direct precipitation can potentially affect environmental conditions in the Delta (Dunton et al. 2001), it was not included in the analysis of dry periods because there was no consistent relationship between precipitation and salinity.

Vegetation and porewater monitoring

The abundance and distribution of emergent plants was monitored quarterly over a 12-year period from 1999 to 2011 at 3 sites in the low marsh. The resulting dataset documents observed changes in seasonal plant community composition and coverage in response to changes in soil porewater characteristics. The abundance of emergent plants for this time period was estimated from percent cover data collected within 0.25-square-meter quadrats (percent cover data was used as a proxy for abundance). Measurements were taken at 2-meter intervals along 6 parallel 10-meter transects (30 quadrats per site) at each of the 3 sites (Figure 1). Soil characteristics were obtained by extracting water from soil cores (2.5 centimeters diameter x 10 centimeters length) by centrifugation. The extracted water was analyzed for salinity using a handheld refractometer (Reichert Scientific Instruments, Buffalo, NY) and porewater ammonium (NH_4+) using standard colorimetric techniques (Parsons et al. 1984). Separate soil cores were collected for determination of soil moisture. Cores were transferred to the laboratory in sealed containers and dried to a constant weight in a 60 °C oven. The soil moisture content was calculated as the change in weight following drying and standardized to initial wet weight. Variations in porewater salinity and corresponding vegetation characteristics were evaluated with respect to freshwater inflow (Nueces River, USGS 2011).

Identification of indicator species

Several vegetation species were evaluated as potential indicators of ecosystem condition, including *B. frutescens*, *S. virginica*, and *S. alterniflora*. Indicator species were ultimately selected based upon documentation of their sensitivity to stress, ease of assessment, and known population distribution (Dale and Beyeler 2001). Although all 3 species were evaluated, we regarded *S. virginica* and *B. frutescens* as unlikely candidates because *S. virginica* is relatively insensitive to salinity stress (Forbes et al. 2008; Rasser 2009) and *B. frutescens* is primarily found at higher marsh elevations. Literature surveys and preliminary analysis suggested that *S. alterniflora* was a strong indicator species candidate (Webb 1983). The salinity tolerance of indicator species was estimated by comparing vegetation abundance data against corresponding porewater salinity measurements. Determination of freshwater inflow needs was calculated from the relationship between freshwater inflow and porewater salinity targets modeled as an exponential decay function.

Statistical analysis

The relationship between vegetation cover and environmental variables was examined using canonical correspondence analysis (CCA). The CCA procedure begins by regressing a chi-square vegetation matrix on a set of environmental variables. The importance of specific environmental variables is assessed by calculating their correlation with a projected vegetation matrix (the result of eigen-analysis). For this study, CCA was performed on a species-environment matrix that included quarterly measurements of vegetation cover versus corresponding measurements of environmental variables porewater salinity, porewater NH4+, soil moisture, and
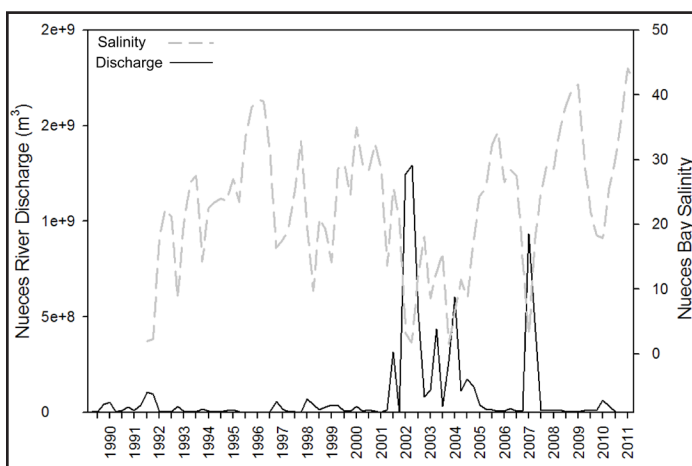

Figure 2: Long-term trends in Nueces River discharge and Nueces Bay salinity (1990–2011).

Table 1: Gauged freshwater inflows to the Nueces Estuary via the Nueces River (USGS gauge #08211500) and estimated annual freshwater inflow needs. Numbers for this study were calculated based on historical attainment of a 25-porewater salinity target for vigorous Spartina alterniflora growth in the Nueces Delta. Estimates are reported as the average or median inflow observed or estimated among specified years.

Inflow type	Sampling method	Freshwater inflow ($m^3 y^{-1}$)	Date range	Source
Gauged	Average	7.87×10^7	1990–1998	This study
	Average	5.57×10^8	1999–2011	
	Median	1.18×10^8	1999–2011	
Estimated need	Average	4.98×10^8	1962–1976	TDWR 1982
	Average	1.12×10^8	1995–present	BOR 2000
	Average	1.71×10^8	1978–1997	Pulich et al. 2002
	Range	$2.20–3.69 \times 10^8$	1999–2011	This study

distance to nearest tidal creek). Vegetation cover data was left unstandardized in order to retain information on the species-environment relationship (Kenkel 2006). Non-metric multidimensional scaling (NMDS), based on a Bray-Curtis similarity index, was used to evaluate changes in the vegetation community with respect to hydroclimatic periods. Vegetation data was log (x +1) transformed prior to NMDS in order to normalize the data. The salinity tolerance of potential indicator species was evaluated using field observations, values reported in the literature, and Bayesian change point analysis (BCPA). BCPA was performed in order to estimate probable salinity thresholds beyond which vegetation cover is reduced. The procedure starts by partitioning the data into segments such that *S. alterniflora* cover is approximately constant within segments. Next, the probability of all possible partitions of the data is evaluated based on those that minimize the with-in group sum of squares while maximizing the between group sum of squares. Finally, a probability distribution is constructed by averaging over all the partitions (Barry and Hartigan 1993). All statistical analyses were carried out in the R statistical program (version 3.0.1). Both CCA and NMDS analyses were carried out using the *vegan* package (Okansen et al. 2007). BCPA was performed using the *bcp* package (Erdman and Emerson 2007).

RESULTS

Climate and hydrology

Freshwater inflows to the Nueces Estuary exhibited significant variation throughout the study period and were charac-terized by distinct wet and dry periods (Figure 2). There were 3 periods with measurable freshwater inflow in 2002–2004, 2007, and 2010. These relatively wet periods were preceded by extended dry periods in 1999–2001, 2005–2006, and 2008–2009 (Figure 2). The end of the study period in 2011 was characterized by an exceptional drought period (see National Climate Data Center, http://www.ncdc.noaa.gov/sotc/drought/2011/). Average annual freshwater inflow to the Nueces Estuary was 5.57×10^8 cubic meters per year over the course of the study period (Table 1). Porewater salinity was lower during wet periods when large freshwater inflow events flushed soils of accumulated salts (Figure 3). During dry periods and in the absence of freshwater inflow, porewater salinity was often elevated to values several times that of standard seawater (Figure 3). In the creekbank areas where *S. alterniflora* was present, porewater salinity was nearly equivalent to the salinity of nearby tidal creeks (Figure 4).

Hydrologic impacts on emergent plants

Hydrology clearly influenced the plant community of the Nueces River Delta (Figure 5, 7). The first 2 CCA ordination axes explained 92% of the variance for emergent plant cover (Table 2). However, the first axis had considerably greater explanatory power (77.9%) than the second axis (14.1%). The first axis was negatively correlated with soil moisture and positively correlated with porewater salinity. This suggests that species' habitat is separated primarily according to soil moisture and porewater salinity (Table 2). While *S. alterniflora* cover was most common in brackish water-logged sediments, *B. frutescens* cover dominated well-drained saline sediments (Figure 8). The
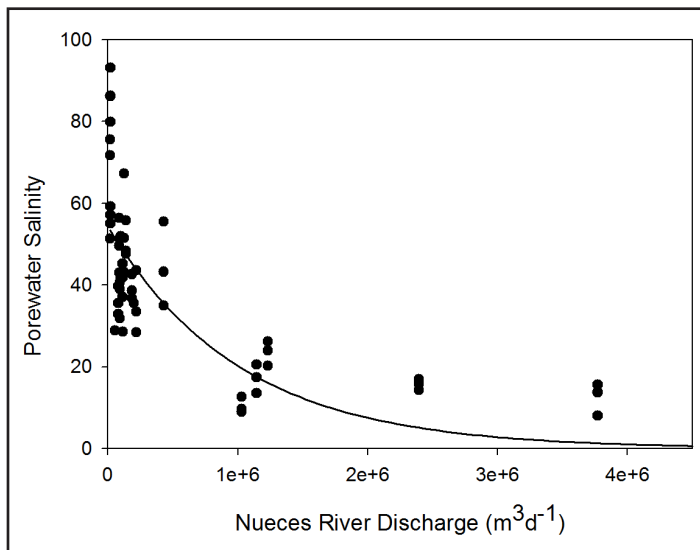
Figure 3: Relationship between freshwater inflow (Nueces River: USGS #08211500) and porewater salinity along the creek bank in the low marsh. Regression curve is a best fit line for an exponential decay function ($y = 54.39$ $e^{(-9.89e-7)x}$, $R2 = 0.63$). A salinity target of 25 yields a freshwater inflow target of approximately 7.86×10^5 m3d-1.
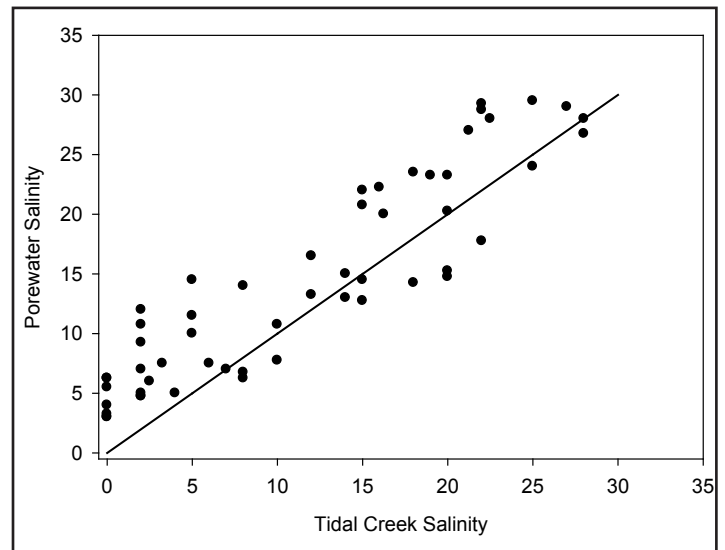

Figure 4: Corresponding measurements of porewater and tidal creek salinity in relation to their theoretical one-to-one relationship (solid line, y=x). The similarity between the areas suggests that emergent plants, which are affected by variations in porewater salinity, are likely to reflect general conditions in the estuary.

composition of vegetation communities immediately following major freshwater inflow events was highly variable (Figure 6). However, *S. alterniflora* was consistently more abundant following freshwater inflow events. Vegetation communities during dry periods were characterized by an abundance of *S. virginica*. Analysis of percent cover data provided evidence of a distinct vegetation assemblage corresponding with identified dry periods (Figure 5). We used non-metric multidimensional scaling of emergent plants according to site and time period in order to test if this vegetation assemblage is unique to dry periods (Figure 6). We found a distinct clustering according to the hydroclimatic periods. For example, almost all (94%) of dry period assemblages at site 254 fell within the same similarity envelope (Figure 6). Likewise, dry period assemblages at site 450 and 270 were also found within the same similarity envelope (73% and 38% respectively). The lack of dry period clustering at site 270 can be attributed to massive disturbance caused by a flooding event in 2002. This flood event eroded almost 4 m from the creekbank and permanently changed the community from a mixed vegetation assemblage to one dominated primarily by *B. frutescens* (Dunton, unpublished data). As a result, early dry period assemblages (1999–2002) at this site are not comparable to post-flood assemblages. The fixed plot design used in this study enabled us to track changes in the plant community over time but did not enable us to examine and quantify spatial variation.

Estimation of Freshwater Inflow Requirements

Although freshwater inflows were concentrated in the summer season, there was no consistent relationship between time of year (season) and standing coverage of *S. alterniflora*. The abundance of *S. alterniflora* fluctuated from a minimum cover near 0% (Spring 2009) to a maximum cover of approximately 66% (Summer 2004, Figure 7). Spatial variations in *S. alterniflora* cover were evident among study sites. The site with the highest cover, site 270, is close to Nueces Bay and has the lowest topographic relief. In contrast, the site with the

Table 2: Results of Canonical Correspondence Analysis.

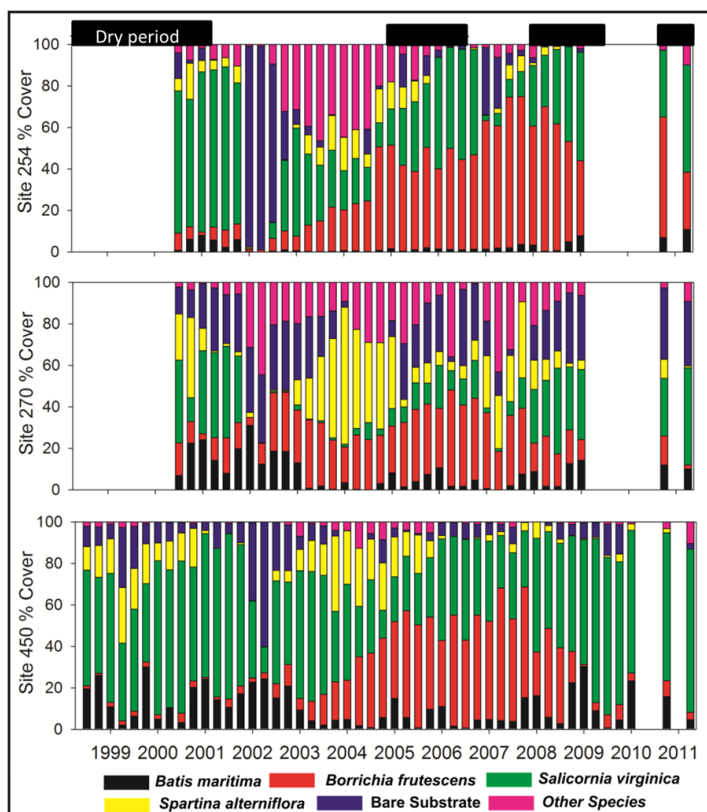| Constraining variables	Axis 1	Axis 2
Porewater salinity	0.59	-0.45
Porewater ammonium	-0.01	0.34
Soil moisture	-0.94	0.27
Distance to tidal creek	0.40	0.37
Distance to Nueces Bay	0.59	0.64
% Variance explained	**77.93**	**14.08**

Figure 5: Quarterly percent cover of emergent plants at selected sites in the Nueces River Delta for the period 1999–2011. Shaded boxes at top indicate the occurrence of dry periods. Dry periods were defined as years with inflows below the median.

Figure 6: Non-metric multidimensional scaling ordination of emergent plant communities averaged by station and quarterly sampling date formatted as YY-Quarter. For example, Winter 2000 is denoted by 00-1. Similarity clusters are defined at 60% similarity by the Bray-Curtis method. Clusters are outlined to show corresponding dry period (dashed circles) and wet period (non-dashed circles) vegetation assemblages. Only selected sampling dates are shown in order to reduce label overlap and increase readability.

lowest maximum cover, site 254, has a pronounced creekbank levee (Rasser 2009). The salinity tolerance of potential indicator species was determined for *S. alterniflora*, *B. frutescens*, and *S. virginica* based on changes in percent cover in relation to porewater salinity (Figure 8). Consistent with our hypothesis, fluctuations in *S. alterniflora* cover were clearly related to porewater salinity and freshwater inflow. Porewater salinities exceeding 25‰ resulted in dramatic declines in *S. alterniflora* cover (Figure 7). There were only 2 outliers where *S. alterniflora* coverage was substantial (>25%) and salinity exceeded 25‰ (Figure 8). These outliers were associated with the lagged response of plants to rapid increases in salinity during the onset of a dry period in 2005. Occasionally, we observed low cover despite favorably low salinities (Figure 9). These observations are likely associated with disturbance caused by flooding events such as channel bank scouring. Figure 8 combines data from multiple sites. Low cover data points (relatively speaking) may occur because of site-specific differences in available habitat due to differences in slope, drainage, or sediment characteristics (Table 2).

The observed relationship between porewater salinity and freshwater inflow was investigated with respect to *S. alterni-*
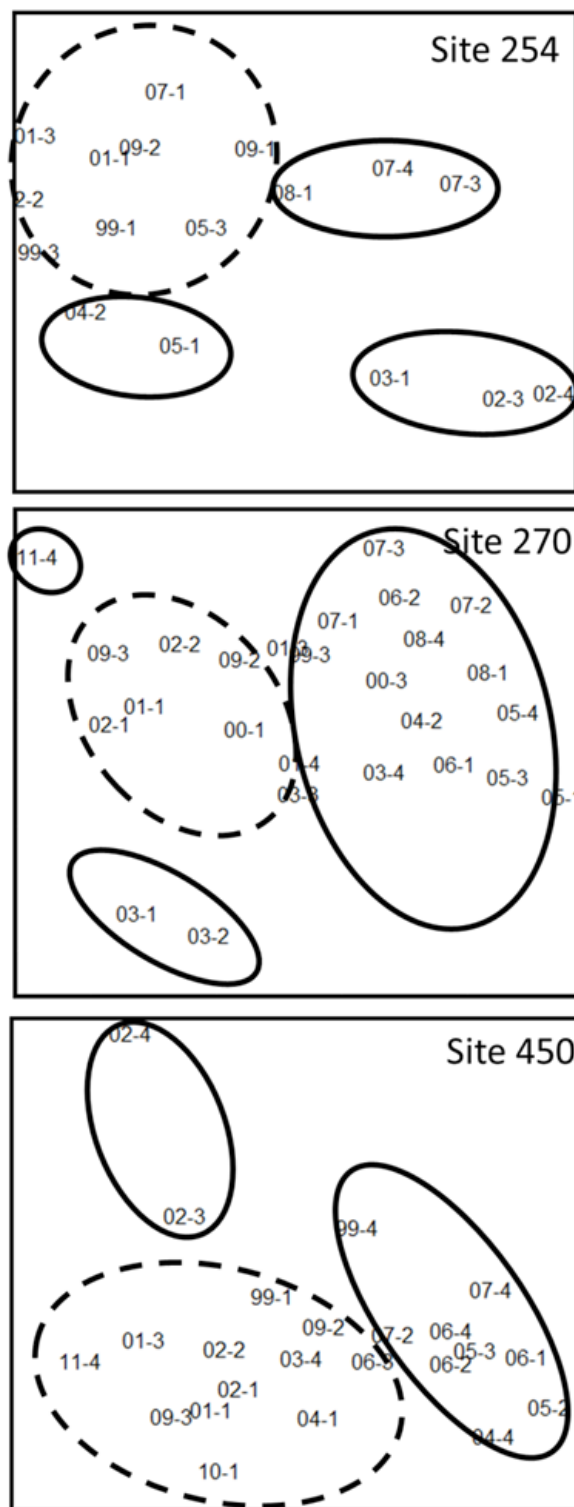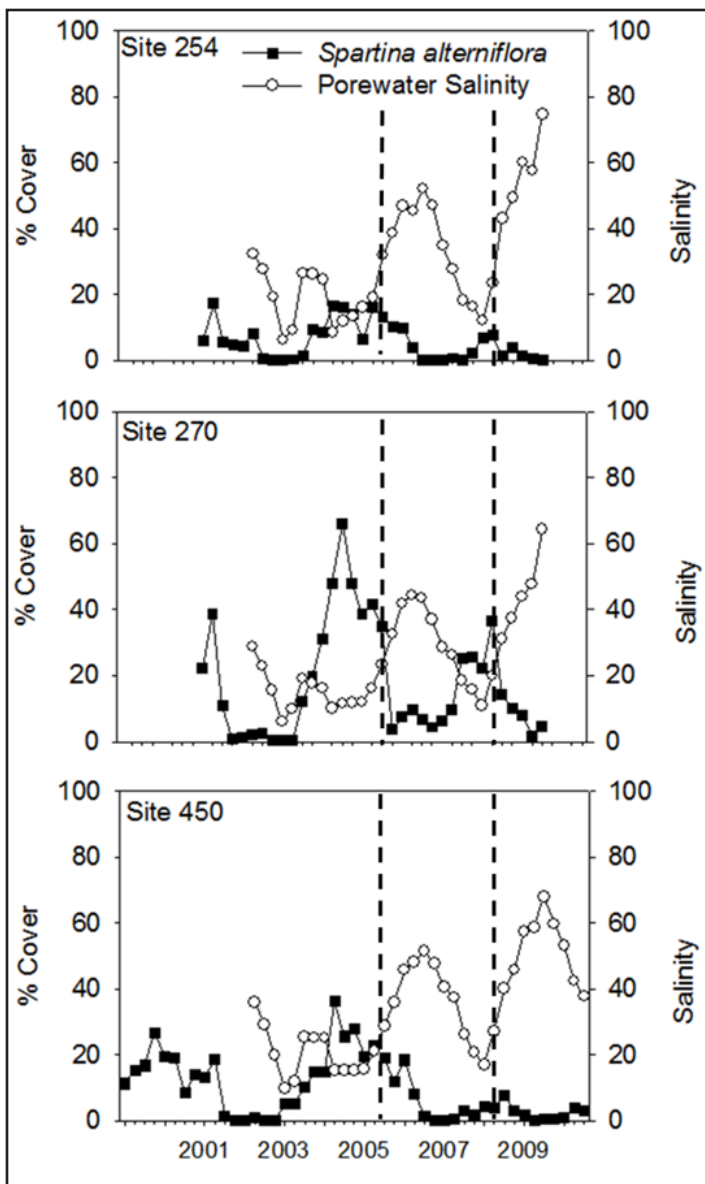
Figure 7: Porewater salinity (white circles) and percent cover of *Spartina alterniflora* (black squares) along the creek bank in the low marsh. Dashed black lines illustrate how the timing of porewater salinities exceeding 25‰ correspond with declines of *S. alterniflora* abundance.

Figure 8: Percent cover of individual plant species (*S. alterniflora*, *B. frutescens*, and *S. virginica*) relative to variations in porewater salinity. The salinity tolerance of *S. alterniflora* was estimated at 25‰ by visual inspection of Figure 7 along with Bayesian breakpoint analysis (vertical line). The uncertainty of this threshold (±5‰) was estimated from published literature values (Webb 1983, Bertness 1991) and Bayesian change point analysis (shaded box).

flora abundance. An exponential decay fit to this relationship provided a means to estimate freshwater inflow corresponding to a given salinity target. This study determined that achieving a porewater salinity target of 25‰ requires a Nueces River discharge of approximately 2.87×10^8 cubic meters per year (Table 1). However, this value can be expressed as a range between 2.2×10^8 and 3.7×10^8 m $\times 10^8$ cubic meters per year owing to the range of probable change points we identified and uncertainties associated with published salinity tolerance values for *S. alterniflora* between 20–30‰ (Webb 1983, Bertness 1991).
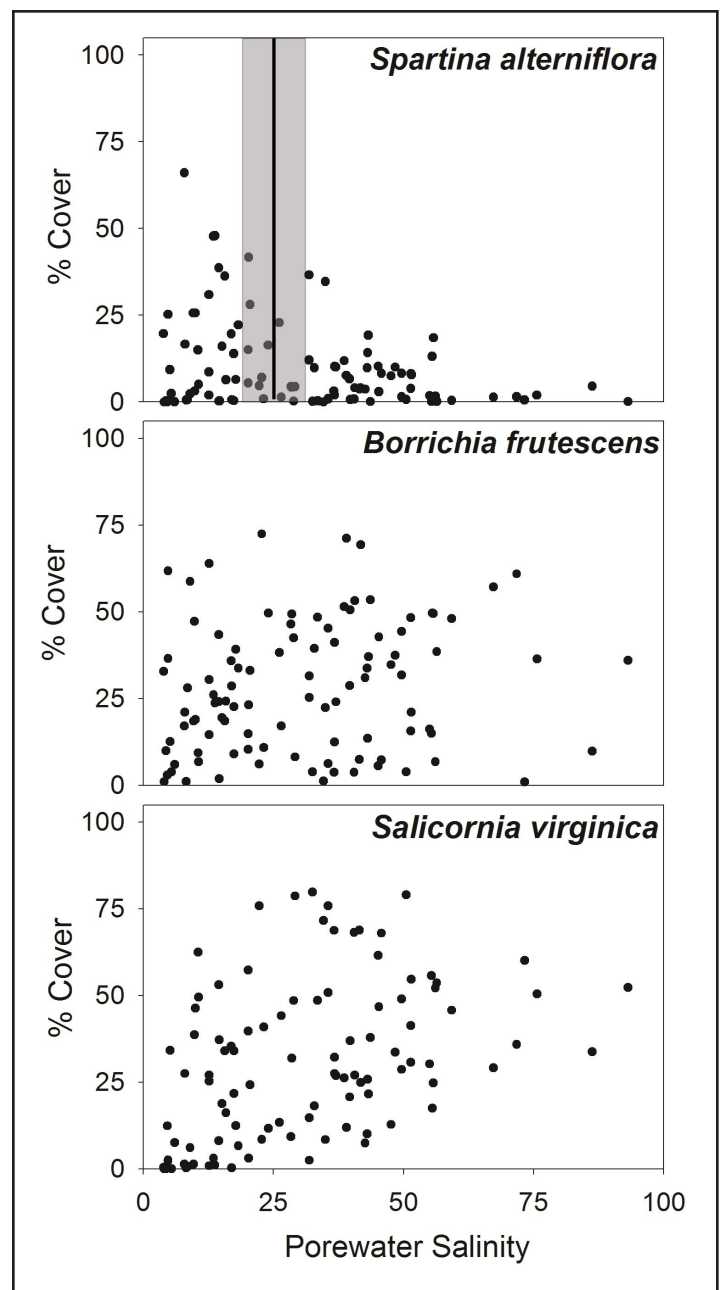
DISCUSSION

Vegetation Response to Freshwater Inflow

Freshwater inflow events impact the Nueces Estuary by flushing salts, delivering nutrients, and distributing sediments

(BOR 2000). The most dramatic of these effects is the flushing of salts following large magnitude freshwater inflow events. For example, flooding in 2002 caused extensive freshening of Nueces Bay, dropping salinity values from near standard seawater (35%) to values typical of freshwater and brackish systems (Figure 2). Previous studies have shown that the emergent plant community is responsive to variations in salinity and freshwater inflow (BOR 2000; Alexander and Dunton 2002; Forbes and Dunton 2006). However, this study is unique in that it considers both the wettest period (2002–2004) and the driest period (2008–2009) since reservoir construction. Our results demonstrate that the vegetation community typical of dry periods is distinct from that of wet periods (Figure 6). In addition, communities observed during early dry periods (1999–2001) reappeared subsequently in the later dry period (2008–2011). These dry period communities were characterized by a high abundance of *S. virginica* and a low abundance of *S. alterniflora* (Figure 5, 7). The time required for the reappearance of dry period assemblages was related to the magnitude of freshwater inflow events during the preceding wet period. High freshwater inflows during 2002–2004, the wettest period during this study, extended the period between the reemergence of dry period vegetation communities (Figure 5, 6). Our results are consistent with previous studies regarding the response of the plant community to salinity and freshwater inflow (Forbes and Dunton 2006).

Large magnitude events, such as floods, are known to cause wholesale reorganization of the vegetation community (Forbes and Dunton 2006). The NMDS analysis from this study confirms a consistent reorganization of the plant community following flood disturbances (Figure 6). This finding is important because the use of emergent vegetation as indicators of ecosystem condition is predicated on the assumption that community structure is predictable under a given set of hydroclimatic conditions. Vegetation communities, in this study, followed a predictable trajectory. First, bare areas were created following large inflow events and were initially colonized by stress-intolerant species such as *S. alterniflora* and *Sueda maritima* (see 2002–2004, Figure 5). Next, in the absence of freshwater inflow, these individuals were eventually replaced by the moderately stress-tolerant *B. frutescens*. Finally, the onset of drought conditions encouraged the replacement of all other species by the stress-tolerant *S. virginica* (see 2008–2011, Figure 5). Our observation that *S. virginica* abundance increases during drought periods is consistent with a study by Forbes and Dunton (2006) that demonstrated the displacement *S. virginica* by *B. frutescens* following freshwater inflow events. In addition, a variety of studies determined that *S. virginica* is resilient to extreme environmental stress (Zedler 1983; Forbes and Dunton 2006; Rasser 2009).

Management of Freshwater Inflows

Reduced freshwater inflows, due to hydroclimatic variability and reservoir construction, prompted legislative mandates calling for ecological assessments of Texas estuaries with the purpose of determining freshwater inflow requirements (TDWR 1982; BBEST 2011). Although studies have utilized numerous methods to derive hydrologic data output, nearly all ecological studies concerning freshwater inflow have used the physiological (salinity) tolerance of indicator species to set inflow bounds (Powell et al. 2002). These tolerances are typically determined from simple correlation analyses (Figure 8) or habitat suitability indexes using a suite of environmentally sensitive or economically important indicator species (Doering et al. 2002). As a result, effective management and allocation of freshwater for the ecological benefit of estuarine wetlands requires detailed knowledge of the physiological tolerances of resident organisms. In many cases, these are estimated from limited and expensive field surveys. This study demonstrates that emergent marsh plants respond predictably to environmental conditions and provide valuable information regarding the ecological condition of estuaries. Salt marsh plants are valued as a substrate stabilizer, a contributor to food webs, and a refuge for a variety of nekton species including fish, invertebrates, and migratory birds (Henley and Rauschuber 1981; Zedler and Kercher 2005). Given that they are also inexpensive to survey, they make ideal candidates to be included in a suite of indicator species.

S. alterniflora is the only emergent plant species considered in this study that consistently reflects environmental conditions in tidal creeks (Figure 4, 8), exhibits a salinity tolerance similar to other faunal estuarine indicator species (BBEST 2011), and provides an ecologically important habitat (Kneib 2003). Our results show that the coverage of *S. alterniflora* is related to variations in porewater salinity (Figure 8). Field observations indicated that the cover of this species was substantially reduced at salinities exceeding 25‰. A study by Webb (1983) also found that porewater salinities exceeding 25‰ resulted in significant reductions in density, height, and standing biomass. However, there is considerable uncertainty associated with this threshold. Previous studies have found that the salinity tolerance of *S. alterniflora* is between 20‰ and 30‰, and our change point analysis found that probable change points were centered on 25‰ within the 15–35‰ interval (Bertness et al. 1991). Although we focus on salinity in this study, it is important to recognize that cover of a single species at any given point in time is a function of many different factors. The plant cover data presented in the study are affected by variables not explicitly considered here. Chief among these are antecedent conditions and site specific environmental differences. We use instantaneous salinity and cover measurements gathered from 3 differ-

ent sites in order to define the relationship between emergent plant species and salinity (Figure 7). Low cover values in Figure 7 may occur even at low salinity because of antecedent flooding or because the creek bank slope, drainage, or sediment characteristics prevent peak abundance (high cover). Given that this study utilizes data from field surveys rather than greenhouse plantings, changes in *S. alterniflora* cover were aligned with changes in salinity with remarkable consistency.

Integrative studies by BBEST (2011) and TDWR (1982) found that the freshwater inflow needs of *S. alterniflora* are nearly identical to that of other common indicator species such as the blue crab (*Callinectes sapidus*), Atlantic croaker (*Micopogonias undulates*), and eastern oyster (*Crassostrea virginica*). Therefore, one would expect that the abundance of *S. alterniflora* serves as a reasonable proxy for the abundance of these higher trophic level organisms. *S. alterniflora* stands represent a unique habitat because it is the only species found at the lowest exposed elevations in the Nueces Delta. Cover of this species is limited to the areas directly adjacent to creekbanks that fall within the range of daily tidal variation (Rasser 2009). Under stressful environmental conditions, *S. alterniflora* habitat is converted to open water habitat. This conversion represents the loss of a unique habitat as *S. alterniflora* is known to promote nekton density and production (Whaley and Minello 2002; Kneib 2003). In the Nueces Delta, the benefits of *S. alterniflora* cover to higher trophic level organisms likely occur indirectly through the provision of habitat rather than direct carbon assimilation (Wallace 2011).

Although numerous studies have examined the freshwater inflow needs of the Nueces Estuary, no study has yet produced a comprehensive comparison of inflow estimates from diverse methodologies and time periods. Previous estimates of freshwater inflow needs in the Nueces Delta vary widely from annual inflows of only 1.12×10^8 to 4.98×10^8 cubic meters per year (Table 1). Estimated freshwater inflow needs have varied among studies because of historical reservoir development, differing analytical methods, and time scales. Early studies estimating freshwater inflow requirements of the Nueces Estuary, prior to reservoir development, determined that adequate ecosystem function is achieved at annual inflows of 4.98×10^8 cubic meters per year (TDWR 1982). Subsequent estimates following reservoir construction were much lower (1.71×10^8 cubic meters per year, Pulich et al. 2002; 1.12×10^8 cubic meters per year, BOR 2000). A study by BOR (1975), predating reservoir construction, determined that average annual inflows from 1972 to 1975 were 5.07×10^8 cubic meters per year. This is well above the average annual inflows observed throughout this study period and clearly not realistic given increasing municipal water demand and upstream reservoir construction. However, more recent estimates by Pulich et al. (2002) and Bureau of Reclamation (2000) barely exceed median observed

inflows and may underestimate actual inflow needs (Table 2). Our estimate, based on the abundance of *S. alterniflora,* falls between historically high estimates and recent low estimates at a conservative 3.13×10^8 cubic meters per year (Table 1). Achieving such annual freshwater inflows requires less than the average annual inflow observed during the study period (Table 1). Although Nueces River flows exceeded our estimated freshwater inflow requirements in 5 of the 11 years encompassed by this study (1999–2011), they only exceeded this target 6 years between 1990 and 2011 (Figure 2, USGS 2011).

We primarily focused on annual and interannual patterns in freshwater inflow because it is consistent with municipal water management strategies discussed in previous studies (BOR 2000, Pulich et al. 2002). However, there are likely important variations in freshwater inflow on time scales not explicitly considered in our analyses. Analysis of historic freshwater inflow patterns suggests that decadal variations in freshwater inflow may be occurring (BOR 2000). For example, while observed annual freshwater inflows regularly exceeded our inflow requirement estimates listed in Table 1, they were met in only 1 year between 1990 and 2000 (USGS 2011). It is also likely that seasonal inflow patterns are important given that seedling germination mostly occurs in the spring (Alexander and Dunton 2002). Furthermore, previous studies have found evidence that seedlings exhibit different physiological tolerances to environmental stress than adult plants (Shumway and Bertness 1992). In the Nueces Delta, Alexander and Dunton (2002) found that seed germination and expansion of *Salicornia bigelovii* was facilitated by freshwater input. Water managers tasked with resolving conflicts between municipal use and ecological benefits should consider altering the timing of freshwater inflows to coincide with critical germination periods of *S. alterniflora.* Future research should assess the impacts of freshwater inflow timing on *S. alterniflora* abundance. Greater knowledge of the importance of inflow timing is required before our recommendations can be applied in a management context.

Future Impacts

The overall extent of emergent salt marsh plants in the Nueces Delta is likely to shrink as a result of continued decreases in freshwater inflow concurrent with more erratic and possibly decreasing precipitation due to global climate change (Forbes and Dunton 2006). Ward and Valdes (1995) evaluated the impact of global climate change on Texas water resources relative to a scenario characterized by a 2 °C increase in temperature and a 5% decrease in precipitation. Based on this scenario, Ward and Valdes (1995) projected a 35% decrease in freshwater inflow to Texas estuaries. Our results suggest that if droughts become longer and more frequent, *S. virginica* will

likely replace *S. alterniflora* and make up a greater proportion of the overall community. This has important implications for the ecological health of the Nueces Delta and provision of ecosystem services. Since the rooting depth of *S. virginica* is much shallower than the rooting depth of *S. alterniflora*, this shift would decrease the ability of vegetation to provide sediment stabilization. Changes in the plant community of the Nueces Delta may provide a forecast of future changes in wetter, more northerly estuaries (Kirwan et al. 2009). Future monitoring efforts in these estuaries should focus on northward latitudinal shifts in *S. alterniflora* in response to freshwater inflow and global climate change.

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