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Experimental River Diversion for Marsh Enhancement

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ABSTRACT: The Nueces River is the primary source of freshwater inflow to Corpus Christi Bay and virtually the only source of freshwater inflow to the Nueces Delta. In association with reservoir development and operation within the Nueces Basin, the magnitude of freshwater inflow has been greatly reduced since 1958. Continually increasing salt concentrations in the soil and water have compromised the function of the delta as a viable component of the estuarine ecosystem. In 1993, the U.S. Bureau of Reclamation began a 5-yr diversion project to increase the opportunity for freshwater flow into the delta. With the excavation of two overflow channels, the minimum flooding threshold for the upper delta was significantly lowered, and more frequent diversions of freshwater from the Nueces River were enabled. During the 50-mo diversion period, the amount of freshwater diverted into the upper Nueces Delta was increased sevenfold. The average salinity gradient in the upper delta reverted to a more natural pattern, with average salinity concentrations decreasing from the lower (bay) to upper (riverine) delta, and a corresponding improvement in abundance and diversity of both intertidal vegetation and benthic communities.

Introduction

One of the defining characteristics of an estuary is an influx of freshwater (Ketchum 1951; Pritchard 1967). The role of freshwater inflow in creating time-space variation in salinity, nutrients, and sediment, among other waterborne properties, is central to maintenance of the estuarine ecosystem (e.g., Ward and Montague 1996). This role is especially critical in those estuaries whose watersheds are semi-arid, such as those on the coasts of Florida, southern California, and south Texas, in which even modest diminutions in inflow can produce marked alterations in the estuarine communities (Copeland 1966; Armstrong 1982; Montagna and Kalke 1992).

One such system is Corpus Christi Bay, one of the major estuarine systems on the Texas coast. The principal inflow to Corpus Christi Bay is the Nueces River, which enters the system in the secondary embayment, Nueces Bay (Fig. 1). With an increase in human population along the south Texas coast, regional municipal and industrial water demands from the Nueces River have also increased, necessitating storage reservoirs to meet these water demands. Two main-stem reservoirs have been constructed in the Nueces Basin: Lake Corpus Christi in 1958 and Choke Canyon Reservoir in 1987. Since 1958, the magnitude of freshwater inflow into Corpus Christi Bay has been reduced for both Corpus Christi Bay (55%, Asquith et al. 1997) and the Nueces Delta (99%, Bureau of Reclamation 2000a). These reductions are not attributable to precipitation differences before and after reservoir construction (Bureau of Reclamation 2000c).

An important intermediary in the ecological response of an estuary to riverine inflow is the delta of that river. These are generally regions of extensive salt marshes and vegetated flats that are periodically inundated by tides and floods, and are a critical transitional environment used by both estuarine and marine plants and animals. Odum (1961) proposed that tidal marshes were intimately and disproportionately important to the productivity of estuaries. The idea is supported by the general correlation between estuarine productivity and the extent of tidal marshes (Daiber 1986), but the exact mechanisms and their relative importance are controversial (Nixon 1980).

Comprising a complex array of channels, pools, marshes, and tidal flats, the delta of the Nueces River is located in the western extreme of Nueces Bay (Fig. 1). The delta is inundated regularly by salt water from the bay via tides and wind, and occasionally by freshwater when the Nueces River spills over its banks. The channel of the Nueces River skirts the delta and debouches into Nueces Bay on its south shore (Fig. 1). River flows enter the delta only when stage is sufficient to broach

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Fig. 1. The Nueces Delta showing the location of the diversion project study area and the sampling locations of the various data sources used. Numerals indicate station identification.

the natural levee of the river channel. The history of this region of Texas is marked by intermittent inflow events of the Nueces flooding the delta, and sustained periods of little or no flow (e.g., Almonte 1835; Howell 1879; Peirce 1894; Collier and Hedgpeth 1950; Hollon 1956). The freshwater inundations by the river, which typically occur during the spring and fall, are essential in maintaining the ecological function of the delta (e.g., Montagna et al. 1996). In addition to reducing the total freshwater inflow in the Nueces River, the operation of the upstream reservoirs has also substantially reduced the peaks of flood hydrographs of the lower basin, thereby diminishing the frequency of over banking and inflow to the delta.

As regular exchange with the Nueces River has diminished with reservoir operations, the hydrography and vegetation of the Nueces Delta have been substantially modified. The freshwater inflow events that occur in the present river hydrology are too small and too infrequent to offset the natural intrusion of salinity into the delta by tide, which is then concentrated by evaporation. Extensive areas of hypersaline water and soils have developed in the delta, resulting in a reverse estuary where salinity values are lowest in Nueces Bay and increase with distance into Rincon Bayou and the delta. While many estuarine species can tolerate this harsher environment for short periods, prolonged conditions of hypersalinity over the past four decades (especially during the past two decades) have reduced biological productivity and species diversity (Montagna et al. 2002).

The fact that the Nueces River channel circumvents the Nueces Delta, prohibiting inflow into the delta unless the river stage is sufficiently high, has suggested the possibility of diverting the flow of the river into the delta by an artificial cut in the river levee. Plans and analyses for such a strategy date back at least 20 years (e.g., Ward 1985) in which the optimum location for such a diversion was judged to be the head of Rincon Bayou, a major distributary in the delta and relict prehistoric channel of the Nueces (Fig. 1). In 1993, the U.S. Bureau of Reclamation initiated an experimental diversion project at this location during which a temporary diversion channel was maintained and the hydrographic and ecological responses of the delta were monitored for 5 years. In this paper, an overview of the Reclamation project is presented, summarizing its principal features, the collection and analysis of data in the marsh and estuary, and some of the major conclusions. A comprehensive report on all aspects of the project is available from the agency (Bureau of Reclamation 2000a), and separate papers in this issue address details of hydrography (Palmer et al. 2002), vegetation and

habitat effects (Alexander and Dunton 2002), and benthic ecology (Montagna et al. 2002).

Materials and Methods

THE DIVERSION EXPERIMENT

The diversion experiment consisted of a program of hydrographic and biological monitoring in the Nueces Delta for an extended period, during part of which the physiography of the delta was modified to divert part of the river flow through the delta. Since the overall objective was to demonstrate by direct experiment the efficacy of such a diversion in improving the ecological functioning of the delta, it is referred to as the Rincon Bayou Demonstration Project. The primary features of the Demonstration Project were two excavated channels: the Nueces Overflow Channel and the Rincon Overflow Channel (Fig. 1). These channels were completed in October 1995.

The Nueces Overflow Channel was a cut through the river levee to lower the minimum flooding threshold of the delta and allow inflow to the delta at river stages below those normally required to overtop the levee. This channel, located approximately 60 m downstream of the Interstate Highway 37 Bridge along the north bank, was excavated to an approximate 274 m length and 12 m width, with a bottom elevation of 0.0 m MSL. Prior to the creation of the Nueces Overflow Channel, flood flows entered the delta by overtopping the natural river levee at several low points, most important of which was the levee at Rincon Bayou where the Nueces Overflow Channel was installed. A river stage of 1.64 m was determined to be the natural overflow threshold, corresponding to a flow in the Nueces River of about 60 m³ s⁻¹ (varying about 10% depending upon water level in Nueces Bay).

The purpose of the Rincon Overflow Channel was to improve the exchange of water within the delta itself by facilitating flow into an extensive tidal flat area in the north section of the delta. It was excavated to an approximate 610 m length and 30 m width, with a bottom elevation of 1.22 m MSL on the upstream (south) end and 0.91 m MSL on the downstream (north) end. This channel did not therefore affect the frequency of inundation by river water, but did improve the distribution of the river water once it was diverted into the delta by the Nueces Overflow Channel.

Monitoring activities used both automatic robot sensors and traditional field sampling, and were focused on hydrographic changes in the area and the response of organisms in the water column, sediments, and tidal flats of the delta. These observations were supplemented by data collection programs already underway in the region (summarized in the next section). The most intense period of data collection was the 50-mo study period, October 1994 through December 1999. This period included 12 mo of data before the Nueces Overflow Channel was opened, and 38 mo of data after. The data collection program was designed to measure the hydrographic changes (reference and treatment) at stations throughout the upper delta, and to compare the responses of biological parameters that would be most responsive to project diversion, namely water column productivity, benthic communities, and vegetation communities. Biological data collection is described in Alexander and Dunton 2002 and Montagna et al. 2002.

Hydrographic Events: Identification and Analysis

Nueces Bay, including the Nueces delta, is subject to numerous hydrometeorological influences, viz. river flow, precipitation, peripheral runoff, and forcing from wind and tide. Each of these, in isolation or in combination, may alter water chemistry (e.g., salinity and nutrients), transport detrital material, induce exchanges between the bay, delta, and river, and make accessible or restrict habitats available for estuarine aquatic organisms. Interpretation and analysis of the effects of the diversion project and the resulting biological responses require a quantitative delineation of the hydrography of the area, specifically with regard to flow, water level (stage), and salinity over the 50-mo study period (October 1994 through December 1999). A longer-term analysis of the effects of river diversions on the salinity gradient of the Nueces delta was also performed using data from selected stations in Nueces Bay and delta for the period of January 1992 through December 1999. This 8-vr interval was divided into two nearly equal periods before (3.8 yr) and after (4.2 yr) the Nueces Overflow Channel was completed on October 26, 1995 and project diversions began.

The sources for data used to evaluate the diversion experiment are summarized in Table 1. Many of these are from automatic monitors. The Texas Coastal Ocean Observing Network stations in Nueces Bay, operated by Texas A&M University-Corpus Christi Conrad Blucher Institute, provided conductivity (SALT03) and water level (White Point) at hourly intervals (Fig. 1). While there is no doubt some slope to the water surface in Nueces Bay occurs in response to meteorology, tides, and storm hydrographs in the river (Ward 1997), this is negligible in comparison to the temporal excursions in water level in the river and marsh. Therefore, stage data from the White Point gauge was regarded as an acceptable indication of the coincident elevation of Nueces Bay. Daily mean flow of the Nueces River is gauged by the U.S. Geological Survey (USGS) at Calallen, located just upstream from the diversion channel (Fig. 1). This is a low, rubble-mound dam, employed to facilitate water-supply diversion by the City of Corpus Christi and the head of tide for the Nueces River. The Rincon Bayou gauge was operated expressly for this project by the USGS. This automatic gauge was located in the channel of Rincon Bayou, approximately 275 m downstream from the Nueces River diversion point (Fig. 1). Instrumentation included sensors for precipitation, stage, and current velocity. Details on the installation and calibration of the gauge are given in Bureau of Reclamation (2000a). The Rincon gauge was activated on May 15, 1996, about 7 mo after the Nueces Overflow Channel was opened, so there is a gap in the data record at this gauge for the period of operation of the Overflow Channel. This 7-mo period proved to be relatively dry with few hydrographic events, so fortuitously the missing data are not critical.

Results and Discussion

The conceptual model of the function of the diversion project is that it should partially divert a storm hydrograph on the Nueces River from the river channel into the upper marsh, resulting in an increase in water elevation in the marsh (and associated inundation) and a decrease in salinity. In order to analyze the response of the marsh during the diversion experiment, it is necessary to identify such events in the data record. A hydrographic event was considered to include one or more of the following responses: occurrence of a substantial volume of freshwater flow in the Nueces River or in the diversion channel, an increase in water level (stage) in the marsh, or a decrease in salinity. The interpretation of the effect of such events on Nueces marsh is complicated by the fact that such responses can occur in isolation and result from processes other than a riverine storm hydrograph.

In order to objectively identify candidate hydrographic events in the data record, criteria were formulated to define an event based upon the separate behaviors of each of the key hydrographic variables. These included water-surface elevation (i.e., stage) in Nueces Bay, Rincon Bayou and the superelevation (defined below) of Rincon over Nueces Bay, flow in the Nueces River and Rincon Bayou, and salinity in Nueces Bay (Table 2). Precipitation and wind were not treated as separate criterion variables because they provide no information on hydrographic response not independently contained in data on water flow, elevation, or salinity even though these meteorological elements can be useIABLE 1. Summary of data sources. USGS = U.S. Geological Survey, TCOON = Texas Coastal Ocean Observing Network, and CBI = Texas A&M University-Corpus Christi Conrad Blucher Institute.

Data Source	Parameter	Data Type	Measurement Location (Number of Stations)	Period of Record Used
Rincon Bayou near Calallen, USGS (Station 08215503)	Water level, current velocity, cal- culated flow	Data recorded at 15-min inter- vals	Upper Rincon Bayou (1)	May 16, 1996–Dec 31, 1999
Nueces River at Calallen, USGS (Station 08211500)	Daily precipitation Estimated daily flow*	Data archived as daily values Data recorded at 15-min inter- vals	Nueces River (1)	Oct 1, 1994–Dec 31, 1999
rcoon system, CBI	Water level, wind direction and velocity Salinity	Data recorded as 6-min aver- aged values	Nueces and Corpus Christi Bays (2)	Jan 1, 1992–Dec 31, 1999
Corpus Christi Bay NWS	Daily precipitation	Data archived as daily values	Corpus Christi International Airport (1)	Jan 1, 1992–May 15, 1996
Biological Monitoring (water column productivity)	Water quality, nutrients, phyto- plankton	Data sampled monthly	Nueces River and lower Rincon Bayou (3)	Jan 1, 1992–Dec 31, 1999
			Upper and central Kuncon Bay- ou, and upper delta (7)	Oct 1, 1994–Dec 31, 1999
Biological Monitoring (benthics)	Macrofauna, meiofauna	Data sampled quarterly	Upper and central Rincon Bay- ou, and upper delta (6)	Oct 1, 1994–Dec 31, 1999
Biological Monitoring (vegeta- tion)	Surface and porewater quality, macrophytes	Data sampled bi-annually	Upper delta and central Rincon Bayou (3)	Oct 1, 1994–Dec 31, 1999
* Reliable data for discharge val review) were estimated by extrapc	ues above 77.87 m ³ s ⁻¹ were not ava dation.	ulable; all daily flow values in exces	s of this amount (of which there we	tre 3 in the record under

Response Parameter	Location	Defining Criteria of a Hydrographic Event								
Flow	Nueces River	A 24-h mean (daily) flow in the Nueces River at Calallen exceeding 14.2 m ³ s ⁻¹ .								
	Rincon Bayou	A 24-h mean (daily) flow in Rincon Bayou, either positive or negative, exceeding 0.28 m ³ s ⁻¹ .								
Stage	Nueces Bay	A 24-h mean (daily) stage in the water elevation of Nueces Bay exceeding 0.30 m, referenced to the consistent CBI datum from Ward (1997), established by empirical leveling.								
	Rincon Bayou	A 24-h mean (daily) stage in the water elevation of Rincon Bayou exceeding 0.61 m, relative to Rin- con gauge datum, which is 422 cm above the consistent datum for CBI gauges.								
	Super-elevation	The difference of Rincon Bayou minus Nueces Bay daily stage values exceeding 0.15 m, referenced to common datum.								
Salinity	Nueces Bay	Change in salinity concentrations of Nueces Bay exceeding 5 psu over a 5-d period.								

TABLE 2. Criteria used to define hydrographic events in the data record. CBI = Texas A&M University-Corpus Christi Conrad Blucher Institute.

ful and important in understanding the response of the delta ecology. Individual occurrences within the data record which met at least one of the six criteria of Table 2 were identified as hydrographic events. Each identified event occurring between October 1, 1994 and December 31, 1999 was numbered sequentially. As an example, a single year is plotted in Fig. 2 showing the time series (smoothed by 24-h averaging) for the various hydrographic variables, and the hydrographic events 28–37 are identified.

For each event, the integrated values for all hydrographic variables are summarized in Table 3. The term integrated means either averaged or accumulated over the duration of the event, whichever is more useful for the parameter under consideration. The duration period for each event was at least that for which the defining criterion was satisfied, though often a longer event period was specified to be sure that the complete response of

the bay or delta was included. When several hydrographic events overlapped (i.e., when several variables each satisfied criteria separately and simultaneously), the event duration was at least the period from the first occurrence of the earliest criterion threshold for any parameter to the latest sub-threshold occurrence for all parameters. Separation of the record into events was frustrated when the response to one event overlapped that of the next. For example, a series of river storm hydrographs might occur, each of which raised the Rincon stage or Calallen flow above the threshold defining an event, and a new surge of inflow occurred before the recession of the preceding event has subsided (e.g., Events 12-14, 16-17, 21-27, 35-36, etc.). These instances are identified in Table 3 by an asterisk following the event number, and some may be observed in Fig. 2.

The super-elevation of Rincon Bayou over Nueces Bay is the algebraic difference of Rincon Bayou



Fig. 2. Selected hydrographic data for the calendar year 1999.

TABLE 3. Summary of hydrographic events that occurred during the study period October 1, 1994 through December 31, 1999. Response variables that met event criteria are in bold. An asterisk (*) indicates an event that begins immediately following the conclusion of the previous event.

						Flow Volume (10 ⁸ m ⁸)		Event Mean Stage (m MSL)			Salinity in Nueces Bay (psu)	
	Starting Date					Total	Net					
Event Number	Year	Month	Day	Duration (d)	Rainfall (cm)	Nueces River	Rincon Bayou	Nueces Bay	Rincon Bayou	Super- elevation	Start	Net Change
1	1994	12	20	14	97	4,950	0	0.35			26.6	-6.6
2	1995	5	29	6	61	801	0	0.55	_		28.8	-3.2
3		6	18	13	35	7,489	0	0.42			27.1	-8.8
4		8	5	10	113	191	0	0.63			25.1	-0.7
5		9	22	19	91	10,978		0.69			30.4	-3.7
6		10	26	10	297	1.781		0.69			23.8	-0.9
7		12	1	12	1	1,617		0.32			25.1	-2.4
8		12	17	6	16	276		0.33			24.2	1.5
9		12	25	5	0	241		0.26			23.2	4.9
10	1996	1	1	4	0	1,221		0.27			23.7	-0.1
11		8	21	15	205	602	32	0.46	0.51	0.05	43.8	-0.9
12		10	1	18	17	1,248	229	0.72	0.74	0.02	40.9	-2.6
13*		10	19	5	6	41	17	0.59	0.66	0.07	44.4	0.4
14*		10	24	10	5	591	42	0.64	0.68	0.04	39.6	0.2
15	1997	4	1	13	130	280	-15	0.66	0.73	0.06	31.4	-5.6
16		6	21	13	59	45,369	973	0.42	1.16	0.73	26.8	-23.0
17*		7	4	23	2	66,249	940	0.38	1.01	0.63	3.7	0.3
18		10	6	20	290	28,892	329	0.68	0.94	0.26	26.5	-17.2
19	1998	3	25	9	0	1,491	-31	0.55	0.61	0.06	24.0	2.8
20		6	6	9	0	0	14	0.55	0.62	0.07	31.8	2.2
21		8	12	11	142	907	21	0.40	0.44	0.04	38.5	-7.2
22*		8	23	8	2	4,894	-7	0.53	0.60	0.07	31.6	-3.0
23*		9	1	28	127	65,283	771	0.73	0.94	0.20	30.8	-19.9
24*		9	29	17	93	36,759	218	0.59	0.80	0.21	12.3	-7.9
25*		10	16	14	201	49,092	3,764	0.76	1.39	0.63	5.4	-3.2
26*		10	30	13	29	30,002	189	0.64	0.90	0.26	2.1	3.1
27*		11	12	16	76	32,883	80	0.48	0.75	0.28	5.7	-2.5
28	1999	3	5	12	1	322	10	0.48	0.59	0.10	23.2	2.7
29		3	24	23	66	24,216	165	0.52	0.71	0.18	25.0	-9.1
30		4	27	10	0	595	-27	0.63	0.69	0.06	19.7	2.5
31*		5	7	17	41	221	-121	0.63	0.69	0.06	22.7	2.4
32		6	2	6	0	4,600	12	0.50	0.62	0.12	23.2	-1.4
33		6	19	8	58	2,948	-133	0.56	0.63	0.07	27.3	-8.0
34*		6	28	15	37	27,571	162	0.43	0.72	0.29	18.9	-9.1
35		8	19	16	190	10,491	-60	0.45	0.65	0.20	22.7	-6.2
36*		9	4	17	31	38,192	1,052	0.48	0.95	0.47	16.3	-9.5
37		9	27	21	69	2,901	-47	0.62	0.65	0.03	10.0	8.6

stage minus Nueces Bay stage, after correction to a common datum. Super-elevation is the direct hydraulic force driving discharge into the delta through the Nueces Overflow Channel. This was computed at hourly intervals from the respective data records, and then further integrated as necessary for long-term analyses.

The hydraulic variables of flow and stage respond quickly to river freshets and other hydrodynamic forcings. Salinity exhibits a much slower response. In upper Nueces Bay, this would be expected to be an initial drop in concentration, followed by a recovery or re-intrusion period of a slow increase with time (Ward and Montague 1996). While several indicators of salinity response were employed, only one is shown in Table 3, the net incremental change over the duration of the event, for which the initial salinity is also given.

For the entire study period, a total of 37 hydrographic events were identified (Table 3), of which five occurred prior to the opening of the Nueces Overflow Channel. These 37 events were highly variable in the magnitude and duration of their responses, and in the subset of hydrographic variables in which a response occurred. Some were associated with seasonally high waters in Nueces Bay (driven by the secular variation of the Gulf of Mexico, see Ward 1997), some were salinity responses elicited only by internal circulations of the bay, some were responses to intense rainfall, and some were due to inflow from storm hydrographs in the Nueces River. Most (28) of these events occurred when the USGS Rincon gauge was operating in the Nueces Overflow Channel, allowing the direct measurement of flow diverted by the diversion project, the associated water level rise and local precipitation.

During the diversion experiment period, the Nueces River exceeded the natural flooding threshold for the delta (1.64 m) on only four occasions. Except for these events (Events 16, 18, 25, and 36), all of the water exchanged between the Nueces River and Rincon Bayou during the study period was due to the Nueces Overflow Channel, and the Rincon Bayou flow volumes in Table 3 are those measured in this channel. For the extreme high-water Events 16, 18, 25, and 36, an additional amount of water also entered Rincon Bayou via the low depressions along the natural bank of the river, water which would have spilled into the upper delta independent of the Nueces Overflow Channel. This additional volume (totaling $1.2 \times 10^6 \text{ m}^3$) was estimated by application of the Corps of Engineers HEC-2 hydraulic model (Bureau of Reclamation 2000d) and included in the totals presented in Table 3.

Because each of the hydrographic variable responses can occur in isolation without the involvement of the others, a certain degree of care must be used in determining how a hydrographic event has influenced the chemistry and ecology of the project area. Of the 37 events in Table 3, 15 met the flow criteria for a flow event in the Nueces River, 16 met the criteria for a stage event in Nueces Bay, and 21 met the criteria for a salinity event.

For a flood hydrograph in the Nueces River channel, we might anticipate an association between the total flow volume in the Nueces River and the flow diverted through the Nueces Overflow Channel (Fig. 3). The volume diverted generally increases with the flow in the river, and the actual proportion of the flow amount diverted is on the order of 2% of that in the river. There is considerable scatter in this relationship. The proportion of river flow diverted into the marsh by the Nueces Overflow Channel is a complex function of the hydraulics of the channel and the time signal of the flood hydrograph in the river. For present purposes, we observe that this proportion is dictated by the difference in water levels between the river stage at the point of diversion and upper Nueces Bay (in turn governed by the river hydrograph and the tidal variation in the bay) and by the capacity of the Nueces Overflow Channel (in turn governed by the cross section and frictional resistance of the channel).

To explore this further, the data of Fig. 3 are segregated by 0.3-m intervals in water level in Rincon Bayou. Within each water level class, the volume transported through the Nueces Overflow Channel proves to be substantially independent of the volume in the Nueces River. This is a manifestation of the phenomenon of hydraulic capacity.

Fig. 3. Positive flow volume diverted through Rincon Bayou (or through the Nueces Overflow Channel) versus total flow volume carried in the Nueces River. Only events that met criteria for a flow event in the Nueces River were used to account for the corruptive influence that tide has on flow into Rincon Bayou, especially at low river flow values. The solid line represents a linear regression of all data points, and the dashed lines represent linear regressions of data points grouped by stage interval.

The Nueces Overflow Channel (and upper Rincon Bayou) achieves hydraulic capacity shortly after a flood event begins, so additional increases in the volume diverted through the overflow channel require disproportional increases in the flow (and stage) of the Nueces River. A similar sorting by water levels is also evident when the flow volume in Rincon Bayou is plotted against the super-elevation (not shown).

Unlike a river channel system in which the head gradient and the water level (stage) are closely related (e.g., Grover and Harrington 1943), there is no direct relation between water level and flow in the Nueces River below Calallen Dam because of the corrupting effect of tidal and meteorological water-level variations in Nueces Bay. In the Nueces Overflow Channel, the Nueces River hydraulic head (i.e., the super-elevation) is superimposed on whatever water level is present in Nueces Bay. This water level still affects how the river head can drive flow through the overflow channel, because the deeper the water, the greater the cross-section area of the channel (and upper delta), and the lower the frictional resistance. For a given hydraulic head from the Nueces River to Nueces Bay, there is a greater flow through the diversion channel when the Nueces Bay water levels are higher.

For the purpose of salinity-response analysis, all hydrographic events occurring from 1992 through 1999 were considered so that a larger database of pre-diversion events could be included in the analysis. The incremental salinity responses in Nueces Bay of each event (as a percentage of initial salin-

Fig. 4. Total event flow volume in Nueces River (measured at Calallen gauge) versus the fractional salinity response of Nueces Bay. The solid line represents a linear regression of postproject event data.

ity) are plotted against the total event flow volume in the Nueces River in Fig. 4. Data for events for which the initial salinity was less than 5 psu are excluded due to noise introduced by determining percentages from such small salinity values. The same general relation of diminishing salinity response with increasing event flow volume is evident for both pre-diversion and post-diversion conditions. Operation of the overflow channel does not measurably affect the response of bay salinity, which is not a surprising conclusion given the very small proportion of flow volume diverted through the overflow channel compared with that in the river. For event flow volumes less than about 10 imes10⁶ m³, the fractional salinity response in Nueces Bay is noisy, even positive for a number of the events, because non-hydrological factors become increasingly important in affecting the salinity of Nueces Bay. Such multivariable controls on estuary salinity are theoretically anticipated (e.g., Ward and Montague 1996) and there is a level of inflow below which its effects on estuary salinity are nil. Although quantification of this threshold for Nueces Bay is not relevant to evaluating the effects of the diversion project, it may be useful in devising operating strategies for a future permanent controlled diversion.

The diversion project had no obvious effect on the long-term salinity pattern of the Nueces River (Fig. 5). In both pre-project and post-project periods, salinity concentrations in the river channel increase with distance downstream toward Nueces Bay. The effect of diversion was observed in the salinity of the delta. In the upper and central segments of Rincon Bayou, the average salinity and its longitudinal gradient changed dramatically after

BEFORE diversion channel (1992-1995)
AFTER diversion channel (1995-1999)

Fig. 5. Relative mean salinity concentrations for selected stations in the Nueces River and Rincon Bayou (before and after construction of the Nueces Overflow Channel) presented as a fraction of mean bay salinity. Error bars are based on between 10 and 111 profile surveys for each station in the BEFORE period (total of 856), and between 51 and 82 for each station in the AFTER period (total of 903). The Nueces Overflow Channel connects the Nueces River with Rincon Bayou immediately below the IH 37 Bridge at about 0 km (see Fig. 1).

the opening of the Nueces Overflow Channel (Fig. 5). During the period prior to the diversion project, these reaches of Rincon Bayou exhibited the highest average salinity concentrations in the Nueces delta, while during the period of project diversions, salinity concentrations were the lowest in the delta. This alteration was due not only to the diversion of freshwater inflows into the delta during flood events, but also to the opportunity of regular daily exchange between Rincon Bayou and the Nueces River, which were too small in magnitude to meet the criteria for a flow event (see Table 2). Before the diversion project, there was no regular exchange with the Nueces River, and the resulting salinity gradient in the upper Rincon Bayou channel may be termed a reverse estuary, opposite that of an estuary channel with regular freshwater influx at its head. Without the diversion project, average salinity concentrations in upper Rincon channel during the second period would have remained strongly hypersaline, likely greater than 50 psu instead of the observed range of 21 to 28 psu.

The ecological response of the delta to increased freshwater inflow and reduced salinity concentrations in the soil and water was positive (Bureau of Reclamation 2000a; Montagna et al. 2002; Alexander and Dunton 2002). Nutrient import and primary production in the water column were increased (Bureau of Reclamation 2000a), as were benthic community abundance, biomass and diversity (Montagna et al. 2002). The percent cover of annual marsh plants was increased at rates greater than areas not directly influenced by river diversions (Alexander and Dunton 2002).

Conclusions

With the natural physiography of the Nueces River levee and post-reservoir hydrology, the minimum flooding threshold required for the Nueces River to spill freshwater into the upper Nueces Delta was rarely attained (Ward 1985; Bureau of Reclamation 2000a). From 1982 (the completion of Choke Canyon Dam) through 1999, the Nueces River has only significantly exceeded its banks in the delta on five occasions. Excavation of the overflow channel fundamentally changed this condition, lowering the minimum flooding threshold for the delta from 1.64 m to about 0.0 m MSL. During the 50-mo period when the overflow channels of the Demonstration Project were operating, over 8 \times 10⁶ m³ was diverted from the Nueces River into Rincon Bayou and the upper delta. Of this total amount, only about 1.2×10^6 m³ would have spilled into the marsh without the Nueces Overflow Channel. During the diversion period, the total volume of freshwater inflow into the upper Nueces Delta was increased about seven-fold over what would have occurred without the project.

Though the diversion had no effect on the salinity of the Nueces River channel or Nueces Bay (as expected), its effects on salinities and the salinity gradient in Rincon Bayou were substantial. In a relatively short period of time (only 4.2 yr after the opening of the Nueces Overflow Channel), the reverse estuary salinity gradient in the upper delta before the diversion project reverted to a more natural form, with average salinity concentrations lowered in upper Rincon Bayou and diminishing with distance toward the overflow channel. While beyond the scope of monitoring and analysis of this project, we postulate that an ecologically healthier Nueces delta will indirectly benefit the communities of the larger Nueces Bay estuary system.

Because of limitations in program authority and landowner participation, the U.S. Bureau of Reclamation's Rincon Bayou Demonstration Project was declared complete in September 2000 and the Nucces Overflow Channel was filled in. Based upon the findings of Reclamation's Concluding Report for the project, the City of Corpus Christi implemented a permanent diversion project and reopened the Nueces Overflow Channel in October 2001. The overflow channel will be maintained by the City and is to remain open in perpetuity.

Despite the significance of a seven-fold increase in the amount of freshwater diverted during the study period and the positive ecological response,

the project modifications did not restore the natural flow regime to the Nueces Delta. Assuming that the overflow channel had been in place from 1982 (or, since the completion of Choke Canyon Dam, the last reservoir to be built in the Nueces watershed) through 1999, the total amount of freshwater diverted would only have represented about 2% of the volume naturally diverted during the pre-1958 (and therefore, pre-reservoir) period (Bureau of Reclamation 2000b). Therefore, the effect of the reservoir system on the natural flow regime of the Nueces River was not negated by the project diversions. This project, however, demonstrates that the location of freshwater inflow can be as important as its magnitude, and optimizing the location of its introduction into the estuary can provide benefits without necessarily altering the volume of freshwater inflow. This observation has potential implications for management of inflow to water-deficient systems such as Corpus Christi Bay.

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