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Cover photo: Sunrise over Coastal Bend Bays & Esturaries Program land. See winning photos at WildlifeinFocus.org

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Effects of the Rincon Bayou Pipeline on salinity in the upper Nueces Delta

Elizabeth A. Del Rosario[1]*, Paul A. Montagna[1]

Abstract: A pipeline to pump water from the Nueces River to the upper delta at Rincon Bayou was constructed to mitigate the reduction of inflow from impoundments. Pumping has restored ecological function to the Nueces Estuary by increasing inflow and decreasing salinity, and transitioned the marsh into a positive estuary (lower salinities upstream increasing downstream towards the bay). Pumping has decreased the occurrences of salinities greater than 35 practical salinity units during drought conditions; however the current pumping regime causes a disturbed environment by creating extreme fluctuations in salinities in a very short time period. Immediately after pumping salinity fluctuations at the pumping outfall commence from hypersaline to fresh. When pumping ceases, salinity fluctuates from fresh to hypersaline until the next pumping event. Pumping often occurs during rainfall and flooding events when reservoir levels meet certain capacities that trigger pass-through requirements. This strategy provides inflow when it is not needed, and inhibits pumping during drought conditions when inflow is needed to maintain the quality of the estuarine ecosystem. While the current pumping regime has restored estuary conditions to Rincon Bayou by increasing inflow and decreasing salinity, it also causes extreme fluctuations in salinity that act as a disturbance. A lower magnitude, longer duration pumping strategy would create a more stable environment by providing freshwater continuously and would be an improved hydrological restoration strategy.

Keywords: freshwater inflow, freshwater management, pumped inflow, estuary, salinity, hydrology, restoration

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Terms used in paper

Short name or acronym	Descriptive name
BOR	U.S. Bureau of Reclamation
CBBEP	Coastal Bend Bays & Estuaries Program
CBI	Conrad Blucher Institute for Surveying and Science
cfs	cubic feet per second
m^3/s	cubic meters per second
NRA	Nueces River Authority
psu	practical salinity units
RBP	Rincon Bayou Pipeline
TCEQ	Texas Commission on Environmental Quality
TNRCC	Texas Natural Resource Conservation Commission
USGS	U.S. Geological Survey

INTRODUCTION

The amount of freshwater reaching the Nueces Estuary has been reduced by the construction of two dams in the Nueces River Basin: the Wesley E. Seale Dam (Lake Corpus Christi) on the Nueces River and the Choke Canyon Reservoir on the Frio River (tributary to the Nueces River) (HDR Engineering Inc. 2001). Irlbeck and Ward (2000) reported that the change in the annual mean flow into the Nueces Delta from the river during the period after the construction of the Wesley Seale Dam was decreased by about 39% (1958 to 1982), and that the change during the period after construction of Choke Canyon Dam was decreased by more than 99% (1982 to 1999) from that of historic flows (1940 to 1957) (BOR 2000). In response to this reduction of flows, the State of Texas issued an Agreed Order that required the City of Corpus Christi to provide not less than 185 million cubic meters (149,982 acre-feet) of water per year to the Nueces Estuary by a combination of releases (stored water that is let out) and spills (overflows) (Montagna et al. 2009). In April 1995, the Texas Natural Resource Conservation Commission—formerly Texas Water Commission, but now the Texas Commission on Environmental Quality (TCEQ)—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. Three other revisions also took effect: (1) the minimum mandatory inflows were changed to targeted monthly inflows, (2) the releases were changed to be based on the passage of reservoir inflows, known as "pass-through or (*sic*) Pass-Thru," rather than the release of previously stored water, and (3) drought relief was granted in the form of different pass-through requirements based on the reservoir level (TCEQ 1995). The concept of letting water pass-through is meant to mimic the natural inflows of nature while also taking into account area water demands. This is accomplished by placing constraints on pass-throughs that are based on a combination of reservoir elevation level, precipitation, and bay salinity (Spruill 2013). These constrains require the water to be released only when these conditions are met.

Rincon Bayou Demonstration Project

From the combined effects of reservoir construction, changes in land use patterns, increased groundwater withdrawals, and other human activities, the mean annual flow of freshwater diverted into the upper Nueces Delta has been reduced from that of historical flows (127,997 acre-feet (1940–1957) to 537 acre-feet (1983–1996)) (BOR 2000). In October 1995, the U.S. 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 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).

Rincon Bayou Pipeline

In 2001, the 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. The pass-through was 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, a diversion channel dug during the demonstration project; (2) construct a pipeline (Rincon Bayou pump station and pipeline) to convey up to 3,000 acre-feet per month 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 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 (Figure 1) (HDR Engineering, Inc. 1993). The pump

Figure 1. Map of station locations for measuring flow, salinity, and rainfall in Rincon Bayou. Stations C, F, G, and 467 are historical locations sampled by Montagna. Image source (USDA-NRCS 2006).

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-feet/day)	Sept. 2009–Dec. 2015	Nueces River Authority (NRA)	http://www.nueces–ra.org/CP/CITY/rincon/
USGS 08211503 Rincon Bayou 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
CBI 042-NUDE2 CBI 074-SALT03	Salinity	Every 15 minutes (psu)	May 2009–Dec. 2015	Conrad Blucher Institute for Surveying and Science (CBI)	http://cbi.tamucc.edu/datums/042 http://cbi.tamucc.edu/datums/074
CBI 069-NUDEWX	Computed cumulative rainfall	Daily total at midnight (cm)	Jan. 2014–Dec. 2015		http://cbi.tamucc.edu/datums/069

station consists of three pumps, which are capable of moving up to 3.8 cubic meters per second (m^3/s) (134 cubic feet per second (cfs)) when all pumps are in operation (Lloyd et al. 2013; Hill et al. 2012).

During flooding events, water would flow over the Calallen Saltwater Barrier Dam into the upper marsh supplying the estuarine ecosystem with freshwater. In 2009, the pipeline and pumping station began pumping freshwater from the Calallen Pool into the Nueces Delta at the Rincon Bayou headwaters so that inflow would no longer rely on overflowing of the Calallen Saltwater Barrier Dam (Figure 1). Pumping events typically occur when salinities in the Nueces Delta are greater than 30 practical salinity units (psu) and when reservoir levels and rainfall events allow for pass-through conditions (Lloyd et al. 2013). The purpose of this study was to determine the effects of the Rincon Bayou Pipeline on the salinity of the upper Nueces Delta.

STUDY SITE

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. The Nueces River provides freshwater to the City of Corpus Christi and the surrounding Coastal Bend area. The Calallen Pool (Saltwater Barrier Dam) (Figure 1) is located adjacent to Interstate 37 and was constructed in 1898 to restrict saltwater intrusion to the upstream non-tidal segment of the Nueces River (Montagna et al. 2009).

The main stem channel of the Nueces Delta marsh is located at Rincon Bayou, a creek connecting the tidal segment of the Nueces River to the delta (Figure 1). Rincon Bayou was the historic location of river inundation events in the northeastern portion of the upper Nueces Delta following seasonal rainfall events farther inland along the Nueces River. This provided nutrients and enough freshwater to reduce salinity in the estuarine system (Montagna et al. 2015).

METHODS

Hydrographic measurements were taken with an YSI 6600 multi-parameter sonde at Station C and Station G. Station C is located at 27.89878 °N latitude and 97.60417 °W longitude (Figure 1). Salinity observations were collected every 15 minutes for a duration of two weeks at a time from January 2014 through December 2015. Salinity was automatically corrected to 25 °C. Long-term salinity data was collected at Station G located at 27.88992 °N latitude and 97.56910 °W longitude (Figure 1). Salinity observations were collected on a quarterly and monthly basis. Stations C and G are historic stations and previously named 466C and 463G respectively.

Hydrology data were downloaded from the corresponding websites listed in Table 1 as follows: Natural inflow and discharge data were collected at the U.S. Geological Survey (USGS) Rincon Bayou Channel Gage No. 08211503 located at 27.896667 °N latitude and 97.625278 °W longitude; salinity data were collected at Nueces Delta 2 (CBI 042-NUDE2) located at 27.8888 °N latitude and 97.5696 °W longitude and CBI 074-SALT03 located at 27.85155 °N latitude and 97.48203 °W longitude; and rainfall data were collected at the

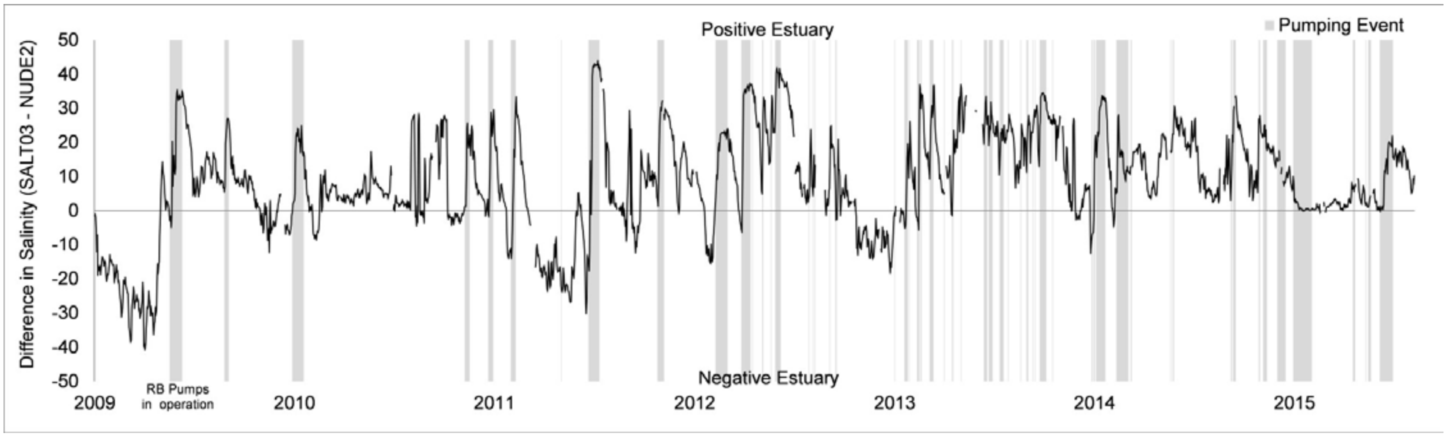

Figure 2. Salinity gradient for the Nueces Estuary (i.e., difference between downstream SALT03 and upstream NUDE2) and pumping event daily totals May 2009 to December 2015. The Rincon Bayou Pipeline became operational in September 2009 (Appendix 1). The width of the bar indicates pumping event duration.

Nueces Delta Weather Station (CBI 069-NUDEWX) located at 27.8975 °N latitude and 97.616389 °W longitude (Figure 1).

Data analysis

Data manipulation, calculations, and statistical analyses were performed using SAS 9.3 software (SAS Institute Inc. 2013). 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.

Pumped inflow and gaged inflow were converted to m^3/s. Pumped inflow data were assigned pumping event numbers based on breaks in the pumping duration. The number of days of inflow and the total pumped inflow rate per pumping event number was calculated. Total inflow rate into Rincon Bayou was calculated per day by summing the pumped inflow rate and the inflow rate at the USGS Gage.

Percent occurrence is defined as how often the event has occurred in a time period. Percent occurrences were derived from histogram frequencies and converted to percent for the salinity range at NUDE2, for natural inflow (USGS Gage), and for the long-term salinity range at Station G.

Percent exceedance was calculated for natural inflow (USGS Gage), pumped inflow (RBP), and total inflow (USGS Gaged inflow + RBP). Inflows were ranked 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.

Drought conditions data were obtained from the U.S. Drought Monitor (USDM 2017) from October 2001 to December 2015 for Lower Nueces watershed and the Texas-Gulf watershed. The Lower Nueces watershed contains the data for the following counties: Nueces, Live Oak, Bee, Duval, Jim Wells, Karnes, San Patricio, and McMullen (EPA 2017). D0 through D4 describes the drought severity classification using five key indicators (Appendix 3), drought impacts, and local reports from more than 350 expert observers around the country (USDM 2017). Drought conditions were reported as percent area of the watershed in moderate drought and above (D1-D4) and maximum monthly percent area was plotted with the monthly mean salinities at Station G. Missing salinity values were extrapolated.

RESULTS

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 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 (Figure 2) with a mean daily salinity upstream at NUDE2 being higher than the mean daily salinity downstream in the Nueces Bay at SALT03. The Nueces Estuary oscillates between positive and negative conditions with pump-

Table 2. Daily means for USGS Rincon Bayou (Channel) Gage, CBI salinity stations (SALT03, NUDE2) and weather station (NUDEWX), Station C, and the Rincon Bayou Pipeline (September 2009 to December 2015). Note: 1 m^3/s = 35.31 cfs.

Sampling location	Unit	Number of observations	Mean	Std. dev.	Min. mean	Max. mean
USGS Rincon Channel 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	cm	2182	1.92	7.78	0.00	142.00
SALT03	psu	2413	31.65	9.96	0.36	47.28
NUDE2	psu	2301	23.22	18.17	0.00	86.29
Station C	psu	734	6.77	6.65	0.01	34.41

Std, dev., standard deviation; Min., minimum; Max., maximum; cm, cubic meter

ing events (Figure 2). Pumping events coincided with periods of positive estuary conditions with salinities at NUDE2 rapidly decreasing when pumping begins and gradually increasing when pumping ceases. 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 (Appendix 1). With pumping, the mean daily salinity at NUDE2 was 23.22 psu with a maximum daily mean salinity of 86.29 psu and a minimum daily mean salinity of 0 psu (Table 2). NUDE2 salinity data began in May of 2009. Rincon Bayou has transitioned from a negative hypersaline estuary to a positive mesohaline estuary with lower salinity ranges occurring most often since pumping began (Figures 3a, 3b). Seasonal differences were accounted for by comparing salinity ranges that occurred monthly from May to September prior to pumping (2009) and after pumping began (2010–2015) (Figure 3b). Data was not available prior to May of 2009, so the other seasons were not included in the analysis. Figure 3b shows lower salinities occurring most often in the summer with pumping and higher salinities occurring most often in the summer prior to pumping.

Salinity at Station C (Figure 4) declined after each pumping event and gradually increased until the next pumped inflow with a mean daily salinity of 6.77 psu, a maximum daily mean salinity of 34.41 psu, and a minimum daily mean salinity of 0.01 psu (Table 2). The decreased gaged reading is caused by the back-flow preventer that was installed in July 2014. The increased gaged reading in July 2015 is caused by the back-flow preventer becoming inoperable. The back-flow preventer kept inflows from going both upstream into the Nueces River and downstream into Rincon Bayou.

Pumping events, rainfall, and salinity were plotted for a 2-year period (2014–2016) (Figures 5 and 6). Decreases in salinity that occurred when pumping was not occurring was likely due to rainfall (Figure 5). The magnitude and duration of Pumping events coincided with the amount of rainfall and typically occurred after or during rainfall periods (Figure 6). The mean pumped inflow was 1.71 m^3/s (60.4 cfs) with a maximum of 5.04 m^3/s (178 cfs) and a minimum pumped amount of 0.03 m^3/s (1 cfs) (Table 2).

The primary source of inflow into Rincon Bayou was from pumped inflow (Figures 7 and 8). The USGS Gage records downstream flows into Rincon Bayou as positive values and inflows back upstream into the Nueces River as negative values (Figure 7). The absence of a distinct elevation gradient in Rincon Bayou at the pumping (RBP) outfall area (Figure 1) allows pumped inflow to flow both upstream and downstream resulting in both positive inflow and negative discharge readings at the USGS Gage (Figures 4 and 7). A back-flow preventer was in place from July 2014 to July 2015, which restricted inflow and discharge at the USGS Gage (Figures 4 and 7).

A flow duration curve illustrates the percentage of time a given flow was equaled or exceeded during a specified period. 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 (Figure 8). 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 accounted for most of the high or medium flow events. The mean inflow volume from pumping was 1.71 m^3/s (60.4 cfs) with a maximum total inflow rate (pumping and Rincon gaged discharge) of 6.48 m^3/s (229 cfs) (Table 2). The percent of time that inflow from the Rincon Bayou diversion channel was

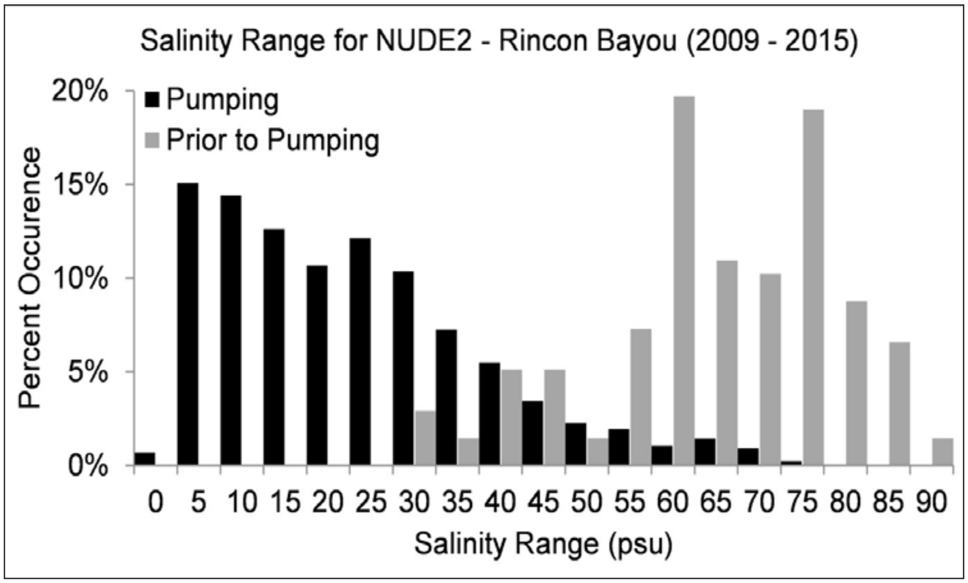

Figure 3a. Percent occurrence of salinity ranges in Rincon Bayou (NUDE2) prior to pumping (14 May 2009 to 28 September 2009) and with pumping (28 September 2009 to 31 December 2015).

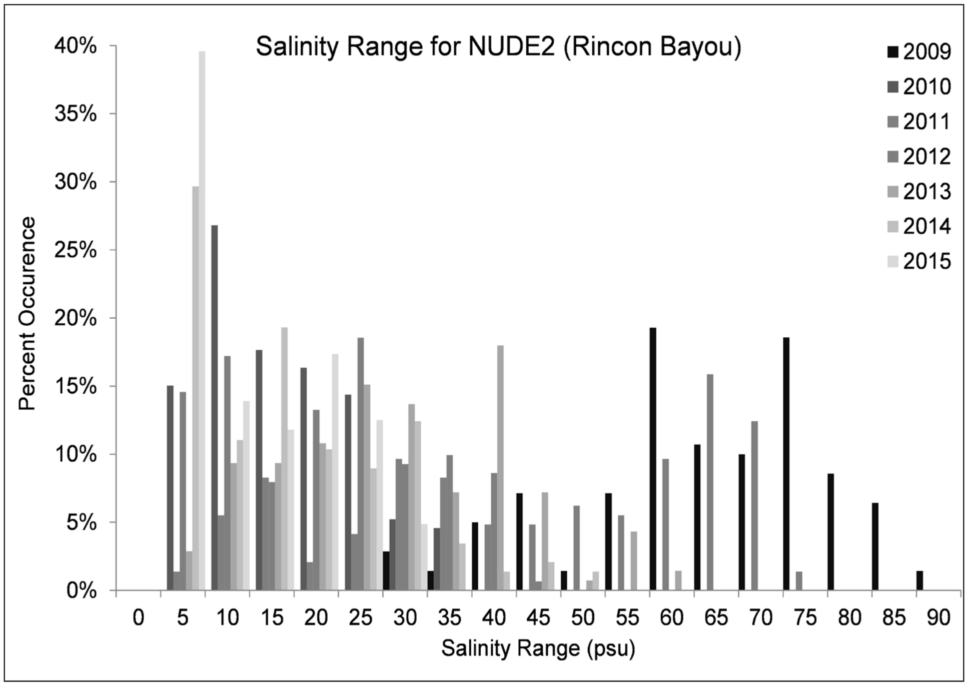

Figure 3b. Percent occurrence of salinity ranges in Rincon Bayou (NUDE2) prior to pumping May through September (2009) and with pumping from May through September (2010 to 2015).

greater than 0.2 m^3/s (7.1 cfs) was less than 10% of the time with an inflow rate between 0 and 0.1 m^3/s (3.5 cfs) occurring most often (Figure 9). The mean of daily inflow rate at the USGS Gage was -0.02 m^3/s (0.7 cfs) with a maximum daily mean discharge rate of 4.93 m^3/s (174 cfs) and a minimum daily mean rate of -2.72 m^3/s (96.8 cfs).

Drought is defined as a moisture deficit bad enough to have social, environmental, or economic effects (USDM 2017). Long duration drought conditions existed in the Lower Nueces watershed from June 2005 to September 2006, January 2008 to February 2010, and April 2011 to November 2014. The long-term salinity data for Rincon Bayou from October 2001

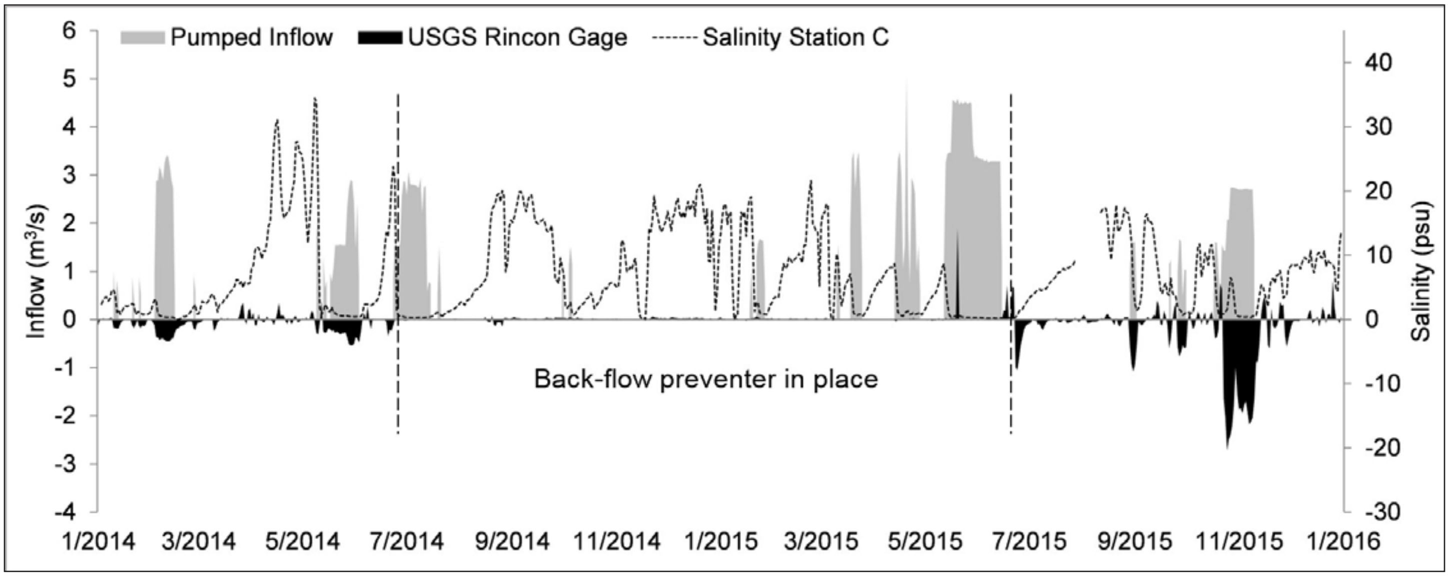

Figure 4. Salinity at Station C in Rincon Bayou, with inflow and discharge from the USGS Rincon Bayou (Channel) Gage and pumped inflow, January 2014 to December 2015.

to December 2015 shows that monthly mean salinities exceeded 35 psu in: April, June, and July of 2006; June of 2008; February, March, May, June, and July of 2009; and March and April of 2013 (Figure 10). Salinities greater than 35 psu in Rincon Bayou only occurred when drought conditions existed in the Lower Nueces watershed (Figure 11a). Percent occurrence of salinities greater than or equal to 35 psu in drought conditions has decreased from 40% (prior to pumping) to 12% (with pumping) (Figures 11b, 11c).

DISCUSSION

The downstream salinity values at SALT03 and upstream salinity values at NUDE2 were used to describe the estuary condition as positive or negative. The Nueces Estuary fluctuates between positive and negative conditions based on inflow and drought conditions, with pumped inflow decreasing the occurrence of salinities greater than 35 psu. Pumped inflow

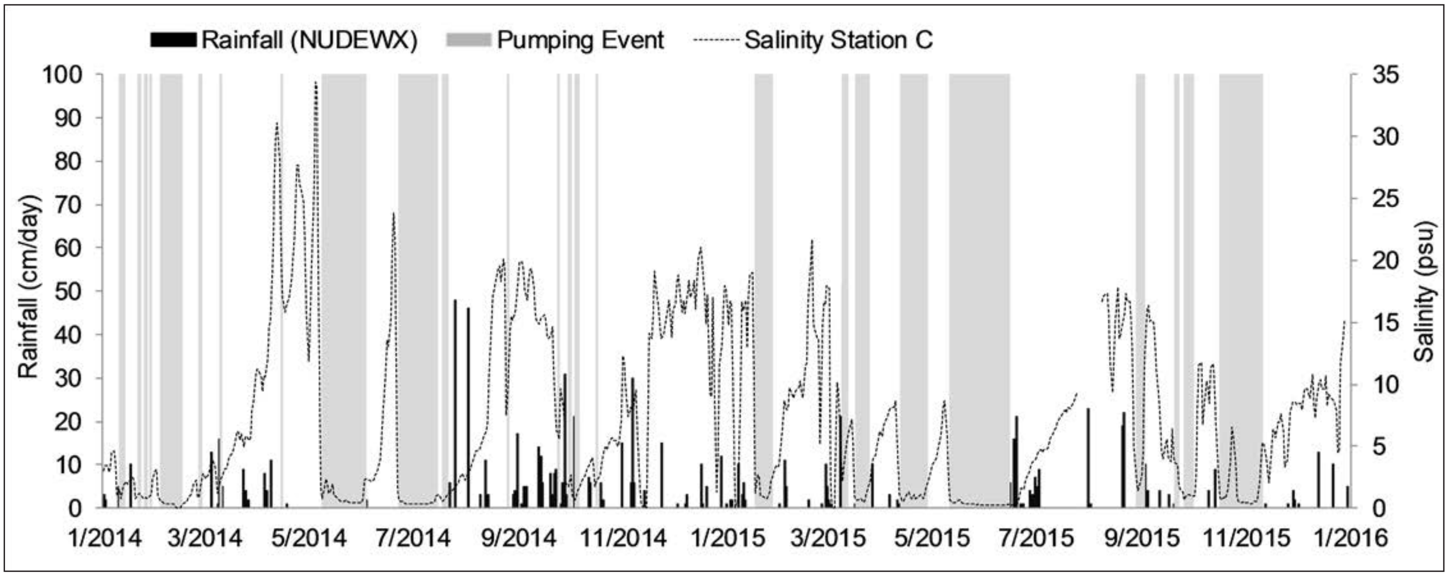

Figure 5. Salinity at Station C in Rincon Bayou, with daily total rainfall from CBI NUDEWX Station, January 2014 to December 2015.

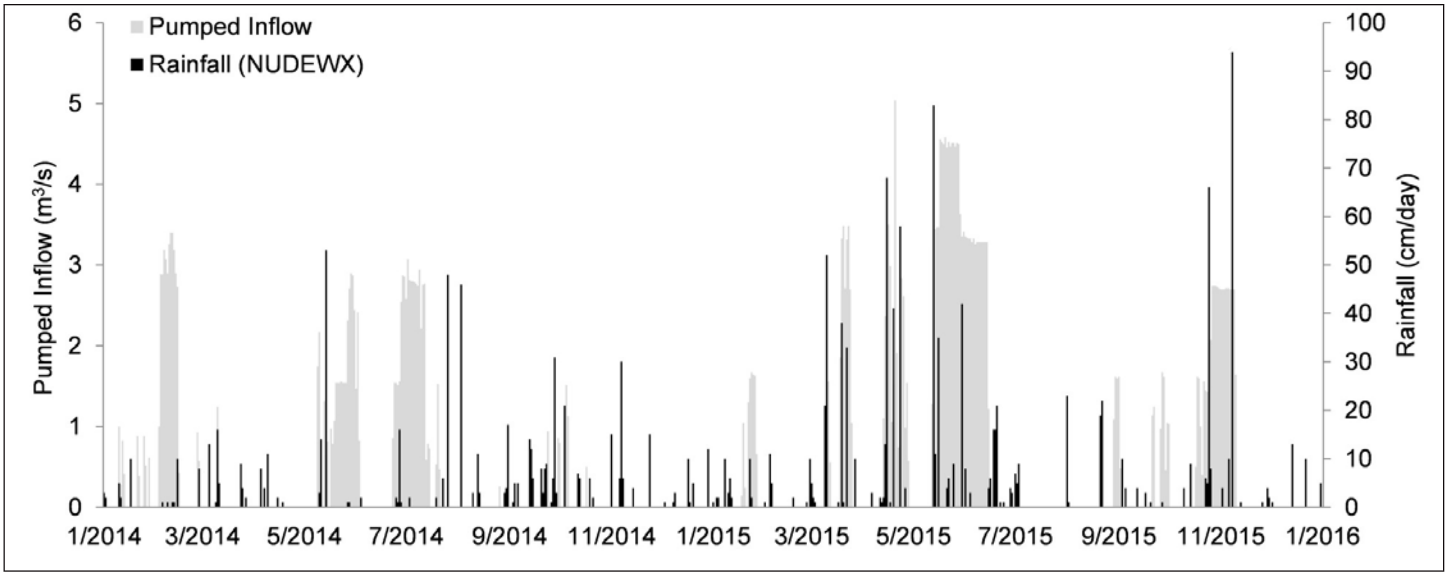

Figure 6. Pumped inflow into Rincon Bayou with daily total rainfall from CBI NUDEWX Station, January 2014 to December 2015. The width of the bar for pumping event indicates duration.

is the primary source of freshwater inflow into Rincon Bayou and has transitioned the ecosystem into a positive estuary, but this dependence can lead to reverse estuary conditions (salinity can fluctuate from fresh to hypersaline and hypersaline to fresh in very short time periods) when pumping is not occurring or occurs for short periods. Pumping has also created a distributed environment with the extreme fluctuations in salinity. The salinity tends to decrease immediately when the pumps are turned on and remain low until the pumps are turned off. The salinity will then steadily increase in Rincon Bayou, taking about 20 days to reach within 5 psu of salinity in Nueces Bay (Adams and Tunnell 2010; Tunnell and Lloyd 2011), until the pumps are turned back on. This cycle continues as the pumps are turned on and off.

A lack of an elevation gradient allows inflows to flow naturally both upstream, to the Nueces River, and downstream, to Rincon Bayou. Adams and Tunnell (2010) found that approximately 20% of pumped inflow goes upstream rather than downstream into Rincon Bayou. A weir was constructed at the pumping outfall in May 2010 to reduce the amount of pumped inflow going upstream (2016 interview with R. Kalke; unreferenced, see "Acknowledgments"). It was replaced in July

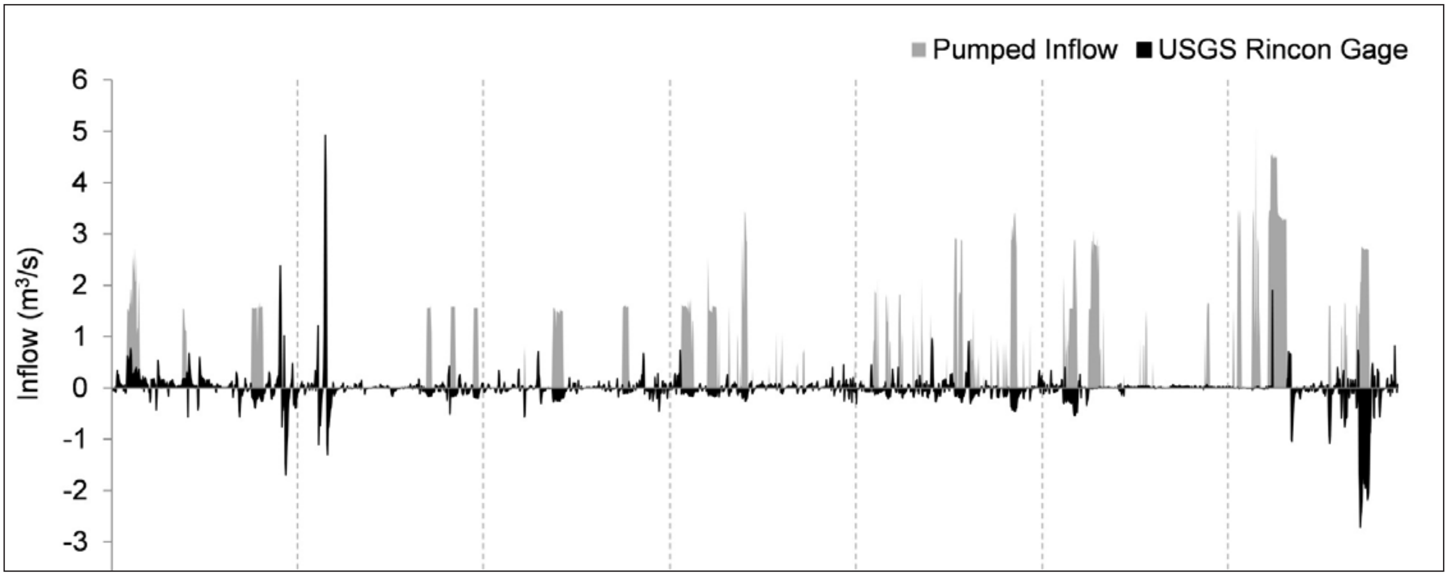

Figure 7. Inflow (+) and discharge (-) at the USGS Rincon Bayou (Channel) Gage, and pumped inflow, September 2009 to December 2015.

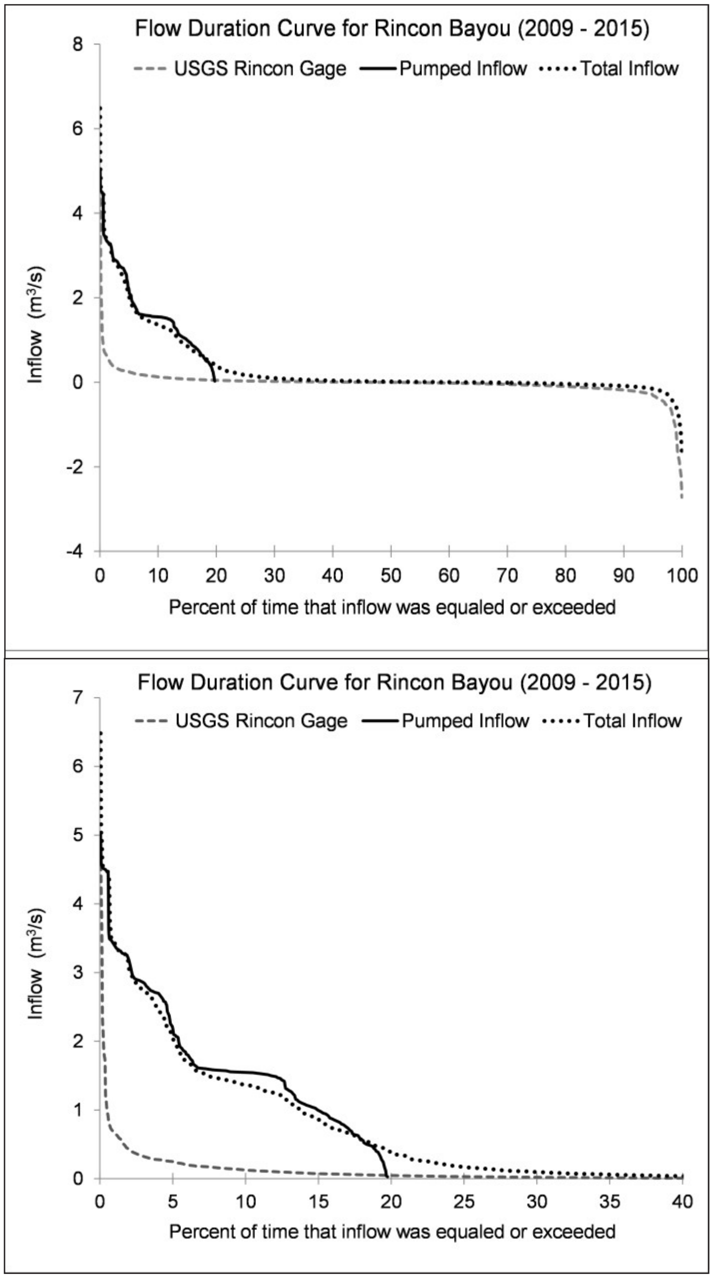

Figure 8. Flow duration curve for Nueces River inflow (+) and discharge (-) at the Rincon (Channel) Gage, September 2009 to December 2015. Top: full inflow scale. Bottom: zoomed to positive inflow values only.

2014 with a freshwater inflow management structure (back-flow preventer) consisting of box culverts with gates that must be manually opened and closed (Lewis 2014; Hill et al. 2012). The gap in the USGS Gage reading in Figure 4 depicts the time in which the structure was in place. The structure was successful at reducing the amount of pumped inflow going upstream and reducing natural inflows downstream into Rincon Bayou. The back-flow preventer washed out in the July 2015 flooding (2015 interview with R. Allen and R. Mooney; unreferenced, see "Acknowledgments") resulting in increased gaged reading of natural flows both upstream and downstream.

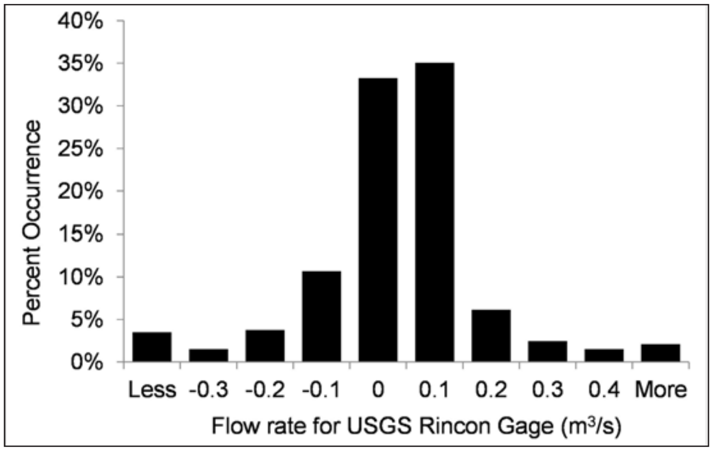

Figure 9. Percent occurrence for the natural flow rate at the USGS Rincon Bayou (Channel) Gage into Rincon Bayou from the Nueces River September 2009 to December 2015.

Pumping constraints

The Rincon Bayou pump station is operated by the Wesley Seale Dam near Mathis, Texas. The Daily Reservoir System and (sic) Pass-Thru Status Report generated by the NRA (2017) is used as a guide as to what amount of water to release based on target pass-through requirements (percent full of reservoir), return flow credits (flow returned to Nueces Bay, such as treated wastewater), and salinity relief credits (low salinity in Nueces Bay) based on the 2001 Agreed Order (TNRCC 2001). 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 (TNRCC 2001). Therefore, water is often held until the end of the month and then released continuously to fulfill the deficit before the deadline (2015 interview with D. Lozano; unreferenced, see "Acknowledgments").

The pumps are often turned on during periods of rainfall because that is when water is coming into the reservoirs to trigger the pass-through requirements, and water is available for pumping. Pumping does not occur during periods of low rainfall because the requirements are not met, and water is not available for pumping. Rainfall is taken into account by the 2001 Agreed Order in which pass-through requirements call for less water to be released downstream for the estuary when there is less rainfall (TNRCC 2001). The reservoir must meet certain water content storage percent levels for pass-throughs

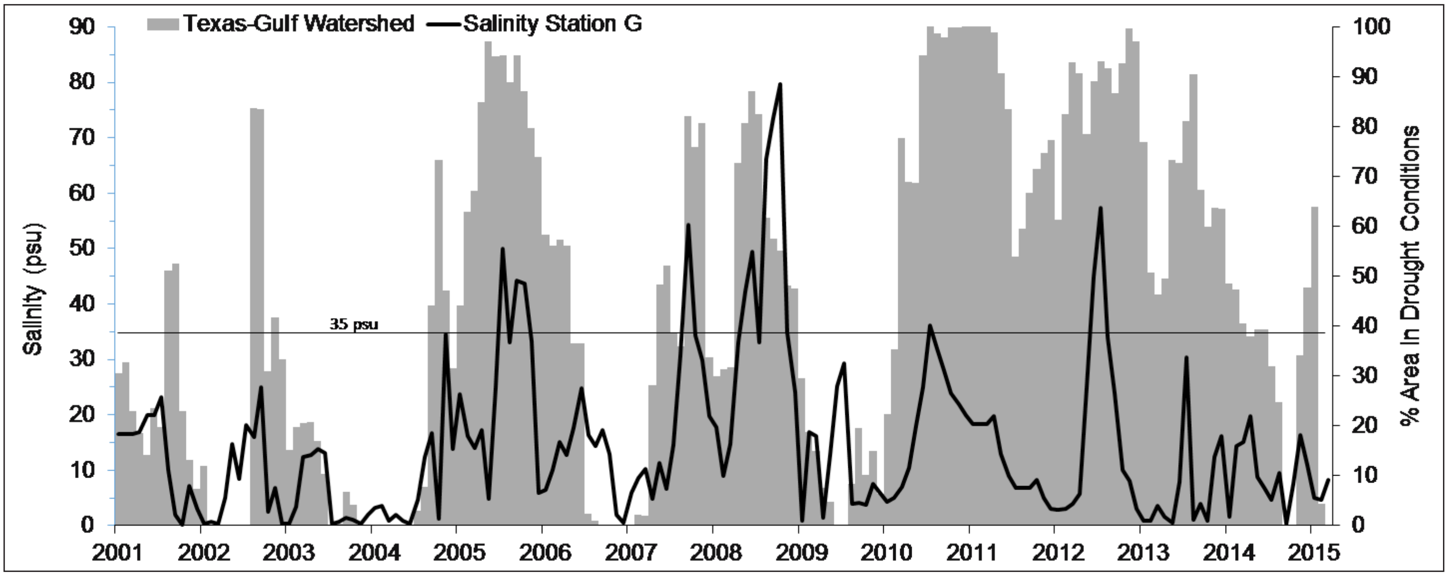

Figure 10. Long-term Rincon Bayou salinity data (Station G) with Texas-Gulf watershed drought conditions (October 2001 to December 2015).

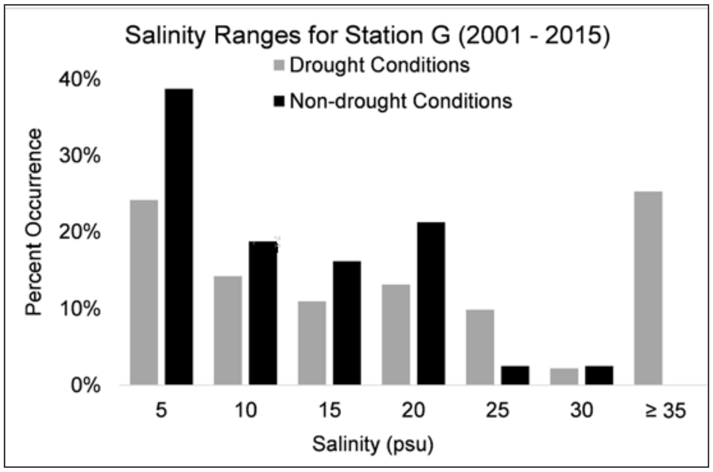

Figure 11a. Percent occurrence for salinity ranges with Lower Nueces watershed drought conditions (October 2001 to December 2015).

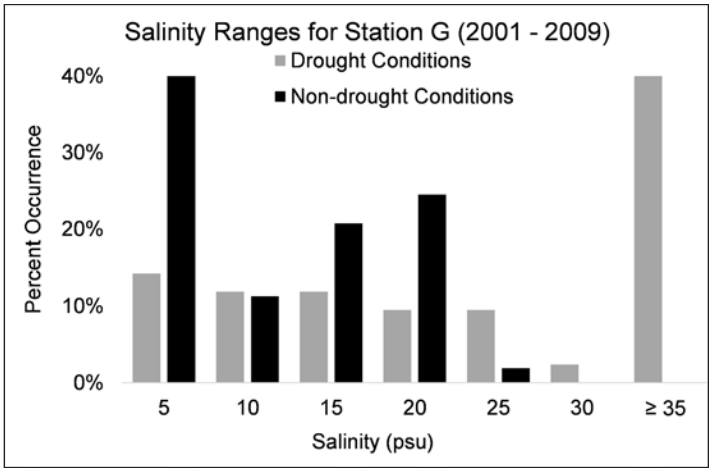

Figure 11b. Percent occurrence for salinity ranges with Lower Nueces watershed drought conditions before pumping began (October 2001 to August 2009).

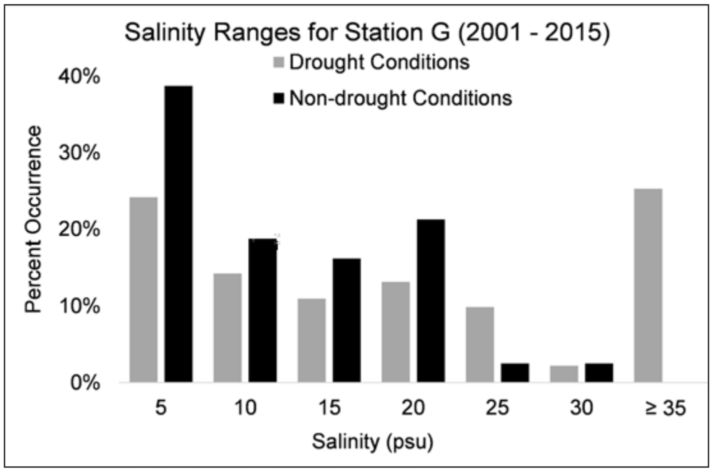

Figure 11c. Percent occurrence for salinity ranges with Lower Nueces watershed drought conditions after pumping began (September 2009 to December 2015).

to be required (Appendix 2), thus if there is not water coming into the reservoir, water does not have to be released (Lloyd et al. 2013; TNRCC 2001). 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. The Agreed Order reflects the natural variation in flow that would have historically been seen for inflow into the upstream reservoirs, but in practice for the downstream estuaries, adding water when water is already present and not supplying water when water is needed is not allowing for an ecologically sustainable environment.

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 until salinity reached a threshold (undefined) (Tunnell and Lloyd 2011). This provided the opportunity to release small quantities of water on a monthly or seasonal basis. During dry years the delta would still receive a small amount of water (~1,500 acre-feet) each month or season to keep salinity below extreme conditions (salinity > 35 psu) (Tunnell and Lloyd 2011). This was shown to be beneficial for the flora and fauna in Rincon Bayou and recommended to be a permanent management tool. However in April 2013, the Nueces Advisory Council was asked by TCEQ to suspend water banking and to continue operating under the 2001 Agreed Order allowing the scheduled monthly amount to be passed-through (Lloyd et al. 2013).

Operator constraints

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 Interstate Highway 37 (Figure 1). 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. During the flooding in 2015, the pumps were left on continuously from May 12 to June 15 to keep from flooding the pump station (2015 interview with D. Lozano; unreferenced, see "Acknowledgments"). This resulted in a total of 10.96 x 106 m^3 (8,884 acre-feet) being pumped into Rincon Bayou coupled with 205 cm of rainfall recorded at NUDEWX. The USGS Rincon Bayou Channel Gage was inoperable from May 21 to June 16 (USGS 2015), so it is not known how much natural inflow entered from the Nueces River. The inflow management structure (back-flow preventer) installed in July of 2014 washed out in the July 2015 flooding and was reinstalled in spring of 2016 (2016 interview R. Kalke; unreferenced, see "Acknowledgments"). The back-flow preventer is controlled by the Coastal Bend Bays & 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 (2015 interview with R. Allen and R. Mooney; unreferenced, see "Acknowledgments")

CONCLUSION

The primary source of freshwater into Rincon Bayou is from pumped inflow, thus salinity can be altered in direct response to management actions. The current pumping regime has restored ecological function (i.e. essential habitat, assimilative capacity, and intrinsic value) to Rincon Bayou by increasing inflow and decreasing salinity but causes extreme fluctuations (Montagna et al. 2002; Alber 2002; Montagna et al. 2015). A lower magnitude, longer duration pumping strategy would create a more stable environment by providing freshwater continuously. This has been modeled to be more beneficial to the estuarine ecosystem and should be considered because of adaptive management (Montagna et al. 2015). Results of the current study demonstrate that hydrological restoration of reverse estuaries is possible.

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APPENDIX

Appendix 1. Rincon Bayou Pipeline pumping events from the Nueces River Authority. Pumped inflow data were assigned pumping event numbers based on breaks in the pumping duration. A test run was conducted in 2007 with the pipeline beginning operation in September 2009.

Pumping event number	Duration	Number of days of inflow	Total pumped inflow		
			Acre-feet/ day	ft^3/s (cfs)	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. 6–14, 2010	9	742	374.12	10.60
3	May 10–31, 2010	22	2,288	1,153.61	32.67
4	March 21–30, 2010	10	1,006	507.23	14.37
5	May 3–12, 2011	10	1,002	505.21	14.31
6	June 13–22, 2011	10	994	501.17	14.19
7	Sept. 13–14, 2011	2	98	49.41	1.40
8	Nov. 2–22, 2011	21	2,027	1,022.01	28.95
9	March 7–19, 2012	13	1,309	660.00	18.69
10	June 21–July 13, 2012	23	2,354	1,186.89	33.62
11	Aug. 7–24, 2012	18	2,004	1,010.42	28.62
12	Aug. 27–28, 2012	2	109	54.96	1.56
13	Sept. 14–16, 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. 8–18, 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. 8–9, 2012	2	95	47.90	1.36
20	Dec. 16–20, 2012	4	159	80.17	2.27
21	Jan. 15–16, 2013	2	62	31.26	0.89
22	Jan. 26–28, 2013	3	152	76.64	2.17
23	April 29, 2013	1	40	20.17	0.57
24	May 14–15, 2013	2	15	7.56	0.21
25	June 1–10, 2013	9	847	427.06	12.10
26	June 24–July 2, 2013	8	731	368.57	10.44
27	July 17–24, 2013	8	665	335.29	9.50
28	Aug. 12–13, 2013	2	161	81.18	2.30
29	Aug. 20–22, 2013	2	124	62.52	1.77
30	Aug. 27–29, 2014	3	273	137.65	3.90
31	Sept. 12–13, 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

Pumping event number	Duration	Number of days of inflow	Total pumped inflow		
			Acre-feet/ day	ft^3/s (cfs)	m^3/s (cms)
34	Oct. 24–30, 2013	7	1,131	570.25	16.15
35	Nov. 2–9, 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. 7–8, 2013	2	73	36.81	1.04
39	Dec. 17, 2013	1	17	8.57	0.24
40	Dec. 30–31, 2013	2	107	53.95	1.53
41	Jan. 10–13, 2014	4	177	89.24	2.53
42	Jan. 21–22, 2014	2	89	44.87	1.27
43	Jan. 25–28, 2014	3	141	71.09	2.01
44	Feb. 3–15, 2014	13	2,466	1,243.36	35.21
45	Feb. 26–27, 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 19–21, 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. 4–6, 2014	3	264	133.11	3.77
55	Oct. 17, 2014	1	35	17.65	0.50
56	Jan. 18–27, 2015	9	695	350.42	9.92
57	March 10–12, 2015	3	210	105.88	3.00
58	March 18–25, 2015	8	1,535	773.95	21.92
59	April 13–28, 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. 21–22, 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

Appendix 2. Monthly (*sic*) Pass-Thru Status Report from the Nueces River Authority (2009 to 2015) with target inflows to Nueces Bay and/or the Nueces Delta established by the 2001 Agreed Order (TNRCC 2001). Estuary inflows are reported as Rincon Bayou Pipeline plus Nueces River at Calallen, Texas. All data is reported in acre-feet (1 ac-ft = 1233.48 m^3). Target % values refer to the amount of water that is presently held in storage (% full of reservoir).

Date		Pumped inflow	Number of days pumped	Estuary inflow	Pass-through	Return flow credit	Previous month's credit	Salinity relief credit	Required release to estuary at target % of full			
									< 30%	< 40% ≥ 30%	< 70% ≥ 40%	≥ 70%
2009	Jan	0	0	301	1,219	500	847	0	0	1,200	2,500	2,500
	Feb	0	0	555	733	500	301	0	0	1,200	2,500	2,500
	Mar	0	0	546	471	500	555	0	0	1,200	3,500	3,500
	Apr	0	0	385	559	500	546	0	0	1,200	3,500	3,500
	May	0	0	1,338	258	500	385	0	0	1,200	23,500	25,500
	Jun	0	0	313	64	500	1,338	0	0	1,200	23,500	25,500
	Jul	0	0	379	150	500	313	0	0	1,200	4,500	6,500
	Aug	0	0	204	100	500	379	0	0	1,200	5,000	6,500
	Sep	278	3	4,815	9,322	500	204	0	0	1,200	11,500	28,500
	Oct	2,709	21	6,009	5,813	500	-3,802	0	0	1,200	9,000	20,000
	Nov	0	0	3,529	4,000	500	-3,106	0	0	1,200	4,000	9,000
	Dec	0	0	1,017	1,743	500	-3,077	0	0	1,200	4,500	4,500
2010	Jan	742	9	7,626	1,875	500	-3,303	625	0	1,200	2,500	2,500
	Feb	0	0	4,698	1,250	500	0	1,250	0	1,200	2,500	2,500
	Mar	0	0	300	2,083	500	1,750	0	0	1,200	3,500	3,500
	Apr	0	0	3,856	2,625	500	0	875	0	1,200	3,500	3,500
	May	2,288	22	10,139	2,500	500	1,731	0	0	1,200	23,500	25,500
	Jun	0	0	24,866	15,500	500	-12,471	0	0	1,200	23,500	25,500
	Jul	0	0	18,552	3,250	500	-2,598	3,250	0	1,200	4,500	6,500
	Aug	0	0	312	1,805	500	3,250	0	0	1,200	5,000	6,500
	Sep	0	0	25,412	12,969	500	312	0	0	1,200	11,500	28,500
	Oct	0	0	551	414	500	0	15,000	0	1,200	9,000	20,000
	Nov	0	0	230	480	500	0	2,250	0	1,200	4,000	9,000
	Dec	0	0	309	251	500	230	0	0	1,200	4,500	4,500

Date		Pumped inflow	Number of days pumped	Estuary inflow	Pass-through	Return flow credit	Previous month's credit	Salinity relief credit	Required release to estuary at target % of full			
									< 30%	< 40% ≥ 30%	< 70% ≥ 40%	≥ 70%
2011	Jan	0	0	1,333	1,533	500	309	0	0	1,200	2,500	2,500
	Feb	0	0	199	772	500	609	0	0	1,200	2,500	2,500
	Mar	1,006	10	1,198	984	500	199	0	0	1,200	3,500	3,500
	Apr	0	0	282	454	500	-90	0	0	1,200	3,500	3,500
	May	1,002	10	1,504	205	500	192	0	0	1,200	23,500	25,500
	Jun	994	10	1,239	167	500	502	0	0	1,200	23,500	25,500
	Jul	0	0	74	317	500	242	0	0	1,200	4,500	6,500
	Aug	0	0	184	23	500	74	0	0	1,200	5,000	6,500
	Sep	98	2	610	273	500	184	0	0	1,200	11,500	28,500
	Oct	0	0	434	7,529	500	610	0	0	1,200	9,000	20,000
	Nov	2,027	21	434	262	500	-5,984	0	0	1,200	4,000	9,000
	Dec	0	0	162	666	500	221	0	0	1,200	4,500	4,500
2012	Jan	0	0	95	279	500	162	0	0	1,200	2,500	2,500
	Feb	0	0	230	209	500	95	0	0	1,200	2,500	2,500
	Mar	1,309	13	1,372	3,500	500	230	0	0	1,200	3,500	3,500
	Apr	0	0	827	2,529	500	0	0	0	1,200	3,500	3,500
	May	0	0	1,110	23,500	500	0	0	0	1,200	23,500	25,500
	Jun	1,083	10	15,990	494	500	0	0	0	1,200	23,500	25,500
	Jul	1,271	13	2,159	297	500	0	0	0	1,200	4,500	6,500
	Aug	2,113	20	2,239	829	500	0	0	0	1,200	5,000	6,500
	Sep	286	4	399	8,156	500	0	0	0	1,200	11,500	28,500
	Oct	2,105	14	2,163	9,000	500	0	0	0	1,200	9,000	20,000
	Nov	31	1	36	686	500	0	0	0	1,200	4,000	9,000
	Dec	254	6	253	77	500	0	0	0	1,200	4,500	4,500
2013	Jan	214	5	214	1,200	500	0	0	0	1,200	2,500	2,500
	Feb	0	0	0	883	500	0	0	0	1,200	2,500	2,500
	Mar	0	0	0	164	500	0	0	0	1,200	3,500	3,500
	Apr	40	1	179	875	500	0	0	0	1,200	3,500	3,500
	May	15	2	198	1,200	500	-195	0	0	1,200	23,500	25,500
	Jun	1,452	15	1,452	1,200	500	-697	0	0	1,200	23,500	25,500
	Jul	791	10	794	1,200	500	55	0	0	1,200	4,500	6,500
	Aug	558	7	558	273	500	149	0	0	1,200	5,000	6,500
	Sep	161	2	1,579	1,200	500	558	0	0	1,200	11,500	28,500
	Oct	1,203	9	9,646	3,213	500	600	0	0	1,200	9,000	20,000
	Nov	1,664	16	7,223	4,000	500	2,000	0	0	1,200	4,000	9,000
	Dec	263	7	283	283	500	2,250	0	0	1,200	4,500	4,500

Date		Pumped inflow	Number of days pumped	Estuary inflow	Pass-through	Return flow credit	Previous month's credit	Salinity relief credit	Required release to estuary at target % of full			
									< 30%	< 40% ≥ 30%	< 70% ≥ 40%	≥ 70%
2014	Jan	407	9	413	220	500	283	0	0	1,200	2,500	2,500
	Feb	2,571	15	2,583	143	500	0	0	0	1,200	2,500	2,500
	Mar	87	1	89	74	500	0	0	0	1,200	3,500	3,500
	Apr	8	1	11	39	500	0	0	0	1,200	3,500	3,500
	May	2,406	21	2,438	21,596	500	0	0	0	1,200	23,500	25,500
	Jun	1,400	11	18,938	14,059	500	-18,658	0	0	1,200	23,500	25,500
	Jul	2,638	18	16,418	1,839	500	-13,279	920	0	1,200	4,500	6,500
	Aug	18	1	134	134	500	600	0	0	1,200	5,000	6,500
	Sep	126	2	302	1,098	500	0	0	0	1,200	11,500	28,500
	Oct	355	5	605	836	500	-297	0	0	1,200	9,000	20,000
	Nov	0	0	433	867	500	-28	0	0	1,200	4,000	9,000
	Dec	0	0	157	150	500	0	0	0	1,200	4,500	4,500
2015	Jan	695	9	709	1,200	500	0	0	0	1,200	2,500	2,500
	Feb	0	0	26	0	500	0	0	0	1,200	2,500	2,500
	Mar	1,745	11	4,720	1,200	500	0	0	0	1,200	3,500	3,500
	Apr	2,455	16	7,039	300	500	0	900	0	1,200	3,500	3,500
	May	5,562	20	124,478	1,704	500	0	6,612	0	1,200	23,500	25,500
	Jun	3,321	15	108,377	5,750	500	0	17,250	0	1,200	23,500	25,500
	Jul	0	0	482	0	500	0	4,500	0	1,200	4,500	6,500
	Aug	302	3	522	1,092	500	0	1,250	0	1,200	5,000	6,500
	Sep	717	9	838	1,282	500	-70	0	0	1,200	11,500	28,500
	Oct	2,075	16	3,516	9,000	500	-14	0	0	1,200	9,000	20,000
	Nov	1,818	10	9,260	3,000	500	-4,998	1,000	0	1,200	4,000	9,000
	Dec	0	0	326	2,910	500	1,762	0	0	1,200	4,500	4,500

Appendix 3. Drought severity classification. U.S. Drought Monitor. D1 is the least intense level and D4 the most intense. D0 areas are not in drought, but are experiencing abnormally dry conditions that could turn into drought or are recovering from drought but are not yet back to normal. Source: http://droughtmonitor.unl.edu/AboutUSDM/DroughtClassification.aspx

Category	Description	Possible impacts	Palmer Drought Severity Index (PDSI)	CPC SoilMoisture Model (Percentiles)	USGS Weekly Streamflow (Percentiles)	Standardized Precipitation Index (SPI)	Objective Drought Indicator Blends (Percentiles)
D0	Abnormally dry	Going into drought: short-term dryness slowing planting, growth of crops or pastures. Coming out of drought: some lingering water deficits pastures or crops not fully recovered.	-1.0 to -1.9	21 to 30	21 to 30	-0.5 to -0.7	21 to 30
D1	Moderate drought	Some damage to crops, pastures. Streams, reservoirs, or wells low, some water shortages developing or imminent. Voluntary water-use restrictions requested	-2.0 to -2.9	11 to 20	11 to 20	-0.8 to -1.2	11 to 20
D2	Severe drought	Crop or pasture losses likely. Water shortages common. Water restrictions imposed.	-3.0 to -3.9	6 to 10	6 to 10	-1.3 to -1.5	6 to 10
D3	Extreme drought	Major crop/pasture losses. Widespread water shortages or restrictions.	-4.0 to -4.9	3 to 5	3 to 5	-1.6 to -1.9	3 to 5
D4	Exceptional drought	Exceptional and widespread crop/pasture losses. Shortages of water in reservoirs, streams, and wells creating water emergencies.	-5.0 or less	0 to 2	0 to 2	-2.0 or less	0 to 2