Effects of Pumped Flows into Rincon Bayou on Water Quality and Benthic Macrofauna

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Prepared by:

Dr. Paul A. Montagna, Principal Investigator
Harte Research Institute for Gulf of Mexico Studies
Texas A&M University-Corpus Christi
6300 Ocean Dr., Unit 5869
Corpus Christi, Texas 78412
Phone: 361-825-2040
Email: paul.montagna@tamucc.edu

Submitted to:
Coastal Bend Bays & Estuaries Program
615 N. Upper Broadway, Suite 1200
Corpus Christi, TX 78401

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Principal Investigator:
Dr. Paul A. Montagna

Co-Authors:
Leslie Adams, Crystal Chaloupka, Elizabeth DelRosario, Amanda Gordon, Meredyth Herdener, Richard D. Kalke, Terry A. Palmer, and Evan L. Turner

Harte Research Institute for Gulf of Mexico Studies
Texas A&M University - Corpus Christi
6300 Ocean Drive, Unit 5869
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Phone: 361-825-2040
Email: paul.montagna@tamucc.edu

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Abstract

The purpose of the current project is to determine the effects of pumped inflows into Rincon Bayou on benthic macrofauna during normal and drought precipitation events. This information is needed by managers to create an effective pumping strategy for the Rincon Bayou pipeline that maximizes the ecological benefit from freshwater placement in the Nueces Delta, near Corpus Christi, Texas.

Hydrologically, Rincon Bayou is still a reverse estuary that still occasionally exhibits hypersaline conditions. The salinity can fluctuate from fresh to hypersaline, and hypersaline to fresh in very short time periods. Pumping from the Calallen Pool into Rincon Bayou occurs only when there is also natural inflow because that is the only time when pass-throughs are required. Nutrients are high when salinity is low.

The diversity of macro-infauna and macro-epifauna is low. There are very high fluctuations of abundance and biomass related to fluctuations in inflow. The low diversity and population fluctuations are characteristic of a very disturbed ecosystem.

There are several recommendations for pumping regimes that could improve the ecological soundness of Rincon Bayou based upon results presented here and a review of previous studies.

- Salinity should be maintained between 6 and 18 psu at Station C.
- Water depth at Station C should be maintained between 0.2 m to 0.3 m.
- To achieve the salinity and depth target above, inflows on the order of 2 to 5 cfs are required on a routine basis.
- To improve ecological stability, inflows should be a trickle, not a flood. Therefore inflows from pumping should be continuous and not haphazard, and not dependent on pass-through requirements.

Introduction

The Nueces River System has been subject to adaptive management since construction of the Choke Canyon Reservoir in 1982 (Montagna et al. 2009). Special condition required the City of Corpus Christi to provide not less than 185 million cubic meters (151,000 ac-ft) of water per year to the Nueces Estuary through a combination of spills, releases, and return flows to maintain ecological health and productivity of living marine resources. However, no releases were made and after public complaints, the Texas Water Commission issued an order in May 1990 requiring the City to meet the special conditions contained in their water right permit that required freshwater inflows to the estuary.

In April 1995, the Texas Natural Resource Conservation Commission (formerly TWC, but now the Texas Commission on Environmental Quality) issued a Final Agreed Order in April 1995 to amend earlier provisions. The minimum annual inflow requirement was reduced to 138,000 ac-ft per year to be delivered in a monthly regimen to mimic natural hydrographic conditions in the Nueces Basin. There were three other revisions: 1) the minimum mandatory inflows were changed to targeted monthly inflows, 2) the releases were changed to pass-throughs, and 3) drought relief was granted in the form of different pass-through requirements based on the reservoir level.

In October 1995, the U.S. Bureau of Reclamation (BOR 2000) constructed a demonstration project to open an overflow channel at a depth of 1.0 ft-msl from the Nueces River to Rincon Bayou, which is the main stem channel of the Nueces Delta marsh. The purpose of the overflow channel was to increase opportunities for freshwater inflow into the delta to improve ecological value of the marsh. The project was very successful improving hydrology (Ward et al. 2002) by restoring the number of overflow events from one in three years to three in each year; however, the historical volumes of the floods were not restored. At first, the initial flooding events actually increased salinity because of the large amount of salt that had evaporated in the delta over the years. By 1997, the restored flow began to reduce salinities in the delta during floods. The reduced salinities led to reduced increased productivity of the marsh and living resources (Montagna et al. 2002, Palmer et al. 2002, Alexander and Dunton 2002). However, because this demonstration project did not have permanent easements and additional easements could not be obtained, the channel was closed in September 2000.

In April 2001, changes were made to revise drought management measures in the 1995 order. Water use restrictions, such as lawn and outdoor water usage, are now tied to the reservoir level to provide relief during drought. Also, new bathymetric surveys were performed that increased the total water storage capacity by 16,019 ac-ft because of sediment retention. In exchange for these benefits the City agreed to 1) reconstruct the Nueces River Overflow Channel to Rincon Bayou, 2) construct a pipeline to convey up to 3,000 ac-ft directly to the Nueces Delta, and 3) implement an on-going monitoring and assessment program to facilitate adaptive management for freshwater flows into the Nueces Estuary.

In 2009, the pipeline and pumping station was constructed to pump freshwater from the Calallen Pool directly to Rincon Bayou so that flow would not rely on overflowing the Calallen Dam.

The pumping station contains three pumps that can be used alone or in unison. The time needed to pump 3,000 ac-ft depends on the number of pumps running at one time. It takes roughly one week to pump the required amount if all three pumps are running, or three weeks if one pump is running. Thus the most beneficial pumping regime (i.e., the timing and quantity of pumped inflow) has yet to be resolved. The purpose of the current project is to determine the effects of pumped inflows into Rincon Bayou on benthic macrofauna during normal and drought precipitation events. This information is needed by managers to create an effective pumping strategy for the Rincon Bayou pipeline that maximizes the ecological benefit from freshwater placement in the Nueces Delta, near Corpus Christi, Texas.

Methods

The primary project objective of the current study will be to determine the effects of pumped inflows into Rincon Bayou on benthic macrofauna in order to inform water managers on how to create an ecologically effective pumping strategy. Benthic organisms have been especially useful in environmental research for several reasons: 1) benthos are usually the first organisms affected by pollution, 2) because of gravity, everything ends up in bottom sediments, 3) materials from watersheds and freshwater will be transported downstream to the coastal sea bottoms, 4) everything dies and ends up in the detrital food chain, which is utilized by the benthos, 5) pollutants are usually tightly coupled to organic matrices, therefore benthos have great exposure through their niche (food) and habitat (living spaces) to pollutants, 6) benthos are relatively long-lived and sessile, so they integrate pollutants effects of over long temporal and spatial scales, 7) benthic invertebrates are sensitive to change in environmental conditions and pollutants in particular, thus biodiversity loss is an excellent indicator of environmental stress, and 8) bioturbation and irrigation of sediments by benthos effect the mobilization and burial of xenobiotic materials. The approach used here is to relate samples of water quality and benthic macrofauna response to inflow and pumping events.

Sampling

The Nueces Estuary is one of seven major estuarine systems along the Texas Coast. The Nueces Estuary includes the marsh system in Nueces Delta, Nueces River tidal segment, one primary bay Corpus Christi Bay (connected to the Gulf of Mexico by Aransas Pass), one secondary bay Nueces Bay (that connects the river and delta to the primary bay), and two tertiary bays Oso and Redfish Bay (Fig. 1). The Nueces River Saltwater Barrier Dam, located adjacent to IH 37, was originally constructed in 1898 to restrict saltwater intrusion to the upstream nontidal segment of the river. The Nueces Estuary is odd in that the Nueces River runs parallel to and on the south side of the Nueces Delta and the river empties in to Nueces Bay below the delta. Rincon Bayou is a creek connecting to the tidal segment of the Nueces River to the delta during flood events, and the bayou runs down the main stem of the Nueces Delta.

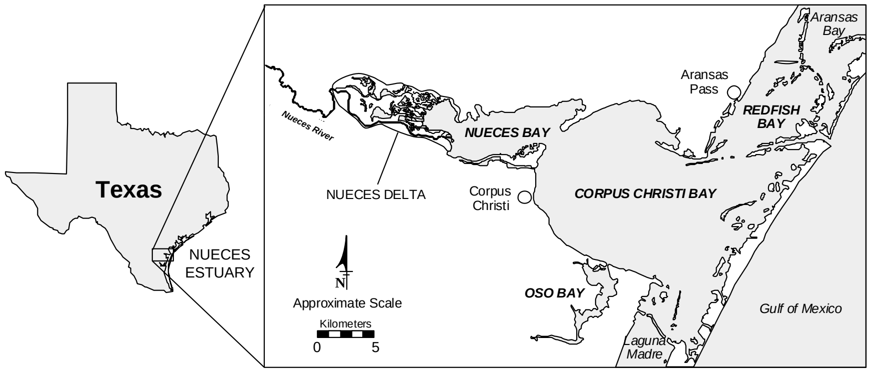

Figure 1. Location of the Nueces Delta within the Nueces Estuary.

Three stations were sampled for study here. Station C is located at 27.89878 °N latitude and 97.60417 °W longitude and is sampled every two weeks. Two other stations (F and G) will be sampled quarterly (beginning October 1, 2015 and ending April 30, 2016) to capture changes over larger spatial scales. Station F is located at 27.87760 °N latitude and 97.57873 °W longitude. Station G is located at 27.88992°N latitude and 97.56910 °W longitude. These are historical stations sampled since 2002 and previously named 466C, 400F, and 463G respectively (Montagna et al. 2009).

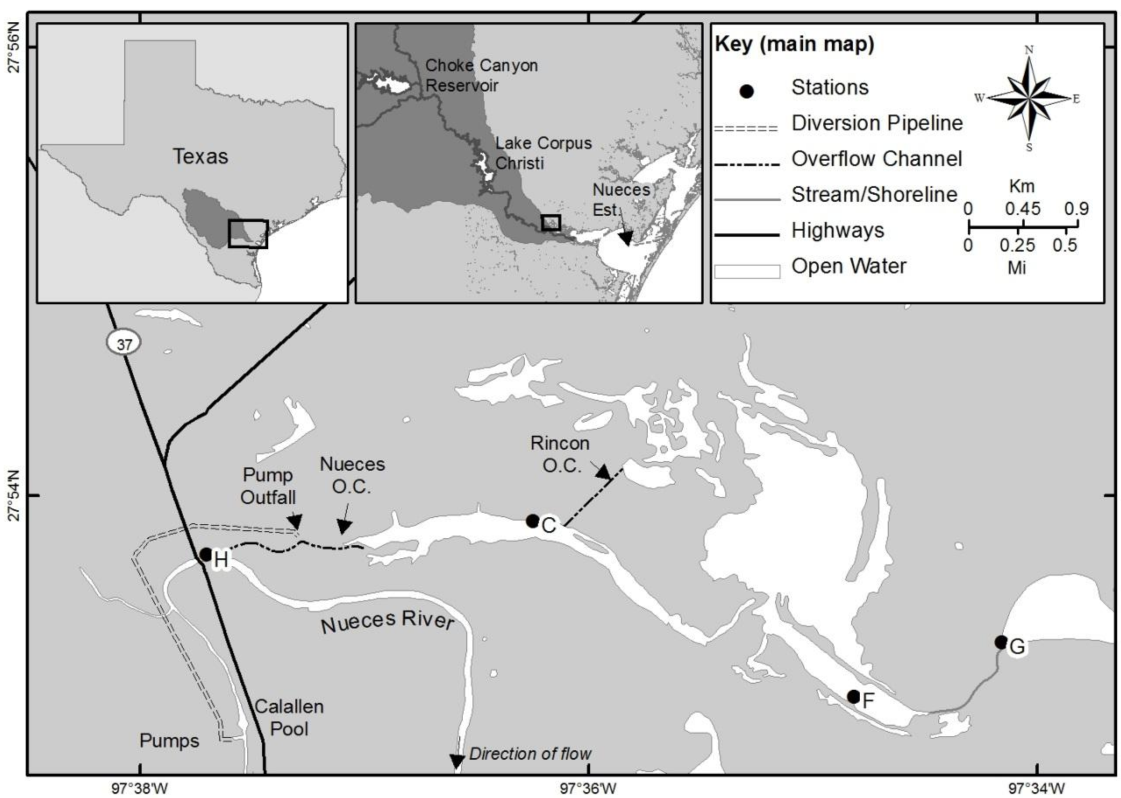

Figure 2. Study area with sample locations. a) State of Texas with the Nueces Basin highlighted. b) Location of Choke Canyon Reservoir and Lake Corpus Christi within the Nueces Basin. c) Location of the Nueces Delta marsh containing Rincon Bayou.

Originally we proposed to sample before, during and after pumping events, but this proved to be impossible because we were always notified of pumping until after pumping began. So, to resolve the problem, we sampled one station (C) every two weeks to ensure that we captured all inflow events including natural flooding. Bi-weekly sampling began 29 October 2013 and continued through 30 April 2015.

Water Quality

Hydrographic measurements in addition to chlorophyll and nutrients were sampled just beneath the surface and at the bottom of the water column at all stations on each sampling date. Chlorophyll and nutrients were sampled in duplicate.

Hydrographic measurements were made at each station with a YSI 6600 multi parameter instrument. The following parameters were read from the digital display unit (accuracy and units): temperature (∀ 0.15 EC), pH (∀ 0.2 units), dissolved oxygen (∀ 1.0% of reading or 0.1 mg l^{-1} whichever is greater), depth (∀ 0.018 m), and salinity (∀ 1.0% of reading or 0.1 ppt, whichever is greater). Salinity is automatically corrected to 25 ^{o}C.

Chlorophyll samples were filtered onto glass fiber filters and placed on ice. Chlorophyll is extracted overnight and read fluorometrically on a Turner Model 10-AU using the non-acidification technique (Welschmeyer, 1994; EPA method 445.0).

Nutrient samples were filtered to remove biological activity (0.45 μm polycarbonate filters) and placed on ice (<0.4 EC). Water samples were analyzed at the Harte Research Institute using a OAI Flow-4 autoanalyzer with computer controlled sample selection and peak processing. Typical lowest concentration minimum reportable levels (LCMRL) are: nitrate+nitrate (0.25-10.0 μM; O.I. Analytical method 15040908, OIA 2008), silicate (10.0-300.0 μM; O.I. Analytical method 15061001, OAI 2001a), and ammonium (0.25-10.0 μM; O.I. Analytical method 15031107, OIA 2007). The orthophosphate method has a LCMRL of 0.10-10.0 μM (Perstorp Analytical method 000589, OIA 2001b), but is a modification of the Alpkem chemistries method (Alpkem 1993).

Multivariate analyses were used to analyze how the physical-chemical environmental changes over time. 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 order to discover the underlying structure in a data set (Clarke and Warwick 2001). In this study, only the first two principal components were used.

Macrofauna-Infauna

Benthic infaunal biomass, abundance and community structure was measured using the standard techniques that we have been using since 1984 (Kalke and Montagna, 1991; Montagna and Kalke, 1992, Montagna et al. 2002). The sediment cores were taken by hand within a 2 m radius. The cores are 6.715 cm diameter, covering an area of 35.4 cm^2. The cores were sectioned (at 0-3 cm, and 3-10 cm) to examine the vertical distribution of macrofauna. Animals were extracted using a 0.5 mm mesh sieve, and identified to the lowest taxonomic unity possible.

In the laboratory, animals were enumerated, identified, and dried at 50℃ for 24 hours and weighed. Mollusk shells are removed by an acidic vaporization technique (Hedges and Stern, 1984).

Diversity was calculated using Hill's diversity number one (N1) (Hill, 1973). Hill’s N1 is a measure of the effective number of species in a sample, and indicates the number of numerically dominant species. It is calculated as the exponentiated form of the Shannon diversity index:

$$N1 = e^{H'}$$

As diversity decreases N1 will tend toward 1. The Shannon index, H', is the average uncertainty per species in an infinite community made up of species with known proportional abundances (Shannon and Weaver, 1949).

Richness is an index of the number of species present. The obvious richness index is simply the total number of all species found in a sample regardless of their abundances. Hill (1973) named this index N0.

Macrofauna-Epifauna

Benthic macro-epifauna are those animals that live on the surface of the sediments. Epifaunal samples were taken beginning 2010 and then from 2013 to 2015. Samples were taken using a push net, which measures one meter by one meter with window-screen meshing 5.0 millimeters wide. Sampling was performed parallel to the shoreline in a 50 by 50 square foot area at each station (C, F or G) in Rincon Bayou. Samples were immediately preserved in 7% buffered formalin and analyzed afterward. Final sample preservation was in a 70% ethanol solution. Samples were sorted and each specimen identified to the furthest taxonomic classification possible.

Analytics

Water Quality Response to Inflow

Mean water quality parameters (salinity, temperature, dissolved oxygen, nutrients, chlorophyll a, and pH) and water depth were calculated for each date-station combination. All variables, except pH, were $\log_e(x+1)$ transformed to remove the skewness \of the data, and then standardized to a normal distribution with a mean of 0 and variance of 1 using PROC STANDARD in SAS. The standardized data has the same scale for all variables so that scaling will not affect multivariate analysis.

Principal components analyses (PCA) was used to classify the water quality variables. The PCA is a variable reduction technique that can be used to reduce a large number of variables to a reduced set of new variables, which are uncorrelated and contain most of the variance in the original data set. PCA was performed using the PROC FACTOR in SAS software suite. The FACTOR analysis was run using the PCA method on the correlation matrix.

Two PCA analyses were run: one to identify spatial trends and one to identify temporal trends. All water quality parameters were measured simultaneously at Stations C, F, and G every 1-3 months from August 2004 to June 2005 (8 dates) and every 3-12 months from April 2010 to

April 2015 (16 dates); and this data set was used to identify spatial trends. All water quality variables were also sampled at Station C only either monthly or biweekly since October 2013 (an additional 31 dates sampled); and this data set was used to identify temporal trends.

Community Structure

Benthic community structure was analyzed using Primer-e software (Clarke and Warwick 2001; Clarke and Gorley 2006). Community structure was classified using non-metric multidmensional scaling (MDS) and cluster analysis using a Bray-Curtis similarity matrix (Clarke 1993, Clarke and Warwick 2001). Prior to analysis, the data was natural logarithm transformed. Log transformations improve the performance of the analysis by decreasing the weight of the dominant species. MDS was used to compare numbers of individuals of each species for each station-date combination. The distance between station-date combinations can be related to community similarities or differences between different stations. Cluster analysis determines how much each station-date combination resembles each other based on species abundances. The percent resemblance can then be displayed on the MDS plot to elucidate grouping of station-date combinations. The group average cluster mode was used for the cluster analysis.

The most influential infaunal species on overall community structure were determined with the BIO-BIO procedure, a deviation of the BIO-ENV procedure. The BIO-BIO procedure calculates weighted Spearman rank correlations (ρw) between sample ordinations from all of the species and an ordination of species' abundances so that a subset of species that best matches the multivariate response pattern of the whole community can be identified (Clarke and Warwick 1998, Clarke and Gorley 2006).

Biotic Response to Salinity

Salinity is often used as a proxy for freshwater inflow because inflow dilutes sea water and thus decreases salinity. The relationship between macrofauna abundance, diversity, and salinity has been examined using a non-linear model, which was used successfully in Texas (Montagna et al. 2002) and Florida estuaries (Montagna et al. 2008). The assumption behind the model is that there is an optimal range for salinity and values decline prior to and after reaching this optimum salinity value. That is, the relationship resembles a bell-shaped curve. The shape of this curve can be predicted with a three-parameter, log normal model:

$$Y = a \times \exp\left(-0.5 \times \left(\ln \frac{\left(\frac{X}{c}\right)}{b}\right)^2\right)$$

The model was used to characterize the nonlinear relationship between a biological characteristic (Y, *e.g.*, abundance, biomass, or diversity) and salinity (X). The three parameters characterizes different attributes of the curve, where *a* is the peak abundance value, *b* is the skewness or rate of change of the response as a function of salinity, and *c* the location of the peak response value on the salinity axis (Montagna et al. 2002). One issue is that the relationship between salinity and macrofauna density is variable depending on variability in inflow and in life cycles. For example, if a species has cyclical reproductive cycles, then the density will be low regardless of the salinity. This will result in an area under a curve rather than points lining up along a curve.

What is wanted to run the model is the relationship between the maximum number of organisms and the salinity. Therefore, salinity can be binned into 2 psu units, and the maximum number of individuals present within a bin is used to fit the model.

The same statistical method was used to identify biotic responses to temperature and water depth, i.e., temperature or depth replaces salinity as X in the equation.

Infaunal community structure was linked with environmental variables using the BIO-ENV procedure in Primer-e software (Clarke and Warwick 2001; Clarke and Gorley 2006. The data was square-root transformed prior to analysis. The BIO-ENV procedure calculates weighted Spearman rank correlations (ρw) between sample ordinations from all of the environmental variables and an ordination of biotic variables (Clarke 1993).

Hydrology

Salinity was measured continuously by HRI using a YSI 6600 sonde at Station C (Fig. 3) from January 2014 to May 2015. Pumped inflow data from September 2009 to May 2015 was obtained from the Nueces River Authority (NRA) website: http://www.nueces-ra.org/CP/CITY/rincon/. Flow through the Nueces River Overflow Channel into Rincon Bayou was measured at the United States Geological Survey (USGS) Rincon Bayou Channel Gage No. 08211503 (Fig. 3). Flow data from September 2009 to May 2015 was obtained from the USGS website: http://nwis.waterdata.usgs.gov. Rainfall data from January 2014 to May 2015 was obtained from the Conrad Blucher Institute for Surveying and Science (CBI) website: http://www.cbi.tamucc.edu/dnr/station for the Nueces Delta Weather Station (NUDEWX). Salinity data from May 2009 to May 2015 was obtained from the CBI website: http://www.cbi.tamucc.edu/dnr/station for salinity stations Nueces Delta 2 (NUDE2) and SALT03 (Fig. 3).

Figure 3. Map of station locations for measuring flow, salinity, and weather in Rincon Bayou.

Results

Hydrology and Salinity

The salinity gradient from the Nueces River overflow channel extending to Nueces Bay defines whether the Rincon Bayou has either positive or negative hydrology. An increasing salinity gradient results in a positive estuary with high freshwater input near the Rincon Bayou overflow channel; a decreasing salinity gradient results in a negative estuary with higher salinities near the overflow channel. The Nueces Estuary can shift between a positive and negative estuary depending on the volumes of inflow and precipitation. In the five-month period prior to the Rincon Bayou pipeline becoming operational in September of 2009, the Nueces Estuary was negative (Fig. 4) with a mean daily salinity at NUDE2 (adjacent to station G, Fig. 3) of 62 psu with a maximum daily mean salinity of 86 psu and a minimum daily mean salinity of 26 psu. Rincon Bayou oscillates between positive and negative conditions with pumping events coinciding with periods of positive estuary conditions and the greatest difference in salinity between the bay and the upper delta happening immediately after pumping events.

Pumping began into Rincon Bayou from the pipeline in September 2009. Since then Rincon Bayou has transitioned from a negative hypersaline estuary to a positive mesohaline estuary (Fig. 5) with a mean daily salinity at NUDE2 of 22 psu with a maximum daily mean salinity of 79 psu and a minimum daily mean salinity of 0 psu.

The mean of daily salinities at station C during the sampling period (January 1, 2014 – May 1, 2015) was 7.4 psu, with a maximum daily mean salinity of 34 psu, and a minimum daily mean salinity of 0.01 psu. Salinity declined after each pumping event and gradually increased until the next pumped inflow (Fig. 6).

The mean rainfall was 2.16 mm/day (0.08 inch/day) with a maximum of 68 mm/day (2.7 inch/day) and may account for decreases in salinity when pumping was not occurring (Fig. 7). Pumping events correlate with rainfall and typically occur after or during rainfall periods (Fig. 8). The mean pumped inflow was 124 ac-ft/day with a maximum of 353 ac-ft/day and a minimum pumped amount of 8 ac-ft/day.

The absence of a distinct elevation gradient in Rincon Bayou at the pumping outfall area allows pumped inflow to flow both upstream and downstream resulting in both positive inflow and negative discharge readings at the USGS Rincon Bayou channel gage (Fig. 9). A back-flow gate was installed in July 2014, which must be manually operated, but this reduced negative flows back to the Nueces River.

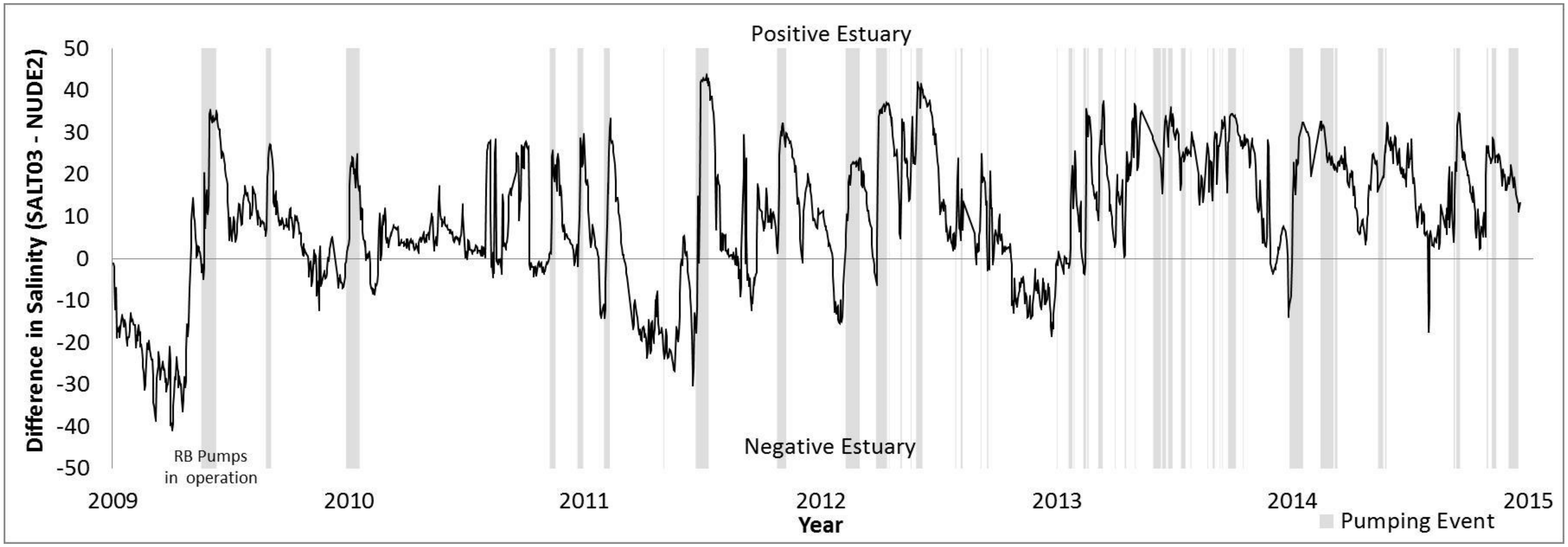

Figure 4. Salinity gradient (i.e., difference between downstream SALT03 and upstream NUDE2) and pumping events. The Rincon Bayou pipeline became operation in September 2009, and width of the box indicates pumping duration.

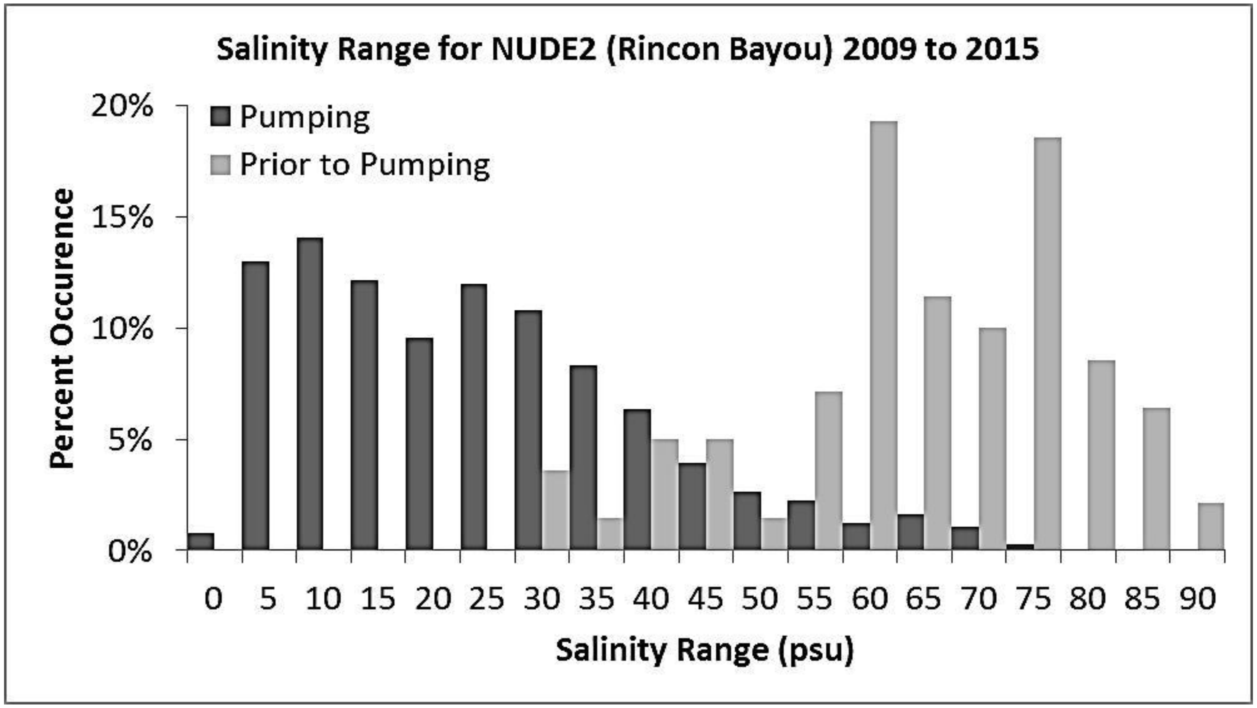

Figure 5. Percent occurrence of salinity ranges in Rincon Bayou (NUDE2) from May 2009 to May 2015.

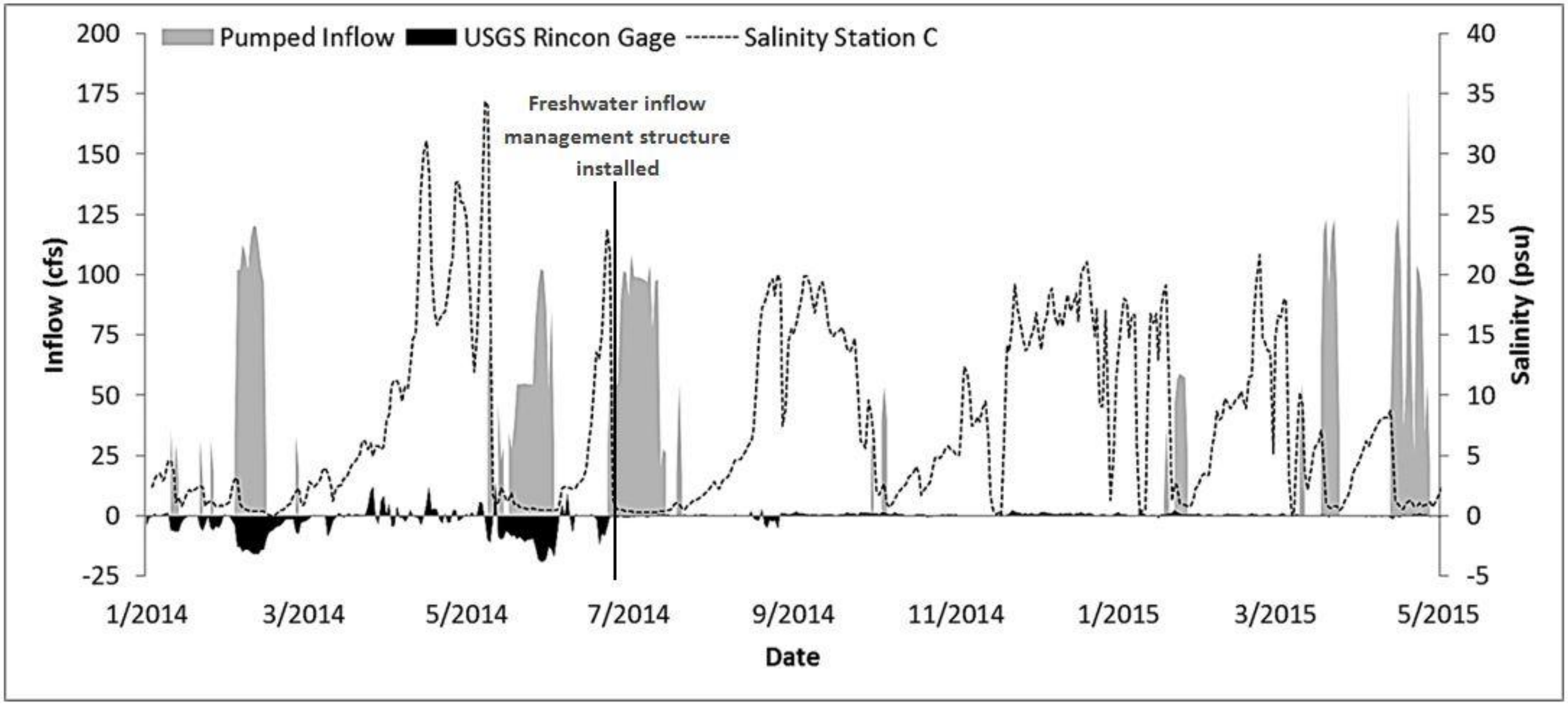

Figure 6. Salinity at Station C in Rincon Bayou TX, with inflow and discharge from the Rincon Bayou channel gage and pumped inflow, 2014 to 2015.

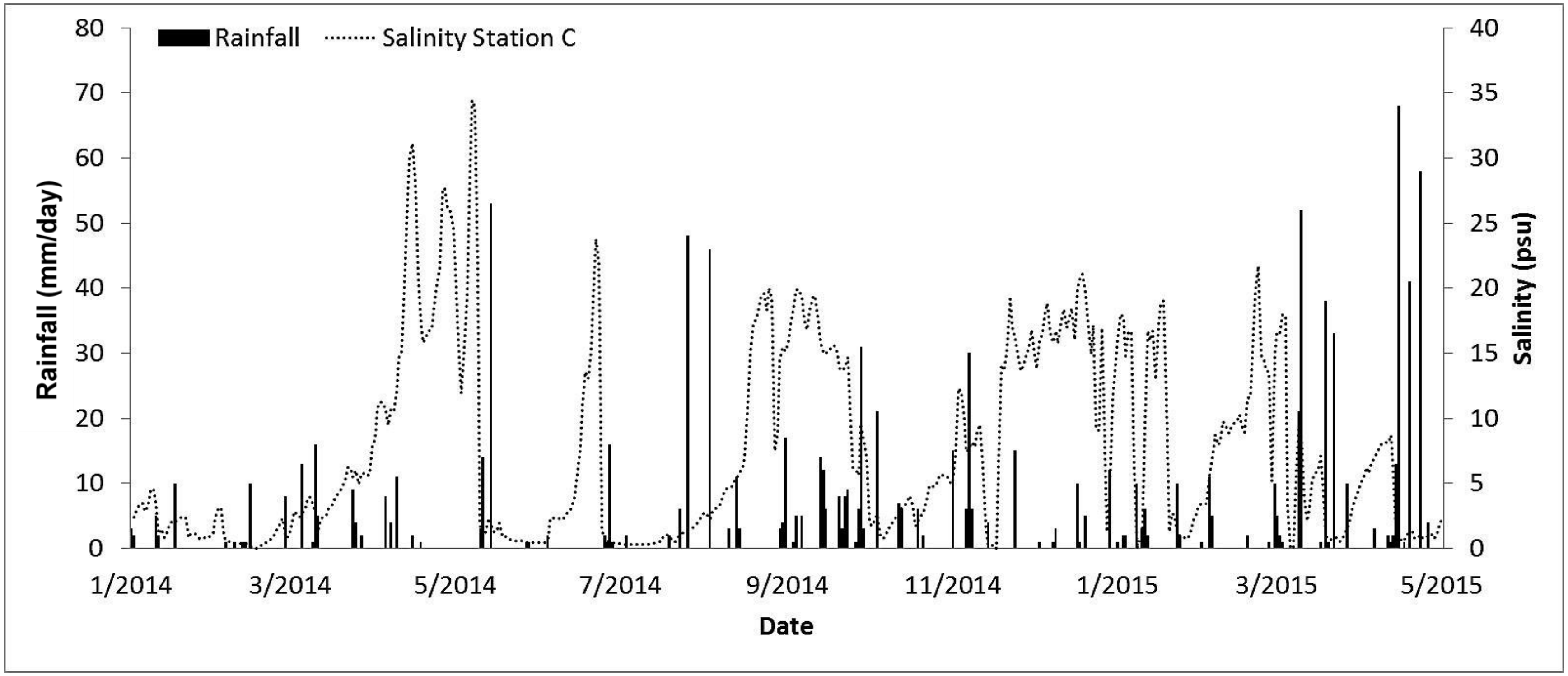

Figure 7. Salinity at Station C in Rincon Bayou TX, with Rainfall from CBI NUDEWX station, 2014 to 2015.

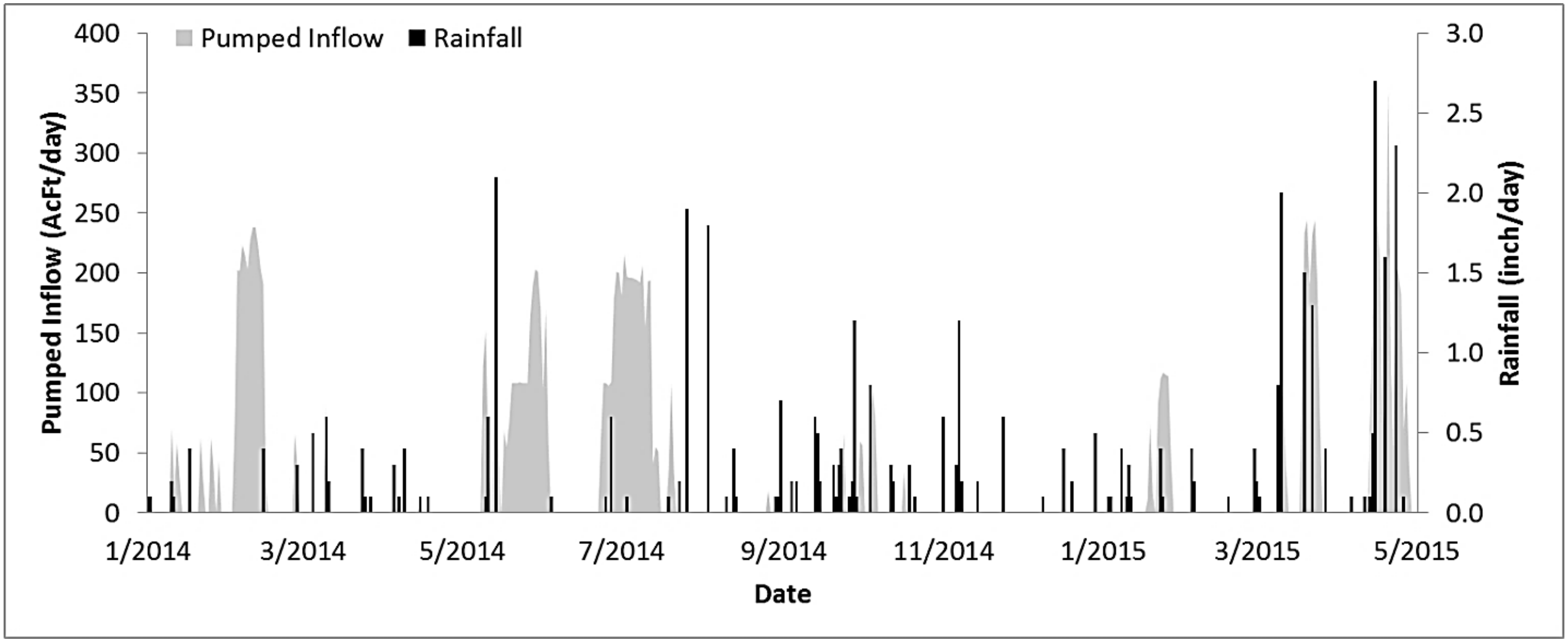

Figure 8. Pumped inflow into Rincon Bayou, TX with rainfall from CBI NUDEWX station, 2014 to 2015.

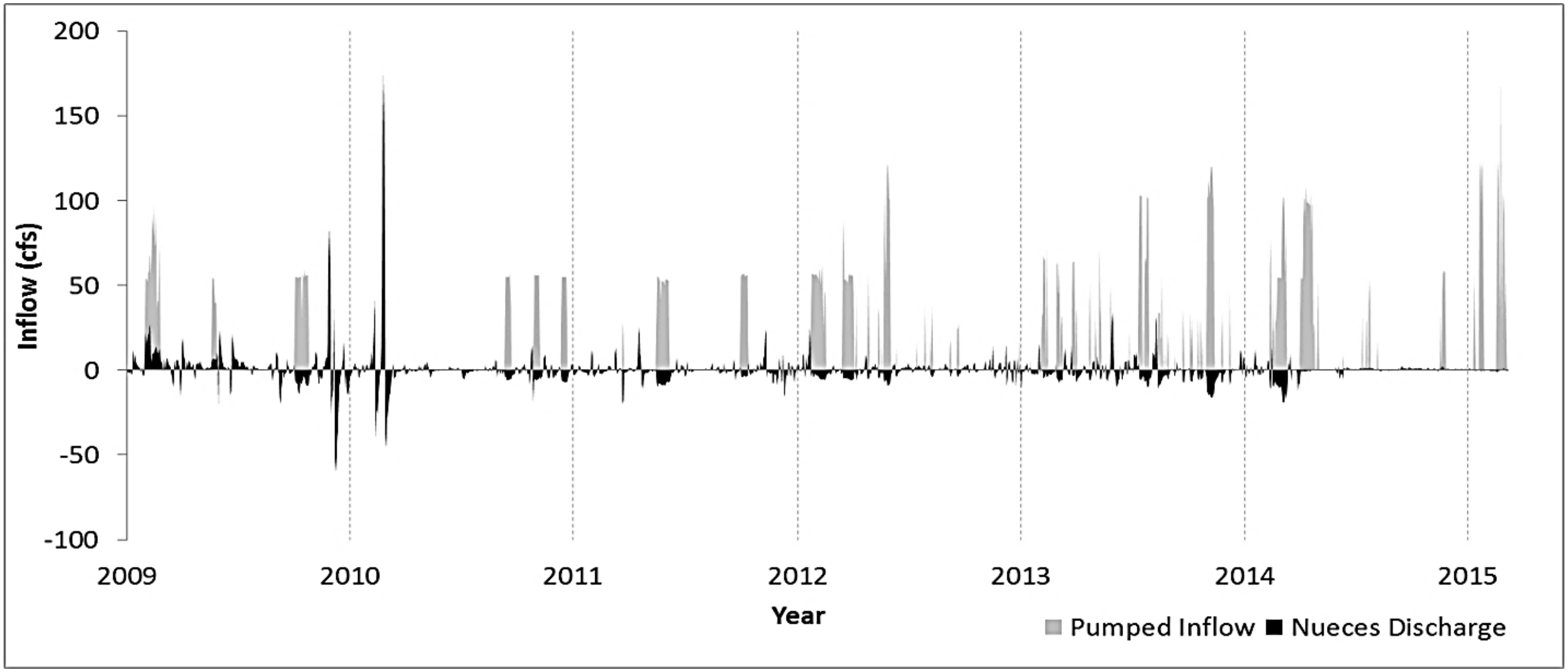

Figure 9. Inflow and discharge at the Rincon Bayou overflow channel gage, and pumped inflow from 2009 - 2015.

A flow duration curve illustrates the percentage of time a given flow was equaled or exceeded during a specified period of time. From 2009 to 2015 positive inflow into Rincon Bayou was equaled or exceeded 40% of the time with pumped inflow accounting for most of the inflow into Rincon Bayou (Fig. 10). Natural inflows into Rincon Bayou have been reduced by river impoundment to low flow or drought flow, with events over 100 ft^3/sec (cfs) being equaled or exceeded 0.14% of the time. Freshwater pumped into Rincon Bayou was equaled or exceeded 20% of the time and accounted for most of the high / medium flow events. The mean inflow volume from pumping was 10 ft^3/sec with a maximum total inflow rate (pumping and Rincon gage discharge) of 178 ft^3/sec.

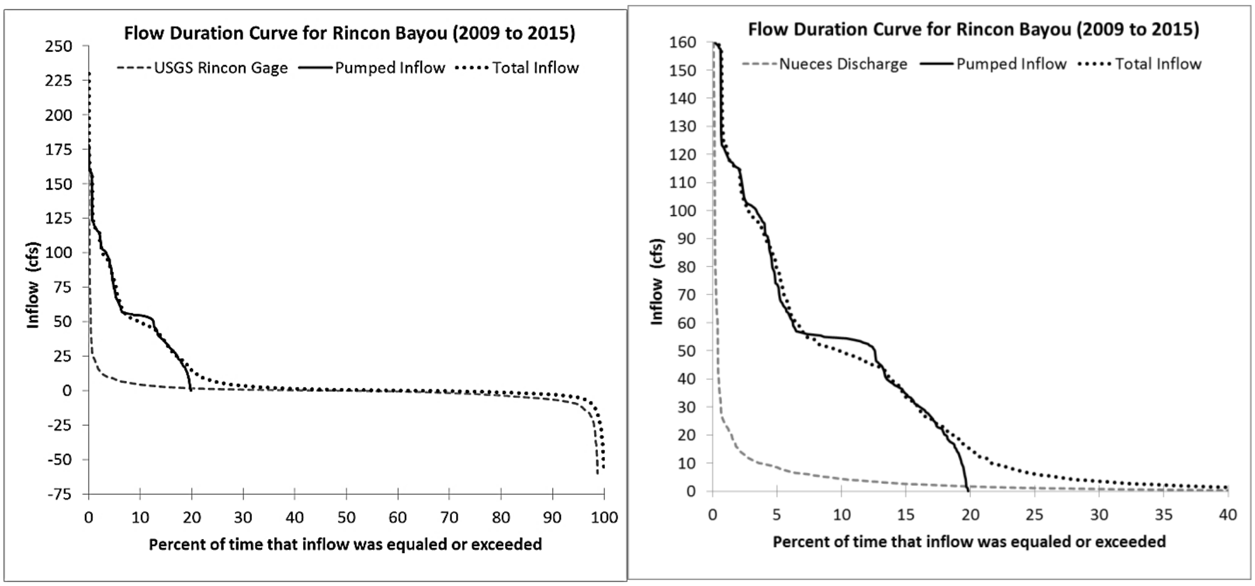

Figure 10. Flow duration curve for Nueces River inflow and discharge at the Rincon Bayou channel gage, September 2009 to May 2015. Left: full inflow scale. Right: zoom to positive inflow values only.

The percent of time that inflow from the Nueces River overflow channel was greater than 6 ft^3/sec less than 8% of the time with an inflow rate between 0 and 2 ft^3/sec occurring most often (Fig. 11). The mean of daily inflow rate at the USGS Rincon Bayou channel gage was -0.13 ft^3/sec with a maximum daily mean discharge rate of 174 ft^3/sec and a minimum daily mean rate of -60 ft^3/sec.

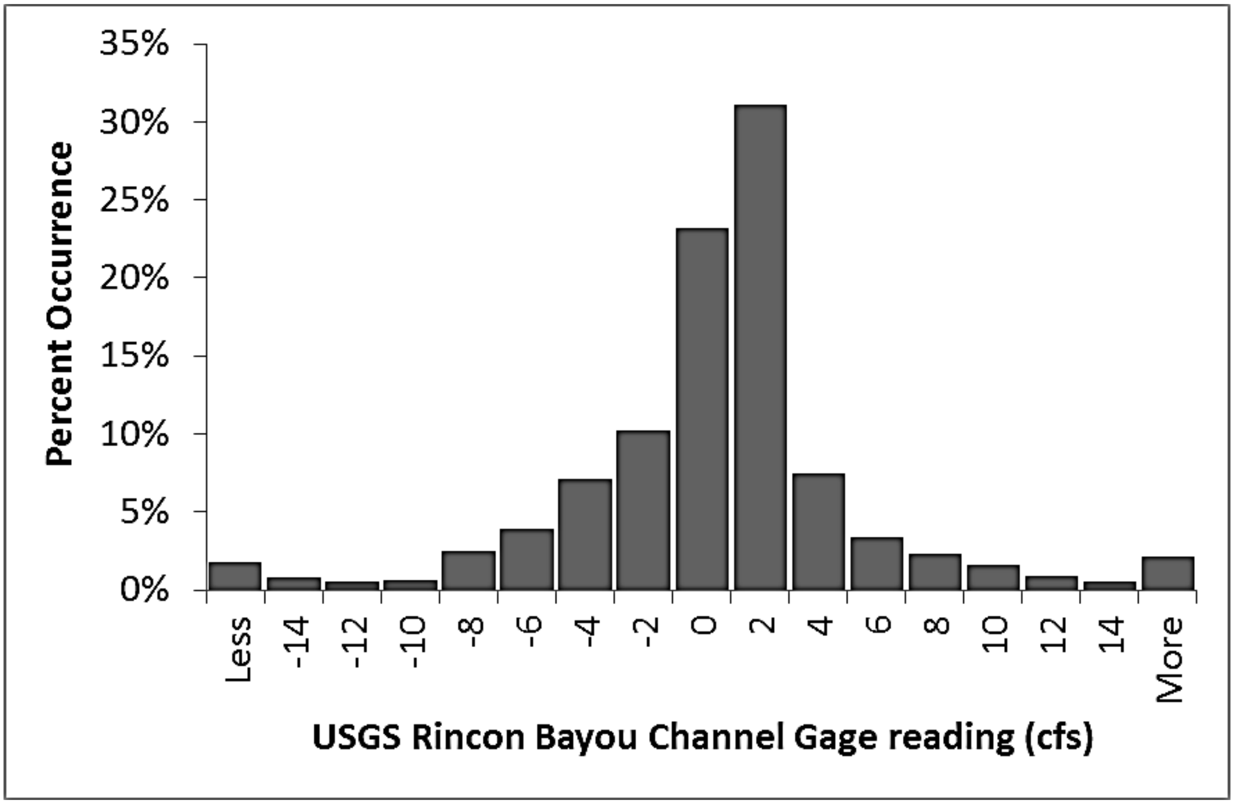

Figure 11. Percent occurrence for Nueces River inflow and discharge at the Rincon Bayou channel gage September 2009 to May 2015.

To mitigate the discharge back to the Nueces River, the Coastal Bend Bays & Estuaries Program (CBBEP) installed a freshwater inflow management structure in July 2014 in Rincon Bayou at the Nueces Delta Preserve (outfall area). This structure consists of box culverts that when closed prevent pumped water from going upstream and natural flow from the Nueces River from going downstream into Rincon Bayou. From July 2014 to May 2015, inflow from the Nueces River was reduced (Figs. 6 and 9) by the installation of the freshwater inflow management structure to a mean of 0.3 ft^3/sec with a maximum mean of 2.9 ft^3/sec and a minimum mean of -5.3 ft^3/sec. Before the structure was installed inflow from the Nueces River was greater than 6 ft^3/sec less than 10% of the time with inflows less than 1 ft^3/sec occurring most often (Fig. 5a). After the structure was installed inflow from Nueces River has not exceeded 4 ft^3/sec and inflows between 0 and 2 ft^3/sec occurs most often (Fig. 12). Before the management structure was installed, inflow through the overflow channel into Rincon Bayou was equaled or exceeded 45% of the time and after it is equaled or exceeded almost 80% of the time (Fig. 13).

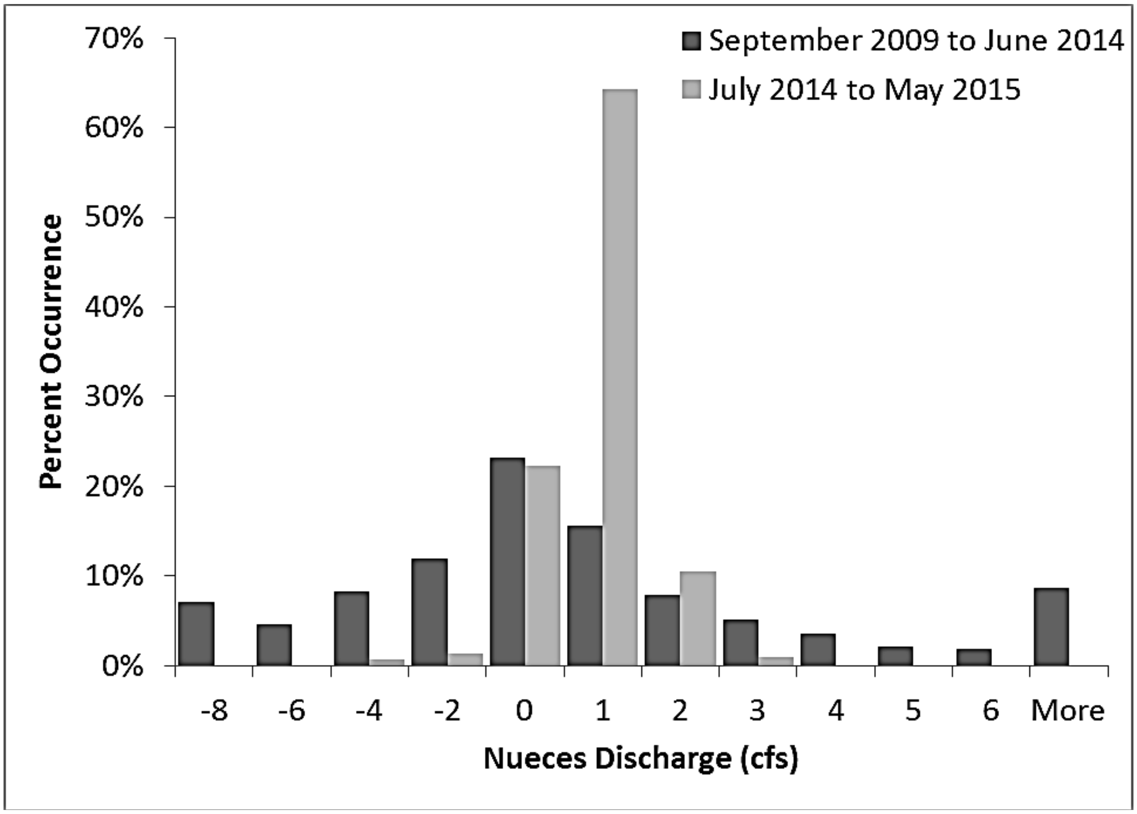

Figure 12. Percent occurrence for inflow and discharge at the Rincon Bayou channel gage before (September 2009 to June 2014) and after the installation of the freshwater inflow management structure (July 2014 to May 2015).

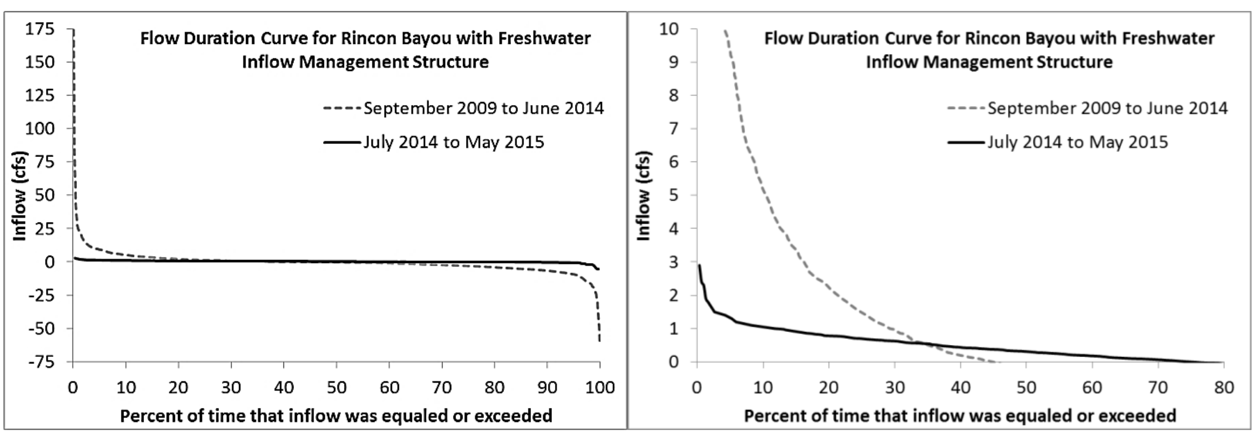

Figure 13. Flow duration curve for Rincon Bayou before (September 2009 to June 2014) and after the installation of the freshwater inflow management structure (July 2014 to May 2015). Left: full inflow scale. Right: zoomed to positive inflow scale only.

Water Quality

Several relationships among water quality variables are observed when comparing temporal variations in water quality at Station C only (Fig. 14). Salinity, and chlorophyll concentrations are inversely proportional to nutrient concentrations (ammonium, nitrate+nitrite, silicate, phosphate) and depth. This salinity-nutrient relationship represents an inflow gradient along the principal component axis one (PC1). The PC1 axis represents 33.8% of the variation of water quality among sample dates. Dissolved oxygen (DO) concentrations are inversely proportional to water temperature and to a lesser extent, pH. This relationship lies along the PC2 axis, which represents 20.8% of the variation in water quality among dates and represents a seasonal change because temperatures are high and DO is low in summer.

The relationships among water quality variable loads at all three stations (C, F, and G) (Fig. 15) are similar to when comparing water quality of only Station C (Fig. 14). The inverse relationship between depth and salinity is somewhat diminished for all stations, but PC1 still represents the inflow gradient and PC2 still represents the seasonal gradient (Fig. 15). Also, the station scores are relatively well mixed along the PC2 axis indicating there are no seasonal differences among the stations. However, Station C has a tendency to group to the right (i.e., have mostly positive values) of PC1, which indicates that it is more influenced by inflow (i.e., have high nutrients and low salinities) than stations F and G. Stations F and G mostly have negative PC1 values and are mostly mixed together indicating these two stations are not very different in their response to inflow.

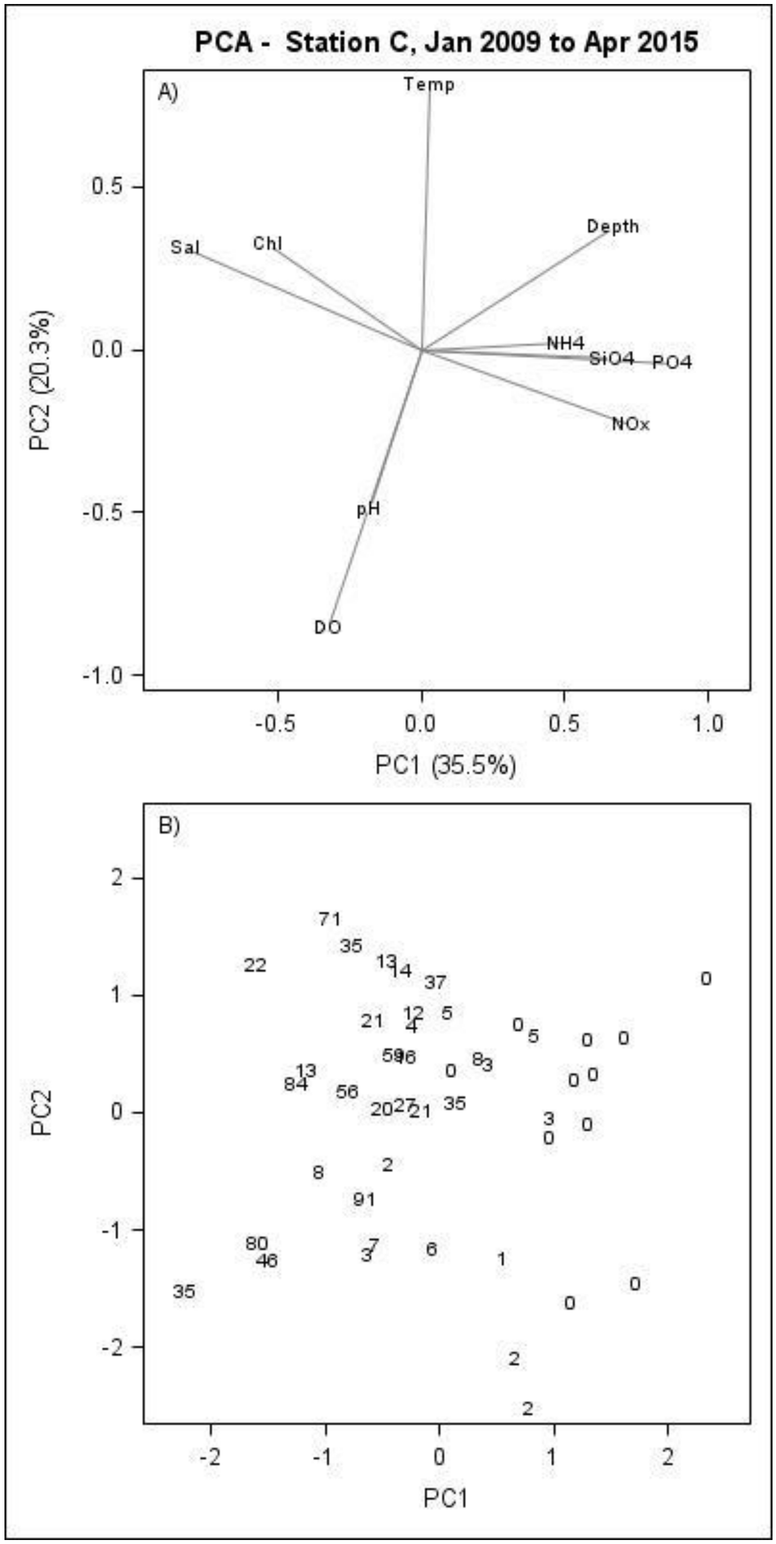

Figure 14. Principal Components Analysis (PCA) of water quality variables from Station C in Rincon Bayou. Top: Variable loads. Bottom: Sample scores using the number of days since the last pumping day for each sampling date as the symbol.

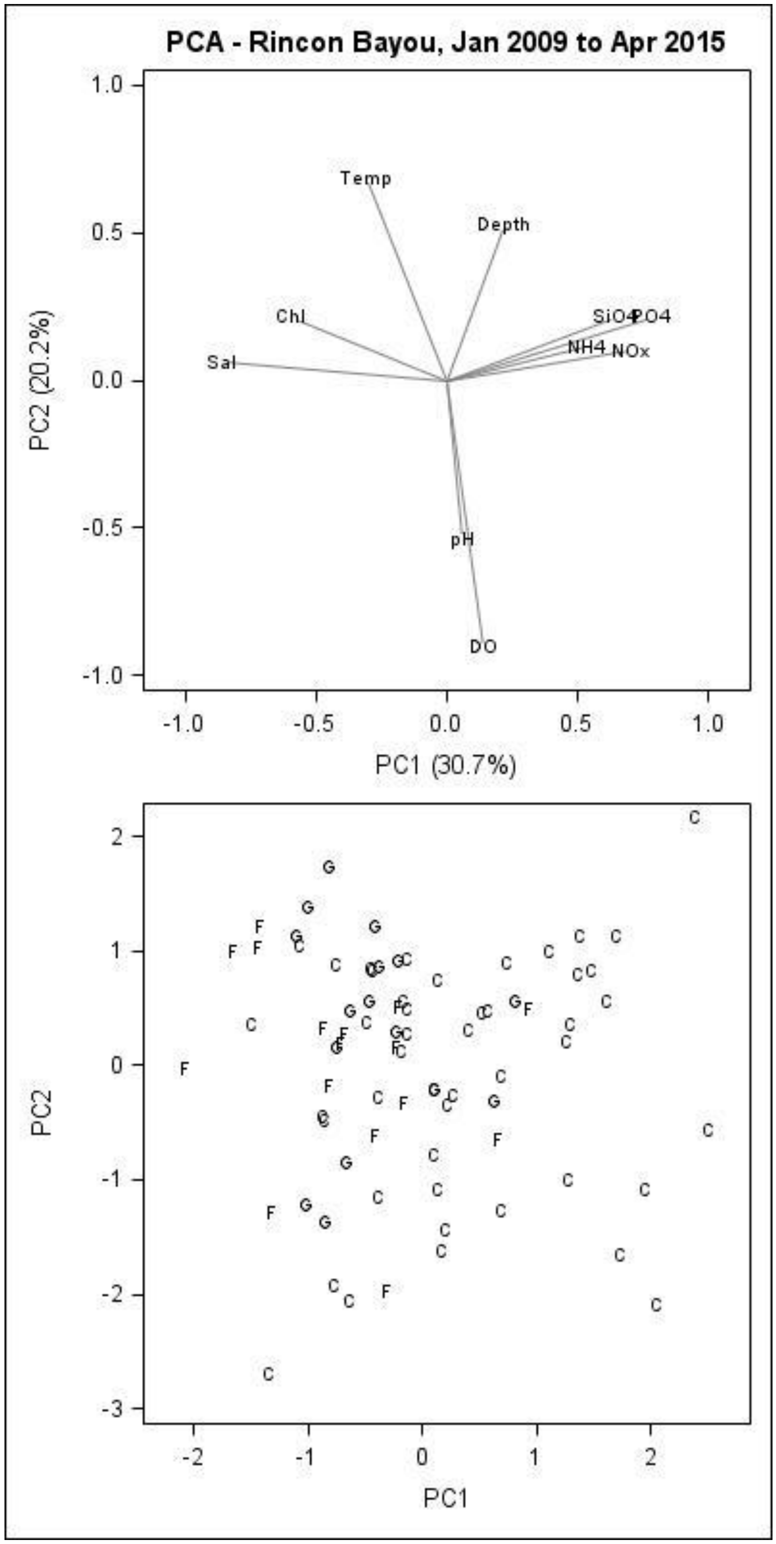

Figure 15. Principal Components Analysis (PCA) of water quality variables from Station C in Rincon Bayou. Top: Variable loads. Bottom: Sample scores using the station name as the symbol.

Macroinfauna

Long-term Trend

The time series of infaunal abundance, biomass, and diversity show that there is a great fluctuation over time for all the metrics of benthic biological response. The benthic infaunal abundances in Rincon Bayou are as high as 125,000 individuals m^{-2} (Fig. 16). Biomass is usually low with values usually ranging from near 0 to 4 g m^{-2}, but one high value over 7 g m^{-2} was reported (Fig. 17). Diversity however, is very low, ranging from only 1 to 3 dominant species (N1, Fig. 18).

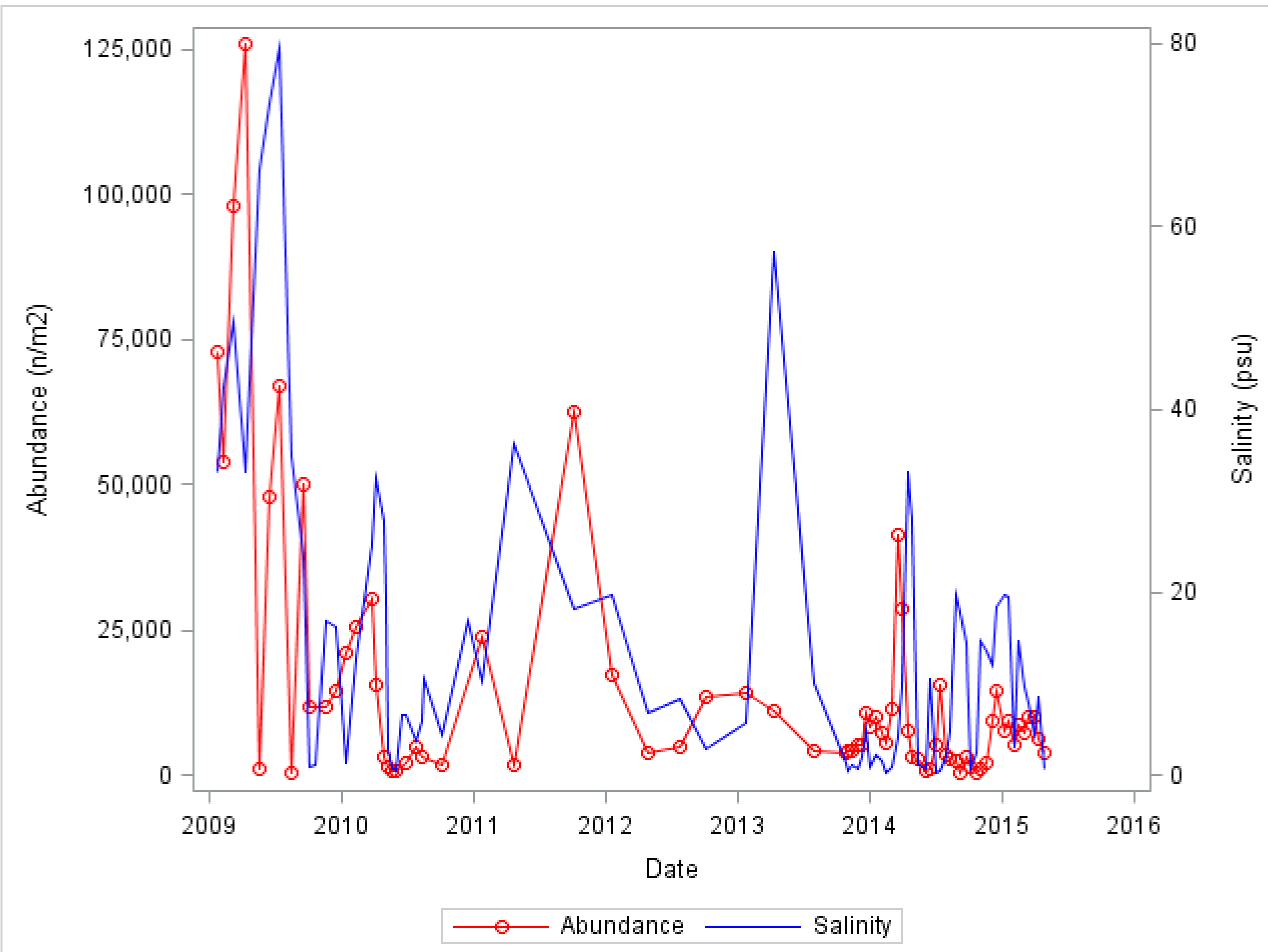

Figure 16. Macroinfauna abundance and salinity over time since pumping began.

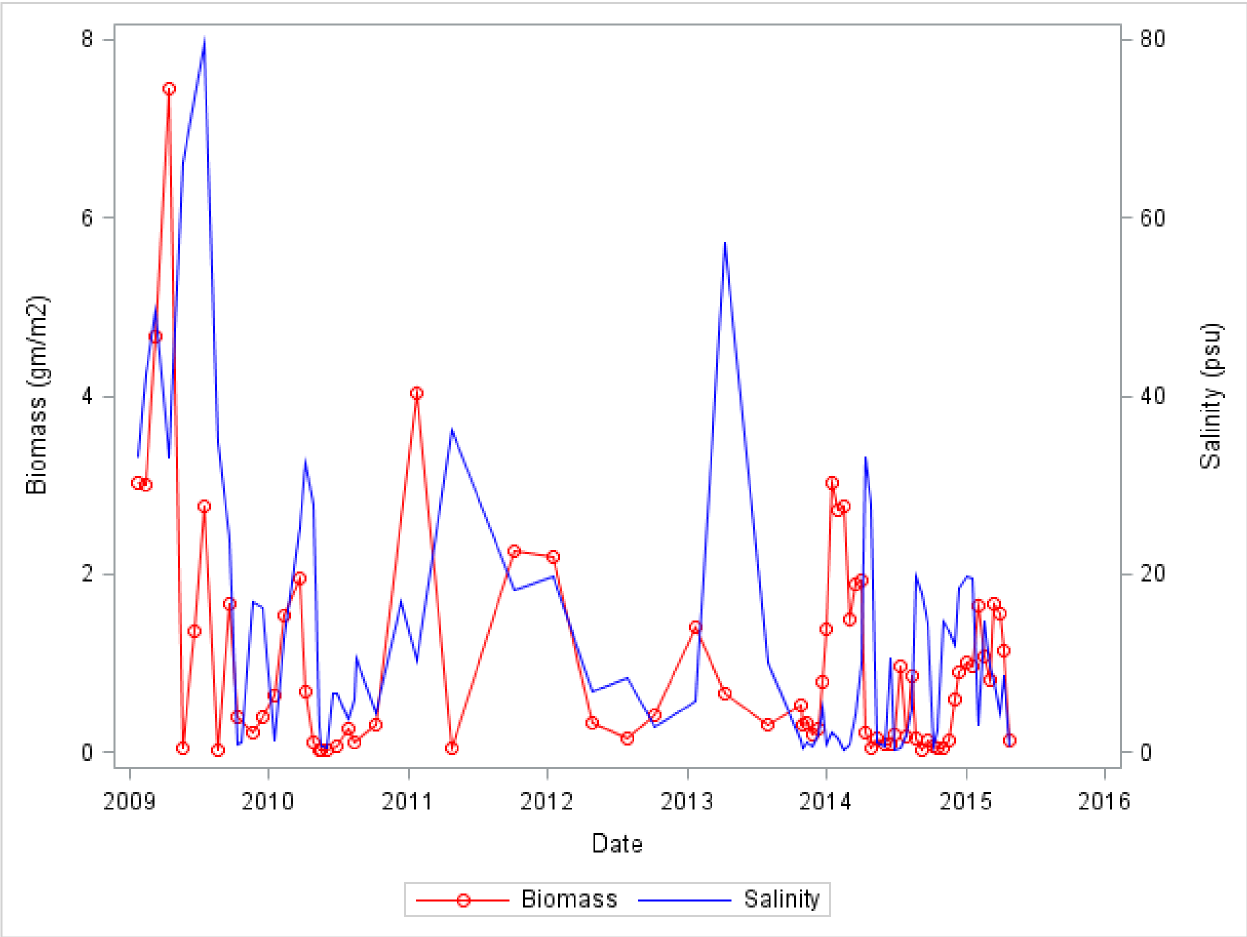

Figure 17. Macroinfauna biomass and salinity over time since pumping began.

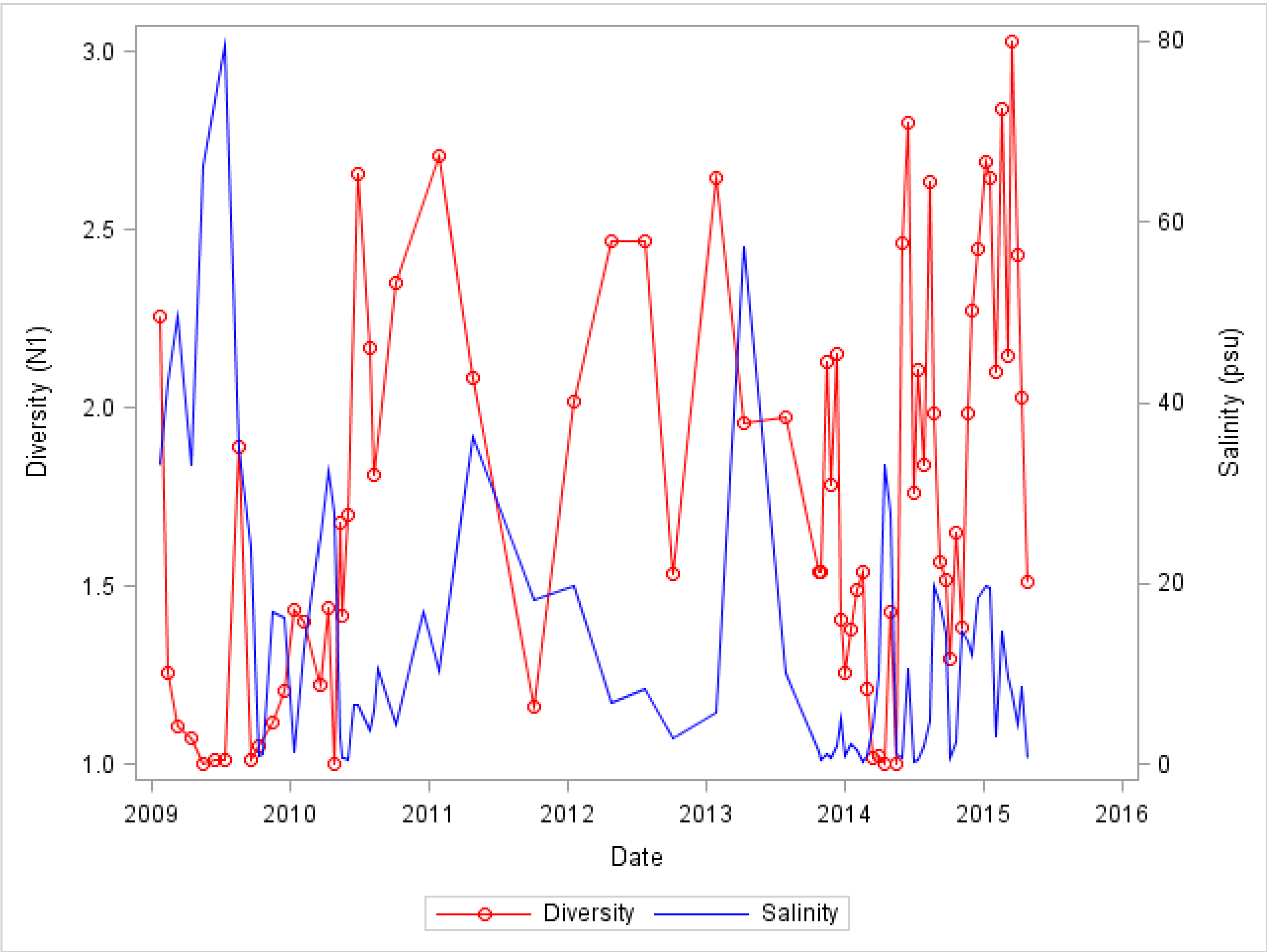

Figure 18. Macroinfauna diversity and salinity over time since pumping began.

Temporal samples of infaunal community structure at station C were at least 30 % similar to each other (Fig. 19). Community structure was not grouped by month or year. The five taxa that have the highest correlation with overall changes in community structure are *Streblospio benedicti*, Chironomidae larvae, *Laeonereis culveri*, unidentified Oligochaeta, and unidentified Nemertea (combined ρw = 0.99). The single species that represented changes in overall community structure the best is *Streblospio benedicti* (ρw = 0.77).

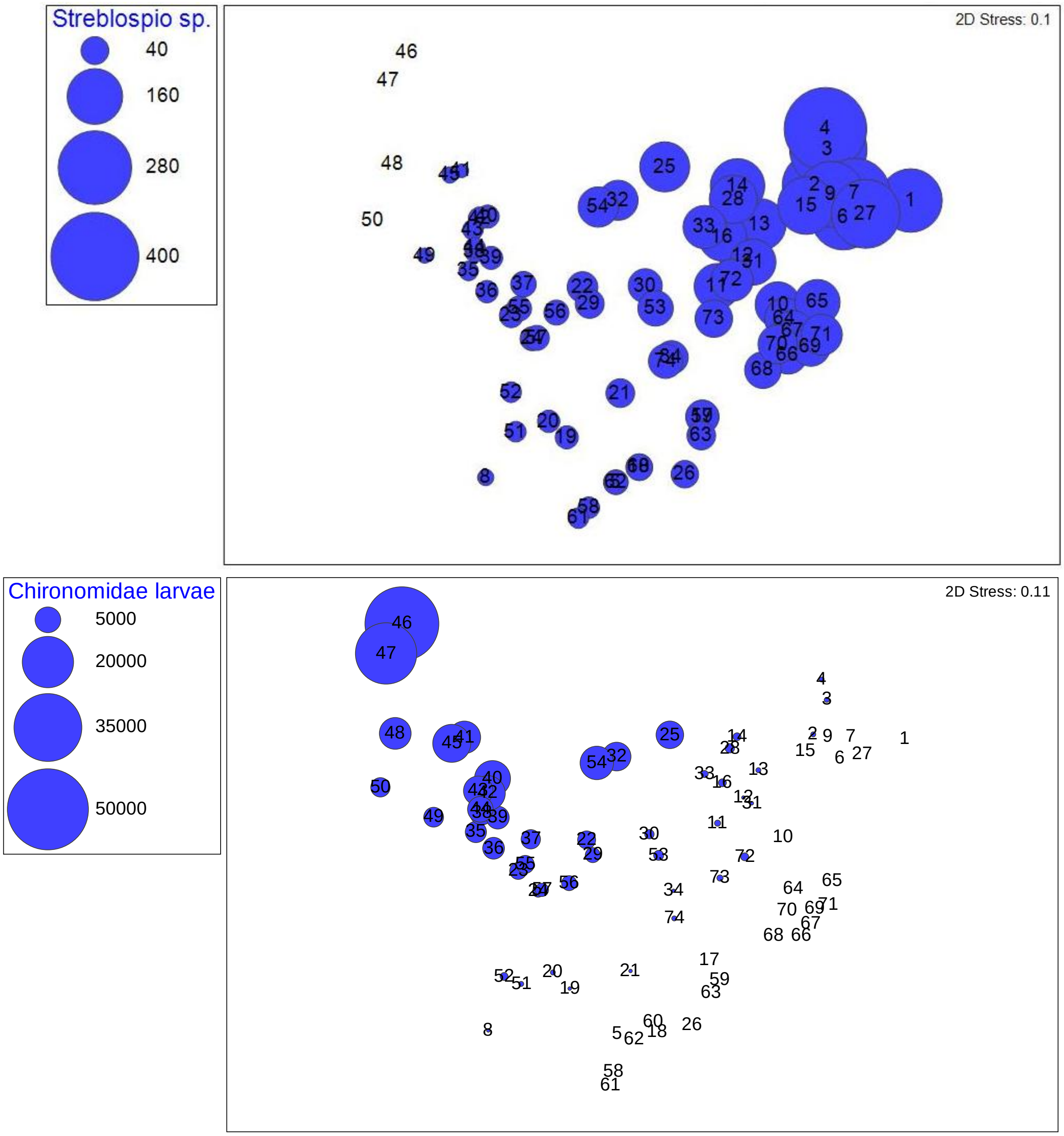

Figure 19. Non-metric multi-dimensional scaling (MDS) plot of infaunal community structure at Station C overlaid with abundances (root-transformed) of *Streblospio benedicti* (top) and Chironomidae larve (bottom).

Only 18 species were found over the entire study period (Table 1). Polychaetes are the dominant species found in the benthic infaunal samples (Table 1). One species, *Streblspio benedicti* averages 75% of the community. Chironmidae larvae represent 17% of the community. The community is very high in dominance because 5 species represent 99% of the community on average. A total of 13 species are rare, making up less than 0.5% of the community each.

Table 1. Taxonomic list of all species found in infaunal samples. Mean over all samples.

Phyla	Class	Order	Family	Genus Species	n/m^2	Percent
Nemertea						
				Nemertea (unidentified)	69.0	0.46%
Mollusca						
	Bivalvia					
		Veneroida				
			Mactridae			
				Mulinia lateralis	17.9	0.12%
				Rangia cuneata	1.3	0.01%
			Tellinidae			
				Macoma mitchelli	2.6	0.02%
Annelida						
	Polychaeta					
		Errantia				
			Phyllodocidae			
				Hypereteone heteropoda	3.8	0.03%
			Nereididae			
				Laeonereis culveri	299.0	1.98%
		Canalipalpata				
			Spionidae			
				Streblospio benedicti	11,307.9	74.98%
				Streblospio gymnobranchiata	199.3	1.32%
			Ampharetidae			
				Hobsonia florida	10.2	0.07%
		Polychaete Order Not Assigned				
			Capitellidae			
				Capitella capitata	1.3	0.01%
				Mediomastus ambiseta	52.4	0.35%
	Oligochaeta					
				Oligochaeta (unidentified)	474.0	3.14%
Crustacea						
	Ostracoda					
				Ostracoda (unidentified)	37.7	0.25%
	Malacostraca					
		Decapoda (Natantia)				
			Penaeidae			
				Farfantepenaeus setiferus	1.3	0.01%
		Mysida				
				Americamysis almyra	1.3	0.01%
Insecta						
	Pterygota					
		Diptera				
			Chironomidae			
				Chironomidae (larvae)	2,590.5	17.18%
			Ceratogonidae			
				Ceratopogonidae (larvae)	10.2	0.07%
			Chaoboridae			
				Chaoborus sp. (larvae)	1.3	0.01%
Total					15,081	100.00%

Response to Physical Variables

Relationship to Water Quality

Infaunal abundance (from January 2009 to April 2015) is positively correlated with salinity (Fig. 16, Table 2) and inversely correlated to PC1, the inflow axis from PCA (Fig. 14, Table 2). This means that infaunal abundances are lowest with the highest inflows. Salinity is also positively correlated with infaunal biomass (dry weight) (Fig. 17) and negatively correlated with N1 diversity (Fig. 18). PC2, the seasonal axis from PCA, is negatively correlated with PC2, meaning that more biomass occurs in cooler months.

Table 2. Pearson correlations of infaunal abundance, biomass and diversity with salinity, and principal components one and two (PC1 and 2) for January 2009 to April 2015. Principle components are derived from principle components analysis (Figure 15).

Benthic Metrics	Pearson Correlation Coefficients Prob > |r| under H_0: Rho=0 Number of Observations		
	Salinity	PC1	PC2
Abundance (n/m^2)	0.49368	-0.36082	0.05142
	<0.0001	0.0138	0.7343
	74	46	46
Dry Wt Biomass (g/m^2)	0.27209	-0.25759	-0.33509
	0.0190	0.0839	0.0228
	74	46	46
Diversity (N1)	-0.27840	-0.18337	0.04751
	0.0163	0.2225	0.7538
	74	46	46

The water quality variable most highly correlated with infaunal community structure is salinity ($\rho w = 0.18$). Temperature, dissolved oxygen, water depth and pH are all poor individual indicators of infaunal community structure ($\rho w < 0.07$).

Relationship to Salinity

The biological response (abundance, biomass, and diversity) to three physical variables (salinity, temperature and depth) at Station C was examined. But first, it is important to determine if these variables are correlated. A log normal regression line was fitted against binned maximum salinities for depth and temperature.

A log-normal regression line fitted among maximum depth values within 1 psu salinity bins represents the maximum possible salinity at a specific depth (Fig. 20). Depth above 0.5 m at Station C indicates positive freshwater inflow because the salinities drop to near 0.

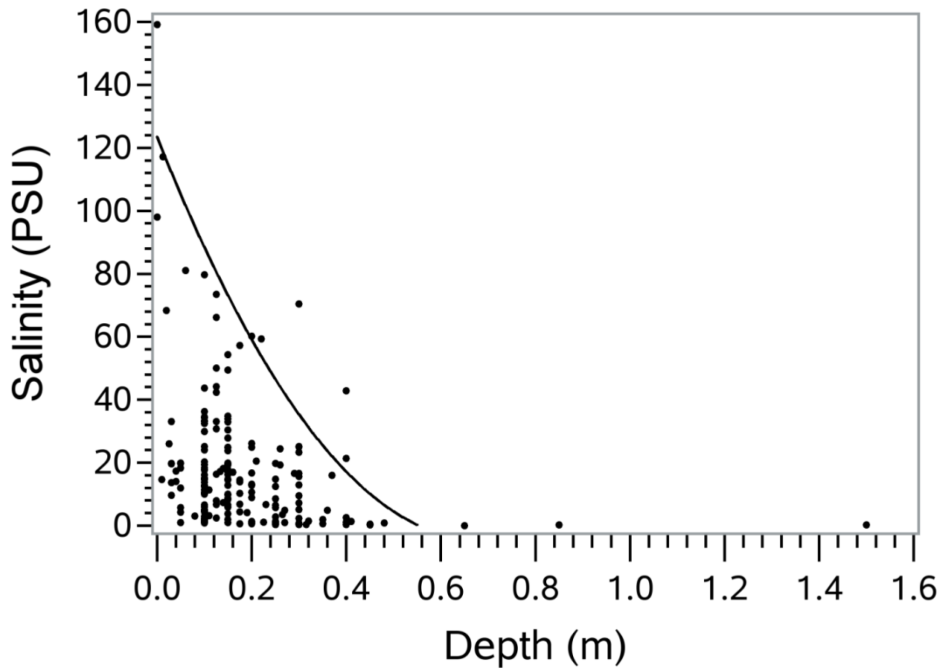

Figure 20. Relationship between depth and salinity at Station C.

Although lower salinities representing freshwater inflow were found throughout the temperature range, hyper saline conditions above 50 psu are only observed when temperature is greater than 20 °C (Fig. 21).

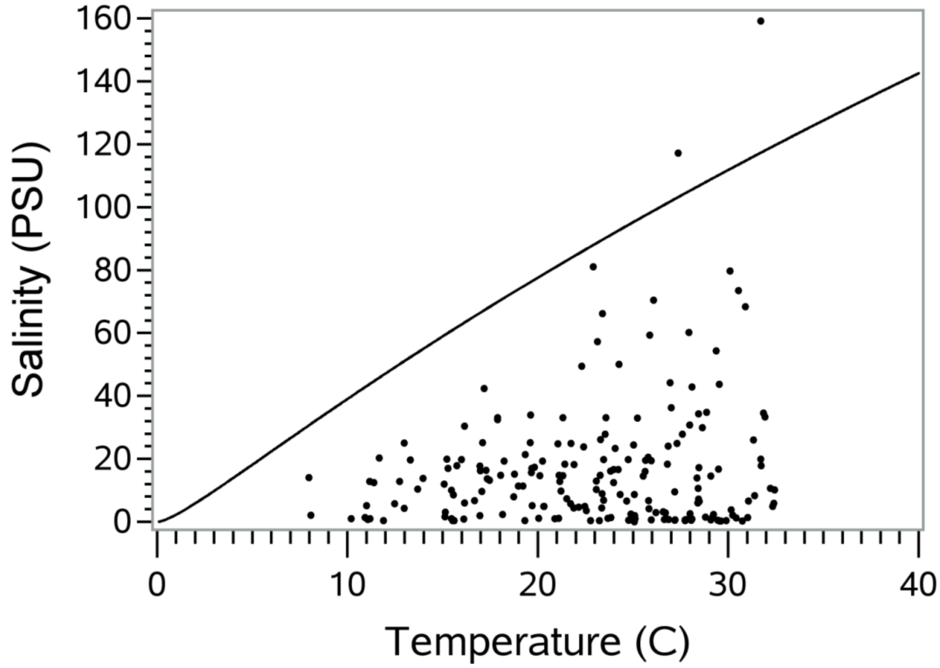

Figure 21. Relationship between temperature and salinity at Station C.

Linear regressions were determined between hydrographical variables (salinity, temperature, water depth) and the biomass of the three most numerically dominant species *Streblospio benedicti*, *Laeoneris culveri*, and Chironomidae larvae. The species specific dry weight biomass was collected from May 2010 to May 2015 from all sites in Rincon Bayou. The log normal response curve was fitted against the maximum mg values within 4 psu bins.

The maximum biomass was found for *Streblospio benedicti* when salinity is 3 psu (Fig. 22), when temperature is 15 °C (Fig. 23), and when depth is 0.2 m (Fig. 24).

Chironomidae larvae biomass is highest when salinity is 1.3 psu (Fig. 25), when temperature is 14.0 °C (Fig. 26), and when water depth is 0.14 m (Fig. 27).

Laeoneris culveri predicted biomass maximums are when salinity is 1.4 psu (Fig. 28), when temperature is 15.7 °C (Fig. 29), and when depth is 0.24 m (Fig. 30)

The maximum biomass values for responses to physical measurements as predicted by the log-normal model for all three species is summarized in Table 3.

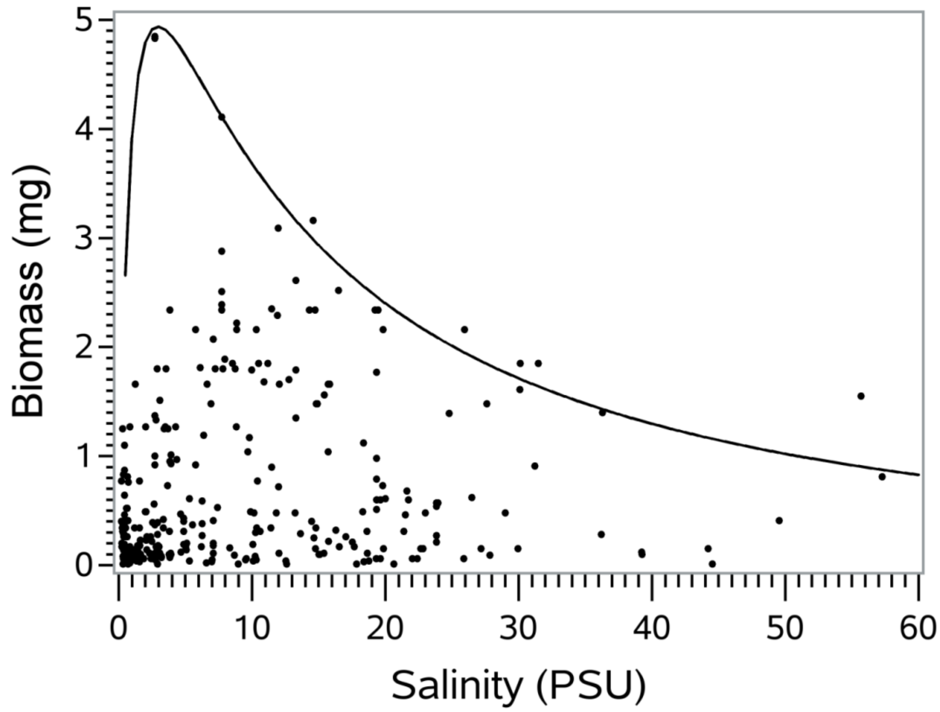

Figure 22. *Streblospio benedicti* biomass response to salinity in 4 psu bins.

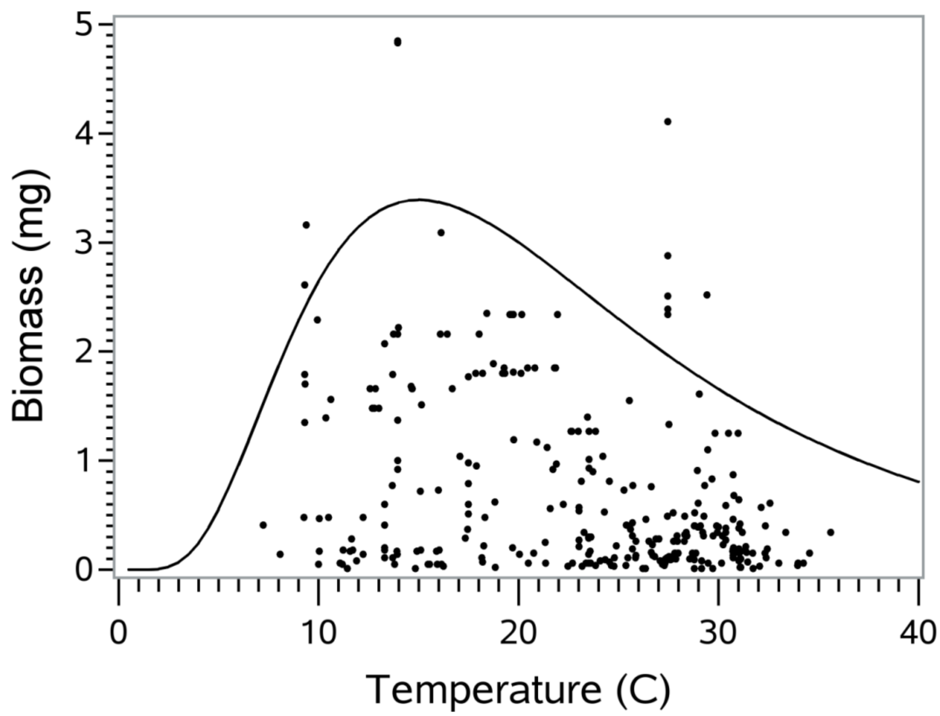

Figure 23. *Streblospio benedicti* biomass response to temperature in 3 °C bins.

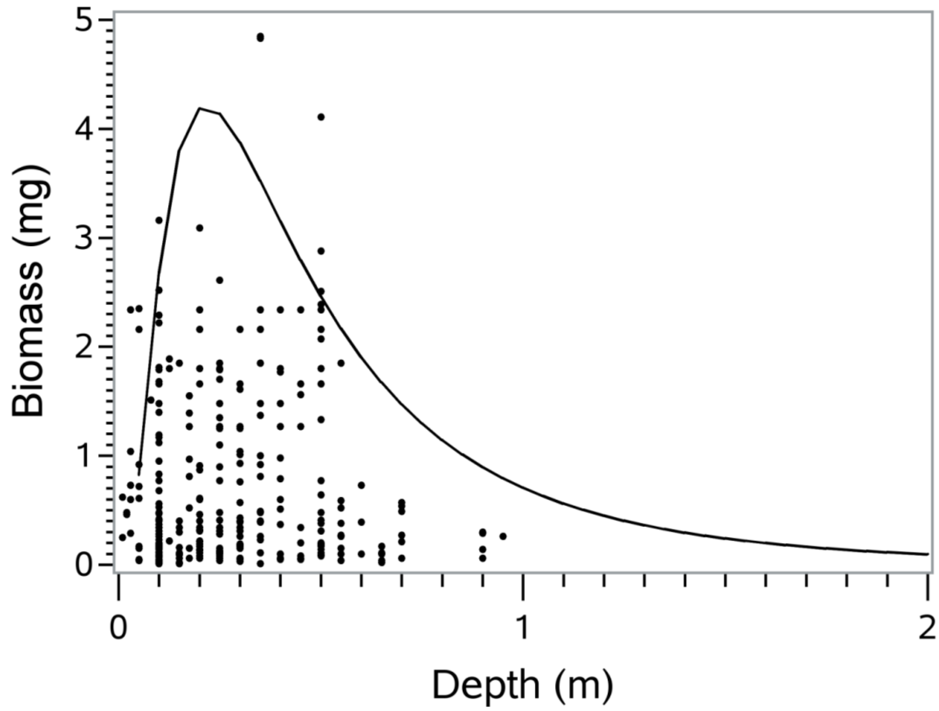

Figure 24. *Streblospio benedicti* biomass response to depth in 0.1 m bins.

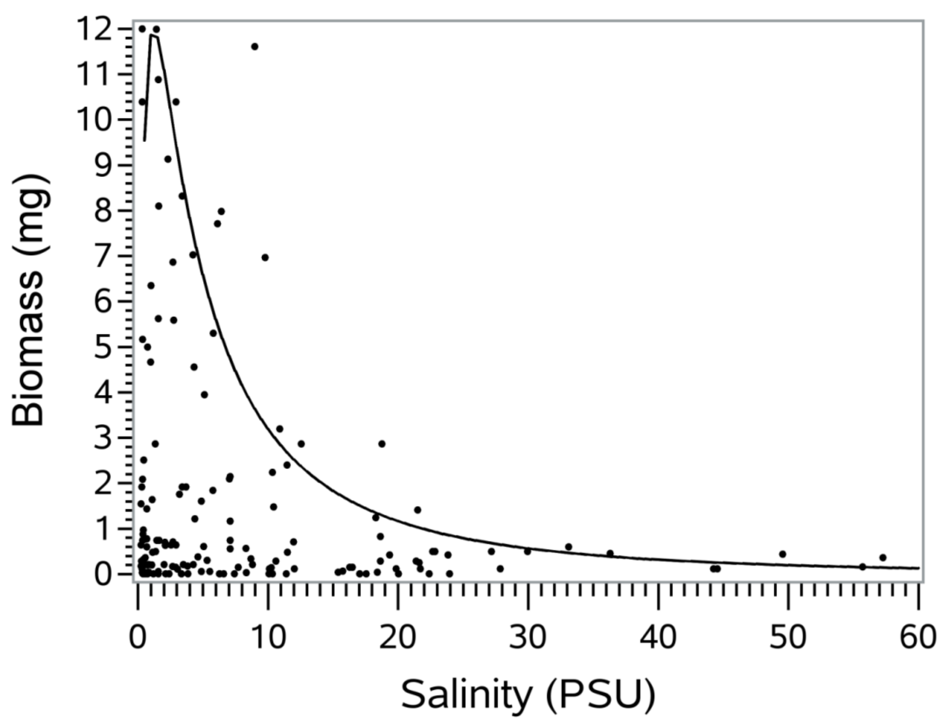

Figure 25. Chironomid larvae biomass response to salinity in 4 psu bins.

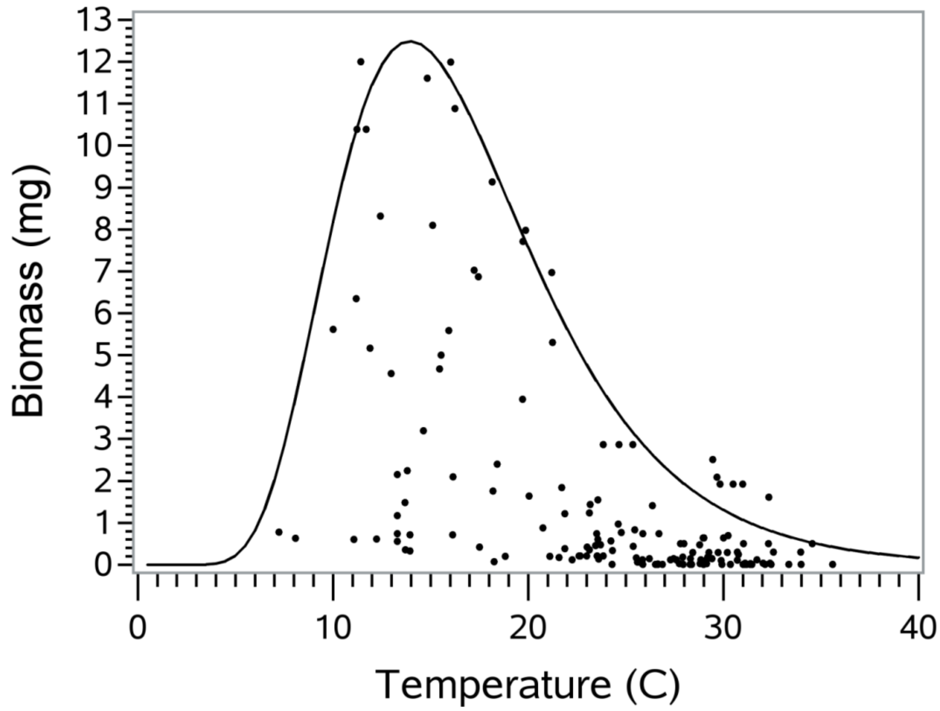

Figure 26. Chironomid larvae biomass response to temperature in 3 °C bins.

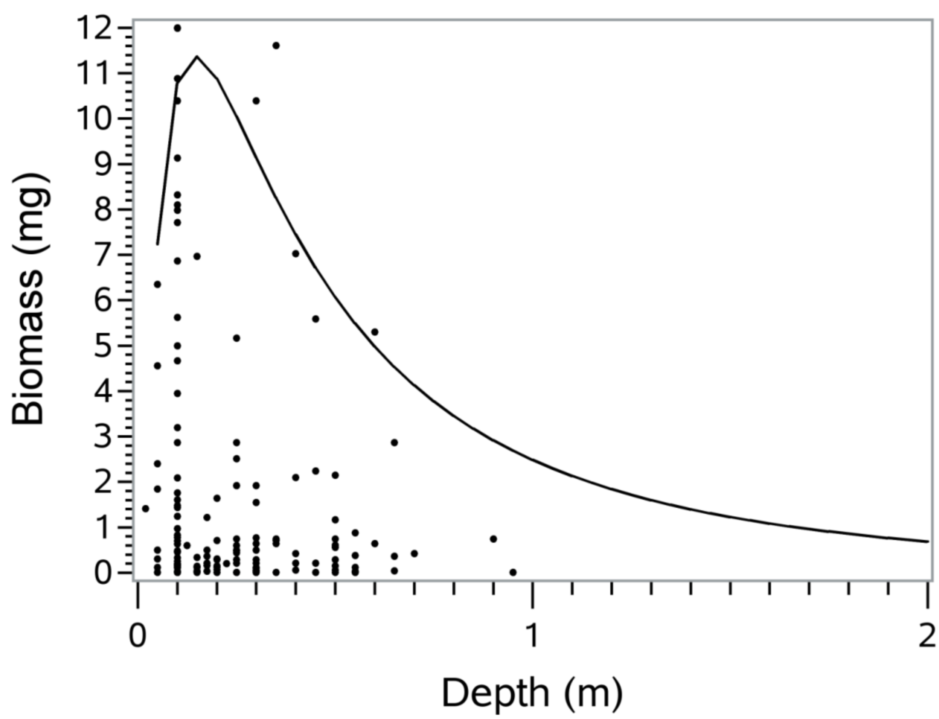

Figure 27. Chironomid larvae biomass response to depth in 0.1 m bins.

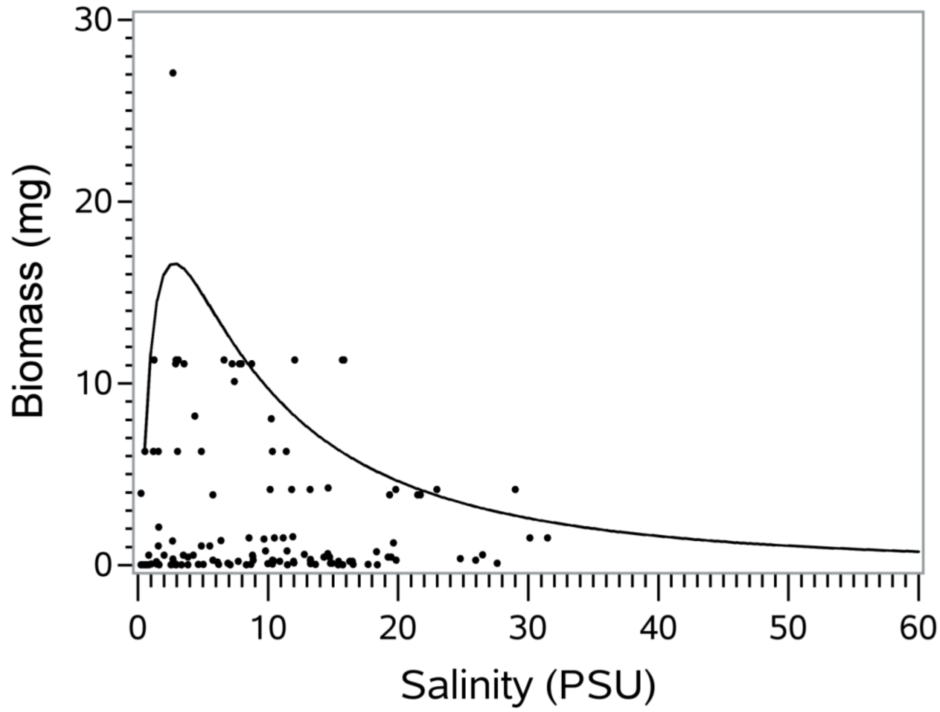

Figure 28. *Laeoneris culveri* biomass reponse to salinity in 1.5 psu bins.

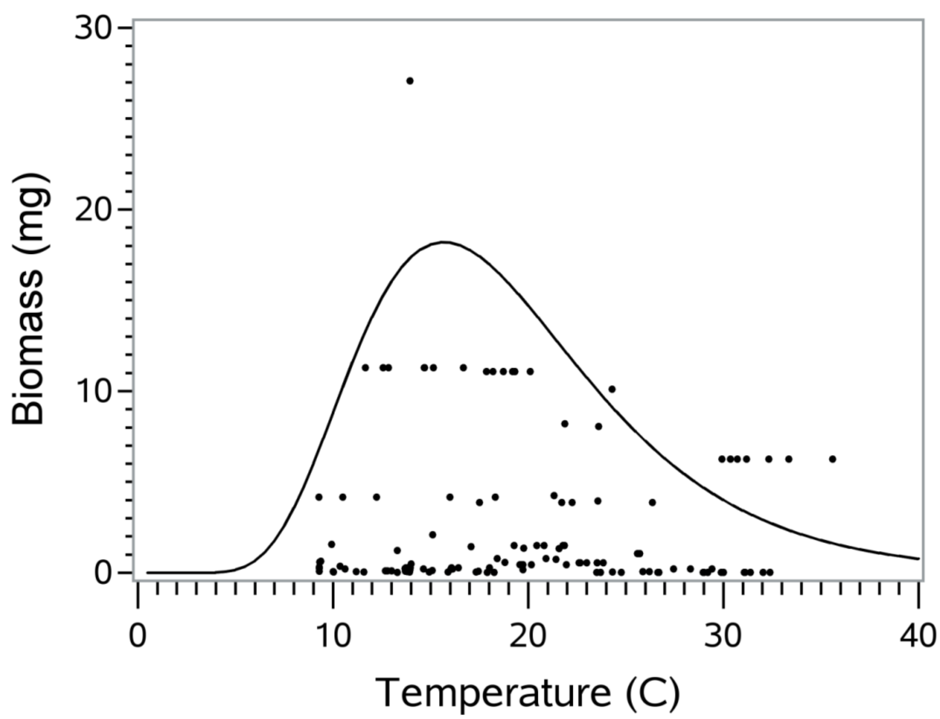

Figure 29. *Laeoneris culveri* biomass response to temperature in 3 °C bins.

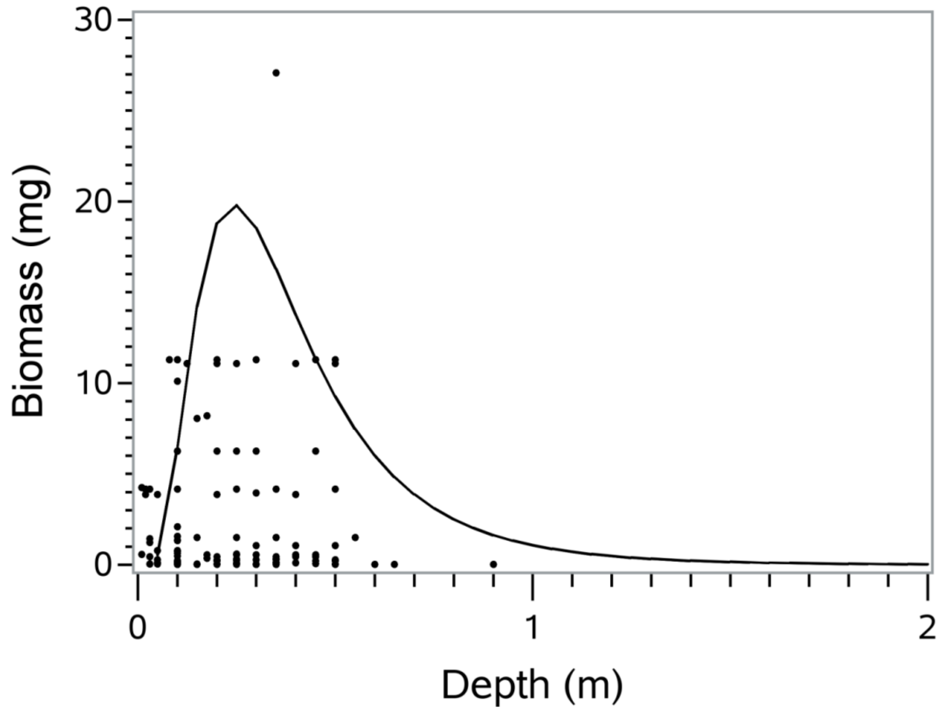

Figure 30. *Laeoneris culveri* biomass response in 0.1 m bins.

Table 3. Parameter estimates for the log-normal model in Figures 22-30. Where *a* is the peak abundance value, *b* is the rate of change of the response, and *c* the location of the peak response value for salinity.

		Parameter Estimates			Unit	Range
Species	Variable	a	b	c	Bins	units
Streblospio benedicti	Salinity	4.938	1.595	2.95	4	0 - 40 psu
	Depth	4.206	0.811	0.216	0.1	0 - 1 m
	Temperature	3.392	0.578	15.02	3	0 - 40 c
Chironomidae Larvae	Salinity	11.986	1.302	1.204	1	0 - 40 psu
	Depth	11.376	1.114	0.144	0.1	0 - 1 m
	Temperature	12.491	0.361	13.944	3	0 - 40 c
Laeoneris culveri	Salinity	16.607	1.23	2.803	1.5	0 - 20 psu
	Depth	19.823	0.588	0.242	0.1	0 - 1 m
	Temperature	18.203	0.373	15.677	3	0 - 40 c

Epifauna

There were no significant differences in community structure among three stations (C, F, and G) sampled by push nets (ANOSIM: $p \leq 0.46$, Fig. 31). However, there are indications of differences among the three sampling dates because September 2014 is on the right side of the graph, and December 2014 and March 2015 are in the center and the left side.

There was a times series succession (i.e., seriation) in the push-net sampled community structure at Station C, which showed that variation in community structure was seasonally influenced (Fig. 32A). Communities collected from October 20 to December 15 2014 were different than the rest of the communities (bottom of the MDS plot) because they contained higher abundances of grass shrimp (*Palaemonetes* sp., 681/tow), water boatmen (*Trichocorixa* sp., 35 per tow) and sheepshead minnow (*Cyprinodon variegatus*, 16/tow) than in other dates (means of 55, 2, 6 per tow respectively). These winter tows also had lower abundances of brown shrimp (*Farfantepenaeus aztecus*, 0/tow) mysid shrimp (*Mysidopsis* sp., 1 per tow), and mayflies (Potamanthidae, 0/tow) than the other dates sampled (means of 4, 4, 7 per tow respectively). November and December 2014 periods were subject to higher salinities (Fig. 32B) and dissolved oxygen levels were moderate for each of the three periods (Fig. 32C).

The total number of epifauna individuals collected in push net samples were related to salinity in Rincon Bayou from April 2010 to May 2015 (Fig. 33). Using the log-normal model, the maximum number of epifauna individuals was computed to be 6.4 psu using a maximum bin of individuals in a bin of 4 psu units wide.

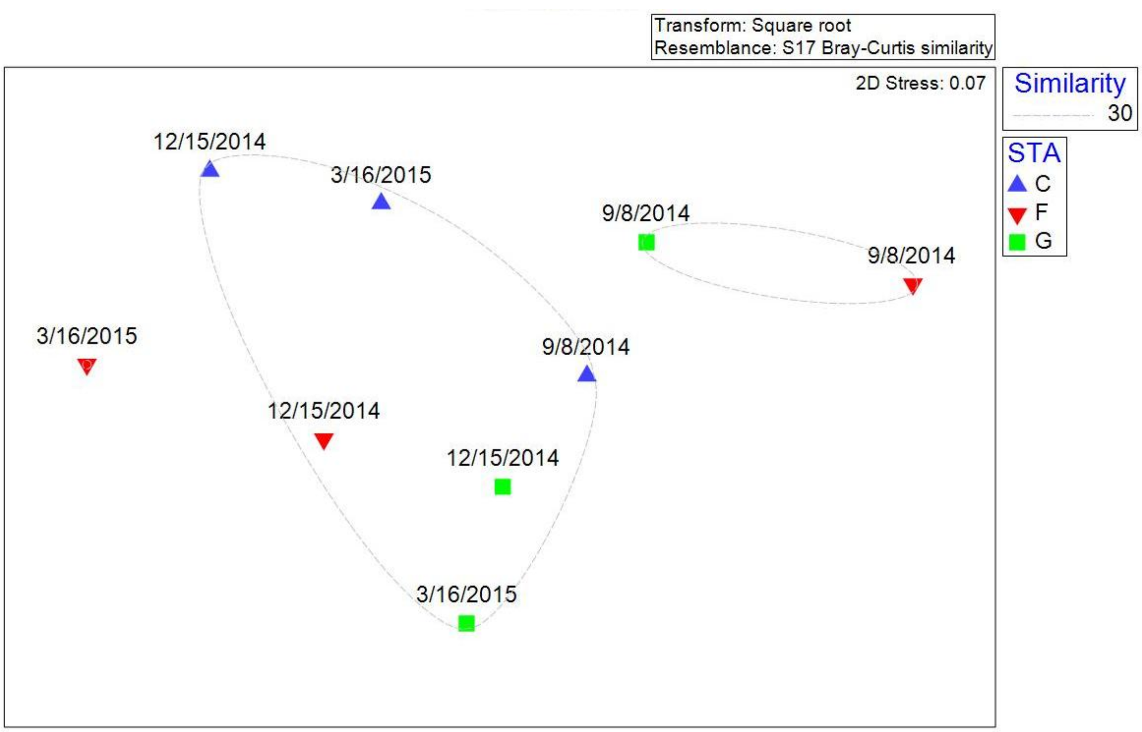

Figure 31. Non-metric multidimensional scaling plot of push net-sampled communities at Stations C, F, and G overlaid with non-significant clusters from cluster analysis.

A)

B)

C)

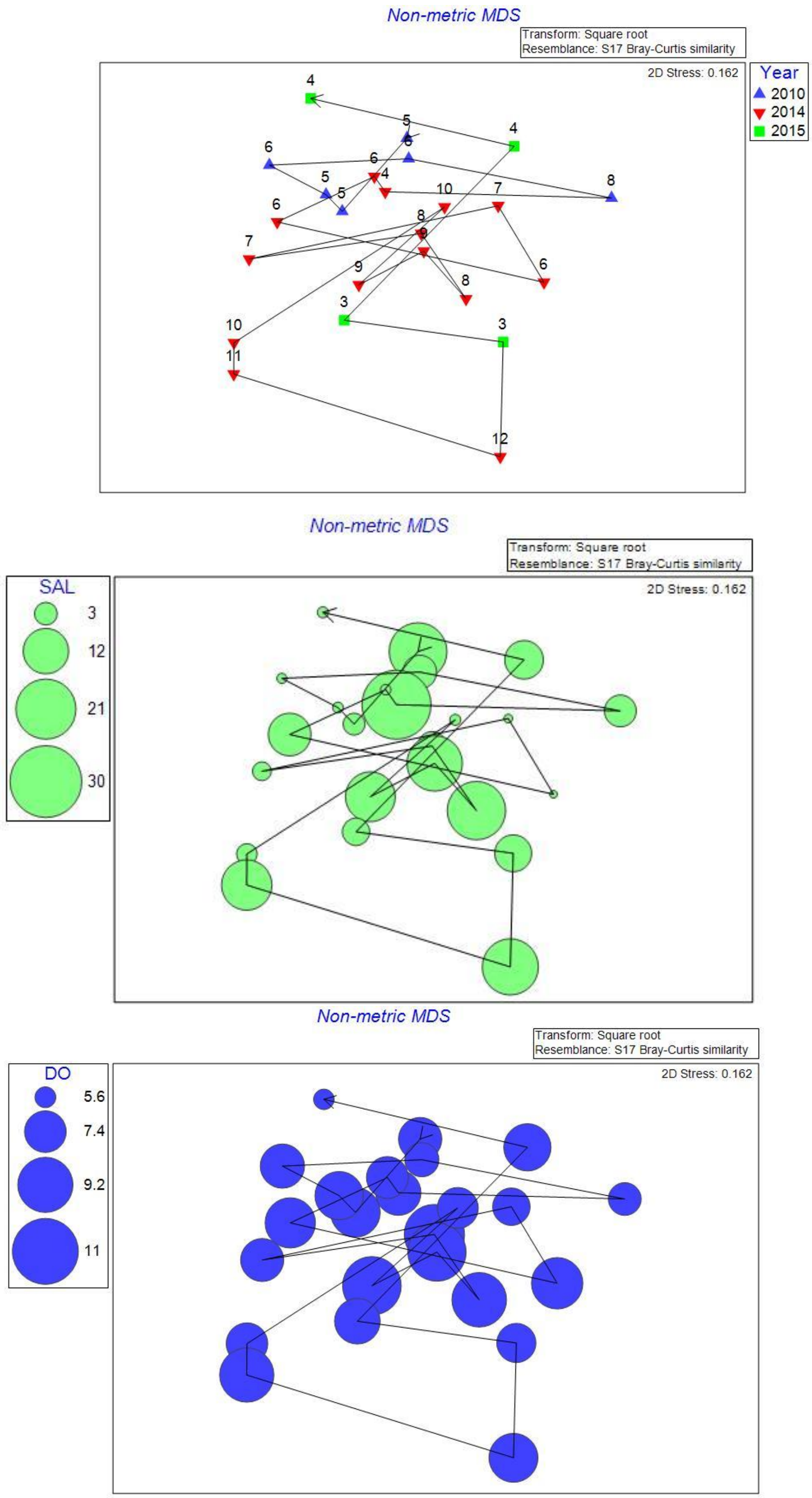

Figure 32. MDS plot of pushnet -sampled communities at Station C with seriation vectors. Symbols: A) month, B) salinity, and C) dissolved oxygen concentration.

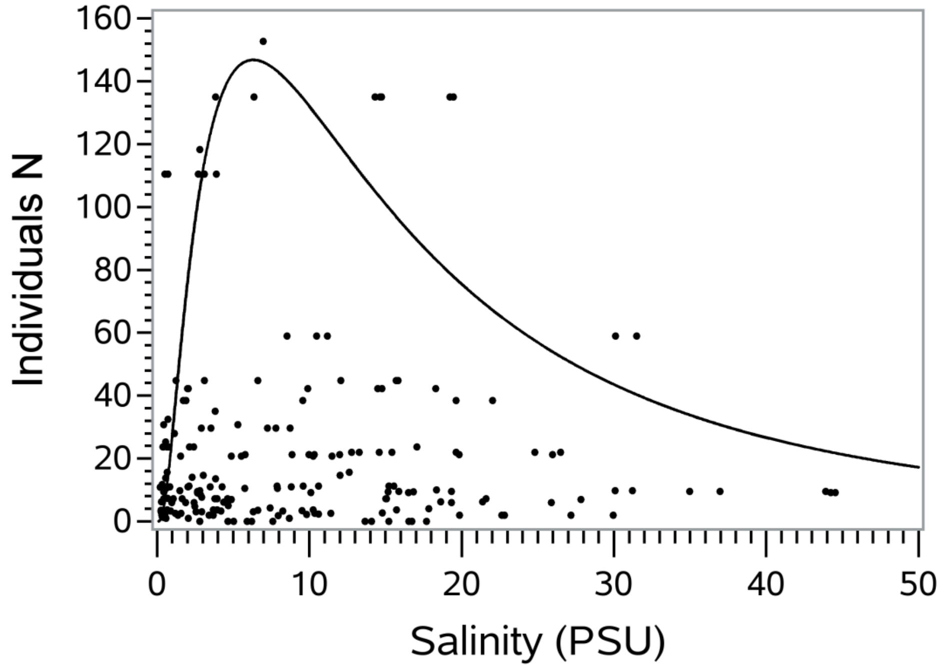

Figure 33. Log-normal model fit to epifauna total abundance per sample.

A total of 36 species were found in the push net samples (Table 4), which is much more diverse that the infauna (Table 1). The dominant species found in the push net samples were *Palaemonetes* spp. (grass shrimp), *Cyprinodon variegatus* (sheepshead minnow), Potamanthidae spp. (Mayflies), *Tricho corixa* (water boatman), and *Farfantepenaeus aztecus* (brown shrimp) (Table 4).

Table 4. Taxonomic list of all species found in push net samples. Mean of all samples.

Phyla	Class	Order	Family	Genus species	n/sample
Mollusca					
	Gastropoda				
				Gastropoda (unidentified)	0.04
	Bivalvia				
				Bivalvia (unidentified)	0.08
Annelida					
	Polychaeta				
		Errantia			
			Nereididae		
				Nereididae (unidentified)	0.08
		Canalipalpata			
			Spionidae		
				Spionidae (unidentified)	0.08
				Streblospio benedicti	0.04
		Polychaete Order Not Assigned			
				Polychaeta (unidentified)	0.04
	Hirudinea				
				Hirudinea (unidentified)	0.27
Crustacea					
	Branchiopoda				
			Daphnidae		
				Daphnidae (unidentified)	0.04
	Branchiura				
			Argulidae		
				Argulus sp.	0.04
	Malacostraca				
		Decapoda (Natantia)			
			Palaemonidae		
				Palaemonetes sp.	127.15
			Penaeidae		
				Farfantepenaeus aztecus	4.12
				Farfantepenaeus setiferus	1.15
		Decapoda (Reptantia)			
			Portunidae		
				Callinectes sapidus	2.08
		Mysida			
				Americamysis sp.	3.27
		Cumacea			
			Diastylidae		
				Diastylis sp.	0.12
			Leuconidae		
				Eudorella sp.	0.08
		Amphipoda			
			Gammaridae		
				Gammarus mucronatus	0.69
		Isopoda			
				Isopoda (unidentified)	0.27

Arachnida					
				Arachnida unidentified	0.12
	Acarina				
			Halacaridae		
				Halacaridae (unidentified)	2.15
Insecta					
				Insecta (unidentified)	0.08
	Pterygota				
		Diptera			
				Diptera (unidentified)	0.96
			Ceratogonidae		
				Ceratopogonidae (larvae)	0.88
		Coleoptera			
			Hydrophilidae		
				Hydrophilidae (unidentified)	0.08
		Hemiptera			
			Corixidae		
				Tricho corixa	6.12
		Odonata			
			Zygoptera		
				Damselfly nymphs	2.27
		Ephemeroptera			
			Potamanthidae		
				Potamanthidae (unidentified)	6.46
Chordata					
	Actinopterygii				
		Atheriniformes			
			Atherinopsidae		
				Menidia beryllina	0.38
		Clupeiformes			
			Clupeidae		
				Brevoortia patronus	0.35
			Engraulidae		
				Anchoa mitchilli	0.04
		Cyprinodontiformes			
			Cyprinodontidae		
				Cyprinodon variegatus	7.23
			Fundulidae		
				Lucania parva	0.19
		Elopiformes			
			Elopidae		
				Elops saurus	0.04
		Perciformes			
			Gobiidae		
				Gobisoma bosc	0.12
			Sciaenidae		
				Leiostomus xanthurus	0.04
			Sparidae		
				Lagodon rhomboides	0.04

Discussion

Biotic Response to Salinity

Infauna

Detailed analyses of changes in biomass over time for three dominant species (*Streblospio benedicti*, *Laeoneris culveri*, and Chironomidae Larvae) were made to determine relationships with physical parameters of salinity, depth, and temperature in Rincon Bayou. Biomass is an indicator of secondary productivity (Banse and Mosher 1980, Montagna and Li 2010, Kim and Montagna 2012). *Streblospio* is the dominant species in Rincon Bayou benthos and the most resilient to higher salinities and salinity changes. *Laeoneris culveri* and Chironomidae Larvae were predominantly found in upper Rincon Bayou Station C and are typically associated with lower salinity levels. Chironomidae Larvae in particular are well documented as freshwater and water quality indicators (Rosenburg, 1992; Saether, 1979). This indicates sustained freshwater input to upper Rincon Bayou has altered the diversity and community structure to be favorable to freshwater indicator species such as Chironomidae.

There is a strong relationship between higher depth values to low biomass. No benthic communities are observed when water is absent (i.e., < 0.01 m) from the sample location. However, a strong link between lowered biomass and higher depth (> 0.4 m) is observed for all species. Because higher water depth is associated with freshwater, higher biomass' of *Laeoneris culveri* and Chironomidae Larvae are expected. Additionally, great care is taken to collect sediment core samples at the same locations regardless of depth. From examining the raw time series core data from before and after flooding events a logical explanation is that higher floodwaters physically dislocate benthos species from the upper marsh. This is corroborated by historical physical examinations of the topology of the marsh after flooding events where floods often relocate channels, roadways, and structures. The maximum biomass for all species was found at depths between 0.2 m to 0.3 m (Figs. 24, 27, and 30).

Epifauna

Addition of the epifauna to the study adds a component at a higher trophic level. The MDS results indicated that dissimilarities in community structure were minimal, indicating that no spatial differences among sampling stations (C, F, and G) exist. There are strong differences with respect to time. Samples collected in the period between October and December of 2014 were different from other sampling periods in that the counts of grass shrimp, water boatmen, and sheepshead minnow were significantly higher than in other samples. In this period, the minimum salinity was 0.7 psu and the maximum was 30.1 psu, indicating that species with a high tolerance for salinity variations would be most abundant. Additionally, species that overwinter in estuarine waters would more plentiful.

Grass Shrimp are somewhat opportunistic and euryhaline species that spend their entire life cycle in a single marsh habitat (Kneib 1985). Because they do not overwinter, temperature would not be a driving factor in their relocation. Their presence in the October, November, and December 2014 sampling periods is expected as they are found in other months as well. Water Boatmen are an aquatic species of the Hetioptera family that typically overwinter in streams and temporary bodies of water. However, they are air-breathers, so they are not as sensitive to water pollutants and can tolerate varying salinities (DeWalt et al 2010). Sheepshead minnow have been identified as a euryhaline fish species that are capable of withstanding salinity ranges of 0.3 psu to 78 psu and an equally wide range of temperatures (Haney 1999 and Raimondo et al 2013). It is possible that water quality and/or temperatures affected this sampling period.

There is a seasonal influence for brown shrimp abundance. A general characteristic of the brown shrimp is that they are temperature-dependent spawners, usually releasing eggs when water temperatures rise above 17 °C, which is typically around March in South Texas. Post-larval shrimp move into estuarine waters between 11 and 17 temperature-dependent days post-hatch. Post-larval and juvenile members of this species can be expected to enter nursery habitats in late March or early April, and development takes about three months. They will begin emigration towards open water around late June through July (Larson 1989).

The reduced number of mysids and mayflies could also be explained in colder months. Mayflies are a freshwater species of the Ephemeroptera family that emerge in summer months. Their absence during colder months is to be expected (DeWalt et al 2010). Mysids emerge in Spring and Fall, but will typically overwinter by moving to deeper waters when temperatures drop (Lesutiene 2008).

High abundances of freshwater organisms, such as mayflies (DeWalt et al, 2010), can be explained by periods in which the region was inundated with freshwater. In these periods, there is also a decline in marine species. Rincon Bayou has become a reverse estuary over the past several years. Freshwater delivered to the delta region is necessary to reduce the typical hypersaline environment and freshwater provides nutrients for primary producers and other estuary-dependent species (Montagna et al 2002).

Similar studies performed in Rincon Bayou that focused on the benthic organisms have shown that there is variation is species composition based on varying salinities. The major difference in the benthic organisms studied and the epifaunal targets of this study is mobility. It is not surprising to see that organisms unable to tolerate major variation show a major reduction in their presence. Higher trophic organisms, such as grass shrimp, are capable of relocating to escape undesirable conditions. There is a difference in species composition seasonally, but not necessarily spatially. To date, there are no studies for Rincon Bayou that have investigated the structure of the epifaunal communities, so it is difficult to compare these conclusions with prior knowledge. The investigation of the epifaunal community dynamics of Rincon Bayou should be an ongoing effort subject to further analysis.

In summary, the optimum salinity range in Rincon Bayou Station C during the current study is between 1 and 6 psu (Table 5). This is considerably lower than optimal salinities found in previous studies for macrofauna. For example, Montagna et al. (2002b) found the optimal salinity to be 32.7 psu for abundance, 18.7 psu for biomass, and 9.08 psu for diversity, which averages to 20.2 for all metrics. The Nueces BBEST team (NBBEST 2011) found a target salinity to produce a sound ecological environment of 18 psu for the Nueces Delta as a whole based on five indicators: smooth cordgrass (*Spartina alterniflora*), benthic macroinfauna, eastern oyster (*Crassostrea virginica*), blue crabs (*Callinectes sapidus*), and Atlantic croaker (*Micropogonias undulatus*).

Table 5. Summary of optimal salinities at Station C from log-normal models.

Bioindicator		**Salinity Optimum**
Infauna	*Streblospio benedicti*	3.0
	Chironomidae Larvae	1.2
	Laeoneris culveri	2.8
Epifauna	Total abundance	6.4

Salinity Flow Relationships

When fresh water flows into Rincon Bayou, salinity decreases and nutrient concentrations increase. (Fig. 14). Salinity is highly correlated with depth and temperature in Station C of Rincon Bayou (Figs. 20 and 21).

However temperature and depth are only weakly correlated with each other (Figs. 14 and 15). This is an expected result as evaporation increases with temperature, and depth increases with freshwater inflow from both pumping activities and the Nueces River.

Although tidal influences are an important driver of salinity in Rincon Bayou, depth at Station C above 0.4 m is exclusively caused by freshwater inflow. Additionally, hypersaline conditions in Station C above 50 psu will not occur during wintertime. These correlations indicate that salinity at Station C may be managed by increasing depth through freshwater pumping activities seasonally.

There are strong season differences because there is an inverse relationship between temperature and dissolved oxygen. As surface water temperatures increase, the solubility of oxygen in water decreases, and respiration rates increase, so the available amount of free oxygen is reduced.

Empirically, we can predict the flows needed to provide specific salinities by regressing the data in Figs. 5-9 using a negative exponential model, i.e., $Inflow = a * e^{-b*Salinity}$. While this is the opposite of what is usually done, i.e., predicting salinity from flow, it is a good way to determine what flows would produce what salinity ranges in Rincon Bayou (Fig. 34).

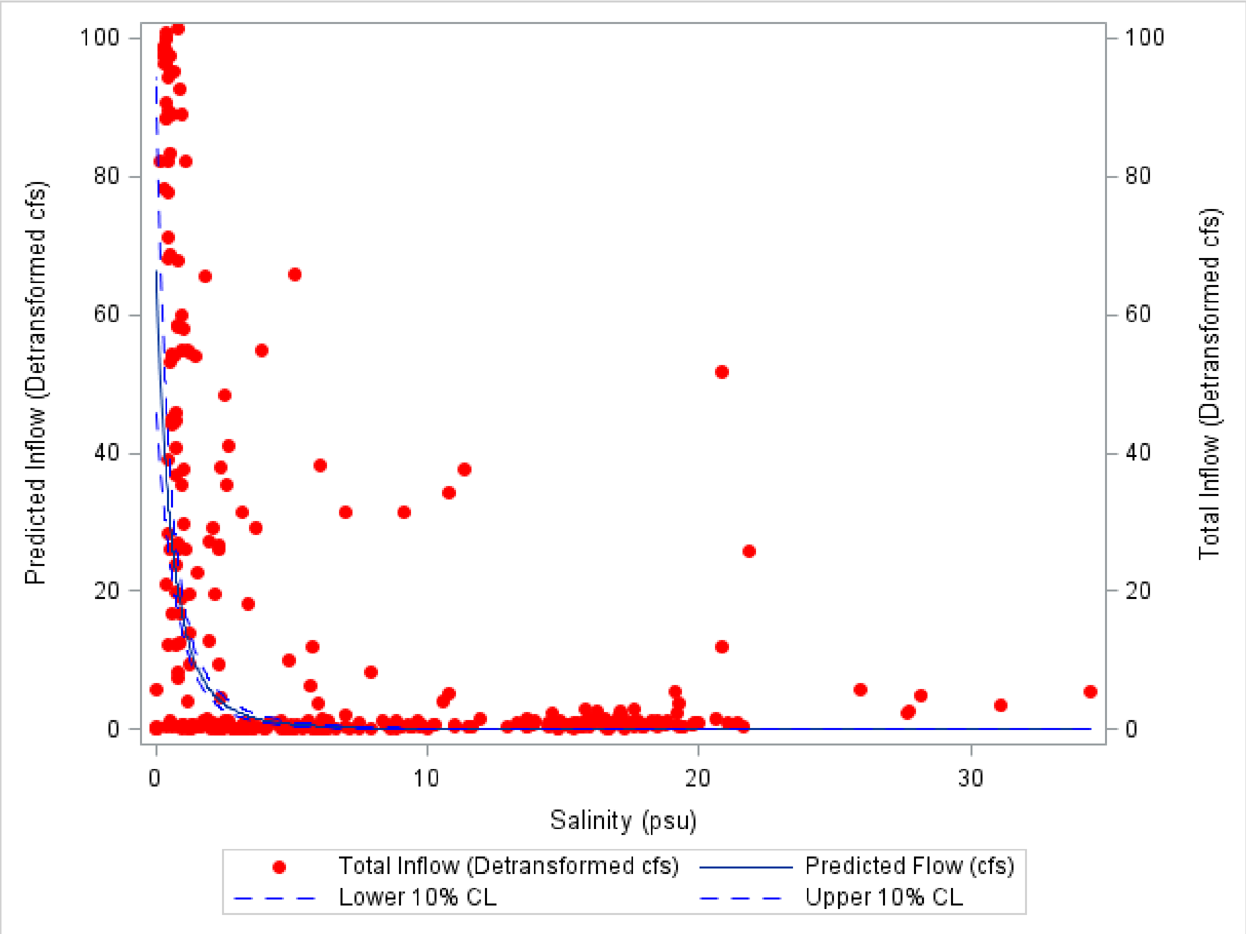

Figure 34. Prediction of inflow needed to produce salinities in the range of 0 to 35 psu.

Management Recommendations

Rincon Bayou is still a reverse estuary that still occasionally exhibits hypersaline conditions. The salinity can fluctuate from fresh to hypersaline, and hypersaline to fresh in very short time periods. Based on the low diversity and high fluctuations of abundance and biomass, the inflow fluctuations are resulting in a very disturbed ecosystem. There are several recommendations that can be made to improve the ecology of Rincon Bayou Station C based upon results presented here and a review of previous studies.

- Salinity should be maintained between 6 and 18 psu.
- Water depth should be maintained between 0.2 m to 0.3 m.
- To achieve the salinity and depth target, inflows on the order of 2 to 5 cfs are required.
- To improve ecological stability, inflows should be a trickle, not a flood. Therefore inflows from pumping should be continuous and not haphazard, and not dependent on pass-through requirements.

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