ECOSYSTEM RESPONSE TO FRESHWATER INFLOW: DETERMINING A LINK BETWEEN FRESHWATER PUMPING REGIMES, SALINITY, AND BENTHIC MACROFAUNA

By

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Abstract

The Nueces River Basin is one of the 15 major river basins in Texas, and is an important water supply for the Nueces-Rio Grande Coastal Basin area. The construction of two large reservoir dams in the Nueces River Basin has reduced the amount of freshwater reaching the Nueces Estuary by 99% from that of its historical flows. The reduction of freshwater to the marsh has created a reverse estuary condition, where lowest salinity values are near Nueces Bay and the highest are in the upper delta. The City of Corpus Christi has been required to provide not less than 185 million cubic meters (151,000 ac-ft) of water per year to the Nueces Estuary by a combination of releases, spills, and return flows to maintain ecological health and productivity of living marine resources. The City constructed a pump station and pipeline (RBP) to convey up to 3.7 x 10^6 m^3 (3,000 ac-ft) of freshwater directly into the Nueces Delta at Rincon Bayou. Inflow into Rincon Bayou is dependent upon pumped inflow with salinity and depth regimes in the Nueces Delta being controlled through management release actions. Haphazard pumping release, along with drought conditions, cause the salinity in Rincon Bayou to fluctuate from fresh to hypersaline, and hypersaline to fresh in very short time periods.

The presence of benthos was represented by indicator species that were determined by the most numerically dominant species: *Streblospio benedicti*, Chironomidae larvae, and *Laeonereis culveri*. The biological responses of the indicator species to three physical variables (salinity, temperature, and depth) were examined. The optimal ranges in Rincon Bayou during the current study were determined by combining the ranges for the indicator species. The optimal salinity was between 1 and 15 psu for biomass and 1 and 14 psu for abundance, and the optimal depth range between 0.05 m and 0.2 m (2 – 7.9 inches).

There are several management recommendations that can be made for Station C in Rincon Bayou: 1) to improve ecological stability: inflows should be a trickle, not a flood, releases should be continuous and not haphazard, only one pump should be used at a time, and releases should not be dependent on pass-through requirements; 2) to maximize ecological function: salinity should be maintained under 20 psu, and water depth should be maintained between 0.05 m and 0.2 m; 3) to maintain ranges: inflows rates on the order of ≥ 0.00102 m^3/s (0.084 ac-ft/day) are required to maintain salinities ≤ 20 psu, inflows on the order of ≤ 0.689 m^3/s (48.261 ac-ft/day) are required to maintain a depth ≤ 0.5 m, and inflow on the order of 0.41 m^3/s (28.72 ac-ft/day) will obtain an optimal value for both salinity at 2.2 psu and depth at 0.2 m (7.9 inches).

1. Introduction

The state of Texas has been on the forefront of water management since the Texas Water Planning Act of 1957 with communities historically relying on reservoirs to supply water in times of drought. The Nueces River Basin is one of the 15 major river basins in Texas, and is an important water supply for the Nueces-Rio Grande Coastal Basin area. The Nueces Estuary is contained within the Nueces River Basin and is supplied with inflow from the Nueces River that flows into the Nueces Bay in the Gulf of Mexico near Corpus Christi (Fig. 1).

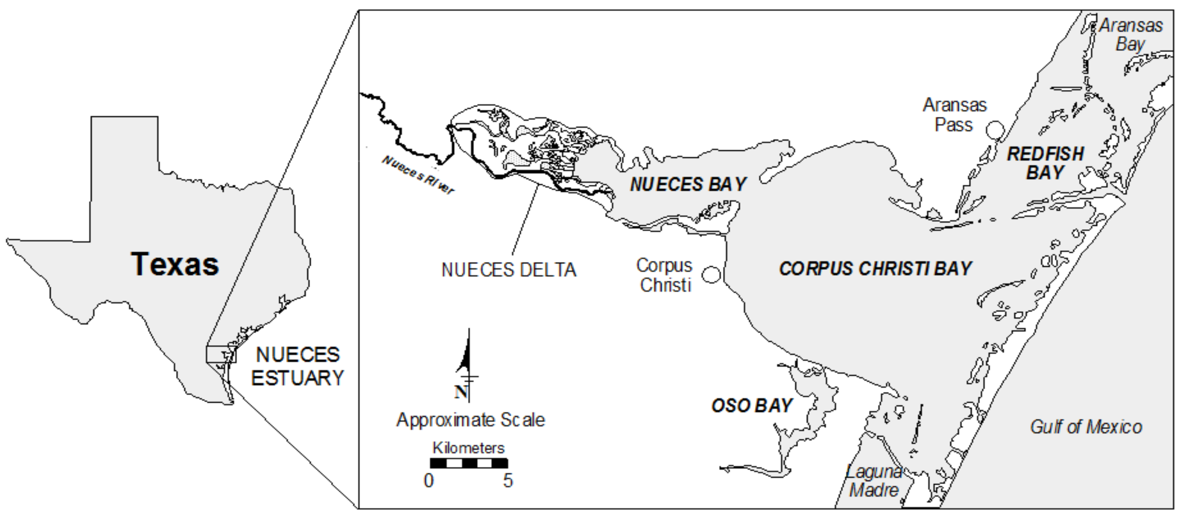

Figure 1. Location of the Nueces Delta within the Nueces Estuary

The Calallen Saltwater Barrier Dam, located adjacent to IH 37 (Fig. 2), was constructed in 1898 to restrict saltwater intrusion to the upstream nontidal segment of the Nueces River. The main stem channel of the Nueces Delta marsh is located at Rincon Bayou (Fig. 2) and historically connected to the Nueces River by way of a diversion channel. During flooding events, water would flow over the Calallen Saltwater Barrier Dam into the upper marsh supplying the estuarine ecosystem with freshwater. The construction of two large reservoir dams in the Nueces River Basin (Fig. 2); the Wesley E. Seale Dam (Lake Corpus Christi) on the Nueces River in 1958, and the Choke Canyon Reservoir on the Frio River (tributary to the Nueces River) in 1982, reduced the amount of inflow reaching the estuary by approximately 99% from that of its historical flows (HDR Engineering Inc. 2001; BOR 2000; Irlbeck and Ward 2000).

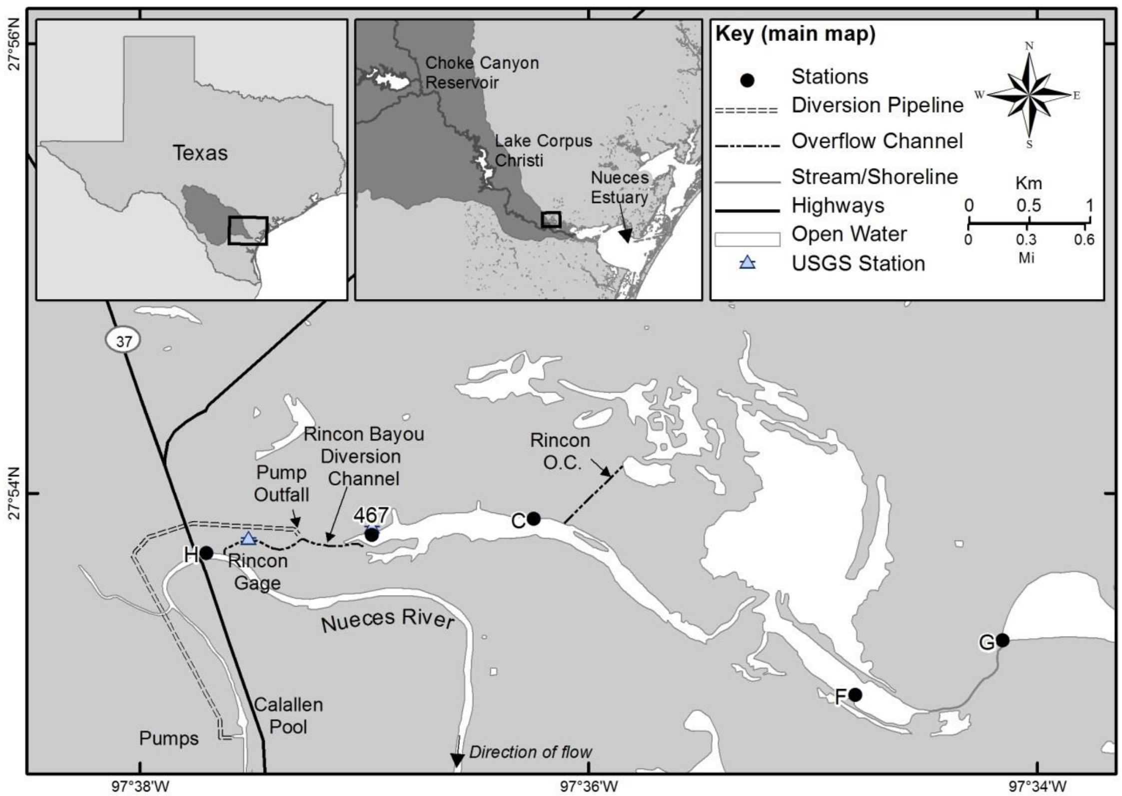

Figure 2. a) State of Texas with the Nueces Basin highlighted. b) Location of Choke Canyon Reservoir and Lake Corpus Christi within the Nueces Basin. c) Location of the Nueces Diversion Channel (Source: Palmer 2016).

After the completion of the Choke Canyon Dam, the State of Texas required that the City of Corpus Christi provide not less than 185 million cubic meters of water per year to the Nueces Estuary by a combination of releases (stored water that is let out) and spills (overflows) (TWRC

1976). 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 (Montagna et al. 2015). In April 1995, the Texas Natural Resource Conservation Commission (formerly TWC, but now the Texas Commission on Environmental Quality) issued an amendment to the Final Agreed Order reducing the amount required to be released per year. The amendment required inflows 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 (TECQ 1995). The "pass-through" concept is meant to mimic nature while taking into account area water demands, occurring only when it is required based on a combination of reservoir elevation level, precipitation, and bay salinity (Spurill 2013).

In October 1995, the Bureau of Reclamation undertook the Rincon Bayou demonstration project to provide scientific information regarding the freshwater needs of the Nueces delta and its response to changes in freshwater inflows. A diversion channel (Fig. 2) was excavated from the Nueces River to the headwaters of Rincon Bayou to increase the opportunity for more frequent and higher magnitude inflow events (BOR 2000). The diversion channel successfully increased the amount of freshwater diverted into the upper Nueces Delta returning a significant degree of ecological function to the Nueces Estuary ecosystems (BOR 2000; Montagna et al. 2009). The diversion channel was filled in after the completion of the demonstration project in 2000 as required in the initial contract (BOR 2000).

In 2001, the Texas Commission on Environmental Quality (TCEQ), the City of Corpus Christi, the Nueces River Authority (NRA), and the City of Three Rivers adopted an Agreed Operating Order for the Lake Corpus Christi and Choke Canyon Reservoir System requiring the City of Corpus Christi to "pass-through" freshwater to the Nueces Estuary based on seasonal requirements of estuarine organisms and inflows into the Reservoir System, up to a monthly target amount, if sufficient flows enter the reservoir (Lloyd et al. 2013; TNRCC 2001). To meet the Order's pass-through requirement, the City of Corpus Christi agreed to 1) reconstruct the Nueces River Overflow Channel (diversion channel) to Rincon Bayou, 2) construct a pipeline (Rincon Bayou pump station and pipeline - RBP) to convey up to 3,000 ac-ft directly to the Nueces Delta, and 3) implement an ongoing monitoring and assessment program to facilitate adaptive management for freshwater flow into the Nueces Estuary (TNRCC 2001; Montagna et al. 2009; Lloyd et al. 2013; Hill et al. 2012).

In 2009, the pipeline and pumping station became operational to pump freshwater from the Calallen Pool, above the saltwater barrier dam, into the Nueces Delta at the Rincon Bayou headwaters so that inflow would no longer rely on overflowing of the Calallen Saltwater Barrier Dam (Fig.2). Pumping events typically occur when salinities in the Nueces Delta are > 30 psu and when reservoir levels and rainfall events allow for "pass-through" conditions (Lloyd et al. 2013). 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. Inflow into Rincon Bayou is dependent upon pumped inflow so consequently, salinity and depth regimes in the Nueces Delta can be controlled through management actions, with the most beneficial pumping regime (i.e., the timing and quantity of pumped inflow) yet to be resolved. 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. The purpose of this project was to determine a relationship among pumped inflows, salinity, and benthic macrofauna at Station C in Rincon Bayou to provide management recommendation for the pipeline. It was also determined that water depth was a factor for the presence of benthos, so it was also considered in the recommendations for this project.

2. Methods

The primary project objective was to determine the effects of pumped inflows into Rincon Bayou on benthic macrofauna (invertebrates with a body length > 0.5 mm) to inform water resource managers on how to create an ecologically effective pumping strategy. This study looked at whether or not benthic macrofauna were present at given salinity and depth values, in which the most numerically dominant species (indicator species) optimal values were determined. Their values were then combined to determine the optimal salinity and depth ranges for the production on benthic macrofauna.

Benthic organisms (benthos) 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 environmental changes, 6) benthos are relatively long-lived and sessile, so they integrate effects over long temporal and spatial scales, 7) benthos are sensitive to change in environmental conditions, 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 (Montagna and Kalke 1992; Montagna et al. 2002; Bilyard 1987; Remane and Schlieper 1971). The approach used for this project was to relate inflow, salinity, and other freshwater inflow factors with benthic macrofauna response, to provide evidence of the freshwater inflow regimes necessary for the maintenance of estuarine health (Poff et al. 1997; Pulich Jr. et al. 2002).

2.1. Study Site

Rincon Bayou is a creek connecting the tidal segment of the Nueces River to the delta and is the historic location of river inundation events in the northeastern portion of the upper Nueces Delta (Fig. 2) (Montagna et al. 2015). Historically, Rincon Bayou was subject to freshwater flooding following seasonal rainfall events farther inland along the Nueces River which provided nutrients and enough freshwater to remove the saline water from the estuarine system. From the combined effects of reservoir construction, changes in land use patterns, increased ground water withdrawals, and other human activities, the average annual volume of freshwater diverted into the upper Nueces Delta since 1982 has been reduced by over 99% from that of before 1958 (Irlbeck and Ward 2000).

In November 2007, the pipeline was completed from the San Patricio Municipal Water District, W. A. Edwards Pump Station location, northward along the Nueces River, and then eastward across U.S. Highway 77 to the headwaters of Rincon Bayou (Fig. 3) (HDR Engineering, Inc. 1993). The pump station consists of three pumps which are capable of moving up to 3.8 m^3/s with all three pumps in operation with the number of days to deliver a given volume of freshwater through the pipeline depending on the number of pumps used (Lloyd et al.

2013; Hill et al. 2012). The Nueces River provides freshwater to the City of Corpus Christi and the surrounding Coastal Bend area. The Calallen Pool (Saltwater Barrier Dam) is located adjacent to IH 37, and was constructed in 1898 to restrict saltwater intrusion to the upstream non-tidal segment of the river (Montagna et al. 2009). The RBP pumps freshwater from above the saltwater barrier dam into the Nueces Delta at the Rincon Bayou headwaters at the pumping outfall (Fig. 3).

2.2. Sampling Locations

Hydrology data were collected in the upper and lower parts of the marsh in Rincon Bayou and in the Nueces Bay (Fig. 3). Hydrographic measurements were taken at: Station C located at 27.89878 °N latitude and 97.60417 °W longitude, Station F located at 27.87760 °N latitude and 97.57873 °W longitude, and 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). Natural inflow and discharge data were collected at the USGS Rincon Bayou Channel Gage No. 08211503 located at 27.896667 °N latitude and 97.625278 °W longitude. Rainfall data were collected at the Nueces Delta Weather Station (NUDEWX) located at 27.8975 °N latitude and 97.616389 °W longitude. Salinity data were collected at Nueces Delta 2 (NUDE2) located at 27.8888 °N latitude and 97.5696 °W longitude and SALT03 located at 27.85155 °N latitude and 97.48203 °W longitude.

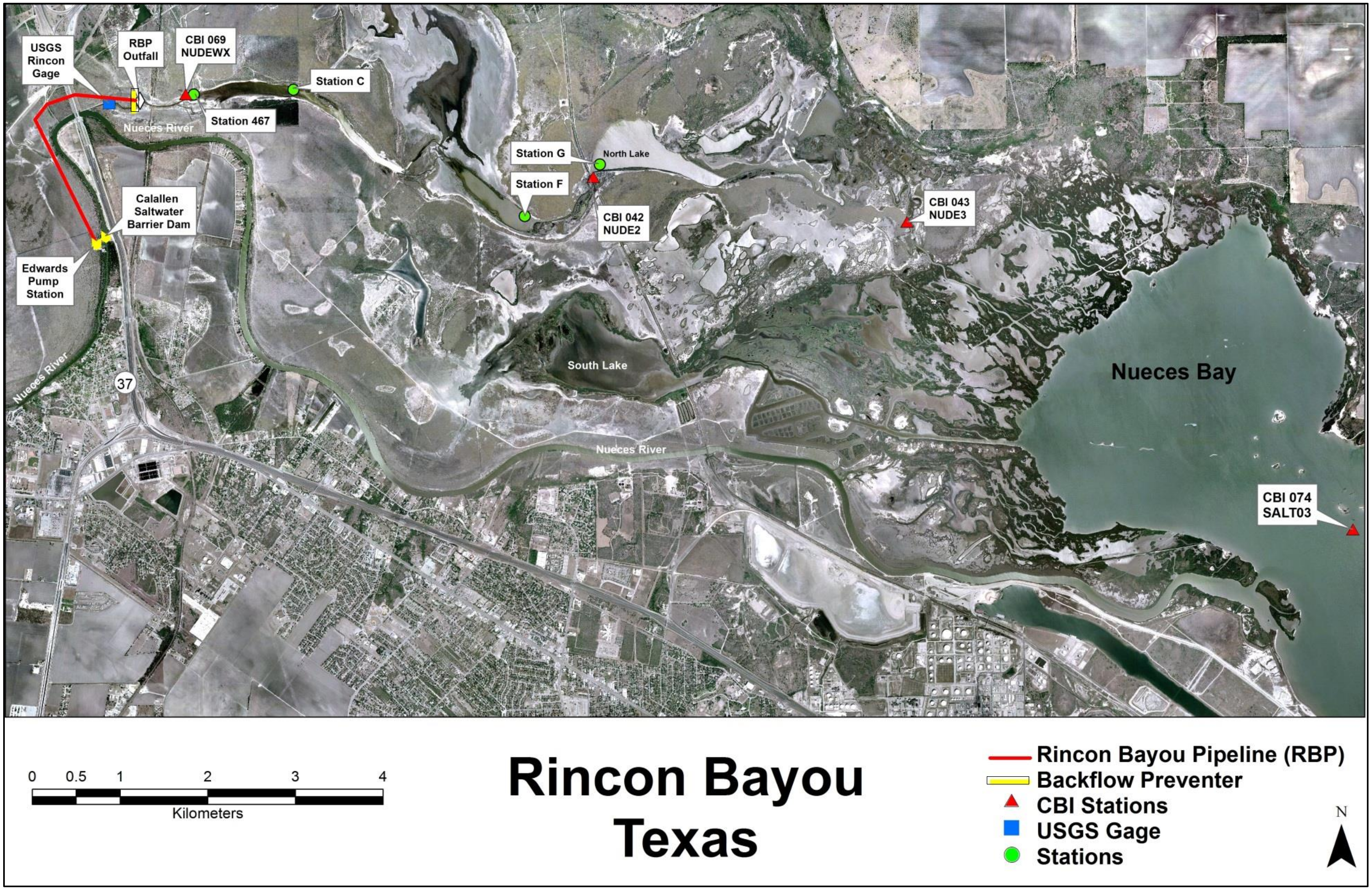

Figure 3. Map of benthic macrofauna sample locations and station locations for measuring flow, salinity, and rainfall in Rincon Bayou (image source: USDA-NRCS 2006).

2.3. Hydrology

Hydrographic measurements were made just beneath the surface and at the bottom of the water column at Stations C, F, and G on each sampling date with a YSI 6600 multi parameter sonde. The following variables were read from the digital display unit (accuracy and units): temperature (∀ 0.15 EC), depth (∀ 0.1 m), and salinity (psu). Salinity is automatically corrected to 25 ^{o}C. Continuous data (observations every 15 minutes for duration of two weeks) were collected at Station C from January 2014 through December 2015 and averaged by daily means. Discrete data (single observation per sample date) were collected at Stations C, F, and G from October 1994 through December 2015. Station C is located closest to the pumping outfall area and will be the only sampling station examined at for hydrology data comparisons.

2.4. Macrofauna

Originally it was proposed to sample before, during, and after pumping events, but this proved to be impossible because we were never notified until after pumping began. So, to resolve the problem, Station C was sampled 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. Two other stations (F and G) have been sampled quarterly to capture changes over larger spatial scales. Biomass, abundance and community structure were measured for each station using standard techniques that have been used since 1984 (Kalke and Montagna 1991; Montagna and Kalke 1992; Montagna et al. 2002b). Three sediment core replicates were taken by hand within a 2 m radius of the sample station. The cores are 6.715 cm diameter, covering an area of 35.4 cm^2 to a depth of 10 cm. Animals were extracted using a 0.5 mm mesh sieve, and identified to the lowest taxonomic unit possible. In the laboratory, animals were enumerated, identified, and dried at 50℃ for 24 hours and weighed. Mollusk shells were removed by an acidic vaporization technique (Hedges and Stern 1984).

2.5. Analytics

2.5.1. Hydrology

The hydrology data were downloaded from the corresponding websites listed in Table 1. Pumped inflow and gauged inflow were converted to m^3/s. SAS 9.3 software was used to compile the downloaded datasets and the Station C sonde data and Microsoft Excel 2010 was used to create the graphs. The PROC MEANS procedure was used to calculate the mean, standard deviation, minimum, and maximum values for all the hydrology data. Pumped inflow data were assigned pumping event numbers based on breaks in the pumping duration (Table 2). The PROC MEANS procedure was used to calculate the number of days of inflow and the total pumped inflow rate per pumping event number. Total inflow rate into Rincon Bayou was calculated per day by summing the pumped inflow rate and the inflow rate at the USGS Rincon Channel Gage.

Percent occurrences were derived from histogram frequencies and converted to percent's using Microsoft Excel 2010. Percent exceedance was calculated for natural inflow (USGS Rincon Gage), pumped inflow (RBP), and total inflow (Gage + RBP). The rank function in Excel was used to rank the inflow from highest to lowest. The exceedance probability (P) was calculated as:

$$P = 100 * [M / (n + 1)]$$

Where *P* is the probability that a given flow will be equaled or exceeded (% of time), *M* is the ranked position of the flow amount, and *n* is the number of flow events from September 2009 to December 2015.

The salinity gradient was determined for Rincon Bayou by subtracting the upstream salinity (NUDE2) from the downstream salinity (SALT03). It was determined to be in a negative estuary condition when the difference was negative, i.e. the salinity at SALT03 was less than the salinity at NUDE2, and in a positive estuary condition when the difference was positive, i.e., the salinity at SALT03 was greater than the salinity at NUDE2. Microsoft Excel 2010 was used to graph the difference in salinity. The pumping events were added to the graph as bands that represent pumping duration, the wider the band the longer the pumps were kept running.

2.5.2. Macrofauna

Biomass was measured for benthic macrofauna starting in May 2010, previous to this only benthic abundance was measured. Total species data at Station C (total number, abundance, percent composition, and dry weight) from May 2010 through December 2015 were calculated using the PROC MEANS procedure. Sampling trip numbers were assigned starting with the May 2010 as trip number 0 (Table 3). Bi-weekly sampling began on sampling trip number 10 (October 2013) and continued through trip number 63 (December 2015). Total inflow (USGS Gage + pumped inflow) was summed using the PROC MEANS procedure for the time period prior to the sampling periods. The inflow was broken down into flow rates (negative flow, 0-1, 1-3, 3-5, 5-7, and >9 m^3/s). Species data from sampling trip number 11 onward were merged with the inflow data using SAS and graphed using Microsoft Excel 2010.

The relationship between macrofauna abundance, diversity, and salinity has been examined using a log normal model, which has been used successfully in estuaries in Texas (Montagna et al. 2002) and Florida (Montagna et al. 2008). Salinity is often used as a proxy for freshwater inflow because inflow dilutes sea water and thus decreases salinity. 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. A log normal distribution commonly occurs in ecological population data and resembles a left-skewed bell-shaped curve (Limpert et al. 2001). The shape of the 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 can be used to characterize the nonlinear relationship between a biological characteristic (*Y*), e.g., abundance or biomass and salinity (*X*). The three parameters characterize 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. The marsh system in the Nueces Estuary is a system where physical factors e.g., depth, salinity, and temperature, are highly variable and can control the growth and distribution of benthic macrofauna (Turner and Montagna (in review)).

Analytics were performed using the SAS 9.3 software. The mean of benthic sample replicates and water quality variables (salinity, temperature, and depth) were calculated for each date-station combination. Cores with zero biomass and abundance per taxonomic level were not removed from the dataset. The log + 1 for the biomass and abundance was calculated. The macrofauna data were joined to the respective hydrographic data by date-station combinations. Histograms were produced for indicator species by binning the logged biological response variables (biomass or abundance) values into segments. A curve was then fitted for the binned biological variables versus physical variables (salinity, depth, and temperature) using the max bin method described by Turner and Montagna (in review). The max bin method used the PROC NLIN procedure in SAS with the log normal equation:

$$Bioindicator = a \times \exp\left(-0.5 \times \left(\log \frac{\left(\frac{bin}{c}\right)}{b}\right)^2\right)$$

The bin size number determines how well the PROC NLIN procedure convergence over the data points. The max bin curve was best fitted to the data points by adjusting the number of bins the data was segmented into. Decreasing the bin size moves the curve to the right of the mean, while increasing the bin size move the curve to the left of the mean. Estimating the true mean of the max response of *Y* to *X* can be described as the means along the range of equally spaced bins from 5 (low end) to 20 (high end) for any histogram (He and Meedeen 1997).

Rincon Bayou fluctuates between freshwater and brackish conditions, which resulted in core samples being dominated by either freshwater species or brackish species, thus for the max bin method to predict the optimal ranges it was necessary to select indicator species, instead of running the analysis on all species as a whole community. Indicator species were determined as the three most abundant species from data collected at Station C in Rincon Bayou from May 2010 through December 2015 (Table 7). The objective was to predict the presence of benthos by determining optimal salinity, depth, and temperature values for these indicator species using macrofauna data collected from all three stations (C, F, and G), and sonde data collected from Station C from October 2013 through December 2015 (bi-weekly sampling regime). The task was to determine the maximum potential of Y (biomass or abundance) at given X (salinity, depth, temperature) and use this as a range.

2.5.3. Predicted Inflow, Salinity, and Depth

PROC NLIN procedure was used to plot the predicted regression trend using the continuous sonde data at Station C and total pumped inflow into Rincon Bayou. Negative inflow (upstream gauged flow) values were not used. Empirically, we can predict the flows needed to provide specific ranges by regressing the data and using the negative exponential model:

$$Inflow = a * e^{-b*X},$$

where X is equal to salinity (psu) or depth (m). 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 and depth ranges in Rincon Bayou (Montagna et al. 2015).

3. Results

3.1. Hydrology

The salinity gradient from the upper delta extending to the Nueces Bay defines whether Rincon Bayou has either positive or negative estuarine conditions. An increasing salinity gradient results in a positive estuarine condition with lower salinities upstream; a decreasing salinity gradient results in a negative estuarine condition with higher salinities upstream. The Nueces Estuary can shift between a positive and negative estuarine conditions 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 upstream at NUDE2 (Fig. 3) being higher than the mean daily salinity downstream in the Nueces Bay at SALT03. The Nueces Estuary oscillates between positive and negative conditions with pumping events (Fig. 4). Pumping events coincided with periods of positive estuary conditions and the greatest difference in salinity between the bay and the upper delta happened immediately after pumping ceased (Fig. 4).

A test run of the pipeline was performed in 2007 with pumping beginning into Rincon Bayou in September 2009 (Table 2). The mean pumped inflow per pumping event was 12 m^3/s with a maximum pumping rate of 126.86 m^3/s and a minimum pumping rate of 0.11 m^3/s. With pumping, Rincon Bayou has transitioned from a negative hypersaline estuary to a positive mesohaline estuary (Fig. 5) with a mean daily salinity at NUDE2 of 23.22 psu with a maximum daily mean salinity of 86.29 psu and a minimum daily mean salinity of 0 psu (Table 4). Salinity declined after each pumping event and gradually increased until the next pumped inflow (Fig. 6). The mean of continuous daily salinities at Station C during the sampling period (January 1, 2014 to December 31, 2015) was 6.74 psu, with a maximum daily mean salinity of 46.38 psu, and a minimum daily mean salinity of 0.00 psu (Table 5). The mean of continuous daily depth was 0.49 m with a maximum of 1.82 m and a minimum of 0.00 (Table 5).

The mean rainfall at NUDEWX was 1.92 cm/day with a maximum of 142 cm/day (Table 4). The may have accounted 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 1.71 m^3/s with a maximum of 5.04 m^3/s and a minimum pumped amount of 0.03 m^3/s (Table 4).

The absence of a distinct elevation gradient in Rincon Bayou at the pumping outfall area (Fig. 3) 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 weir was constructed at the pumping outfall in May 2010 to reduce the amount of pumped inflow going back upstream (R.D. Kalke personal communication). It was replaced in July 2014 with a back-flow preventer consisting of gates, which must be manually operated. The back-flow preventer washed out in the summer flooding of 2015 (R.D. Kalke personal communication). It reduced negative flows back to the Nueces River while it was in place (Fig. 6 and 9).

A flow duration curve illustrates the percentage of time a given flow was equaled or exceeded during a specified period of time. From January 2009 through December 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 5 m^3/s being equaled or exceeded < 1% 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 1.71 m^3/s with a maximum total inflow rate (pumping and Rincon gauged discharge) of 6.48 m^3/s (Table 4). The percent of time that inflow from the Rincon Bayou diversion channel was greater than 0.2 m^3/s was less than 10% of the time with an inflow rate between 0 and 0.1 m^3/s occurring most often (Fig. 11). The mean of daily inflow rate at the USGS Rincon Bayou Channel Gage was -0.02 m^3/s with a maximum daily mean discharge rate of 4.93 m^3/s and a minimum daily mean rate of -2.72 m^3/s.

Percent occurrence is defined as how often the event has occurred in a time period. Salinity, depth, and temperature ranges for the discrete sonde data for Station C in Rincon Bayou before pumping began, October 1994 – August 2009, and after pumping began, September 2009 to December 2015 is summarized in Figure 12. In the 15 year before pumping began into Rincon Bayou salinity ranges of less than 5 psu had an occurrence of 26%, salinity ranges over 40 psu occurred approximately 15% of the time, and water depth of 0.2 m occurred most often 36% of the time. In the 6 years since pumping began into Rincon Bayou salinity ranges of less than 5 psu occurred 43% of the time, salinity ranges over 40 psu occurred approximately 2% of the time, and water depth of 0.1 m occurred most often 48% of the time. The percent occurrences for the temperature ranges at Station C were slightly higher before September 2009. Since September 2009, temperatures greater than 30 ºC have occurred 20% of the time vs. 8% of the time prior, and temperatures less than 10 ºC occurred slightly more prior to September 2009. Prior to pumping the mean depth was 0.21 m , mean salinity was 21.37 psu, and the mean temperature was 22.87 ºC; after pumping began the mean depth was 0.15 m , mean salinity was 9.66 psu, and the mean temperature was 23.54 ºC (Table 6).

There is an inverse relationship between salinity and inflow and a direct relationship with depth and inflow (Fig. 13). There is a large scatter in the relationships, especially at the low end of salinity and inflow and the mid-range of depth and inflow, but a non-linear regression yields a small bound of error. The negative regression equation produced the parameters a = 2.834752, b = 0.792677 for salinity and a = 0.291146, b = -1.72153 for depth. Using the equations:

$$inflow = a * \exp(-b * sal) \text{ and } inflow = a * \exp(-b * depth),$$

an inflow rate of 3.69×10^{-7} to 1.02×10^{-3} m^3/s is needed to maintain salinity values between 10 and 20 psu, and an inflow rate of 0.317 to 0.689 m^3/s is needed to maintain a depth between 0.05 m and 0.5 m. An inflow rate of 2.83 m^3/s or greater will result in zero salinity values and a depth of 1.3 m.

3.2. Macrofauna

The indicator species were determined as the three most numerically dominant species at Station C in Rincon Bayou from May 2010 to December 2015, *Streblospio benedicti*, *Laeonereis culveri*, and Chironomidae larvae (Table 7). Out of the total number of individuals found 44.3 % were *Streblospio benedicti*, 43.6% were Chironomidae larvae, and 4% were *Laeonereis culveri*. A shift in dominant species occurred since the bi-week sampling began in October 2013 (Table 8) suggesting a transition to a more predominantly occurring freshwater environment at Station C. Out of the total number of individuals found 50.6 % were Chironomidae larvae, 39.0% were *Streblospio benedicti*, and 4.82% were *Laeonereis culver*i.

Species composition with inflow rates from the bi-weekly sampling (November 2013 to December 2015) is shown in Figure 14. A total of 12 species were found. The highest species biomass (g/m^2) was produced with inflow rates greater than 9 m^3/s, while the highest species abundances are with inflow rates of 0 to 1 m^3/s. Chironomidae larvae compose of the highest species biomass and abundance with inflow of 0 to 1 m^3/s and 1 to 3 m^3/s. *Laeonereis culveri* compose of the species highest biomass with negative inflow rates (upstream flow) and inflow rates of 3 to 5 m^3/s and > 9 m^3/s. *Streblospio benedicti* compose the highest species abundance at inflow > 9 m^3/s but do not compose the highest biomass at any inflow level. The mean number of species was fairly consistent with inflows greater than 9 m^3/s and 3 to 5 m^3/s having the most species.

The max bin log normal regressions were determined between the hydrographical variables (salinity (psu), temperature (ºC), water depth (m)) and the biological response variables (biomass (g/m^2) and abundance (n/m^2)) of *Streblospio benedicti*, Chironomidae larvae, and *Laeonereis culveri* sampled from October 2013 to December 2015 from Stations C, F, and G in

Rincon Bayou. The optimal conditions for biomass and abundance along with the regression parameters are listed in Table 9. For *Streblospio benedicti* the optimal conditions to produce the highest biomass were found to be at a salinity of 14.1 psu, a temperature of 14.8 ºC, and a depth of 0.12 m, with the optimal conditions to produce the highest abundance being at a salinity of 13.5 psu, a temperature of 18.2 ºC, and a water depth of 0.12 m (Fig. 15). For Chironomidae larvae the optimal conditions to produce the highest biomass were found to be at a salinity of 1.8 psu, a temperature of 18.2 ºC, and a depth of 0.08 m, with the optimal conditions to produce the highest abundance being at a salinity of 1.4 psu, a temperature of 15.6 ºC, and a water depth of 0.09 m (Fig. 16). For *Laeonereis culveri* the optimal conditions to produce the highest biomass were found to be at a salinity of 5.4 psu, a temperature of 18 ºC, and a depth of 0.09 m, with the optimal conditions to produce the highest abundance being at a salinity of 11.6 psu, a temperature of 17.7 ºC, and a depth of 0.08 m (Fig. 17).

4. Discussion

4.1. Biotic Response

Freshwater inflow serves a variety of important functions to estuarine ecosystems such as creating and preserving low-salinity nurseries; transporting sediments, nutrients, and organic matter downstream; and affecting estuarine species movements and reproductive timing (Longley 1994; Scheltinga et al. 2006). Decreases in freshwater inflow can lead to reverse estuaries where high salinities occur upstream rather than downstream resulting in loss of species biodiversity and critical habitat (Montagna et al. 2002b; Benson 1981; Yoskowitz and Montagna 2009). Benthic biodiversity has been found to be an important indicator of habitat quality and estuaries with more freshwater inflow supporting greater benthic abundance and biomass (Montagna and Kalke 1992), with biomass being an indicator of secondary productivity (Banse and Mosher 1980; Montagna and Li 2010; Kim and Montagna 2012). Rincon Bayou has been characterized as a region with highly variable water inundations and is dominated by a low diversity and pioneering species (Palmer et al. 2002).

Detailed analyses of changes in biomass and abundance over time for three dominant species (*Streblospio benedicti*, Chironomidae larvae, and *Laeonereis culveri*) were made to determine relationships with physical variables of salinity, depth, and temperature in Rincon Bayou at Station C. Montagna et al. (2002) found *Streblospio benedicti*, Chironomidae larvae, and *Laeonereis culveri* to be the most abundant species in the Nueces Estuary in their study from October 1998 to October 1999. This was after the diversion channel was dug in 1995, but prior to pumping into Rincon Bayou. *Streblospio benedicti* was found to be the dominant species in Rincon Bayou's benthic macrofauna and the most resilient to higher salinities and changes in salinity. The current study supported these findings, except in the study by Montagna et al. (2002), Chironomidae larvae were found to be the least abundant of the three species. Chironomidae larvae are well documented as freshwater and water quality indicators (Rosenburg 1992; Saether 1979; Warwick 1985; Kalke and Montagna 1992). The shift from a brackish species to a freshwater species indicates sustained freshwater input to the upper delta, which has altered the diversity and community structure to be more favorable to freshwater indicator species such as Chironomidae.

In the shallow marsh of the Nueces Delta evaporation coincided with drought and seasonally low tides can cause periods of dry land, while flooding events will raise the water level above 0.4 m. Flooding events as well as seasonal and storm related tides are an important driver of salinity in Rincon Bayou, but depth at Station C above 0.4 m is exclusively caused by freshwater inflow (Montagna et al. 2015). Sediment core samples were collected at the same locations regardless of depth. The maximum biomass and abundance was found at depths between 0.05 m to 0.2 m (Table 9), with decreased numbers when depth is greater than 0.5 m (Fig. 15 - 17), no benthic organisms observed when water is absent (i.e., depth < 0.01 m), and a negative correlation between biomass and depth (> 0.4 m) for all species. From examining the raw time series core data from before and after flooding events a logical explanation is that higher floodwaters physically dislocate benthic 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 (Montagna et al. 2015). This negative correlation is an indication that pumped impulses mimics flooding events and dislocates species.

Higher water depth is associated with freshwater, thus higher optimal values for *Laeonereis culveri* and Chironomidae larvae was expected, but higher optimal depth values for *Streblospio benedicti* was found in this study (Table 9). A logical explanation for this is that, *Streblospio benedicti* are documented as brackish indicator and pioneer species, indicative of disturbed environments (Pollack et al. 2009; Palmer et al. 2002; Levin 1984), providing an indication that the haphazard pumping into Rincon Bayou is creating a disturbed environment. A continuous inflow into Rincon Bayou via pumped inflow or natural inflow from seasonal flooding events would resolve this and create a more stable environment, in which species biomass, abundance, and diversity would be expected to increase. These correlations indicate that salinity at Station C may be managed by increasing depth through freshwater pumping activities seasonally (Montagna et al. 2015).

The optimum salinity range for the current study is between 1 and 15 psu for biomass and 1 and 14 psu for abundance (Table 9), which is in contrast to the optimal salinities found in previous studies for macrofauna. For example: Montagna et al. (2002b) found the optimal salinity for benthic macrofauna in Rincon Bayou to be 18.7 psu for biomass and 32.7 psu for abundance which averages to 25.7 for both; Pollack et al. (2009) found Chironomidae larvae to have a mean salinity of 6.2 psu and Streblospio *benedicti* a mean salinity of 21.3 psu on the Texas coast; and *Laeonereis culveri* has been found at a salinities ranging from 14.8 (Mazurkiewicz 1975) to 54 psu (Klesch 1970). The Nueces BBEST team (NBBEST 2011) found a target salinity of 18 psu to produce a sound ecological environment 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*).

The examination of the biological response (abundance and biomass) to the physical variables (salinity, temperature, and depth) at Station C showed that salinity is highly correlated with depth and with temperature, and temperature and depth are weakly correlated with each other. This is an expected since evaporation increases with temperature, and depth increases with freshwater inflow from both pumping activities and from natural inflow from the Nueces River. Temperature and depth have been related to macrofaunal density i.e. macrofauna used temperature as a controlling factor in populations, but not depth (Kim and Montagna 2009). The optimal temperature for growth for macrofauna species used in pervious analysis was conservatively estimated at 20 ºC, which is higher than the estimates found here (Table 9). The previous study also modeled macrofauna in open bay waters, where water depth had little relationship to macrofauna density (Kim and Montagna 2009). In addition hypersaline conditions above 50 psu have only been observed when temperature is greater than 20 °C, with hypersaline conditions above 50 psu not occuring during wintertime (Montagna et al. 2015).

4.2. Salinity Flow Relations

The reduction of freshwater to the marsh has created a reverse estuary condition, where lowest salinity values are near Nueces Bay and the highest are in the upper delta. The downstream salinity values at SALT03 and upstream salinity values at NUDE2 were used to describe the estuary condition as positive or negative. Negative or reverse estuary conditions have been found to create a non-functioning, often hypersaline estuarine ecosystem (BOR 2000; Montagna et al. 2002b; Ward et al. 2002). The Nueces Estuary fluctuates between positive and negative conditions (Fig. 4) based on inflow and drought conditions. This was also described by Barajas (2011) where it was found that the Nueces Estuary shifted from negative to positive conditions from increased inflow from rainfall and pumping events.

Hill et al. (2012) assessed freshwater inflows coming into the Rincon Bayou via the RBP from November 2011 to June 2012 by measuring salinity at various stations downstream of the outfall and in areas adjacent to the main. They found that RBP inflows during hypersaline conditions result in extreme salinity fluctuations in Rincon Bayou. They concluded that these extreme fluctuations are not the most biologically productive way to manage the system, and that the bayou should be managed so hypersaline conditions are not reached. To restore biological productivity they suggested using the RBP inflows to maintain an estuarine salinity.

A lack of an elevation gradient allows inflows to flow natural both upstream, to the Nueces River, and downstream, to Rincon Bayou. Adams and Tunnell (2010) found that approximately 20% of pumped inflow goes back upstream rather than downstream into Rincon Bayou. The USGS Rincon Channel Gage records downstream flows into Rincon Bayou as positive values and inflows back upstream into the Nueces River as negative values (Fig. 9). To prevent pumped water from going upstream, in July 2014 a freshwater inflow management structure (back-flow preventer) consisting of box culverts with gates that are closed was installed at the RBP outfall in Nueces Delta Preserve (Lewis 2014; Hill et al. 2012). The structure reduced the amount of pumped inflow going back upstream as well as reducing natural inflows into Rincon Bayou (Montagna et al. 2015). The gap in the USGS Gage reading in Figure 6 depicts the time in which the structure was in place. The back-flow preventer washed out in the July 2015 flooding (Allen and Mooney personal communication) resulting in increased natural flows both upstream and downstream.

4.3. Management Models

The environmental flow management approach used in Texas has been an example of a resource-based approach, in which freshwater inflow is linked directly to valued resources. The mathematical programing model for estimating freshwater inflow needs for Texas estuaries is based on key indicator of estuarine conditions; frequency of marsh inundation, salinity, historical monthly inflow, and the assessment of historical commercial fishery harvest (Martin 1987). They recommended the annual freshwater needs of the Nueces Estuary to be approximately 1.24×10^9 m^3 (Martin 1987). This is more than the target pass-through (>70% capacity) required amount of 1.70×10^8 m^3/year by the Agreed Order (TNRCC 2001). The monthly targets were developed by the TWDB and TPWD in 1990 to maximize biological benefits for species inhabiting the estuary (NBBASC 2012). The Texas Estuarine Mathematical Programming (TxEMP) model and the hydrodynamic circulation model (TxBLEND) were used to establish a water-release policy from Choke Canyon Reservoir and Lake Corpus Christi to the Nueces Estuary (Powell et al. 2002; Pulich Jr. et al. 2002). TxEMP is a non-linear optimization model and was used in conjunction with TxBLEND to evaluate freshwater inflows needed to maintain salinity gradients and fisheries harvest in Texas bays and estuaries (NBBASC 2012).

The model uses relationships between historic monthly inflow and the catch of commercially-important fisheries species (Pulich Jr. et al. 2002); however fish are motile and therefore are not reliable indicator species for habitat quality, since they can leave with conditions become unfavorable. Benthic macrofauna are sedentary and thus respond to local environmental conditions which give a record of changes overtime (Bilyard 1987; Montagna et al. 2002). Benthos are especially sensitive to changes in inflow, and can be useful in determining its effects on estuarine systems over time (Remane and Schlieper 1971). The correlation of environmental flow, salinity gradients, and other freshwater inflow factors with benthic macrofauna species provides better evidence of the freshwater inflow regimes necessary for the maintenance of estuarine health (Poff et al. 1997; Pulich Jr. et al. 2002).

4.4. Operator Constraints

The RBP became operational in late 2007 with only one pumping event occurring during the first year due to a persistent drought limiting freshwater supply (NBBASC 2012). The concept of banking water during regional wet periods for future use during regional dry periods was implemented in 2010 (Tunnell and Lloyd 2011; Lloyd et al. 2013). Water scheduled for "pass-through" to the Nueces Delta, based on the reservoir storage capacity level, was held and not pumped into Rincon Bayou, providing the opportunity to release small quantities of water on a monthly or seasonal basis (Tunnell and Lloyd 2011). This was shown to be beneficial and recommended to be a permanent management tool (Tunnell and Lloyd 2011), however in April 2013, the Nueces Advisory Council (NEAC) was asked by TCEQ to suspend water banking and to continue operating under the 2001 Agreed Order allowing the scheduled water to be pass-through (Lloyd et al. 2013).

The Rincon Bayou pump station is controlled by operations at Wesley Seale Dam near Mathis Texas. The Daily Reservoir System and Pass-Thru Status Report generated by the Nueces River Authority is used as a guide as to what amount to release based on target pass-through return flow credits, and salinity relief credits (Lozano personal communication). Pumping events are typically activated when salinities in the Nueces Delta reach a certain threshold (> 30 psu) and when reservoir levels and rainfall events allow for "pass-through" conditions (Lloyd et al. 2013). The current method of pumping is based on an accounting perspective, where credits and deficits are displayed on the report and operators are given 10 days into the following month to make up deficits. Therefore, water is often held till the end of the month and then released all at once to fulfill the deficit before the deadline (Lozano personal communication). Pumping coincides with rainfall (Fig. 7) in which the pumps are turned on when it rains because the water is available, and in times of low rainfall pumping does not occur (Lozano personal communication).

Rainfall is taken into account by the 2001 Agreed Order in which pass-through requirements require that less water be released downstream for the estuary when there is less rainfall (TNRCC 2001). The reservoir must meet certain capacities for pass-through to be required, thus if there is not water coming into the reservoir, water does not have to be released (Lloyd et al. 2013). This is counterintuitive and releases should be made to supply the estuary in times of drought (Allen and Mooney personal communication). This approach has established a method of providing water to the estuary during wet periods and not providing water when it is needed during dry periods.

Currently, the RBP pumps must be manually turned on and off from the pump station that is located next to Edward's Pump station along I37 (Fig. 3) (Lozano personal communication).

At a minimum, the pumps are turned on every three months for 15 minutes resulting in pumped inflow of 56.8 m^3/s for pump maintenance (Lozano personal communication). During the flooding in 2015, the pumps were left on continuously from May 12th to June 15th to keep from flooding the pump station (Lozano personal communication). This resulted in a total of 10.96 x 10^6 m^3 (8,884 ac-ft) (Table 2) being pumped into Rincon Bayou coupled with 205 cm of rainfall recorded at NUDEWX (Fig. 3). The USGS Rincon gage was inoperable from May 21st to June 16th (USGS 2015), so it is not known how much natural inflow entered from the Nueces River. The inflow management structure (back-flow preventer) that was installed in July of 2014 washed out in the flooding July 2015 (Fig. 6) and was reinstalled in spring of 2016 (Allen and Mooney personal communication). The back-flow preventer is controlled by the Costal Bend Bays and Estuaries Program (CBBEP) and consists of three manual control gates that are to be closed when pumping is occurring and reopened when pumping stops. Due to lack of knowledge of when pumping events are going to occur, operation of the gates often does not coincide with pumping (Allen and Mooney personal communication).

4.5. Pumping Constraints

The RBP pumping station includes three 350 horsepower pumps, capable of delivering a minimum of 1.8 m^3/s (126 ac-ft/day) with one pump operating, 2.9 m^3/s (203 ac-ft/day) with two pumps in operation, and 3.8 m^3/s (266 ac-ft/day) with three pumps in operation (Table 11) (Tunnell and Lloyd 2011). With the current pumping capabilities this will result in a maximum salinity of around 0.5 psu and a depth of 1.05 m (41.34 inches) if one pump is operating continuously. The maximum salinity for Station C in Rincon Bayou was found to be 20 psu and the maximum depth was found to be 0.5 m (19.7 inches), with the optimum salinity range for the current study being between 1 and 15 psu for biomass and 1 and 14 psu for abundance, and an optimum depth of 0.05 to 0.2 m (2 to 7.9 inches) for both (Table 10). An inflow rate on the order of 0.41 m^3/s (28.72 ac-ft/day) would achieve a value in both the optimal salinity and depth range, with salinity at approximately 2.2 psu and a depth of approximately 0.2 m (7.9 inches) (Fig. 18). However, to decrease the inflow from 1.8 m^3/s (126 ac-ft/day) to 0.41 $m^{3/}s$ (28.72 ac-ft/day) redesigning the pump station and reducing the pump size would be required (Allen and Mooney personal communication).

With the current pumping capacity, at most one pump should be used and ran continuously to create a stable environment in the upper delta. Running one pump continuously would result in an inflow rate of 1.8 m^3/s (126 ac-ft/day) which would deliver the required 3.7 x 10^6 m^3 (3,000 ac-ft) per month in approximately 24 days, and pump an access of 0.99 to 1.11 x 10^6 m^3/s (800 to 900 ac-ft) per month. Adams and Tunnel (2010) found that it takes approximately 27 days to pump the required 3.7 x 10^6 m^3 (3,000 ac-ft) with one pump in operation which is slightly more than the estimated 24 day from this study. Reducing the pumping capacity to pump the 0.41 m^3/s (28.72 ac-ft/day) continuously would result in approximately 1.06 x 10^6 m^3/s (862 ac-ft) per month of water being delivered to the upper delta. This does not meet the 2001 Agree Order's pass-through requirement of 3.7 x 10^6 m^3 (3,000 ac-ft) per month.

5. Conclusion

The primary source of freshwater into Rincon Bayou is from pumped inflow, thus salinity and depth can be altered in direct response to management actions. Rincon Bayou has transitioned to a positive estuary with pumped inflow, but still occasionally exhibits reverse estuary conditions where salinity can fluctuate from fresh to hypersaline, and hypersaline to fresh in very short time periods when pumping is not occurring. Pumping has restored ecological function to Rincon Bayou by increasing inflow and decreasing salinity, but causes these extreme fluctuations. Salinities decrease immediately when pumping begins and remain low until the pumps are shut off, and then steadily increase until the pumps are turned back on. Other studies show that once the pumped are shut off it take salinities in Rincon Bayou about 20 days to reach within 5 psu of Nueces Bay salinities (Adams and Tunnell 2010; Tunnell and Lloyd 2011). Salinity fluctuations are a disturbance to benthic communities (Boesch et al. 1976; Harrel et al. 1976; Matthews and Fairweather 2004). Based on the low species diversity and frequent fluctuations in abundance and biomass of the indicator species the current method of pumping into Rincon Bayou is creating a disturbed estuary in which benthic succession dynamics are interrupted (Ritter et al. 2005).

There are several recommendations that can be made to improve the ecosystem health and create a stable environment in the upper delta of Rincon Bayou based upon results presented here and a review of previous studies. 1) to improve ecological stability: inflows should be a trickle, not a flood, releases should be continuous and not haphazard, only one pump should be used at a time, and releases should not be dependent on pass-through requirements; 2) to maximize ecological function: salinity should be maintained under 20 psu, and water depth should be maintained between 0.05 m and 0.2 m; 3) to maintain ranges: inflows rates on the order of ≥ 0.00102 m^3/s (0.084 ac-ft/day) are required for salinities ≤ 20 psu, inflows on the order of ≤ 0.689 m^3/s (48.261 ac-ft/day) are required to for a depth ≤ 0.5 m, and inflow on the order of 0.41 m^3/s (28.72 ac-ft/day) would obtain an optimal value for both salinity at 2.2 psu and depth at 0.2 m (7.9 inches).

This study only focused on Station C in Rincon Bayou which is located at the pumping outfall and did not look at downstream effect of pumping. The values obtained here are for this specific area, and for the estuary as a whole, other factor must be taken into account. Environmental factors that influence the spatial coverage of the RBP should be considered when scheduling a pumping release, such as: wind speed and directions, tide level, and rainfall (Hill et al. 2015; Tunnell and Lloyd 2011). This study did not take into account biodiversity but instead looked at whether or not benthos were present at given salinity and depth values. The most numerically dominant species were considered indicator species and their optimal values were predicted using the max bin method. These values were then combined to determine an optimal salinity and depth range for the production of the presence of benthos (Table 10).

Concern over anthropogenic changes to the environment has grown over recent decades, and ever-increasing environmental legislation has brought concern about ecosystem health to the forefront of both scientific and political spheres (Lackey 2001; Montagna et al. 2002a; Farber et al. 2006). The 1957 Texas Water Planning Act led to the establishment of environmental flow requirements which described the quantity, timing, and quality of water flows required to sustain an estuarine ecosystem and the human livelihoods that depend on these ecosystems (Dyson et al. 2008; Alber 2002; Powell et al. 2002; Montagna et al. 2002). The 2007 Senate Bill 3 process utilizes adaptive management, using the results of ongoing monitoring and assessment to modify and optimize the operating decisions, and allows for the ability to tie biological data to observable inflow which is critical for environmental flow management (NBBASC 2012; Kimmerer 2002; Montagna et al. 2002a; Pahl-Wostl 2007).

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Table 1. Hydrology data obtained from the listed sources for the date range specified on 11 January 2016.

Name	Hydrological Parameter	Recorded Interval	Date Range	Agency	Website
Rincon Bayou Pipeline (RBP)	Pumped Inflow	Daily total (Acre-ft/day)	Sept. 2009 - Dec. 2015	Nueces River Authority (NRA)	http://www.nueces-ra.org/CP/CITY/rincon/
USGS Rincon Channel Gage	Natural Inflow and Discharge	Mean daily rate (f ^{3}/sec)	Sept. 2009 - Dec. 2015	United States Geological Survey (USGS)	http://nwis.waterdata.usgs.gov
NUDE2 SALT03	Salinity	Every 15 minutes (psu)	May 2009 - Dec. 2015	Conrad Blucher Institute for Surveying and Science (CBI)	http://www.cbi.tamucc.edu/dnr/station
NUDEWX	Computed Cumulative Rainfall	Daily total at midnight (cm)	Jan. 2014 - Dec. 2015		

Table 2. Rincon Bayou Pipeline pumping events from the Nueces River Authority. A test run was conducted in 2007 with the pipeline becoming operational in September 2009.

Pumping Event Number	Duration	Number of Days of Inflow	Total Pumped Inflow Ac-ft / day	Total Pumped Inflow ft^3/s (cfs)	Total Pumped Inflow m^3/s (cms)
0	April 17, 2007	1	36	18.15	0.51
1	Sept. 28 - Oct 21, 2009	24	2,987	1,506.05	42.65
2	Jan. 6 - Jan. 14, 2010	9	742	374.12	10.60
3	May 10 - May 31, 2010	22	2,288	1,153.61	32.67
4	March 21-March 30, 2010	10	1,006	507.23	14.37
5	May 3 - May 12, 2011	10	1,002	505.21	14.31
6	June 13 - June 22, 2011	10	994	501.17	14.19
7	Sept. 13 - Sept. 14, 2011	2	98	49.41	1.40
8	Nov. 2 - Nov. 22, 2011	21	2,027	1,022.01	28.95
9	March 7 - March 19, 2012	13	1,309	660.00	18.69
10	June 21 - July 13, 2012	23	2,354	1,186.89	33.62
11	Aug. 7 - Aug. 24, 2012	18	2,004	1,010.42	28.62
12	Aug. 27 - Aug. 28, 2012	2	109	54.96	1.56
13	Sept. 14 - Sept. 16, 2012	3	212	106.89	3.03
14	Sept. 30- Oct. 1, 2012	2	135	68.07	1.93
15	Oct. 5, 2012	1	36	18.15	0.51
16	Oct. 8 - Oct. 18, 2012	11	1,981	998.82	28.29
17	Oct. 27, 2012	1	27	13.61	0.39
18	Nov. 26, 2012	1	31	15.63	0.44
19	Dec. 8 - Dec. 9, 2012	2	95	47.90	1.36
20	Dec. 16 - Dec. 20, 2012	4	159	80.17	2.27
21	Jan. 15 - Jan. 16, 2013	2	62	31.26	0.89
22	Jan. 26 - Jan. 28, 2013	3	152	76.64	2.17
23	April 29, 2013	1	40	20.17	0.57
24	May 14 - May 15, 2013	2	15	7.56	0.21
25	June 1 - June 10, 2013	9	847	427.06	12.10
26	June 24 - July 2, 2013	8	731	368.57	10.44
27	July 17 - July 24, 2013	8	665	335.29	9.50
28	Aug. 12 - Aug. 13, 2013	2	161	81.18	2.30
29	Aug. 20 - Aug. 22, 2013	2	124	62.52	1.77
30	Aug. 27- Aug. 29, 2014	3	273	137.65	3.90
31	Sept. 12 - Sept. 13, 2013	2	161	81.18	2.30
32	Oct. 11, 2013	1	45	22.69	0.64
33	Oct. 21, 2013	1	27	13.61	0.39
34	Oct. 24 - Oct. 30, 2013	7	1,131	570.25	16.15
35	Nov. 2 - Nov. 9, 2013	8	1,190	600.00	16.99

36	Nov. 22 - Dec 1, 2013	9	509	256.64	7.27
37	Dec. 4, 2013	1	31	15.63	0.44
38	Dec. 7 - Dec 8, 2013	2	73	36.81	1.04
39	Dec. 17, 2013	1	17	8.57	0.24
40	Dec. 30 - Dec 31, 2013	2	107	53.95	1.53
41	Jan. 10 - Jan. 13, 2014	4	177	89.24	2.53
42	Jan. 21 - Jan. 22, 2014	2	89	44.87	1.27
43	Jan. 25 - Jan. 28, 2014	3	141	71.09	2.01
44	Feb. 3 - Feb. 15, 2014	13	2,466	1,243.36	35.21
45	Feb. 26 - Feb. 27, 2014	2	105	52.94	1.50
46	March 10, 2014	1	87	43.87	1.24
47	April 15, 2014	1	8	4.03	0.11
48	May 9 - June 3, 2014	24	2,736	1,379.49	39.07
49	June 23 - July 15, 2014	23	3,531	1,780.33	50.42
50	July 19 - July 21, 2014	3	177	89.24	2.53
51	Aug. 26, 2014	1	18	9.08	0.26
52	Sept. 24, 2014	1	66	33.28	0.94
53	Sept. 30 - Oct. 1, 2014	2	116	58.49	1.66
54	Oct. 4 - Oct. 6, 2014	3	264	133.11	3.77
55	Oct. 17, 2014	1	35	17.65	0.50
56	Jan. 18 - Jan. 27, 2015	9	695	350.42	9.92
57	March 10 - March 12, 2015	3	210	105.88	3.00
58	March 18 - March 25, 2015	8	1,535	773.95	21.92
59	April 13 - April 28, 2015	16	2,455	1,237.81	35.06
60	May 12 - June 15, 2015	35	8,884	4,479.31	126.86
61	Aug. 29 - Sept. 2. 2015	5	448	225.88	6.40
62	Sept. 21 - Sept. 22, 2015	2	167	84.20	2.38
63	Sept. 26 - Oct. 1, 2015	6	475	239.50	6.78
64	Oct. 17 - Nov. 10, 2015	25	3,734	1,882.68	53.32

Table 3. Sampling trip number with corresponding sample date for Station C, number of days between sampling trips, and total inflow into Rincon Bayou prior to the sampling trip.

Sampling Trip Number	Sampling Date	Number of Days Between Sampling	Total Inflow (Gage + RBP) (m^3/s)
0	11-May-10	-	-
1	28-Jun-10	48	26.27
2	25-Jan-11	211	5.66
3	25-Apr-11	90	12.82
4	25-Jul-12	457	100.97
5	5-Oct-12	72	32.34
6	24-Jan-13	111	32.59
7	9-Apr-13	75	4.20
8	29-Jul-13	111	29.70
9	25-Oct-13	88	16.96
10	29-Oct-13	4	11.03
11	12-Nov-13	14	15.73
12	26-Nov-13	14	5.68
13	10-Dec-13	14	3.18
14	19-Dec-13	9	0.07
15	2-Jan-14	14	1.22
16	16-Jan-14	14	1.75
17	31-Jan-14	15	2.21
18	14-Feb-14	14	30.08
19	28-Feb-14	14	0.14
20	17-Mar-14	17	0.61
21	31-Mar-14	14	1.09
22	14-Apr-14	14	-0.20
23	28-Apr-14	14	0.62
24	15-May-14	17	6.73
25	2-Jun-14	18	24.73
26	17-Jun-14	15	0.29
27	30-Jun-14	13	14.21
28	14-Jul-14	14	34.37
29	29-Jul-14	15	3.35
30	11-Aug-14	13	0.05
31	25-Aug-14	14	-0.43
32	8-Sep-14	14	0.42
33	22-Sep-14	14	0.22
34	6-Oct-14	14	6.77
35	20-Oct-14	14	0.72

36	3-Nov-14	14	0.04
37	18-Nov-14	15	0.02
38	2-Dec-14	14	0.37
39	15-Dec-14	13	0.34
40	5-Jan-15	21	0.36
41	16-Jan-15	11	0.07
42	2-Feb-15	17	10.31
43	16-Feb-15	14	0.16
44	3-Mar-15	15	0.17
45	16-Mar-15	13	3.06
46	30-Mar-15	14	21.92
47	10-Apr-15	11	-0.06
48	27-Apr-15	17	34.52
49	11-May-15	14	0.45
50	8-Jun-15	28	107.99
51	22-Jun-15	14	23.32
52	6-Jul-15	14	-4.49
53	27-Jul-15	21	-1.07
54	11-Aug-15	15	-0.27
55	24-Aug-15	13	-0.11
56	9-Sep-15	16	2.18
57	21-Sep-15	12	1.32
58	9-Oct-15	18	4.53
59	28-Oct-15	19	6.14
60	11-Nov-15	14	9.86
61	23-Nov-15	12	-1.55
62	7-Dec-15	14	-0.84
63	21-Dec-15	14	0.53

Table 4. Daily means for USGS Rincon Gage, CBI salinity stations (SALT03, NUDE2) and weather station (NUDEWX), Station C, and the Rincon Bayou Pipeline (September 2009 to December 2015).

Sampling Location	Number of Observations	Mean	Std Dev	Min. Mean	Max. Mean
USGS Rincon Gage (m^3/s)	2311	-0.02	0.32	-2.72	4.93
Rincon Bayou Pipeline - RBP (m^3/s)	457	1.71	0.97	0.03	5.04
Total inflow - Gage + RBP (m^3/s)	2311	0.31	0.79	-1.70	6.48
NUDEWX - Rainfall (cm)	2182	1.92	7.78	0.00	142.00
SALT03 - Salinity (psu)	2413	31.65	9.96	0.36	47.28
NUDE2 - Salinity (psu)	2301	23.22	18.17	0.00	86.29
Station C - Salinity (psu)	734	6.77	6.65	0.01	34.41
Station C - Depth (m)	734	0.48	0.24	0.00	1.82
Station C - Temperature (°C)	734	22.60	6.61	3.39	34.85

Table 5. Continuous sonde data at Station C in Rincon Bayou from January 2014 to December 2015.

Variable	Number of observations	Mean	Std Dev	Minimum	Maximum
Depth (m)	17810	0.49	0.24	0.00	1.86
Temperature (°C)	17810	22.50	7.08	1.44	41.96
Salinity (psu)	17810	6.74	6.81	0.00	46.38

Table 6. Discrete sonde data at Station C in Rincon Bayou from October 1994 to December 2015.

	Variable	Number of observations	Mean	Std Dev	Minimum	Maximum
Before pumping	Depth (m)	123	0.21	0.17	0.00	1.50
	Temperature (°C)	121	22.87	5.51	7.98	31.93
	Salinity (psu)	123	21.37	25.00	0.00	159.20
After pumping	Depth (m)	87	0.15	0.08	0.01	0.45
	Temperature (°C)	86	23.54	6.61	8.08	36.14
	Salinity (psu)	86	9.66	10.09	0.22	57.27

Table 7. Macrofauna data at Station C in Rincon Bayou (May 2010 to December 2015).

Species name	Total number (n)	Abundance (n/m^2)	Species % composition	Dry Wt (mg)	Dry Wt (g/m^2)
Streblospio benedicti	669	189755	44.3%	33.37	9.47
Chironomidae (larvae)	658	186682	43.6%	73.34	20.80
Laeonereis culveri	61	17207	4.0%	44.60	12.65
Mediomastus ambiseta	32	9076	2.1%	2.91	0.82
Nemertea (unidentified)	24	6807	1.6%	7.36	2.09
Oligochaeta (unidentified)	24	6665	1.6%	0.62	0.18
Mulinia lateralis	10	2695	0.7%	3.05	0.87
Ceratopogonidae (larvae)	10	2836	0.7%	1.49	0.42
Ostracoda (unidentified)	9	2553	0.6%	1.52	0.43
Hobsonia florida	9	2553	0.6%	1.32	0.37
Farfantepenaeus setiferus	1	284	0.1%	27.49	7.80
Americamysis almyra	1	284	0.1%	0.07	0.02
Palaemonetes sp.	1	284	0.1%	0.15	0.04

Table 8. Macrofauna data at Station C in Rincon Bayou for the bi-weekly sampling regime (October 2013 to December 2015).

Species name	Total number (n)	Abundance (n/m^2)	Species % composition	Dry Wt (mg)	Dry Wt (g/m^2)
Chironomidae (larvae)	609	172595	50.6%	66.85	18.96
Streblospio benedicti	470	133405	39.0%	27.49	7.80
Laeonereis culveri	58	16357	4.8%	44.37	12.59
Oligochaeta (unidentified)	18	5106	1.5%	0.44	0.12
Nemertea (unidentified)	14	3829	1.2%	3.84	1.09
Ceratopogonidae (larvae)	10	2836	0.8%	1.49	0.42
Hobsonia florida	9	2553	0.8%	1.32	0.37
Mediomastus ambiseta	8	2269	0.7%	0.54	0.15
Mulinia lateralis	3	851	0.3%	1.81	0.51
Ostracoda (unidentified)	3	851	0.3%	0.23	0.07
Americamysis almyra	1	284	0.1%	0.07	0.02
Palaemonetes sp.	1	284	0.1%	0.15	0.04

Table 9. Parameter estimates for the log-normal model in Figures 15-17 using the max bin method. Where *a* is the peak value, *b* is the rate of change of the response, and *c* is the location of the peak response value for the physical variable (x) and the biological variable (y) for each of the indicator species. Bi-weekly sampling regime (October 2013 to December 2015).

Indicator Species	Variables X	Variables Y	# of Bins	Approx. Pr > F	Biomass Parameters *a* *peak*	*b* *skewness*	*c* *optimal x*	Variables X	Variables Y	# of Bins	Approx. Pr > F	Abundance Parameters *a* *peak*	*b* *skewness*	*c* *optimal x*
Streblospio benedicti	psu	g/m^2	5	0.1113	0.67	0.53	14.14	psu	n/m^2	5	0.1836	10.36	0.77	13.49
	°C	g/m^2	5	0.0035	0.59	0.49	14.83	°C	n/m^2	10	<.0001	9.41	1.02	18.15
	m	g/m^2	5	0.0193	0.56	0.62	0.12	m	n/m^2	5	0.0015	9.48	2.18	0.12
Chironomidae Larvae	psu	g/m^2	12	0.0026	1.44	0.97	1.81	psu	n/m^2	10	0.0157	9.96	1.99	1.84
	°C	g/m^2	6	0.0008	1.48	0.42	15.32	°C	n/m^2	6	0.0002	10.73	0.80	15.55
	m	g/m^2	6	0.0408	1.52	0.66	0.10	m	n/m^2	8	0.0047	11.34	1.00	0.09
Laeonereis culveri	psu	g/m^2	13	<.0001	0.82	0.84	5.38	psu	n/m^2	8	0.0142	9.02	0.71	11.55
	°C	g/m^2	8	0.0035	0.80	0.32	18.03	°C	n/m^2	5	0.0044	8.42	0.59	17.65
	m	g/m^2	10	0.0003	0.82	0.62	0.09	m	n/m^2	9	0.0007	8.21	1.10	0.08

Table 10. Summary of the optimal values for the indicator species and maximum values for salinity and depth.

Indicator species	Optimal Salinity (psu)	Optimal depth (m)	Optimal depth (inches)
Biomass	1 - 15	0.05 - 0.2	2 - 7.9
Abundance	1 - 14	0.05 - 0.2	2 - 7.9
Maximum	20	0.5	19.7

Table 11. Summary of the RBP pumping capacity with resulting salinity and depth values for Station C.

Number of pumps in operation	Minimum pumping capacity (m^3/s)	Minimum pumping capacity (ac-ft/day)	Maximum salinity (psu)	Maximum depth (m)	Maximum depth (inches)
1	1.8	126	0.5	1.05	41.34
2	2.9	203	0	1.35	53.15
3	3.8	266	0	1.50	59.06

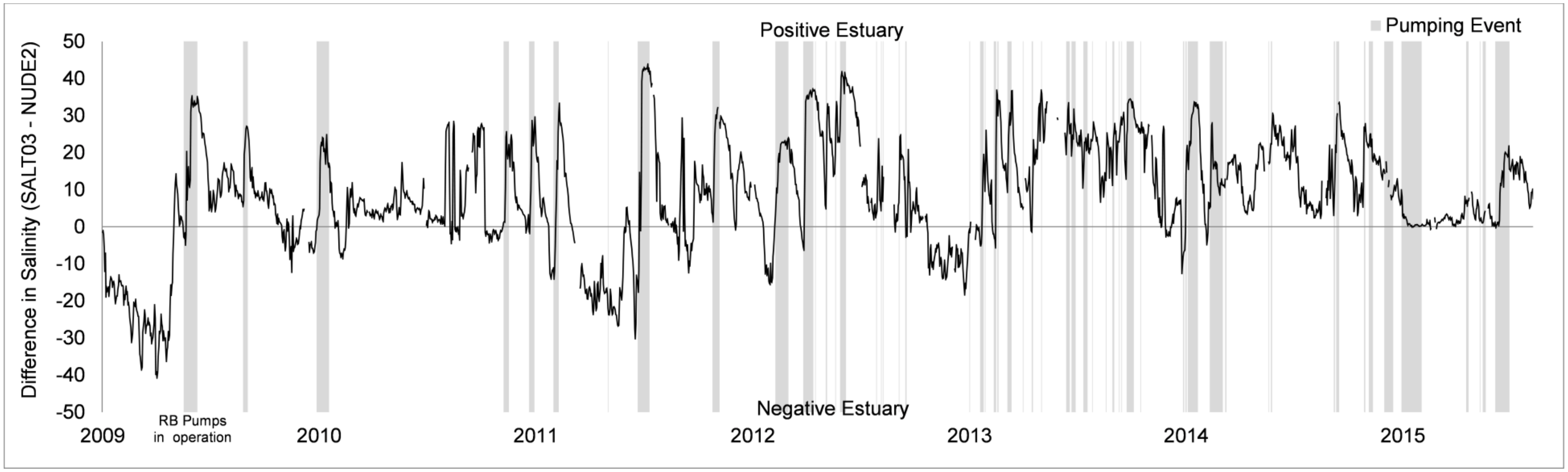

Figure 4. Salinity gradient (i.e., difference between downstream SALT03 and upstream NUDE2) and pumping event daily totals May 2009 to December 2015. The Rincon Bayou pipeline became operational in September 2009. The width of the box indicates pumping event duration.

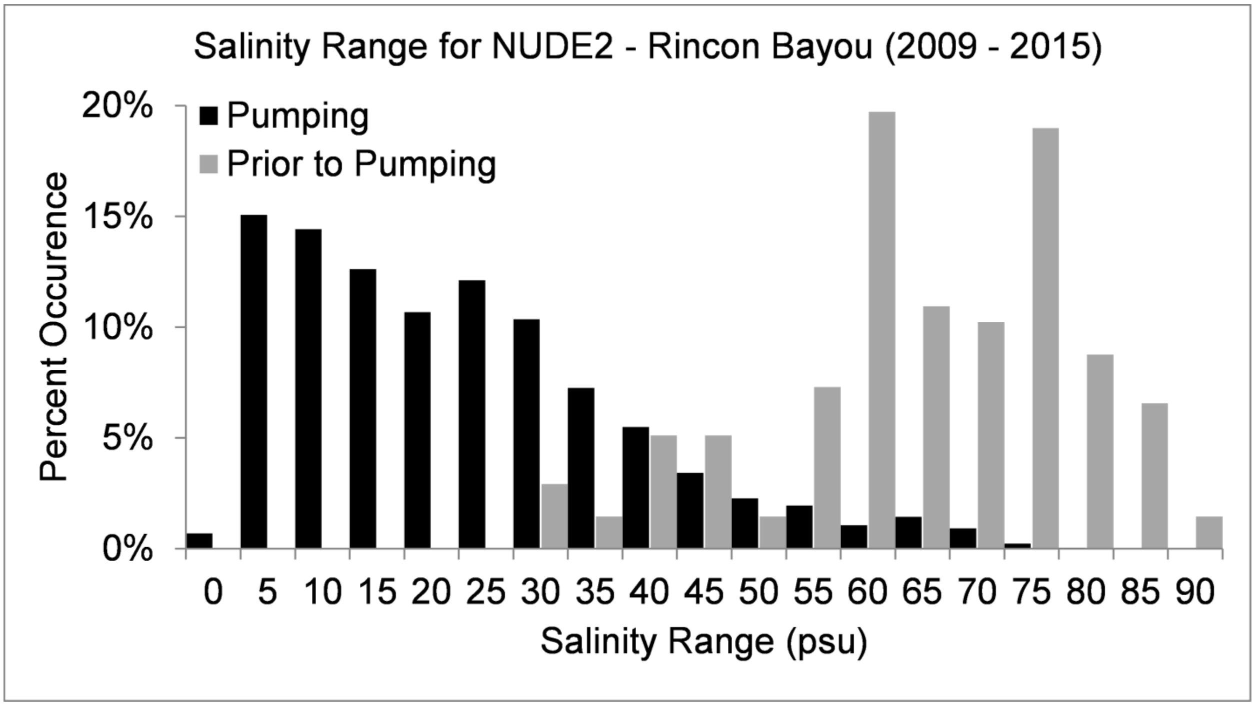

Figure 5. Percent occurrence of salinity ranges in Rincon Bayou (NUDE2) from May 2009 to December 2015.

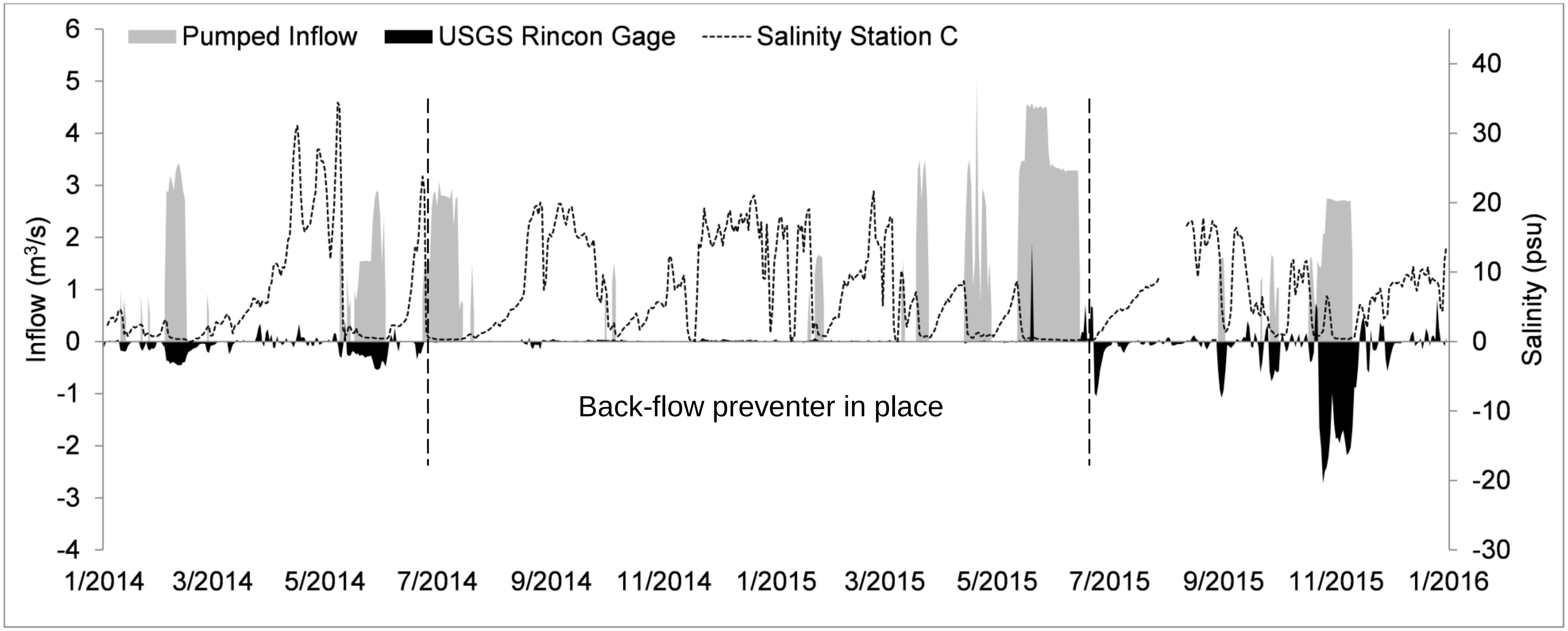

Figure 6. Salinity at Station C in Rincon Bayou TX, with inflow and discharge from the Rincon Bayou channel gage and pumped inflow, January 2014 to December 2015. Back-flow preventer was installed in July 2014 which accounts for the decreased gauge readings. It became inoperable in the flooding of summer 2015.

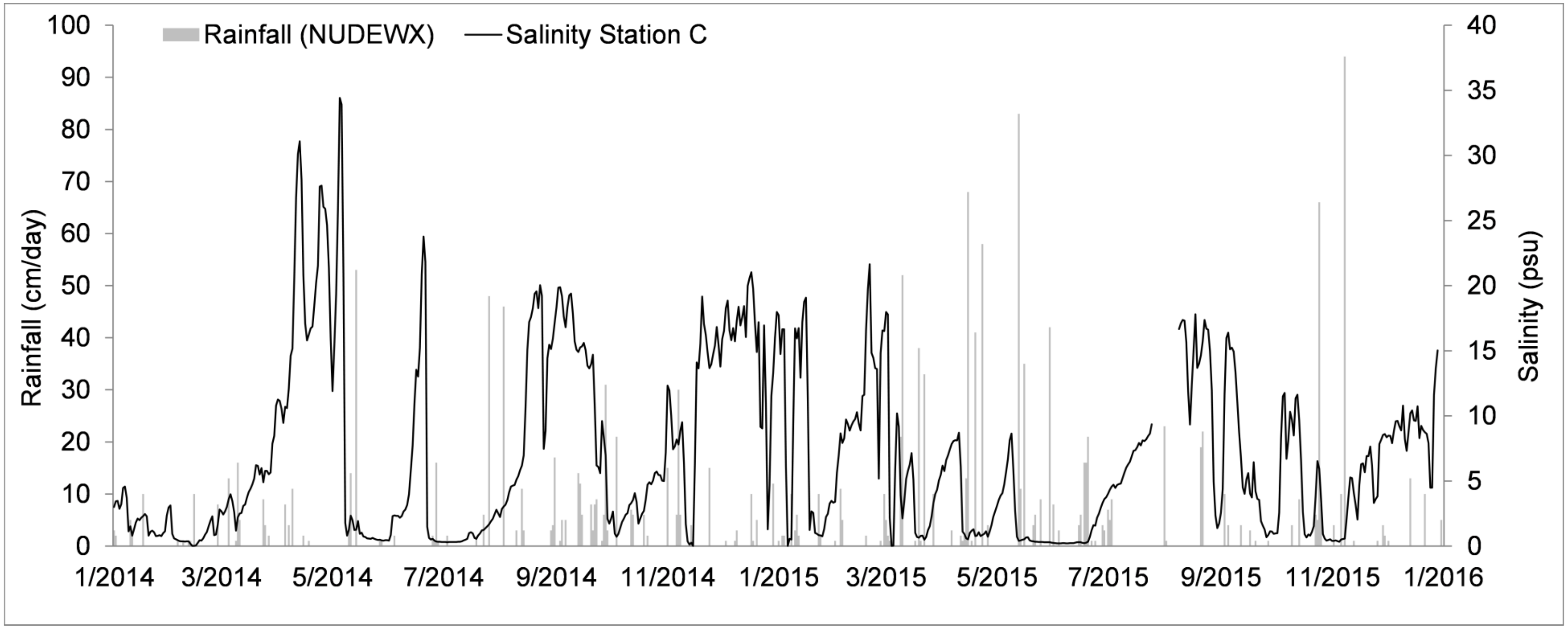

Figure 7. Salinity at Station C in Rincon Bayou TX, with daily total rainfall from CBI NUDEWX Station, January 2014 to December 2015.

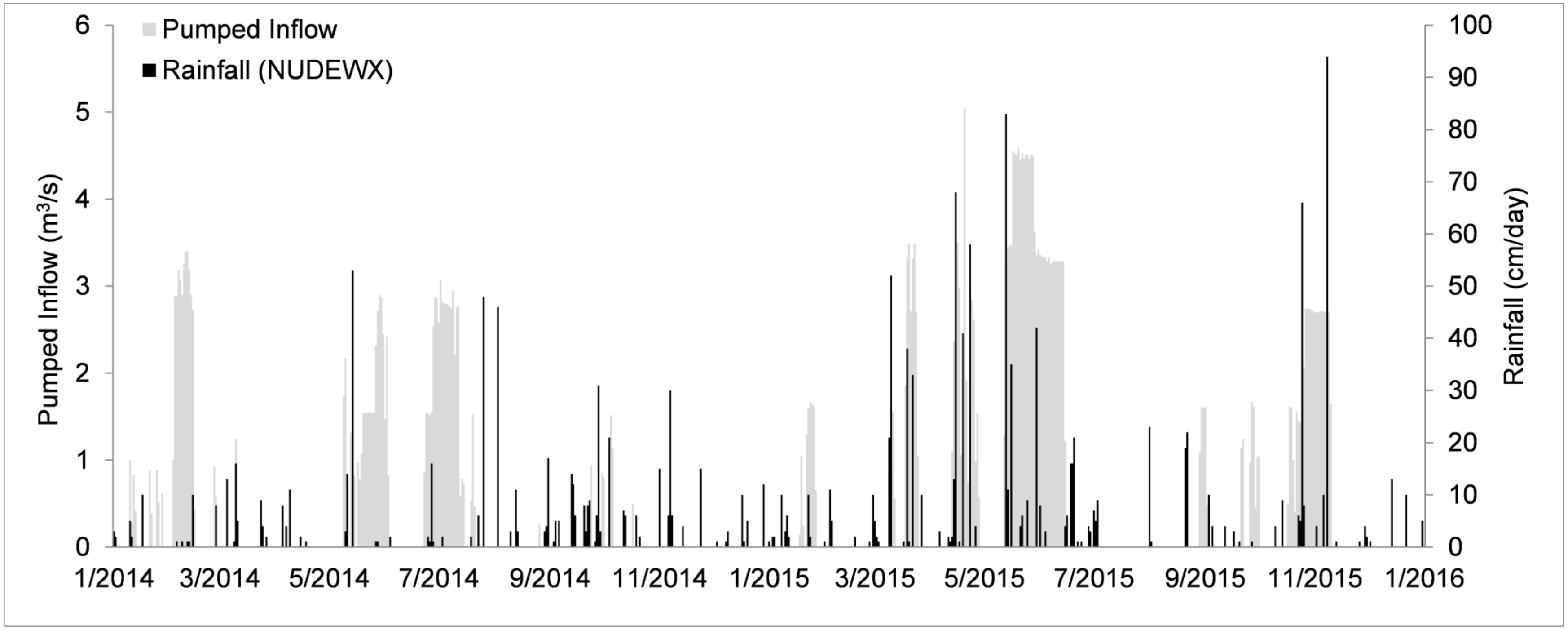

Figure 8. Pumped inflow into Rincon Bayou, TX with daily total rainfall from CBI NUDEWX Station, January 2014 to December 2015.

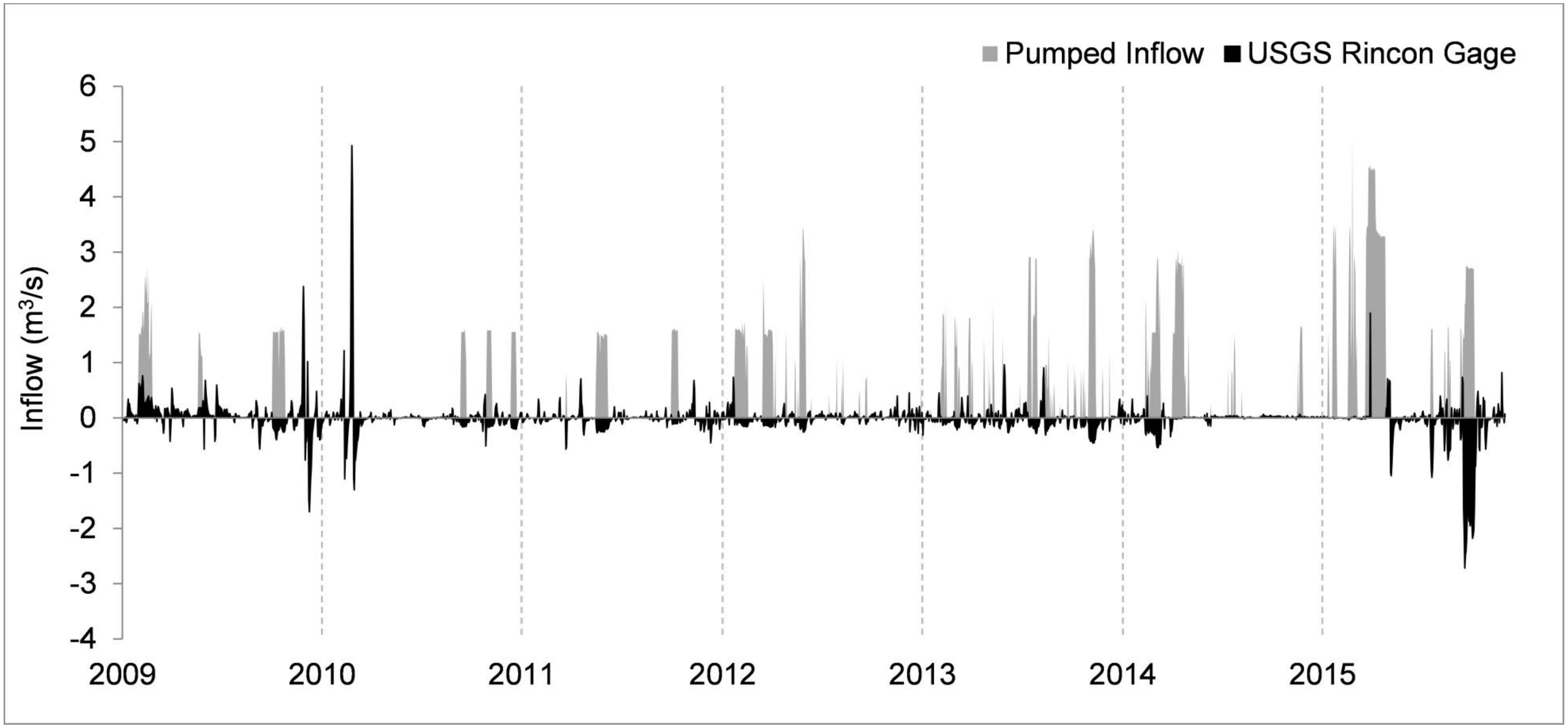

Figure 9. Inflow (+) and discharge (-) at the USGS Rincon Bayou Channel Gage, and pumped inflow, September 2009 to December 2015.

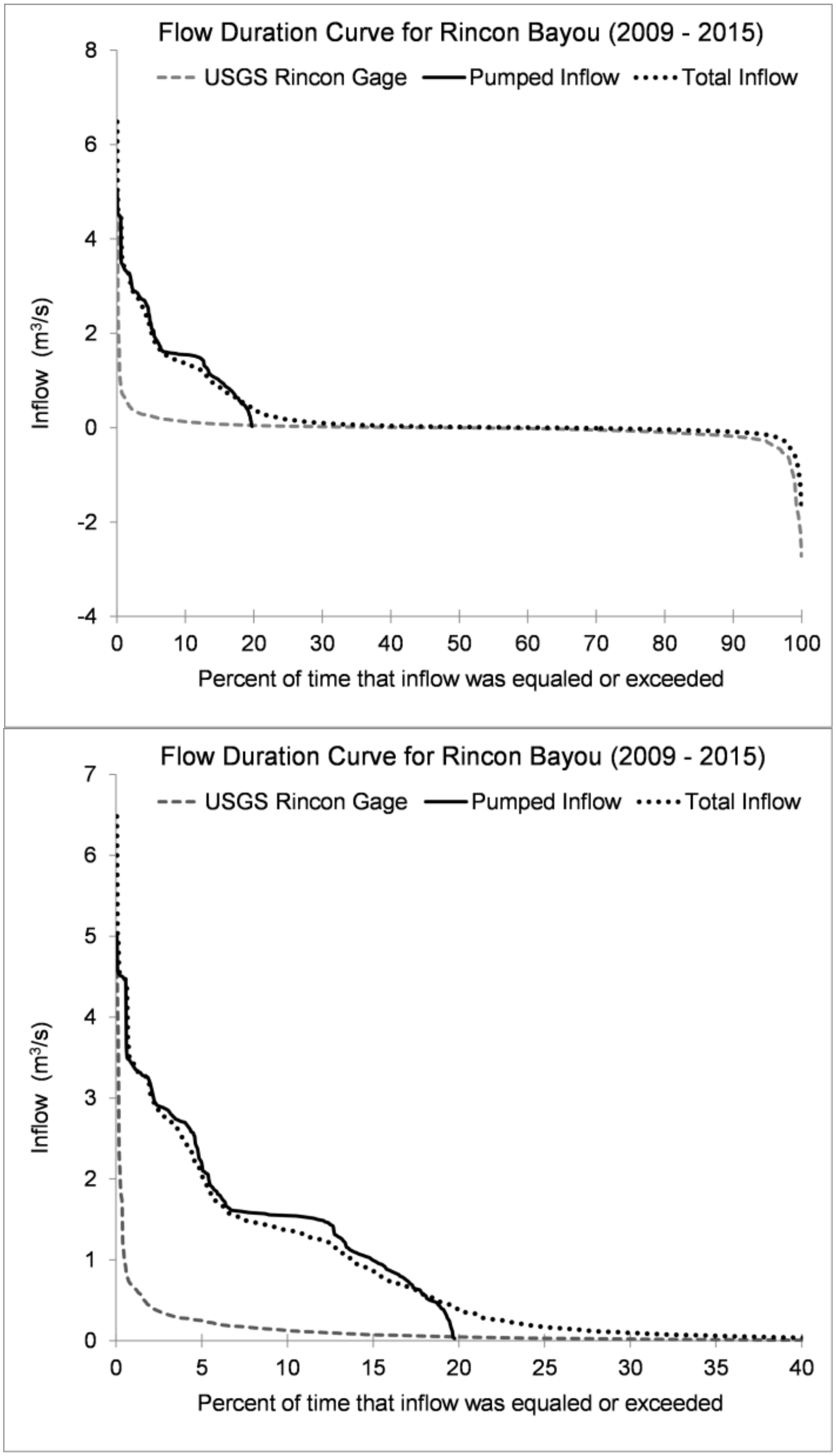

Figure 10. Flow duration curve for Nueces River inflow (+) and discharge (-) at the Rincon Bayou Channel Gage, September 2009 to December 2015. Top: full inflow scale. Bottom: zoom to positive inflow values only.

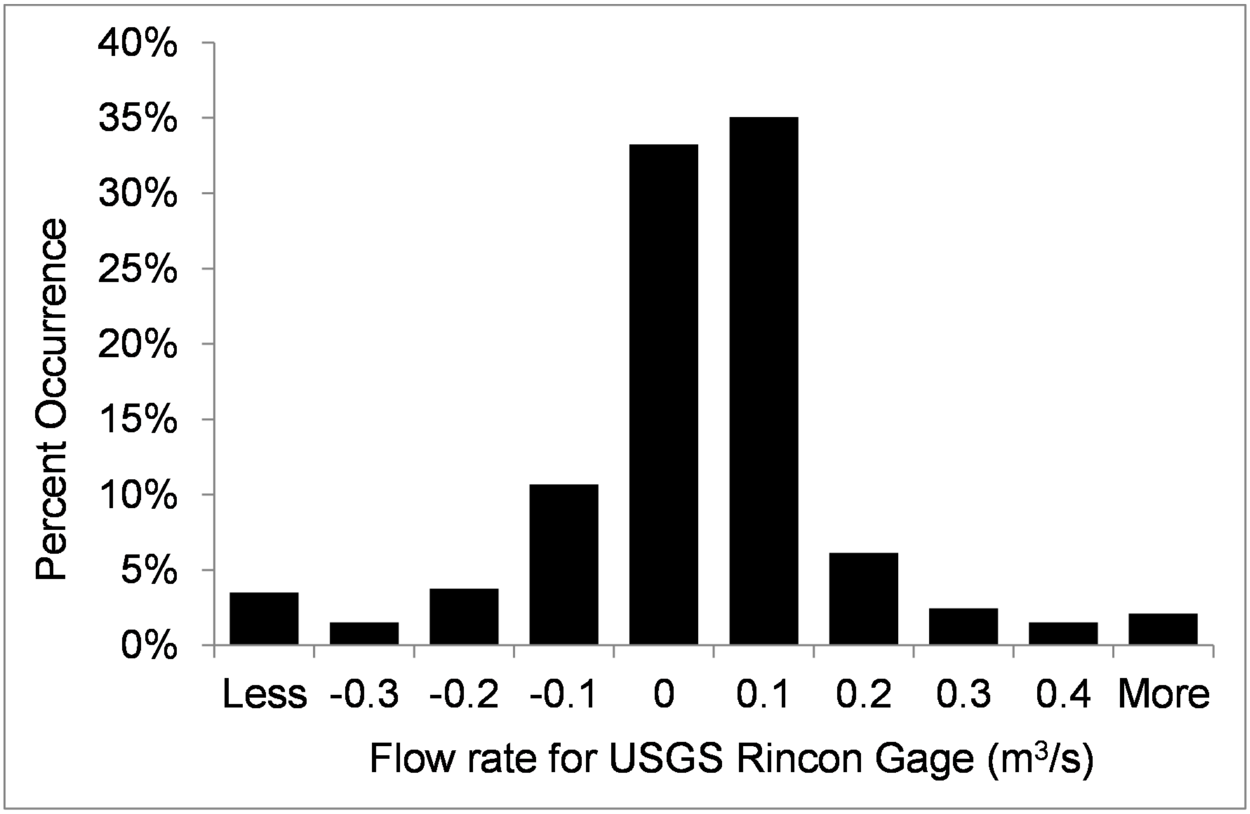

Figure 11. Percent occurrence for Nueces River flow rate at the Rincon Bayou Channel Gage September 2009 to December 2015.

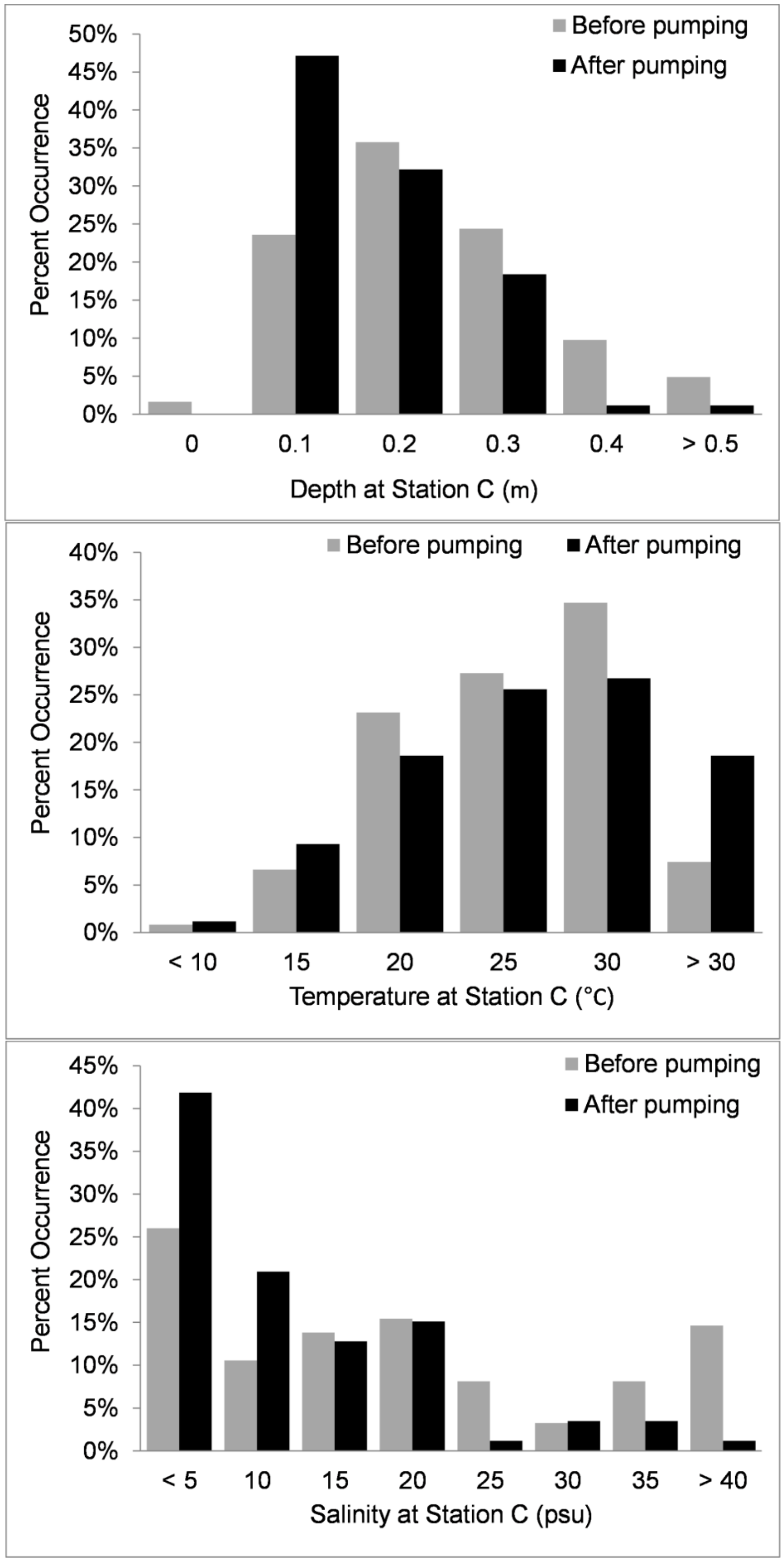

Figure 12. Percent Occurrence of (a) depth (b) temperature, and (c) salinity ranges at Station C in Rincon Bayou, before pumping began (October 1994 to August 2009) and after pumping began (September 2009 to December 2015).

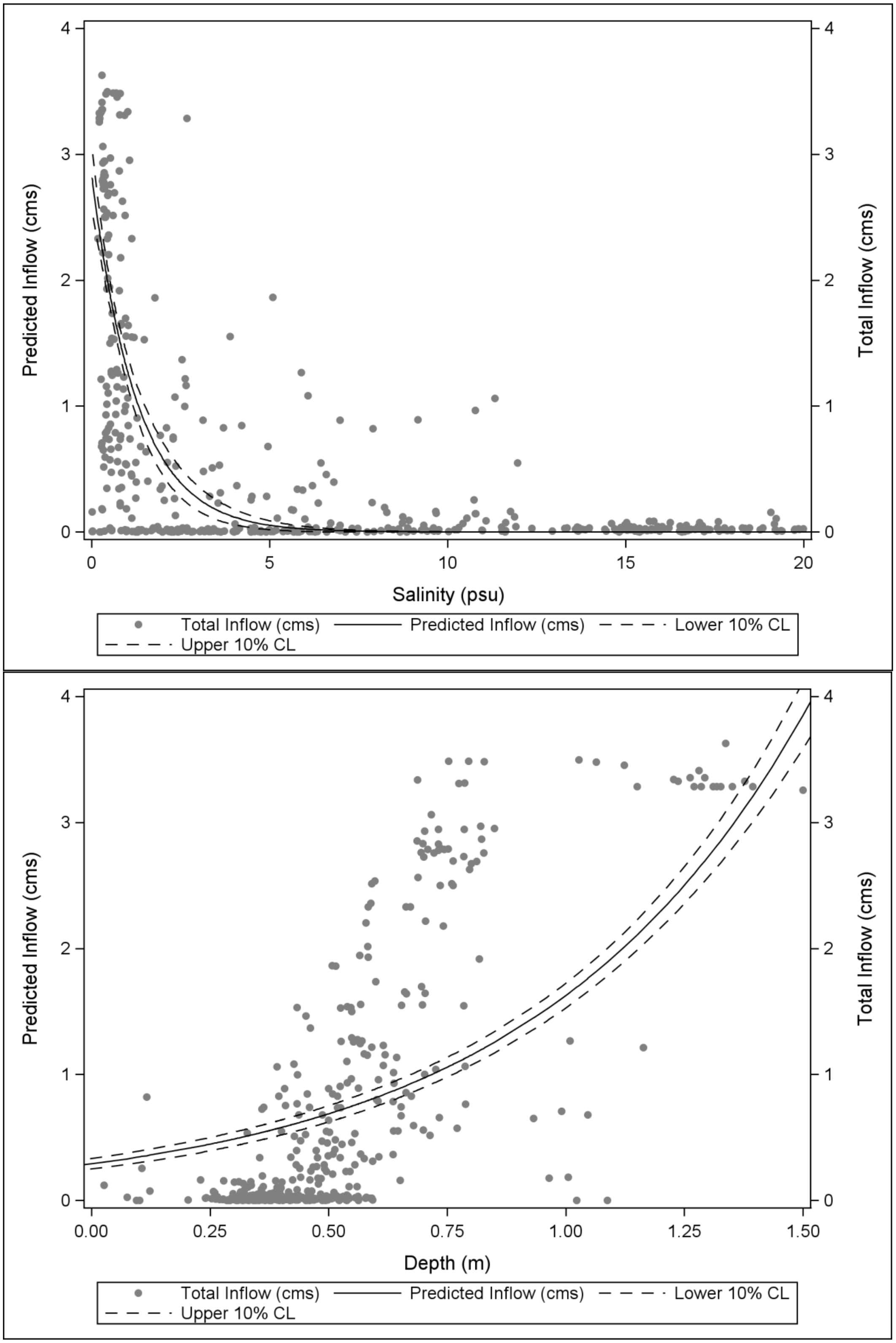

Figure 13. Prediction of inflow needed to produce salinities in the range of 0 to 20 psu (top) and water depths less than 1.50 m (bottom) in Rincon Bayou using the regression equations: inflow = a*exp(-b*Sal) and inflow = a*exp(-b*Depth). Bi-weekly sampling regime (October 2013 to December 2015).

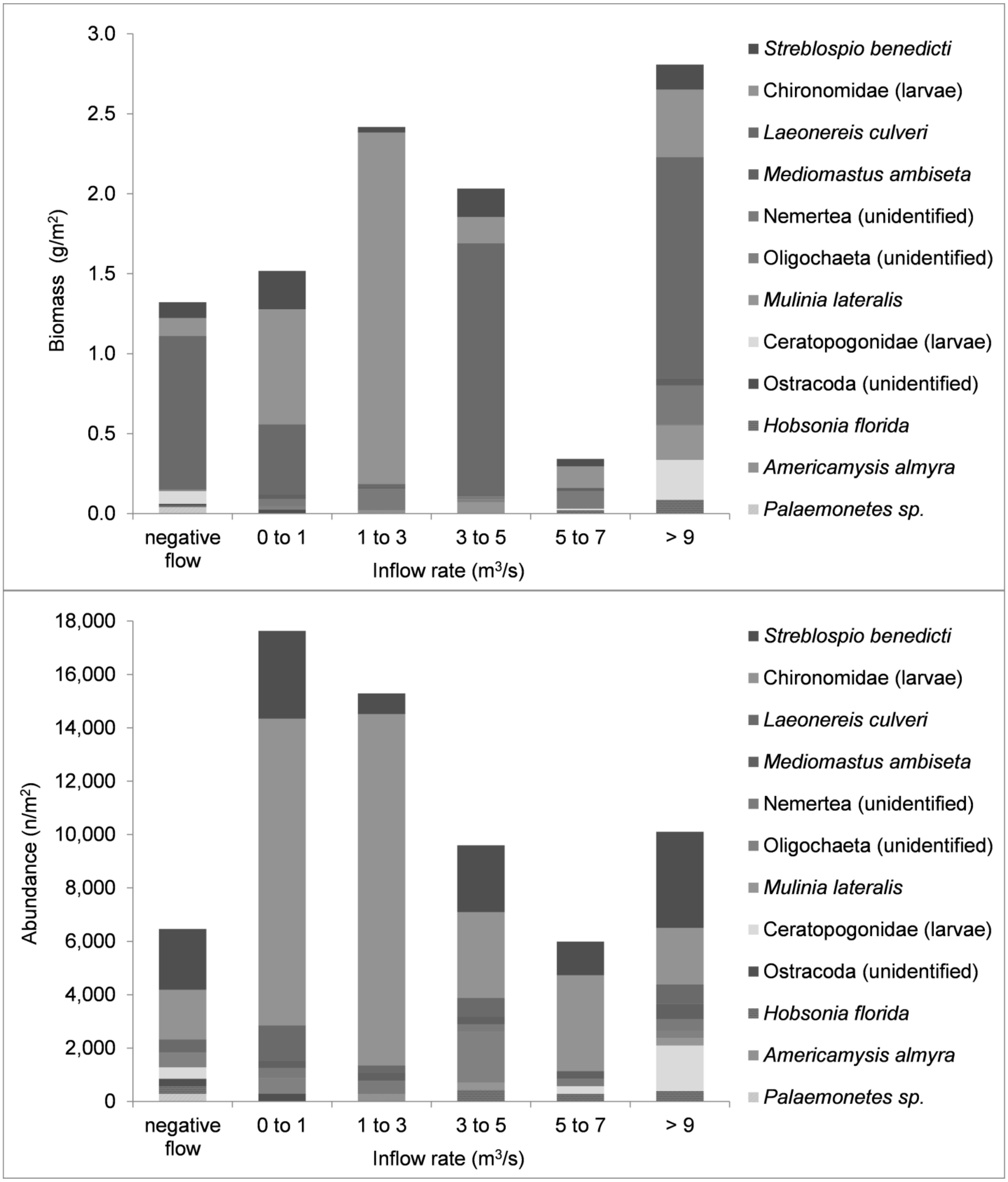

Figure 14. Species community structure (top) biomass and (bottom) abundance with inflow rates into Rincon Bayou. Bi-weekly sampling regime (November 2014 to December 2015).

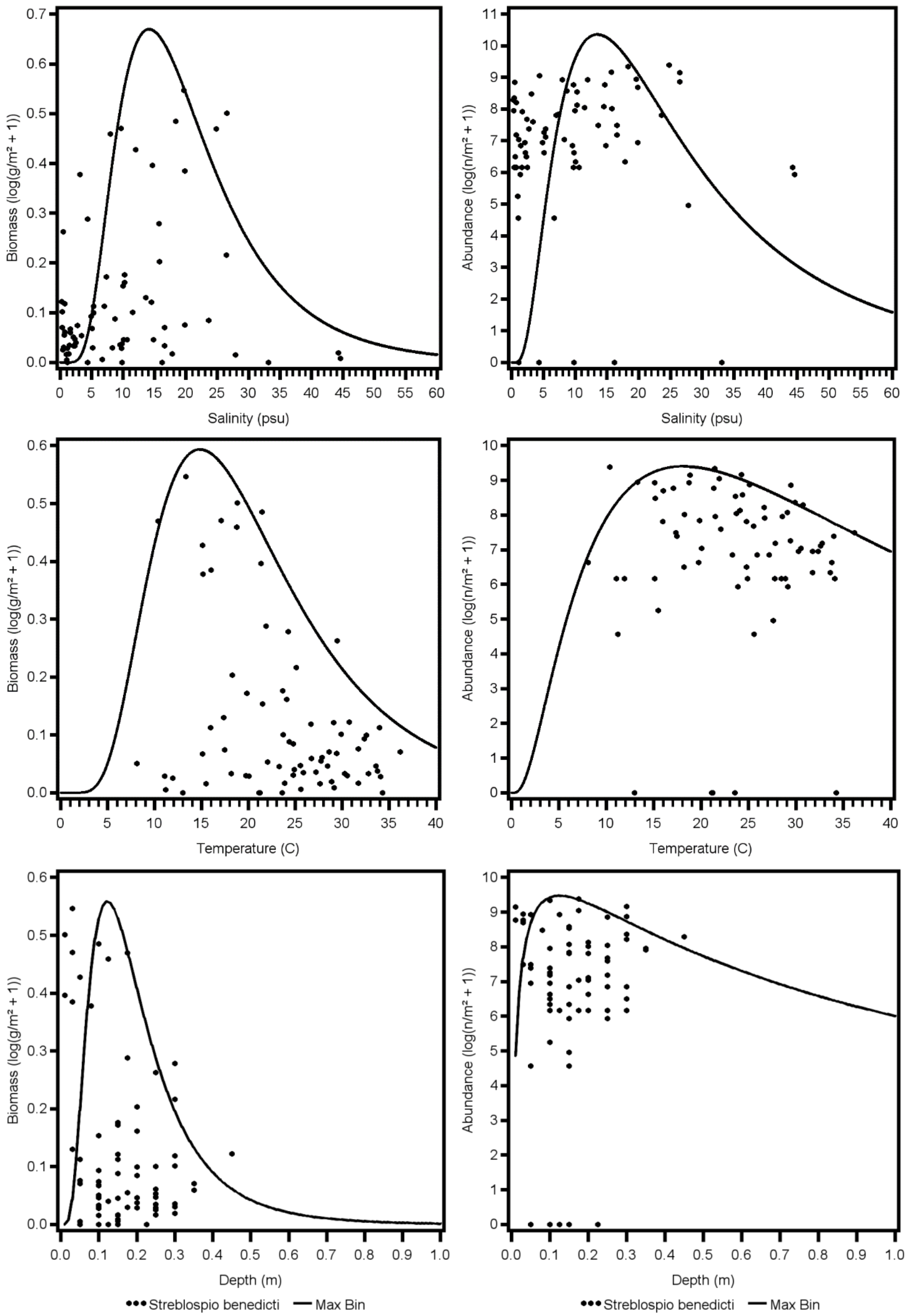

Figure 15. Relationship between hydrographical variables (salinity, temperature, depth) with (left) biomass and (right) abundance for *Strebiospio benedicti*, October 2013 to December 2015.

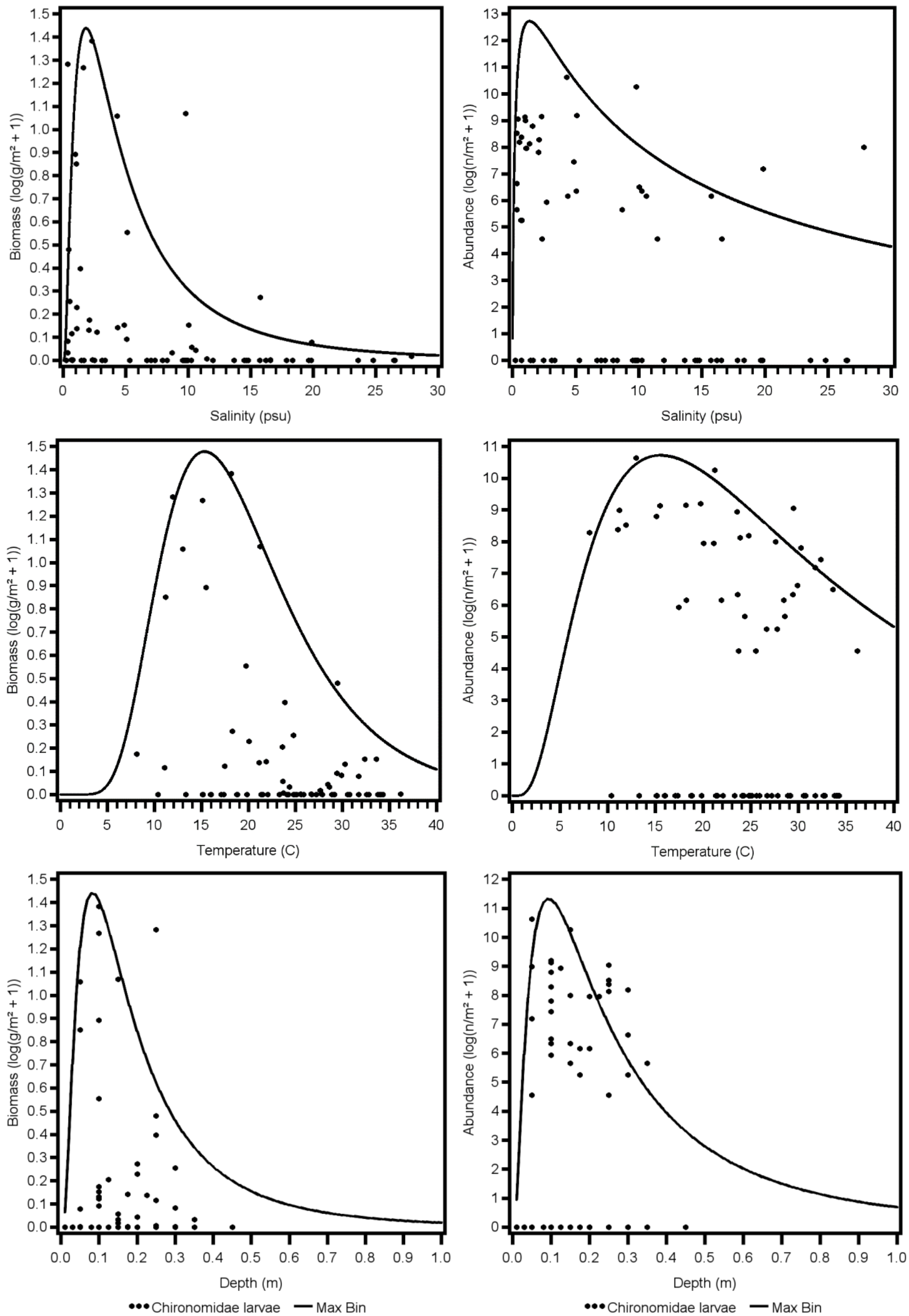

Figure 16. Relationship between hydrographical variables (salinity, temperature, depth) with (left) biomass and (right) abundance for Chironomidae larvae, October 2013 to December 2015.

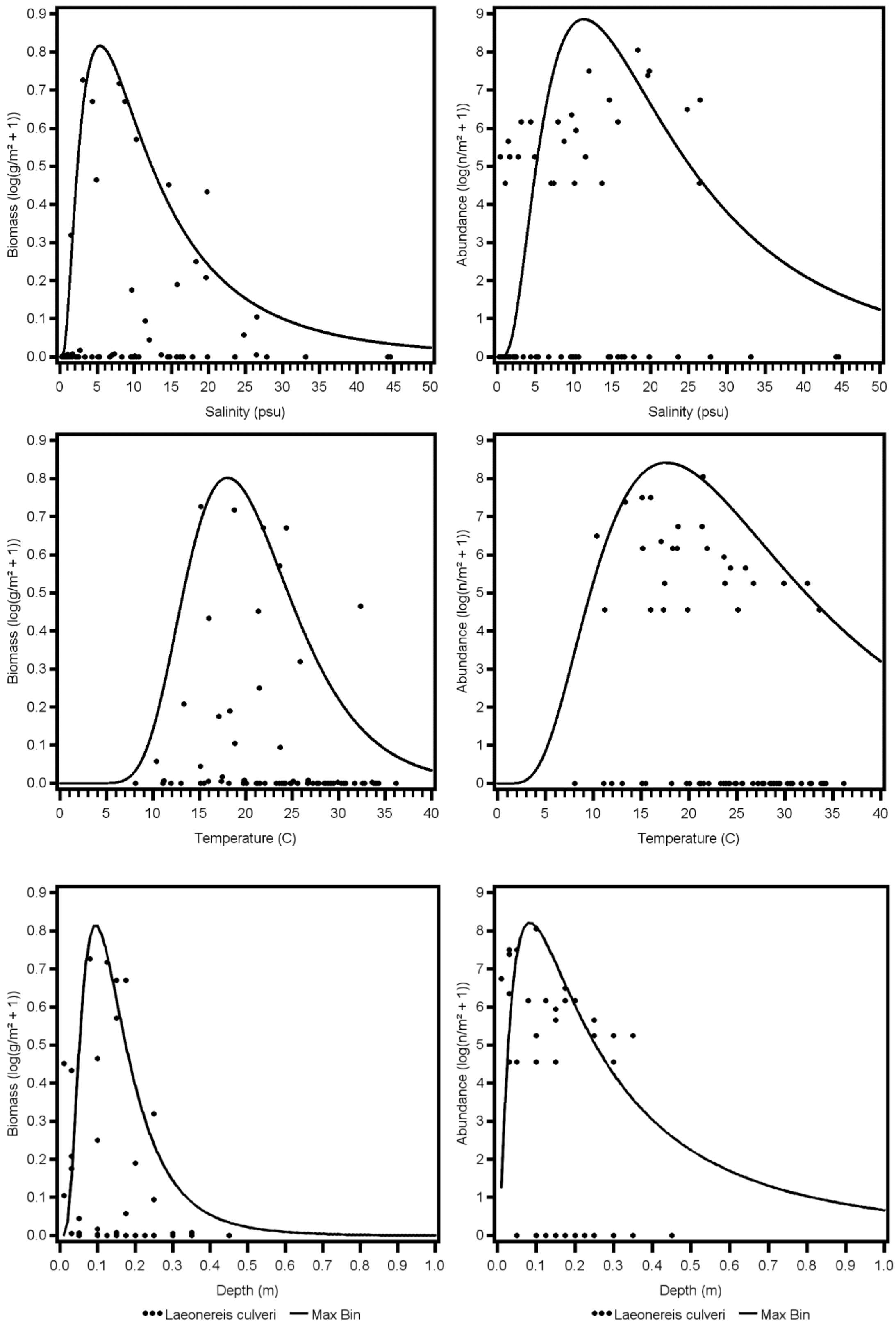

Figure 17. Relationship between hydrographical variables (salinity, temperature, depth) with (left) biomass and (right) abundance for *Laeonereis culveri*, October 2013 to December 2015.

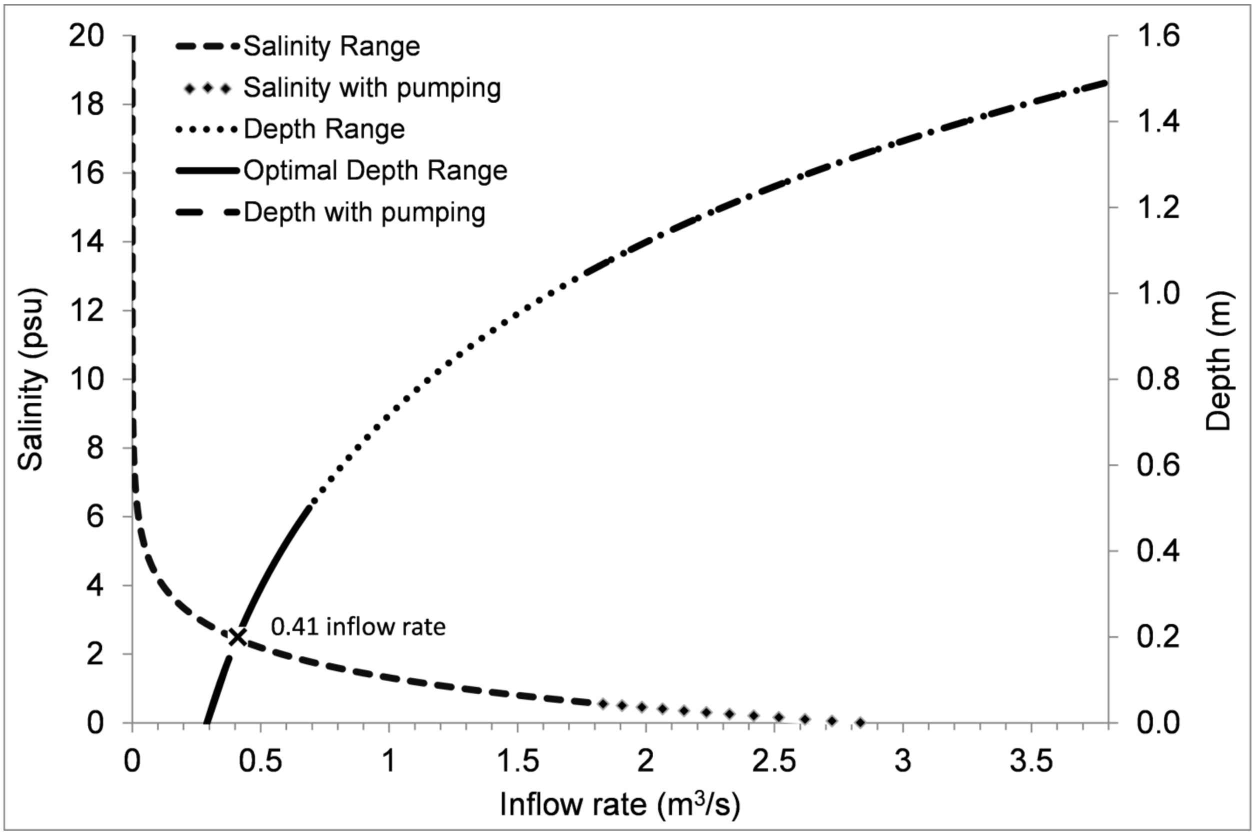

Figure 18. Relationship between RBP pumping capacity, salinity ranges, and depth ranges for the indicator species at Station C.