Response of the Nueces Estuarine Marsh System to Freshwater Inflow:
An Integrative Data Synthesis of Baseline Conditions for Faunal Communities

Publication CBBEP – 62
Project Number – 0821
July 2009

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Submitted to:
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Final report submitted to:

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Abstract

The Nueces estuarine marsh ecosystem has experienced reduced freshwater inflows since at least 1940. The Nueces River Overflow Channel (NOC) was created by the Bureau of Reclamation as a demonstration project to increase the opportunities for freshwater inflow into the marsh. The NOC remained open from October 1995 through October 2000. In October 2001 the NOC was reopened by the City of Corpus Christi to continue the diversions and improve environmental conditions in the marsh. The goal of the present study is to perform a meta-analysis of 12-year long data sets monitoring benthic macrofauna and vegetation to determine the effect of reintroducing flow to the marsh. The first task was to assign the monitoring data into different spatial and temporal cells. Analysis of hydrological variables (water flow and water stage in the Nueces River and Rincon Bayou overflow channels, salinity and stage in Nueces Bay, precipitation, and potential evapotranspiration) indicated that wet and dry periods appeared to occur at a frequency of every two years, thus data were aggregated into 2-year bins. The same data was also analyzed to determine that there were three spatial bins in the data set: upper Rincon Bayou, lower Rincon Bayou, and Nueces Bay. Thus, the analysis was performed for a 2-way design with 6 temporal bins and 3 spatial bins. There is sufficient flow in the Nueces River to activate the NOC and flow into Rincon Bayou only 15% of the time. Water quality (i.e., salinity and nutrients) in all locations varied with changes in wet and dry periods. Water quality in the lower Rincon Bayou was more similar to Nueces Bay than the upper Rincon Bayou for each of the time periods. The change in macrofauna community structure was significantly correlated with spatial and temporal changes in water quality, indicating that changes in water quality cause change in macrofauna community structure. In contrast, the vegetation community structure is not correlated with spatio-temporal changes in water quality. Interestingly, the vegetation community structure is correlated with macrofauna community structure. The lack of correlation with water quality and correlation with macrofauna indicates that vegetation does not respond on the spatio-temporal scales of this study design and/or vegetation responds to some other characteristic not analyzed or measured in this investigation (such as pore water salinity or soil moisture). Macrobenthic and vegetative communities in the upper Rincon Bayou were significantly different from the communities of the lower Rincon Bayou (and Nueces Bay for macrofauna) regardless of whether the time period was wet or dry, indicating that the effects of inflow are limited to the upper Rincon Bayou, even in periods of extended flooding.

Acknowledgements

The data sources used for this project were funded from 1994 – 2000 by the Bureau of Reclamation, and from 2001 onward by the City of Corpus Christi. The current work acknowledges support from the Bureau of Reclamation via a grant to the Coastal Bend Bays and Estuaries Program. The senior authors (PAM and KHD) would like to gratefully acknowledge the participation and contributions made by many of our students and technicians over the years. In particular we thank Kim Jackson, Rick Kalke, and Susan Schonberg for their direct involvement in sampling, analysis, and data synthesis on a continual basis for this project since its inception over 15 years ago. Their direct involvement has permitted a level of continuity that has been simply invaluable to all of us.

Response of the Nueces Estuarine Marsh System to Freshwater Inflow: An Integrative Data Synthesis of Baseline Conditions for Faunal Communities

Introduction

The Nueces estuarine marsh system is the southern-most marsh system in the western Gulf of Mexico, covering some 5,700 ha of salt marsh, mud flats, tidal channels, and open water. The marsh is in the Nueces Estuary, which has a freshwater source from the Nueces River and marine source from Nueces Bay via connections to Corpus Christi Bay and Aransas Pass. The marsh is part of a delta complex that is unusual in that the Nueces River largely by passes the marsh along its southern boundary and empties directly into Nueces Bay. Rincon Bayou, however is at the head of the marsh and delta complex, and serves as the main stem for distribution of freshwater to the marsh during floods. The marsh lies in a semi-arid climate and has experienced reduced freshwater inflows since at least 1940.

In October 2001, the City of Corpus Christi (City) elected to continue freshwater diversions through the Nueces River Overflow Channel (NOC). The NOC was initially created as the primary diversion channel from the Nueces River into Rincon Bayou during a demonstration project funded by the Bureau of Reclamation (BOR) from October 1994 through December 1999 (Ward *et al.* 2002). The BOR concluded that freshwater additions to the upper reaches of the Nueces marsh had positive impacts including decreased soil and water column salinity, improved habitat quality and availability, and increased productivity of some estuarine species (Bureau of Reclamation 2000). Following closure of the channel in September 2000, the City re-opened the channel to a depth of 0.3 m above mean sea level (MSL) in October 2001 to increase freshwater inflows into Rincon Bayou, the natural headwater of the estuary.

Installation of a pipeline, that can deliver up to 3.7×10^6 m^3 mo^{-1} (3,000 acre-ft mo^{-1}) from Calallen Pool directly into Rincon Bayou, was completed in Fall 2008, however it has not been operating (except for test runs) at the time of this writing. A long-term monitoring program was initiated to further understand the affects of these freshwater diversions into the Nueces marsh ecosystem. Monitoring is required under the Texas Commission on Environmental Quality (TCEQ) Agreed Order for the Nueces Estuary adopted 4 April 2001. Specifically, the Order requires the City to “implement an on-going monitoring and assessment program designed to facilitate an adaptive management program for freshwater inflows into the Nueces Estuary.” Monitoring objectives include detecting changes in water column chemical and hydrological characteristics, phytoplankton biomass, emergent vegetation composition and distribution, soil characteristics, benthic, epifaunal, nektonic macrofauna, larval fish, and avian habitat use at several study stations along Rincon Bayou and the Nueces River. Monitoring at many of these stations began during the BOR Demonstration Project and has continued almost uninterrupted since 1994, although Dunton et al. (2001) began monitoring of vegetation assemblages and salinity at three historical stations beginning in December 1991.

Although individual project leaders have produced annual data reports that summarize the results of measurements collected throughout the Nueces delta, there has been no attempt to link these data over temporal and spatial time scales in order to provide an integrated understanding of the baseline conditions and changes brought about by the management activities. One of the large hurdles lies with organizing the massive amount of data that is currently stored in a variety of files and formats dispersed among several investigators from the University of Texas Marine Science Institute, and the Harte Research Institute and Center for Coastal Studies at Texas A&M University-Corpus Christi. The Coastal Bend Bays and Estuaries Program funded a cyberinfrastructure project to organize all the existing and future data in a geodatabase, which has enabled dynamic web-based access to these data. This database has enabled an interdisciplinary analysis of the long-term Nueces Delta dataset for the first time (Montagna and Nelson 2009).

Application of the hydrological data to vegetative community response in the Nueces marsh was recently reported by Forbes and Dunton (2006), who examined the contrasting effects of floods and droughts based on precipitation and Nueces River flow volume over the period 1995 – 2005. Although climate variations were identified by an initial 4-yr period of moderate conditions, followed by a 2-yr drought, and a 4-yr wet period, vegetation assemblages changed most extensively in response to flooding (Forbes and Dunton, 2006). These observations were supported by the recent experimental work by Rasser (2009), who found that pore water salinity and flooding were important abiotic variables that strongly affect plant distributions in the Nueces marsh system.

The current project is a synthesis report based on statistical, geostatistical, and synthetic interdisciplinary analyses. The current analysis is possible using the new database technology developed for the purposes of integrating and publishing the data electronically (Montagna and Nelson 2009). An earlier report (Gil et al., 2008) presented the results of our hydrological analyses based on inflow data from 1994 to 2008 (baseline conditions). This report integrates the hydrological data with the biological responses by resident macrofauna and emergent vascular vegetation. This information is needed to develop both effective restoration and management strategies for the Nueces Delta, and an operating plan for the Corpus Christi water supply system that also complies with environmental flow requirements.

The objective of the present study is to assimilate long-term monitoring datasets of benthic macrofauna and vegetation to determine the relationship with abiotic factors influenced by freshwater inflow events and wet and dry periods in the Nueces marsh. Data have been collected from 1994 - 2008 concerning water quality, percent cover of emergent vegetation and abundance, biomass, and diversity of benthic macrofauna. These data are coupled with hydrography data to establish patterns between shifts in abundance and diversity of vegetation and benthic macrofauna in a highly variable physical-chemical system. Results of this study serve to establish the optimal magnitude, timing, and duration of freshwater inflows in order to maximize the positive ecological response of the Nueces Estuary.

The work in this investigation proceeded in into two parts. The first part was performed to divide time into wet and dry periods using hydrological data (see Gil et al., 2008). The second part combines the wet and dry period information with water quality, benthic macrofauna, and marsh vegetation.

Materials and Methods

The goal of the present study is to perform a meta-analysis of long-term data to determine the effect of enhancing inflow to the Nueces marsh ecosystem. The approach is to aggregate the data into a 2-way experimental design where spatial variability and temporal variability are the two main effects. This assignment of the monitoring data into different spatial and temporal cells is required to perform analyses on a balanced data set and to answer discover links between inflow and biological response. While many biological components were sampled, only two, macrobenthos and marsh vegetation were taken extensively enough over space and time to be used in the meta-analysis. The basic assumption is that wet periods represent inflow effects, and dry periods represent marsh condition without the diversion project.

Determining wet and dry periods

Freshwater inflow events are notoriously variable in frequency, duration, magnitude, and extent. Thus, a quantitative analysis of the hydrographic dynamics of environmental flows affecting the Nueces Delta is essential. Characterization of freshwater inflow events is also needed to aggregate the hydrology data into ecological time scales. Hydrological data were measured over a period from 1 January 1994 to 29 February 2008 using multiple continuous monitors. Variables included water flow and stage in the Nueces River and Rincon Bayou overflow channels, salinity and stage in Nueces Bay, precipitation, and potential evapotranspiration. All variables were reduced to a daily resolution scale so that they all could be compared within a synoptic time frame across the Nueces Estuary.

Mean daily flow and stage data were gathered from the US Geological Survey (USGS) stations 08211500 (Nueces River at Calallen, TX) and 08211503 (Rincon Bayou Channel near Calallen, TX), which automatically record measurements every 15 minutes. Mean daily salinity was also taken from the Rincon Bayou station, although these data were only available for the end of the study period. It is important to note that two extended gaps exist in the Rincon Bayou data: from 1 January 1994 to 15 May 1996, and from 11 August 2000 to 20 December 2003. These gaps are due to the inactivation of the station prior to the implementation of the NOC and during the temporary NOC closure, respectively. Meteorological information, including daily mean precipitation and air temperature data, was obtained from the National Weather Service (NWS) station at Corpus Christi International Airport (CRP), located about 14 km southeast of the Nueces Delta. Air temperature data were used with the Mather-Thornwhite method to calculate daily potential evapotranspiration (PET) (Rosenberry et al. 2004).

Daily averages of hourly measurements of Nueces Bay salinity and water level were obtained from the Texas Coastal Oceans Observing Network (TCOON), which is maintained by the Texas A&M University-Corpus Christi Conrad Blucher Institute (CBI). Nueces Bay salinity data were taken from the centrally-located SALT03 station, while water level data were obtained from the upstream White Point station, just south of the lower Nueces Delta. These Nueces Bay measurements allow for a more complete portrayal of the hydrology of the Nueces Delta by including the frequency and magnitude of potential tidal interactions, which can greatly influence the water quantity of Rincon Bayou.

A flow duration curve of the Nueces River at Calallen was created to establish the base flow rate, distribution, and percent occurrence of daily flow volumes. Linear regressions were run on Nueces River flow versus Rincon Bayou flow to identify the most significant relationship between the datasets, where Nueces River flow initiates the strongest positive correlation with Rincon Bayou flow. The regressions were run from 2×10^6 to 4×10^6 m^3d^{-1} Nueces River flow by 0.1×10^6 m^3d increments and sought the highest significant fit for the two regressions: no flow and positive linear flow into Rincon Bayou. These regressions were run separately because they represent the relationships between Rincon Bayou flow and Nueces River flow below and above the elevation threshold needed for flow into Rincon Bayou, respectively (Table 1). Cutoff values between the best fit regressions and the natural flooding threshold of the Nueces River were used to establish threshold values that would determine inflow events for NOC project periods, and non-NOC periods, respectively.

Freshwater inflow events were aggregated into broader wet periods based on the number of days and the variation in Nueces Bay salinity values between events. To be considered part of a "wet period," the inflow events had to meet one of the two sets of criteria below:

1) the last salinity value of an inflow event is less than 1 psu away from the first salinity value of the next inflow event and the two events are no more than 25 days apart, or
2) the last salinity value of an inflow event is less than 5 psu away from the first salinity value of the next inflow event and the two events are no more than 5 days apart.

While these aggregation criteria were arbitrary, they were formulated with the intent of attaining objective and consistent separation of wet and dry periods for comparative purposes with the associated biological and water quality data that respond to the inflow events.

Table 1. Criteria used to define freshwater inflow events into the Nueces Delta. NOC=Nueces Overflow Channel.

Date Range	Time Period Description	Measurement Parameter	Defining Criteria of Inflow Event
1/1/1994-10/25/1995	Pre-NOC	Nueces River gage height	A 24-h mean (daily) stage in the water elevation of the Nueces River exceeding 1.64 m relative to Nueces gauge datum
10/26/1995-10/26/2000	First NOC project	Nueces River discharge	A 24-h mean (daily) flow in the Nueces River at Calallen exceeding 4.2 million m^3 day^{-1}
10/26/2000-10/12/2001	Closure of first NOC	Nueces River gage height	A 24-h mean (daily) stage in the water elevation of the Nueces River exceeding 1.64 m relative to Nueces gauge datum
10/12/2001-2/29/2008	Second NOC project	Nueces River discharge	A 24-h mean (daily) flow in the Nueces River at Calallen exceeding 2.6 million m^3 day^{-1}

Response of marsh system to changes in inflow

Sampling

Stations have been sampled for both benthic macrofauna and water quality in Rincon Bayou since October 1994 (Table 2). Ten sampling stations are located in the Rincon Bayou and Nueces Marsh for the purposes of this investigation. The stations were divided into three zones; upper Rincon Bayou, lower Rincon Bayou and Nueces Bay (Figure 1). Samples were collected by three research groups. Macrobenthic and water quality (including nutrient) samples from the upper Rincon Bayou were collected and processed by The University of Texas Marine Science Institute (UT) until mid-2006, followed by the Harte Research Institute for Gulf of Mexico Studies (HRI), Texas A&M University- Corpus Christi (TAMUCC) thereafter. Macrobenthic and water quality (excluding nutrient) samples from the lower Rincon Bayou and Nueces Bay were collected and processed by the Center for Coastal Studies, TAMUCC. Vegetation and water quality (including nutrient) samples from the upper and lower Rincon Bayou were collected and processed by (UT). All macrobenthic, vegetation and water quality data was obtained from the Observation Data Model (ODM) for Rincon Bayou, Nueces Delta (Montagna and Nelson 2009).

Macrofauna Community Data

In the upper Rincon Bayou, stations 501, 466C, 465D, and 400F (monitored by HRI) were sampled quarterly between October 1994 and October 1999, followed by a break in sampling for two years. In October 2001, quarterly sampling resumed at stations 466C, 465D, and 400F for one year, after which, the stations were sampled monthly. The most recent sampling frequency and station selection was recommended by the Nueces Estuary Advisory Council (NEAC 2002) monitoring committee. In the lower Rincon Bayou, stations 450 and 451 have been sampled monthly since September 1998. In Nueces Bay, station 301 has been sampled monthly since September 1998. Sampling at station 302 was also initiated in 1998, however was eventually replaced by station 303. A period where both stations were sampled occurred for two years between September 2002 and August 2004.

There were slight differences in methodology for macrofauna samples taken by each agency. For macrofauna samples, HRI took three replicate sediment cores with a 6.7-cm diameter tube, and shells were removed by acidification for biomass measurements (Kalke and Montagna 1991, Montagna *et al.* 2002). Samples taken by CCS were collected with 10.2-cm cores, and biomass includes shell weight (Hill and Nicolau 2008).

Vegetation Community Data

Percent spatial coverage by individual plant species was determined quarterly at five stations within Rincon Bayou (Table 3). Two stations (450 and 451) have been surveyed for plant cover in the lower Rincon Bayou since 1999 and three stations (463, 501 and 562) have been surveyed in the upper Rincon Bayou since 1995 (Table 2, Figure 1).

Water Quality

Temperature, pH, dissolved oxygen, depth and salinity were determined at each station for each sampling period. Samples to determine chlorophyll, nitrate+nitrate, silicate, ammonium and phosphate concentrations were taken simultaneously with benthic and vegetation samples taken by UT and HRI.

Table 2. Number of temporal samples and sampling period of each station. Abbreviations: CCS = Center for Coastal Studies, UT = University of Texas, HRI = Harte Research Institute.

Location	Zone	Sampling Agency	Station	Number of samples	Initial sampling date	Most recent sampling date
Macrofauna						
Rincon Bayou	Upper Rincon	HRI	466C	88	10/28/1994	2/22/2008
Rincon Bayou	Upper Rincon	HRI	465D	25	10/28/1994	8/27/2002
Rincon Bayou	Upper Rincon	HRI	461E	25	10/28/1994	8/27/2002
Rincon Bayou	Upper Rincon	HRI	400F	87	10/28/1994	2/22/2008
Rincon Bayou	Upper Rincon	HRI	463G	62	10/15/2002	2/22/2008
Rincon Bayou	Lower Rincon	CCS	450	113	9/30/1998	2/27/2008
Rincon Bayou	Lower Rincon	CCS	451	113	9/30/1998	2/27/2008
Nueces Bay	Nueces Bay	CCS	301	114	9/30/1998	2/27/2008
Nueces Bay	Nueces Bay	CCS	302	72	9/30/1998	8/23/2004
Nueces Bay	Nueces Bay	CCS	303	66	9/30/2002	2/27/2008
Vegetation						
Rincon Bayou	Lower Rincon	UT	450	37	2/1/1999	2/20/2008
Rincon Bayou	Lower Rincon	UT	451	37	2/1/1999	2/20/2008
Rincon Bayou	Upper Rincon	UT	463	49	7/3/1995	2/22/2008
Rincon Bayou	Upper Rincon	UT	501	50	7/3/1995	2/19/2008
Rincon Bayou	Upper Rincon	UT	562	49	7/3/1995	2/19/2008

Table 3. Number of macrofauna and vegetation samples taken at each station in each two-year period (bin).

Location	Zone	Sampling Agency	Station	Bin1 1995 - 1996	Bin2 1997 - 1998	Bin3 1999 - 2000	Bin4 2001 - 2002	Bin5 2003 - 2004	Bin6 2005 - 2006
Macrofauna									
Rincon	Upper Rincon	HRI	466C	8	8	4	8	23	24
Rincon	Upper Rincon	HRI	465D	8	8	4	4	0	0
Rincon	Upper Rincon	HRI	461E	8	8	4	4	0	0
Rincon	Upper Rincon	HRI	400F	8	8	4	7	23	24
Rincon	Upper Rincon	HRI	463G	0	0	0	3	23	24
Rincon	Lower Rincon	CCS	450	0	4	23	24	24	24
Rincon	Lower Rincon	CCS	451	0	4	23	24	24	24
Nueces Bay	Nueces Bay	CCS	301	0	4	24	24	24	24
Nueces Bay	Nueces Bay	CCS	302	0	4	24	24	20	0
Nueces Bay	Nueces Bay	CCS	303	0	0	0	4	24	24
Vegetation									
Rincon	Lower Rincon	UT	450	0	0	8	8	8	8
Rincon	Lower Rincon	UT	451	0	0	8	8	8	8
Rincon	Upper Rincon	UT	463	7	8	5	8	8	8
Rincon	Upper Rincon	UT	501	7	8	5	8	9	8
Rincon	Upper Rincon	UT	562	7	8	5	8	8	8

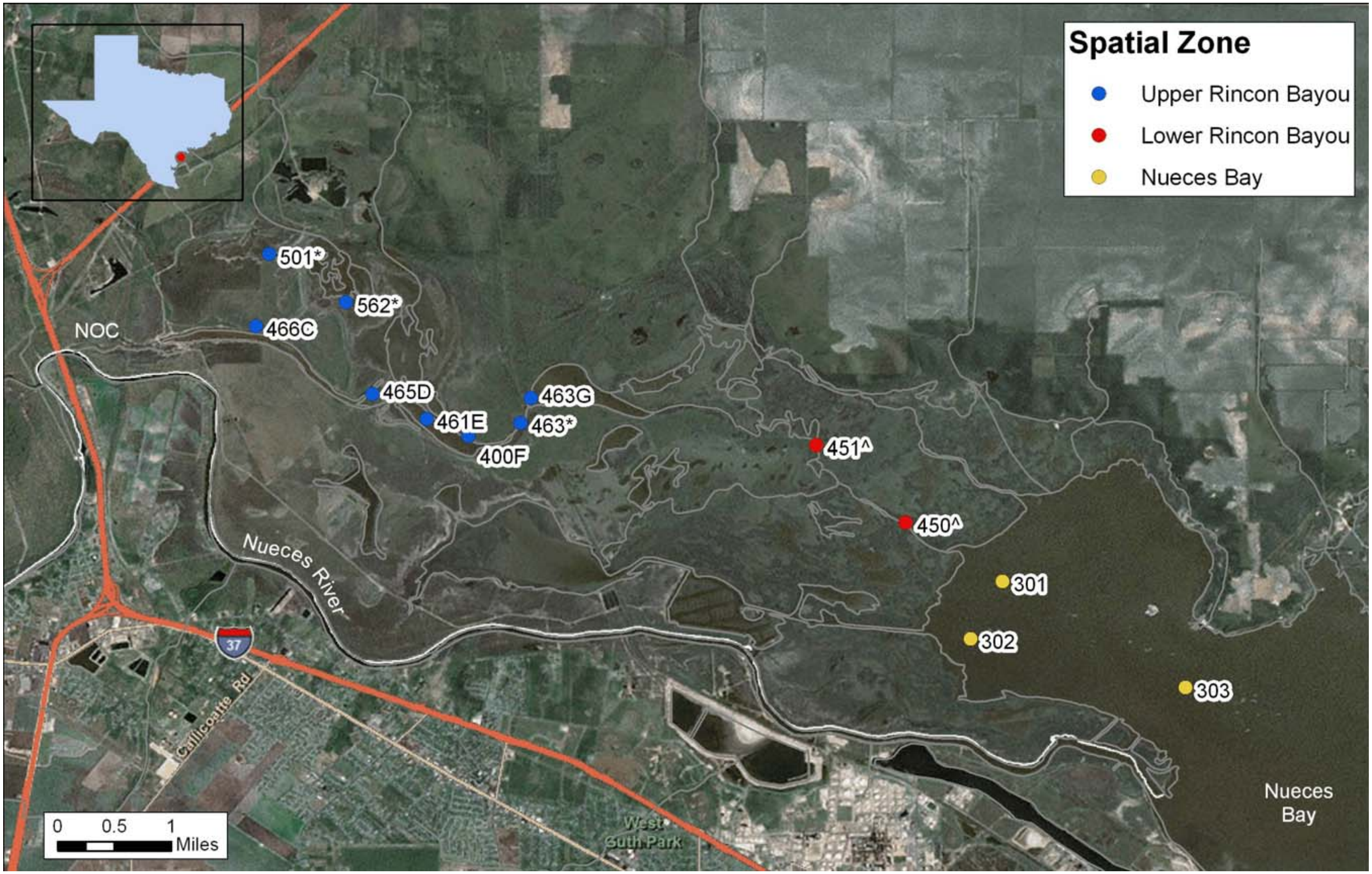

Figure 1. Stations monitored for benthic macrofauna in Rincon Bayou and Nueces Bay. NOC = Nueces Overflow Channel, * = sampled for vegetation and not macrofauna, ^ = sampled for both vegetation and macrofauna.

Statistical Analyses

Community structure of macrofauna and vegetation species (separately) was analyzed by multivariate methods. Ordination of samples was performed using the non-metric multidimensional scaling (MDS) procedure described by Clarke and Warwick (2001) and implemented in Primer software (Clarke and Gorley 2001). The software creates a Bray-Curtis similarity matrix among all samples and then an MDS plot of the spatial relationship among the samples. Significant differences between each cluster were tested using the SIMPROF permutation procedure using a significance level of 0.05. Macrofauna community data sets from HRI and CCS were combined after species names were verified and made consistent across all data sets. The convention for species names and taxonomy used in the current study is based on the Species 2000 and Integrated Taxonomic Information System (ITIS) Catalogue of Life: 2006 Annual Checklist (Bisby et al. 2006, http://www.sp2000.org). The species data was averaged by date and station, then averaged by time bin, and then averaged by zone-time bin combination. A MDS plot was formed using this species-level data. Cluster contours from cluster analysis were overlaid on top of the MDS plot. A second MDS plot was made using macrofauna family abundances rather than species abundances. Macrofauna data was log transformed (ln + 1) and vegetation data was arcsine square-root transformed prior to analysis.

The water column structure was each analyzed using Principal Component Analysis (PCA). PCA reduces multiple environmental variables into component scores, which describe the variance in the data set to discover the underlying structure in a data set. In this study, only the first two principal components were used. The water quality data was averaged by date, merged and then averaged by time bin and then zone-time bin combination. There was no nutrient data for the samples from the Center for Coastal Studies (CCS) so analysis was limited to only the space-time cells that were available for PCA. PCA analysis included only data from UT and HRI and included nutrient data as well as dissolved oxygen, temperature, salinity and pH. PCA and data management was performed using SAS software (SAS 1991).

Relationships between each of the biotic communities (macrofauna and vegetation) with water quality variables were investigated using the Biota-Environment (BIO-ENV) procedure in PRIMER. The BIO-ENV procedure is a multivariate method that matches biotic (i.e., mollusc community structure) with environmental variables (Clarke and Warwick 2001). This is carried out by calculating weighted Spearman rank correlations (ρ_w) between sample ordinations from all of the environmental variables and an ordination of biotic variables (Clarke and Ainsworth, 1993). Correlations are then compared to determine the best match.

Comparisons among the biotic and water quality multivariate datasets were investigated using RELATE. In this statistical test, a rank correlation coefficient (rho) was calculated between each pair of similarity matrices that were created from each data set (vegetation community, macrofauna community and water quality variables).

Results

Hydrology

More than 85% of daily Nueces River flow values occurred below 3.3×10^6 m^3d^{-1} (2700 ac-ft) from 1 January 1994 to 29 February 2008 (Figure 2). Nueces flow rates above this threshold value had a positive relationship with Rincon Bayou flow over the entire dataset (Figure 3). The highest Nueces Bay stage heights occurred most often at lower flow volumes in the Nueces River and Rincon Bayou (Figure 3a), indicating that tidal influence could be counteracting positive Rincon Bayou flow. The Nueces River flow thresholds that have to be overcome to allow overflow into Rincon Bayou are different for the two NOC project periods (Figure 3b). In the 1994 to 2000 period, Nueces River flow had to be approximately 4.2×10^6 m^3d^{-1} (3400 ac-ft) before flow occurred in the Rincon Bayou Overflow Channel, while in the 2001 to 2008 period, flow occurred in the Rincon Bayou Overflow Channel when Nueces River flow was only 2.6×10^6 m^3d^{-1} (1900 ac-ft).

No inflow events were observed for the period prior to the initiation of the original NOC on 26 October 1995, as well as the period from 27 September 2000 to 11 October 2001, because Nueces River flow did not exceed the estimated natural overflow threshold of 5.14×10^6 m^3d^{-1} (4,200 ac-ft) (Irlbeck and Ward 2000). In turn, inflow event criteria were individually designated for four periods from 1994 to 2008, including pre-NOC, first NOC, NOC closure, and 2nd NOC periods (Table 1). The second NOC project appeared to allow for a more pronounced influence by the Nueces River on Rincon Bayou, showing a significant increase in magnitude and frequency of wet periods compared to the first NOC project (Figure 4).

The period of analysis was divided into six two-year time bins (Figure 4) that ran from 1 January to 31 December of the following year. The time bins were 1995 to 1996 (bin 1), 1997 to 1998 (bin 2), 1999 to 2000 (bin 3), 2001 to 2002 (bin 4), 2003 to 2004 (bin 5), 2005 to 2006 (bin 6).

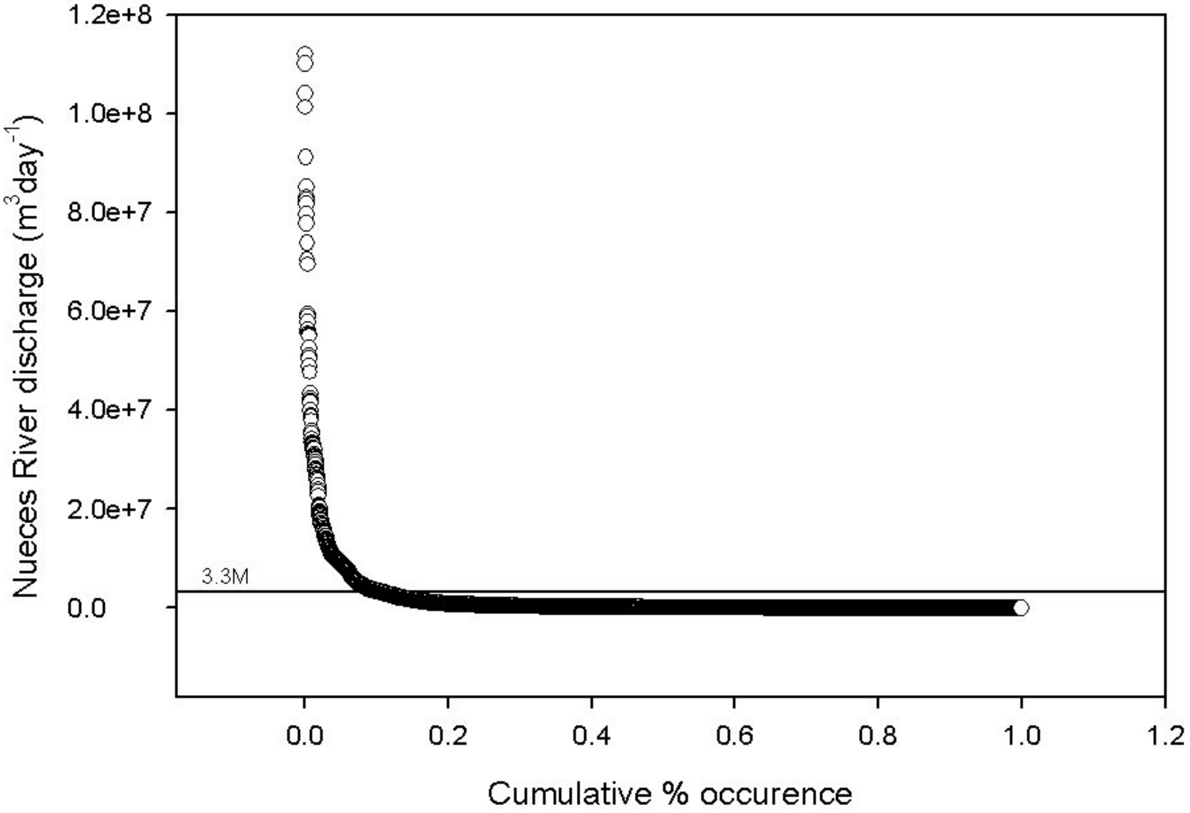

Figure 2. Flow duration curve of the Nueces River at Calallen.

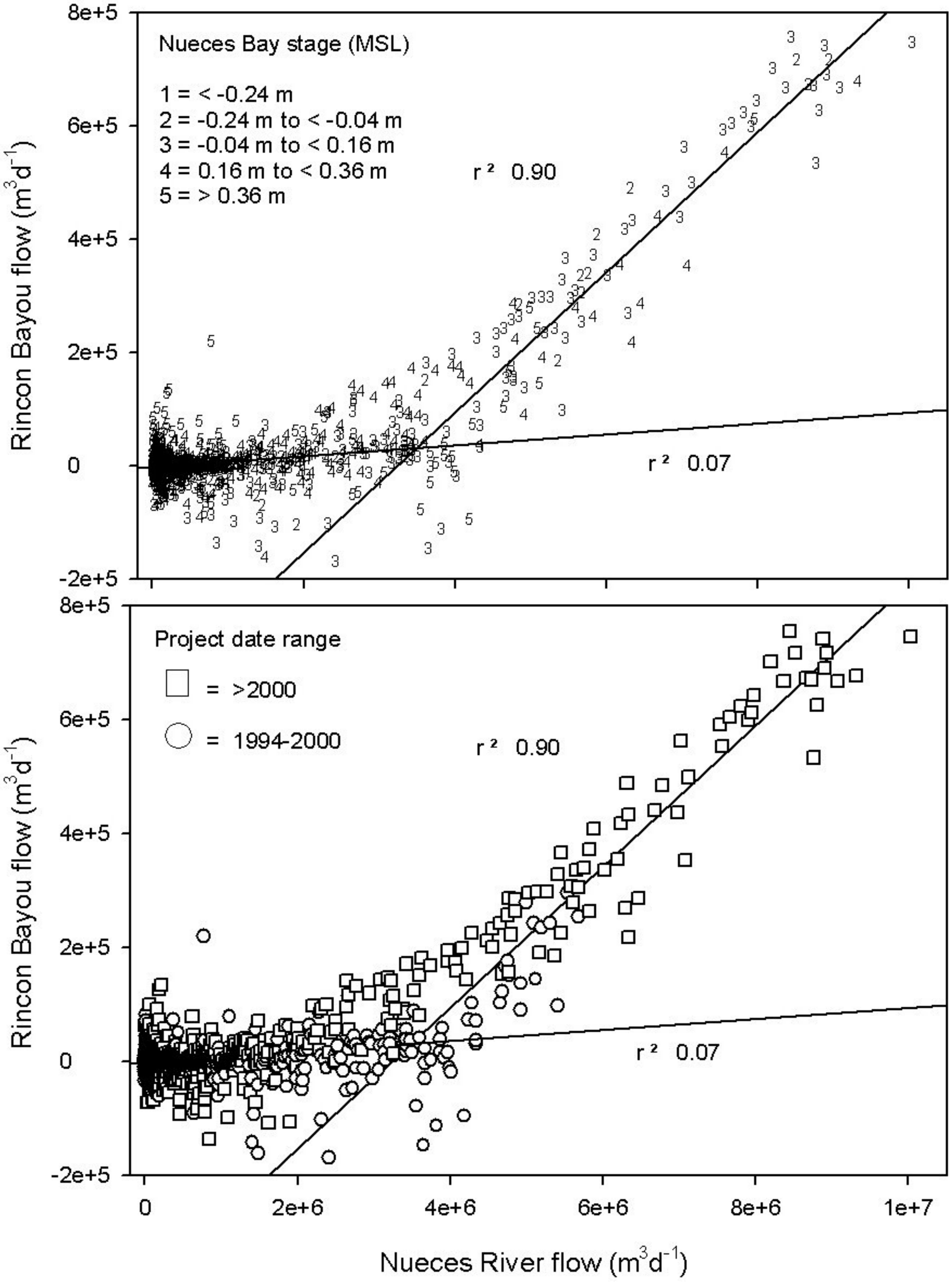

Figure 3. Paired regressions of Rincon Bayou discharge versus Nueces River discharge for no flow and positive flow into Rincon Bayou. Points are labeled by a) Nueces Bay stage and b) Nueces Overflow Channel project periods.

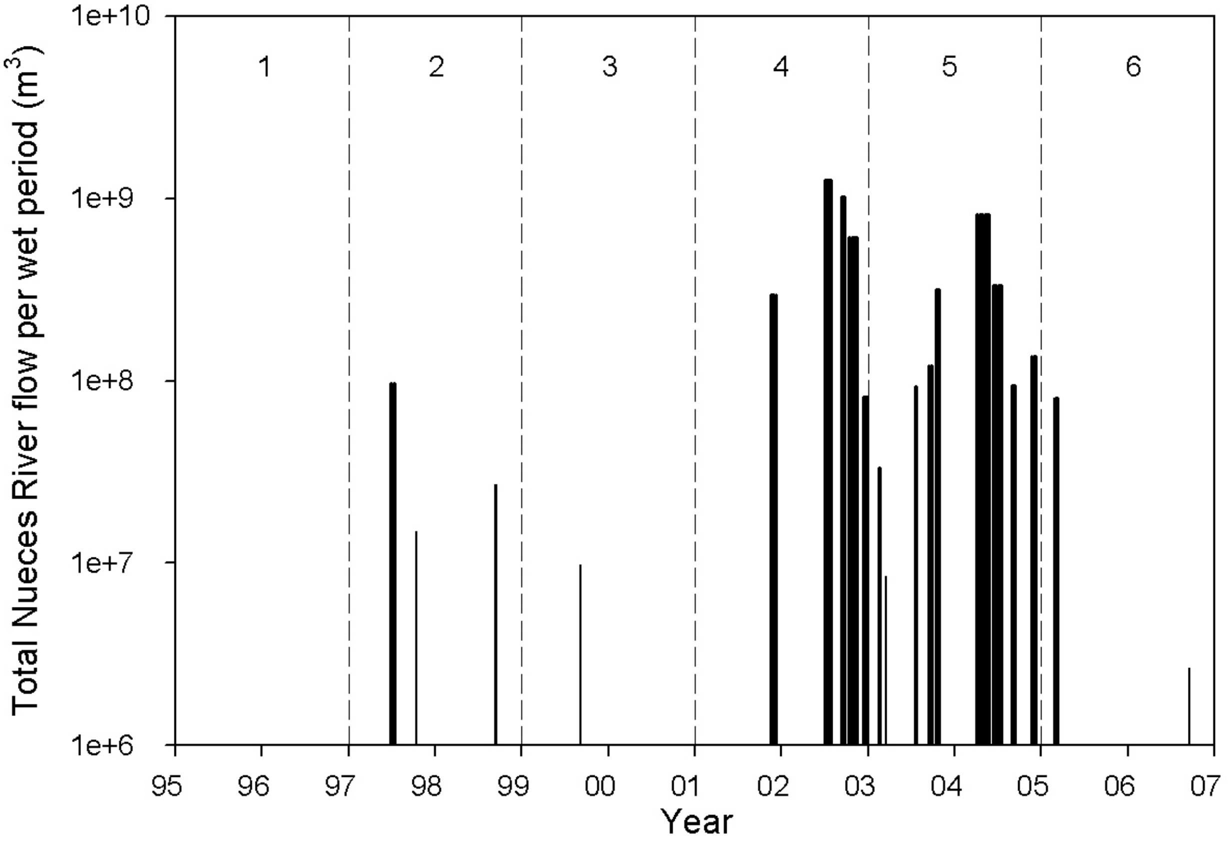

Figure 4. Wet periods over the 170 month study period. From 1 January 1994 to 10 August 2000, wet periods were classified as daily flow rates exceeding 4.2 x 10^6 m^3 Nueces River flow. From 11 August 2000 to 29 February 2008 wet periods were classified as daily flow rates exceeding 2.6 x 10^6 m^3 Nueces River flow.

Downstream response

Water Quantity

Inflow into Rincon Bayou for the first and third time bins was very small (Figure 4). Time bins two and six had a moderate amount of inflow. Time bins four and five were very wet relative to all other time bins.

Water Quality

Salinity was an average of 56 ppt in time bin 1 in the upper Rincon Bayou (Figure 5). The average salinity in the upper Rincon Bayou varied between 21 and 22 ppt in time bins 2 - 4. After a drop in salinity to 9 ppt in time bin 5, the salinity increased to 24 ppt. The standard deviation of salinity was between 4 and 6 ppt in upper Rincon Bayou for all time bins except for time bin 5.

The salinities in Nueces Bay and lower Rincon Bayou were always within 3 ppt of each other and shared the same trends over time. Salinity was lowest in these two zones in time bin 2 (7 - 8 ppt) and increased to 26 - 27 ppt in time bin 3. This was followed by a decrease in salinity to 9 ppt in time bin 5, followed by an increase in salinity to 24 ppt in time bin 6. The standard deviation of salinity at both zones was at most 1 ppt for all time bins except for time bin 4, where the standard deviation reached 3 ppt in Nueces Bay.

The first Principal Component (PC1) of the water quality PCA represented spatial variation in zones, with the lower Rincon Bayou being very similar to each other (Figure 6). This analysis included bins 4 - 6, except for upper Rincon Bayou which also included time bin 3. Water quality in upper Rincon Bayou had higher dissolved oxygen and chlorophyll concentrations but lower phosphate concentrations than the other two zones for the same time bins (time bins 4 - 6). The upper Rincon Bayou in time bin 3 had lower dissolved oxygen and chlorophyll concentrations, but higher phosphate concentrations than those of all zones in time bins 4 - 6.

The second PC of the water quality PCA represented a temporal variation in water quality. Salinity was positively correlated with nitrite plus nitrate, ammonium and nitrogen to phosphorus ratios along PC2 (Figure 6b). Time bin 5 in all zones had lower salinity and nitrogen based nutrients (nitrite plus nitrate concentrations, ammonium concentrations, nitrogen to phosphorus ratios) than time bins 4 and 6 for all other spatial zones (Figure 6).

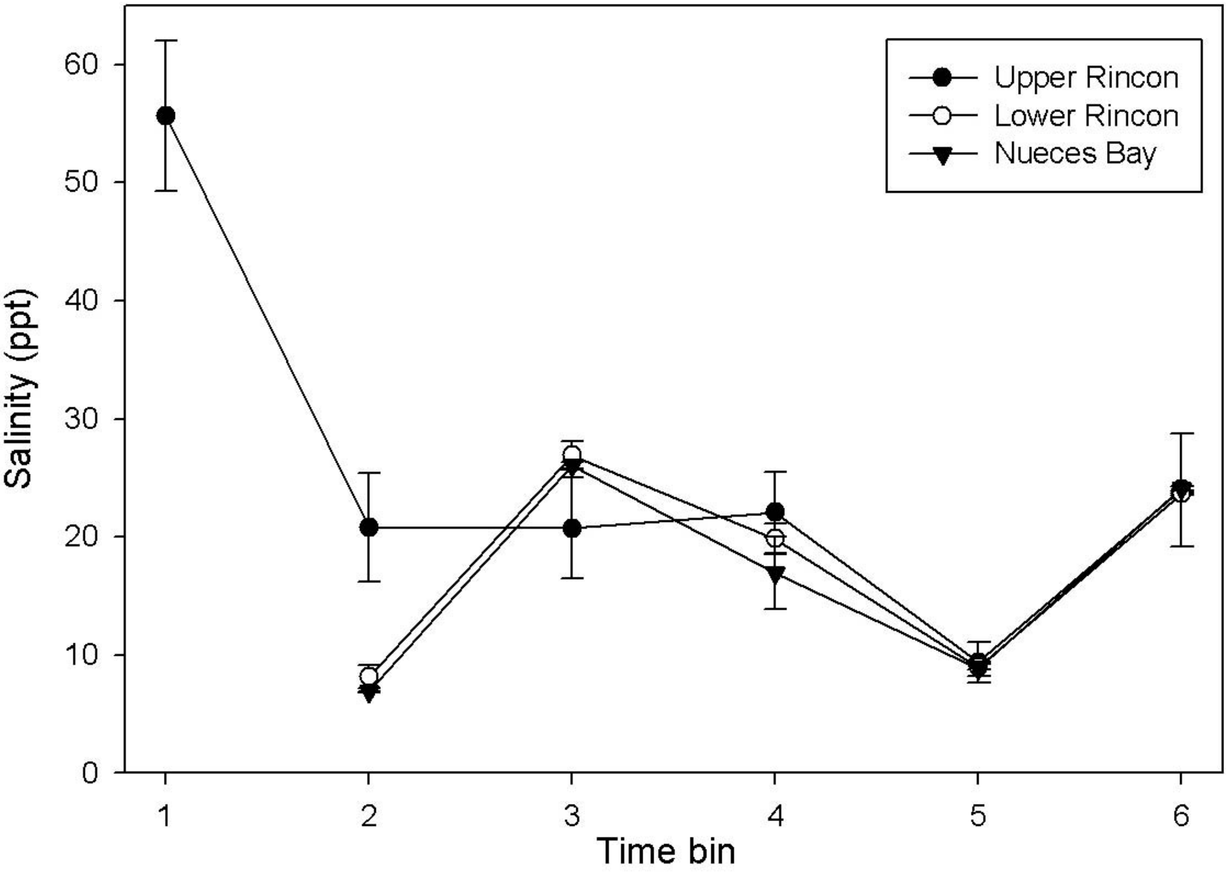

Figure 5. Mean salinity at each zone over time. Error bars equal one standard deviation either side of the mean.

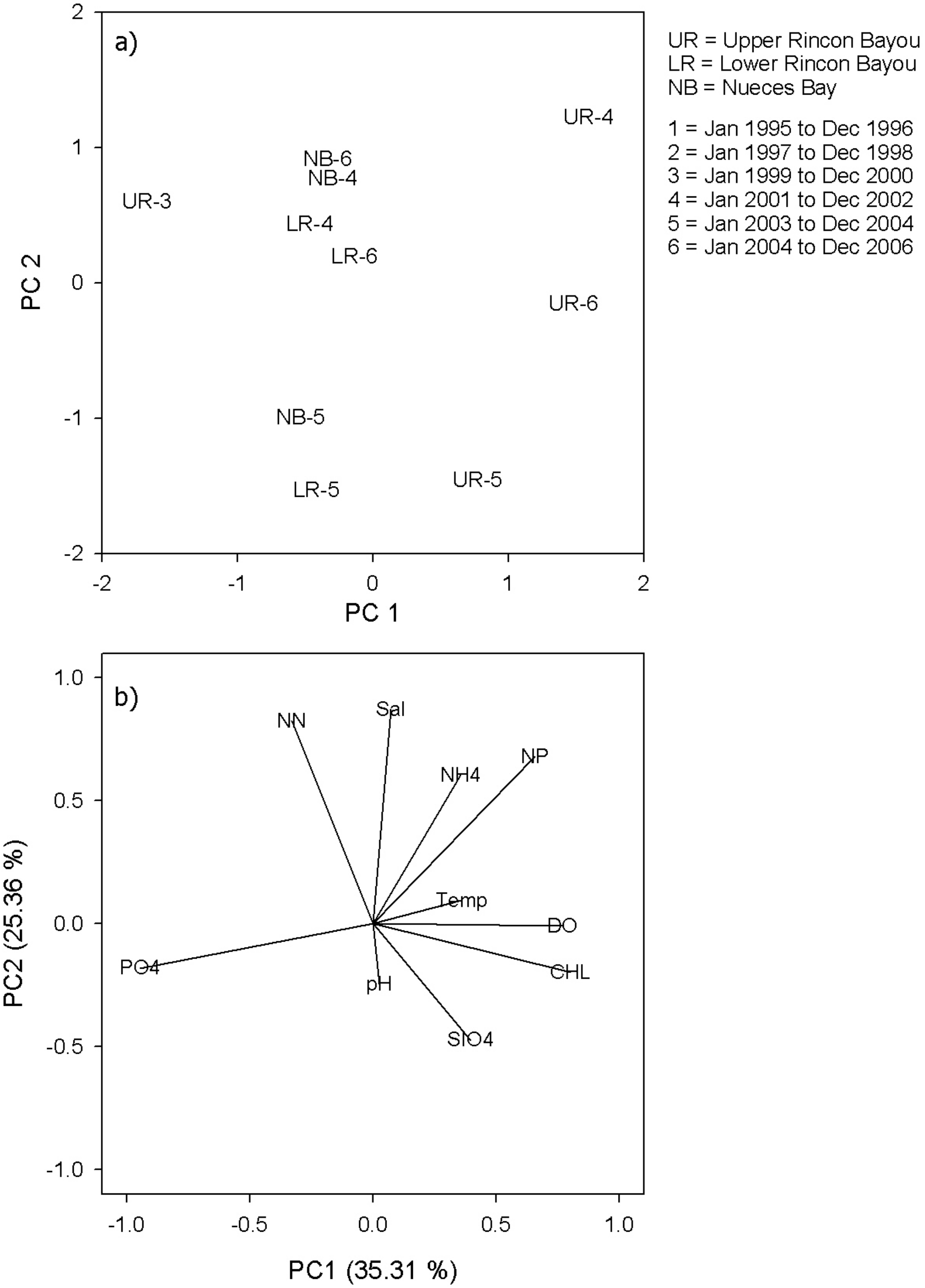

Figure 6. PCA of water quality variables including nutrients. A) PC station scores labeled by zone-time bin and B) PC loadings.

Macrofauna Community Data

The sampling for fauna in the area-zone/time-bin cells was unbalanced (Table 3). The lack of balance is mostly due to a difference in the frequency of sampling. There was predominantly quarterly sampling during bins 1 - 3 and monthly sampling during bins 4 - 6.

There is a clear transition from macrofaunal communities in the upper Rincon Bayou (on the left of the MDS plot; Figure 7) to the communities in the upper Rincon Bayou (in the middle of the MDS plot) to the communities of Nueces Bay (on the right side of the plot). However the macrofauna communities in the upper Rincon Bayou were significantly different from the macrofauna communities in the lower Rincon and Nueces Bay. The difference between the two community groups cannot be attributed to differences in species identifications by the different entities (the upper Rincon Bayou is sampled by HRI and lower Rincon Bayou and Nueces Bay is sampled by CCS, Table 3) because of quality control procedures and the communities are still significantly different at the family level rather than species level (Figure 8).

The different zones are due to a few species. The upper Rincon Bayou has higher abundances of the polychaete *Streblospio benedicti* and Chironomid larvae, but lower abundances of the amphipods *Corophium louisianum* and *Cerapus tubularis*, and the polychaetes *Steninonereis martini* and *Marphysa sanguinea* relative to the lower Rincon Bayou.

There was a similar seriation pattern (i.e., temporal succession) in all spatial zones over the course of the study period (Figure 7). The seriation pattern is most pronounced in the upper Rincon Bayou zone. In all spatial zones, the communities in time bin 6 are in an intermediate state with a community structure partially in between time bins 4 and 5 and partially unique to each spatial zone. The discontinuity between time bins 4 and 6 occurs because the intervening period 5 is the highest cumulative flow (Figure 4) and lowest salinity (Figure 5). In all zones, time bins 3 and 4 are more similar to each other than with time bins 1 (if sampled), 2, 5 and 6.

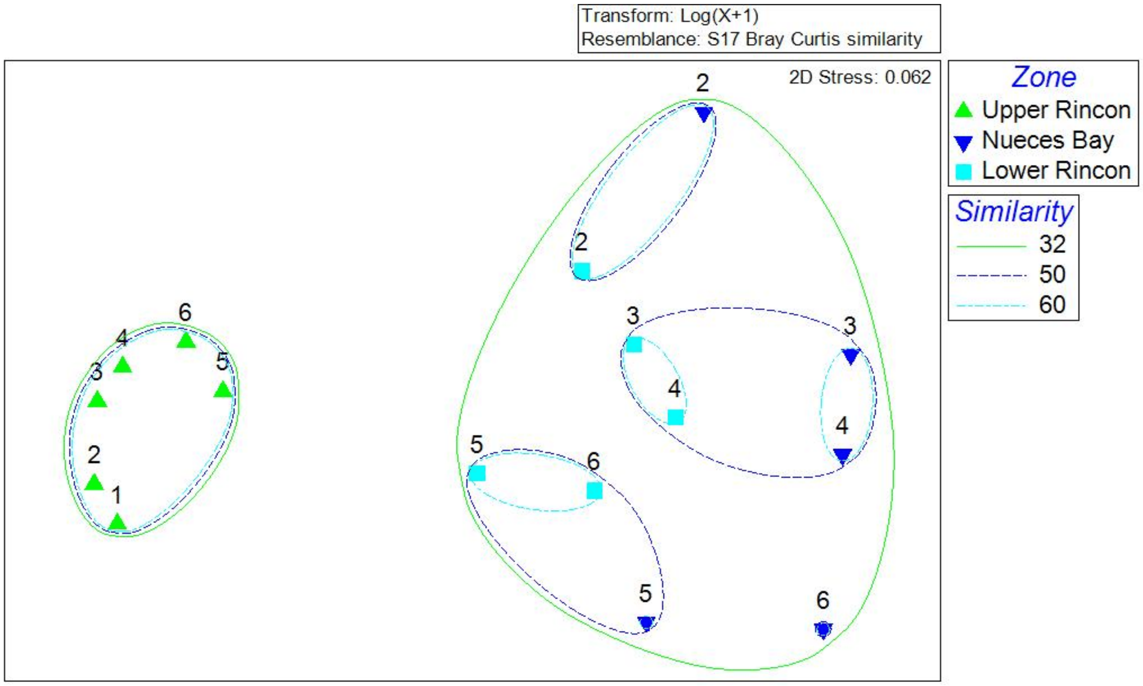

Figure 7. MDS of macrofaunal communities (by species)

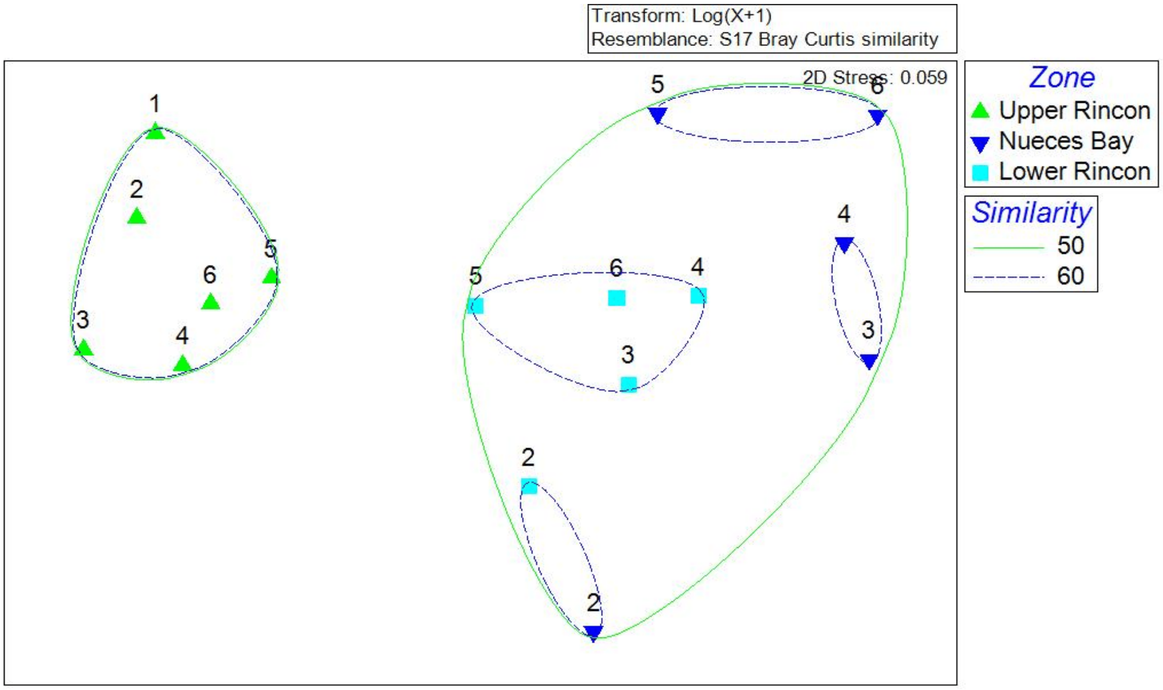

Figure 8. MDS of macrofaunal communities (by family)

Vegetation Community Data

The vegetation communities of the upper Rincon Bayou were significantly different from those of the lower Rincon Bayou (Figure 9). *Spartina alterniflora* (smooth cordgrass) was present almost exclusively at lower Rincon Bayou (4.1 %) and not at all in the upper Rincon Bayou (0 %). There was also consistently more *Salicornia virginica* (woody glasswort) in the lower Rincon Bayou (21 %) than the upper Rincon Bayou (3 %). However, there was consistently more bare (unvegetated) area in the upper Rincon Bayou (mean of 48 %) than in the lower Rincon Bayou (mean of 23 %).

Within upper Rincon Bayou, the first three time bins (Jan 1995 to Dec 2000) were significantly different to the latter three time bins (Jan 2001 to Dec 2006). Both *Spartina spartinae* and *Scirpus maritimus* were only found in the upper Rincon Bayou, but only in three time bins each. Both species were present in the first two periods, however *S. spartinae* was also present in the third time bin while *S. maritimus* was also present in the fifth time bin. Within the upper Rincon Bayou, the plant community of time bin 4 (2001 and 2003) was much more similar to time bin 6 (2005 and 2006) than time bin 5 (2003 and 2004). In the lower Rincon Bayou, the first two time bins sampled (Jan 99 to Dec 02) were significantly different to the last two time bins (Jan 2003 to Dec 2006). The invasive *Cuscuta* spp. (strangleweed) was present in the last two time bins in the lower Rincon Bayou only.

There were also a few long-term trends that occurred in both zones. *Monanthocloe littoralis* (shoregrass) sequentially decreased over time until time-bin 6, when it increased in coverage. Although still rare, *Aster subulatus* and *Iva frutescens* were only found in the last two time bins of both spatial zones.

There was a similar seriation pattern (i.e., temporal succession in upper and lower Rincon Bayou over the course of the study period (Figure 8). The seriation pattern is most pronounced in the upper Rincon Bayou zone. A discontinuity occurs between time bins 4 and 6. This occurs during the intervening period 5, which is the highest cumulative flow (Figure 4) and lowest salinity (Figure 5).

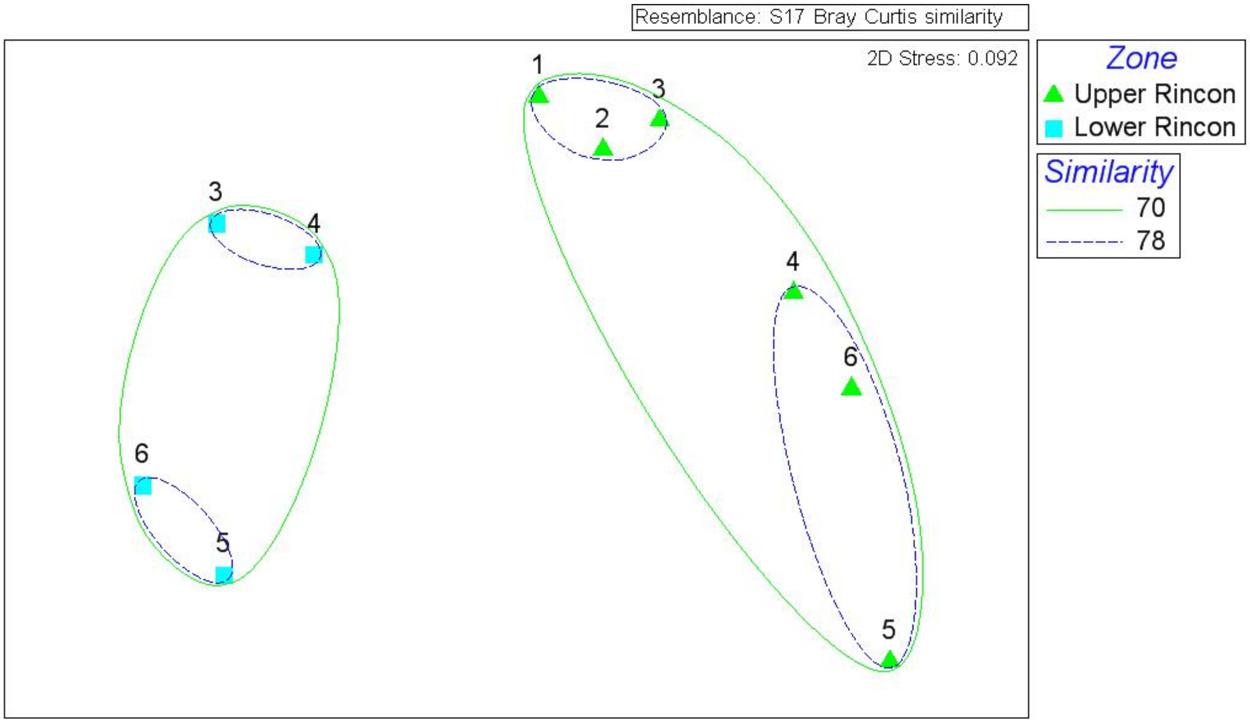

Figure 9. MDS of vegetation communities (by species)

Comparing biota with water quality

The highest correlation (rho) was between macrofauna community structure and a combination of temperature, pH, nitrate plus nitrite and chlorophyll. This correlation between a reduced number of water quality variables and macrofauna community structure was 0.565 ($p = 0.05$). The single water quality variable that correlated highest with macrofauna community structure was pH (rho = 0.532).

The highest correlation between a reduced number of water quality variables and the vegetation community structure was 0.500 ($p = 0.38$). This correlation was between vegetation communities and a combination of dissolved oxygen, pH, salinity and chlorophyll. Dissolved oxygen had the highest correlation with vegetation community structure (0.405) out of all individual water quality variables.

The patterns of macrofauna community structure were significantly similar to and correlated with water quality (rho = 0.299, $p = 0.008$) and vegetation communities (rho = 0.508, $p = 0.009$). The vegetation community structure however, was not significantly correlated with overall water quality (rho = -0.019, $p = 0.500$).

Discussion

Over the 14-year period of this study, there were three distinct climatic periods (Figures 4 – 5). The first time period (1995 – 1997) was a deep drought with nearly no inflow and hypersaline conditions (average salinity around 60 ppt). The fifth time period (2003 – 3005) was an extremely wet period with the highest cumulative flow and near fresh conditions throughout the marsh and bay (average salinity around 10 ppt). Normal conditions occurred during four timer periods (1997-2003 and 2005 -2007) where there were brackish conditions (average salinity around 20 ppt) throughout the ecosystem. Thus over the 14-year period, only one deep drought period and one deep flood period was captured.

There appear to be three spatial zones in this ecosystem: upper and lower Rincon Bayou, and Nueces Bay. As in previous studies, the benthic communities of the upper Rincon Bayou are clearly different from both lower Rincon Bayou and Nueces Bay (Palmer *et al.* 2002). While lower Rincon Bayou is a transition between upper Rincon Bayou and Nueces Bay, the water quality and macrofauna communities are much more similar between Nueces Bay and lower Rincon Bayou than between upper Rincon Bayou and Nueces Bay. These findings provide evidence that the effects of freshwater inflow, even during floods, do not extend all the way from upper Rincon Bayou to Nueces Bay.

The temporal variation of salinity is similar in Nueces Bay and lower Rincon Bayou and follows a distinctly different temporal pattern than that of upper Rincon Bayou (Figure 5). The salinity pattern of upper Rincon Bayou has a slower response to changes in the frequency and quality of wet periods that cause freshwater inflow into the Rincon Bayou (Figures 4 and 5). This slower response may be partially attributed to the greater quantities of residual salt in the upper Rincon Bayou sediments in addition to the smaller amount of tidal exchange that it receives. It is obvious that in terms of water quality, lower Rincon Bayou has a greater amount of water exchange with Nueces Bay than with upper Rincon Bayou (Figures 5 and 6). The larger variation in salinity within each time bin in the upper Rincon Bayou (Figure 5) indicates that although long-term salinities are steady, short-term salinities vary more than locations downstream. This short-term variation in salinity may act as a disturbance to macrobenthic communities and could be the occurrence of the freshwater disturbance indicator organisms *Streblospio benedicti* and Chironomid larvae (unidentified; Montagna *et al.* 2002).

The significant difference between macrofauna communities in upper Rincon Bayou and communities in both lower Rincon Bayou and Nueces Bay reflect the difference in water quality between upper Rincon Bayou and the other two zones. The seriation (i,e., orderly change over time) of the community can be attributed to the amount of freshwater inflow that enters the system and natural successional patterns that occur in the absence of floods and droughts. There is a clear pattern of succession in the benthic communities of each zone over time until time bin

5 (2003 - 2004; Figure 7). Up until time bin 5 with the largest flood and flow, the most similar temporal community (the closest time bin in the MDS plot) is the bin preceding or succeeding each other in sequential order. The macrofauna community of time bin 6 is actually more similar to the community of time bin 4 than that of time bin 5. The salinity is also similar in time bins 4 and 6 (Figure 5). The highest number of wet periods occurred in time bin 5 preceded by relatively large inflow events in the latter part of time bin 4. This is most likely the cause of such a large change in macrofauna communities between time bins 4 and 5. Frequent salinity disturbances, such as in the latter part of time bin 4 and most of time bin 5 are likely to interrupt succession (Ritter *et al.* 2005). In time bin 6 (2005 - 2006), there was only two flood events. This relative dryness may have caused the macrofauna communities to change back toward a community structure that is a transition between the wetter time bin 5 and the drier time bin 4.

There is a significant difference between vegetation community structure in the upper and lower Rincon Bayou (Figure 9). This vegetations pattern is similar to the pattern of the macrobenthos community structure described above. *Spartina alterniflora* and *Salicornia virginica* were more abundant in the lower Rincon Bayou than the upper Rincon Bayou. The upper Rincon Bayou had an average of twice the amount of bare area than the lower Rincon Bayou, however. There were slight differences between the upper and lower Rincon Bayou in the response of the vegetation community to the wet and dry periods. Vegetation in the upper Rincon Bayou had a response pattern similar to the macrofauna communities in that the communities in each time bin progressed sequentially except for in time bin 5 (2003 - 2004), when the community was very different during severe flood conditions.

The seriation pattern in vegetation reported for the upper and lower Rincon Bayou (Figure 8) is supported by a more detailed analysis of vegetation community structure over this time period constructed by Forbes and Dunton (2006). MDS plots of vegetation species composition revealed that vegetation assemblages formed distinct clusters during a “moderate” period (1996-1999), but began to diverge during the ensuing drought, with significant divergence occurring following the 2002 flood; within two years after the flood the assemblages at three sites had become to recover to their original clusters but were not within 80% similarity (Forbes and Dunton; 2006). Recovery of species assemblages and cover has since continued very slowly at all stations but 450, which has been least impacted by drought conditions because of its proximate location on Nueces Bay. More recent studies in the Rincon suggest that persistent drought conditions since spring 2005 have likely played a role in the poor recovery of vegetation assemblages since the 2002 flood event (Forbes et al., 2008; Rasser 2009).

The spatio-temporal macrofauna community structure was significantly correlated with spatio-temporal changes in water quality, indicating that changes in water quality cause an obvious change in macrofauna community structure. Spatio-temporal vegetation community structure however, is not correlated with spatio-temporal changes in community structure. Interestingly, the vegetation community structure is correlated with macrofauna community structure. This lack of correlation with water quality and correlation with macrofauna likely indicates that vegetation does not respond on the spatio-temporal scales of this study design and / or vegetation also responds to some other characteristic not analyzed or measured in this investigation such as water depth or sediment characteristics.

Throughout this study period, there have been a range of inflows into Rincon Bayou (Figure 4). Increased inflow causes salinity in the upper Rincon Bayou to resemble the lower Rincon Bayou and Nueces Bay only in the wettest period (time bin 5, 2003 - 2004; Figure 5). However, even in this period of maximum freshwater inflow, the overall water quality of the lower Rincon is more similar to Nueces Bay then that of the upper Rincon Bayou (Figure 6). The higher similarity between the lower Rincon Bayou and Nueces Bay, rather than with the upper Rincon Bayou is more apparent in the macrofauna community than the vegetation community (Figure 7). This indicates that the effects of inflow impact the lower Rincon Bayou much less than the upper Rincon Bayou, even in periods of extended flooding.

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