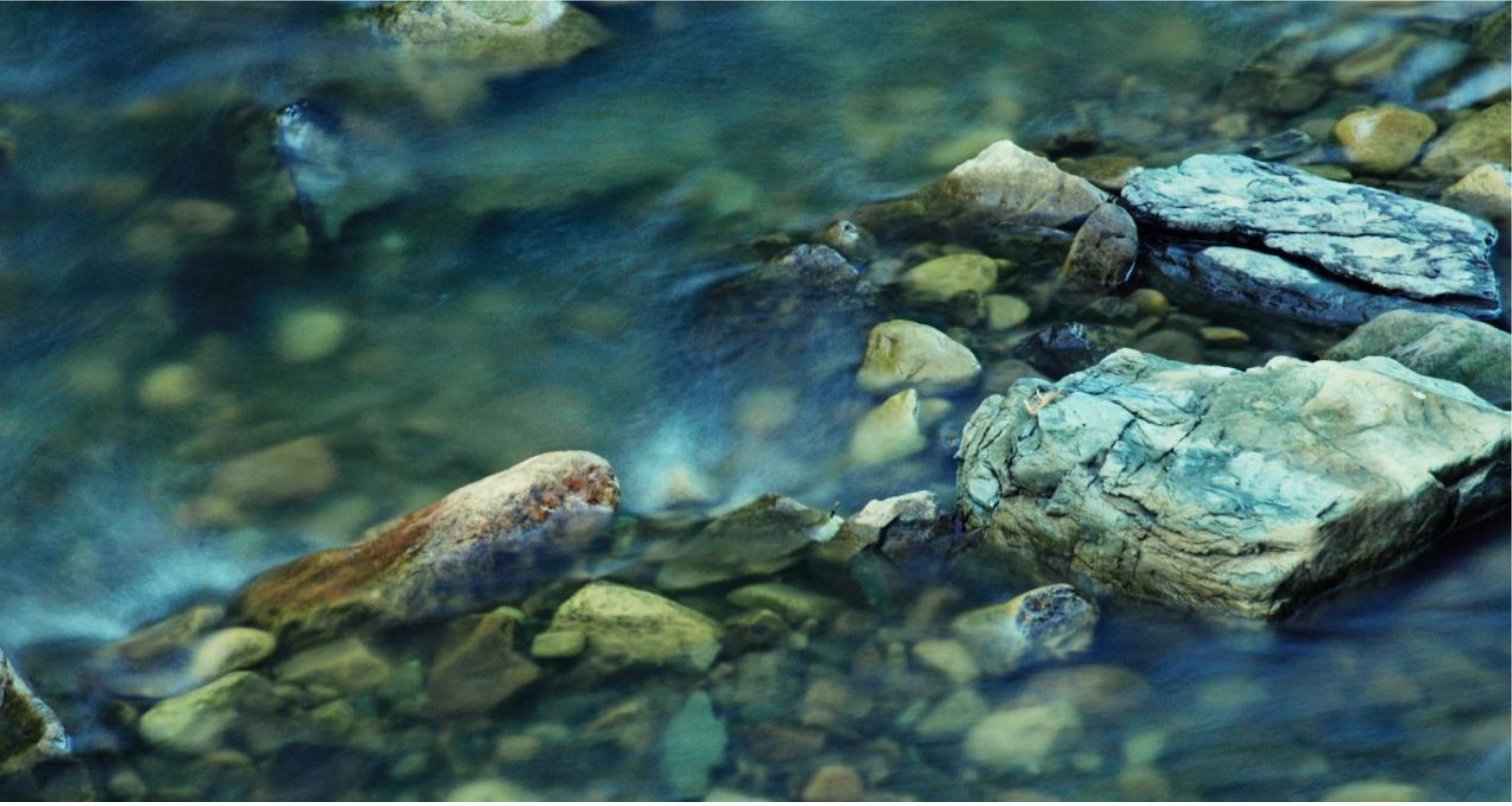
August 2017
TWDB Contract # 1600012015

ANCHOR QEA

Nutrient Budget for Nueces Bay

Prepared for Texas Water Development Board

PURSUANT TO HOUSE BILL 1 AS APPROVED BY THE 84TH TEXAS LEGISLATURE, THIS STUDY REPORT WAS FUNDED FOR THE PURPOSE OF STUDYING ENVIRONMENTAL FLOW NEEDS FOR TEXAS RIVERS AND ESTUARIES AS PART OF THE ADAPTIVE MANAGEMENT PHASE OF THE SENATE BILL 3 PROCESS FOR ENVIRONMENTAL FLOWS ESTABLISHED BY THE 80TH TEXAS LEGISLATURE. THE VIEWS AND CONCLUSIONS EXPRESSED HEREIN ARE THOSE OF THE AUTHOR(S) AND DO NOT NECESSARILY REFLECT THE VIEWS OF THE TEXAS WATER DEVELOPMENT BOARD.



August 2017
TWDB Contract # 1600012015

Nutrient Budget for Nueces Bay

Prepared for Texas Water Development Board

PURSUANT TO HOUSE BILL 1 AS APPROVED BY THE 84TH TEXAS LEGISLATURE, THIS STUDY REPORT WAS FUNDED FOR THE PURPOSE OF STUDYING ENVIRONMENTAL FLOW NEEDS FOR TEXAS RIVERS AND ESTUARIES AS PART OF THE ADAPTIVE MANAGEMENT PHASE OF THE SENATE BILL 3 PROCESS FOR ENVIRONMENTAL FLOWS ESTABLISHED BY THE 80TH TEXAS LEGISLATURE. THE VIEWS AND CONCLUSIONS EXPRESSED HEREIN ARE THOSE OF THE AUTHOR(S) AND DO NOT NECESSARILY REFLECT THE VIEWS OF THE TEXAS WATER DEVELOPMENT BOARD.

August 2017
TWDB Contract # 1600012015

Nutrient Budget for Nueces Bay

Prepared for
Texas Water Development Board
1700 Congress Avenue
Austin, Texas 78701

Prepared by
Anchor QEA, LLC
901 South Mopac Expressway
Barton Oaks Plaza V, Suite 150
Austin, Texas 78746

TABLE OF CONTENTS

TABLES

FIGURES

APPENDICES

ABBREVIATIONS

ac	acre
ac-ft	acre-feet
BBASC	Nueces River and Corpus Christi and Baffin Bays Basin and Bay Area Stakeholder Committee
BBEST	Basin and Bay Expert Science Team
CCBNEP	Corpus Christi Bay National Estuary Program (now known as the Coastal Bend Bays and Estuaries Program)
cfs	cubic feet per second
cm	centimeter
cm^2	square centimeter
cm^3	cubic centimeter
Cs-137	Cesium-137
CSM	conceptual site model
DMR	Discharge Monitoring Report
g	gram
km	kilometers
L	liter
lb	pound
m^2	square meter
mg	milligram
MGD	million gallons per day
N	nitrogen
N_2	nitrogen gas
NADP	National Atmospheric Deposition Program
NEAC	Nueces Estuary Advisory Council
NH_3	total ammonia, as nitrogen
NO_3	nitrate, as nitrogen
NO_{23}	nitrate plus nitrite, as nitrogen
NPDES	National Pollutant Discharge Elimination System
P	phosphorus
Pb-210	lead 210
ppt	parts per thousand
SAV	Submerged aquatic vegetation
SB	Senate Bill
SWQM	Surface Water Quality Monitoring
TAMUCC	Texas A&M University, Corpus Christi

TCEQ	Texas Commission on Environmental Quality
TKN	total Kjeldahl nitrogen
TN	total nitrogen
TPDES	Texas Pollutant Discharge Elimination System
TWDB	Texas Water Development Board
TxRR	Texas Rainfall-Runoff
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
WWTP	wastewater treatment plant
yr	year

Abstract

Senate Bill 3 (SB 3) of the 80th Texas legislative session (2007) established a framework for identifying and promulgating environmental flow standards throughout Texas. As a result, the Texas Commission on Environmental Quality adopted environmental flow standards for the Nueces River, its associated tributaries, the Nueces-Rio Grande Coastal Basin, and Corpus Christi and Baffin bays, effective March 6, 2014, based on recommendations from regional stakeholders and scientific experts. These flow standards include freshwater inflow standards for Nueces Bay and Nueces Delta. Under SB 3's provision for adaptive management, which calls for continued studies to validate and refine environmental flow analyses, recommendations, and standards, this project was funded during the 84th Texas legislature to assist the Texas Water Development Board and the Nueces River and Corpus Christi and Baffin Bays Basin and Bay Area Stakeholder Committee (BBASC) with understanding how nutrient dynamics within Nueces Bay may have changed since pre-development times.

This report describes the development of a nutrient budget for nitrogen, which was determined to be the limiting nutrient, and includes quantitative estimates of loadings to Nueces Bay under average conditions during historical (i.e., pre-development) and present conditions (i.e., post-development) based on available data, model output, and literature. Budget components evaluated include local watershed inputs, groundwater inputs, municipal and industrial point source discharges, tidal exchanges, wet deposition, dry deposition, burial, and biochemical reactions such as denitrification. For each budget component, estimated changes in total nitrogen from pre- to post-development conditions are highlighted and discussed where possible.

While uncertainties in the loading estimates must be recognized, the most important source and sink of nitrogen were found to be the gaged stream component (i.e., Nueces River) and the process of denitrification, respectively. Nitrogen fixation was identified as a moderate source of nitrogen whereas tidal exchange was estimated to be a moderate sink. Of the sources for which data were available to estimate pre- and post-development nitrogen loadings, the largest percentage change between these periods was for gaged streams, which appears to have declined by 75% due to a combination of reduction in flow and N concentration.

Understanding the relative importance of each component in the total nitrogen budget can be used to help guide recommendations for changes to the freshwater inflow standards, understand benefits associated with discharge of municipal wastewater treatment plant effluent, prioritize SB 3 strategies, and evaluate other management options related to nutrients.

Due to the absence of extensive monitoring data for assessing pre-development conditions, this study also evaluated the utility of a paleoecological approach (using ecological markers in sediment cores) to estimate historical conditions. This evaluation found that such an approach may provide insight into the historical nutrient status of Nueces Bay.

1 Introduction

This report describes the development of a nutrient budget and quantification of nutrient loading to Nueces Bay under historical (i.e., pre-development) and present conditions (i.e., post-development). This work was funded by the Texas Water Development Board (TWDB) and performed on behalf of the Nueces River and Corpus Christi and Baffin Bays Basin and Bay Area Stakeholder Committee (BBASC[1]). The purpose of this effort is to provide information and guidance to the BBASC to better understand how nutrients impact the ecological health of Nueces Bay and how these dynamics may have changed since pre-development times.

1.1 Overview of the Senate Bill 3 Environmental Flows Process

Senate Bill 3 (SB 3) of the 80th Texas legislative session (2007) established a framework for identifying and promulgating environmental flow standards throughout Texas. As part of this process, the BBASC (comprised of regional stakeholders) and a Basin and Bay Expert Science Team (BBEST; comprised of regional scientific experts) were established. The BBEST submitted a report containing environmental flow recommendations in October 2011, and the BBASC submitted their report in August 2012. Following a public comment period, the Texas Commission on Environmental Quality (TCEQ) adopted flow standards for the Nueces River, its associated tributaries, the Nueces-Rio Grande Coastal Basin, and Corpus Christi and Baffin Bays, effective March 6, 2014. These flow standards include freshwater inflow standards for Nueces Bay and Nueces Delta.

SB 3 has provisions for adaptive management, which calls for continued studies to validate and refine environmental flow analyses, recommendations, and standards. In support of this effort, the 84th Texas legislature set aside funding to assist the TWDB and several BBASCs with further evaluations of environmental flows and the associated standards. This report documents one such study, with a focus on developing a nutrient budget and quantifying loadings to the tidal segment of the Nueces River and to Nueces Bay. Supplementing the Nueces BBASC 2012 Work Plan (BBASC 2012), this study was identified as a Nueces BBASC priority project for 2015 (Mims 2015).

1.2 Study Area

Figure 1-1 illustrates the Nueces Bay system. Located between Nueces and San Patricio counties of Texas, Nueces Bay is a secondary bay of the Corpus Christi Bay system. It is a shallow, well-mixed, and wind driven bay with a surface area of 17,500 acres (ac; USGS 2001). Salinity in the bay ranges from near fresh during heavy flood events to hypersaline during drought periods (BBEST 2011). At the upper end of Nueces Bay is the Nueces Delta, a complex array of channels, pools, marshes, and tidal flats. Except during periods of low inflow, the main source of freshwater to Nueces Bay is the

[1] The Nueces BBASC is a stakeholder group that is closely related to the Nueces Estuary Advisory Council, and these two groups often hold joint meetings.

Nueces River, which flows along the southern edge of Nueces Delta and enters the bay from the west.

An overview of Nueces Bay and its environs can be found in BBEST (2011), Hill et al. (2011), Montagna et al. (2009), and Ward (2003a through e).

1.3 Overview of Historical Changes to Freshwater Inflows

Flows in the Nueces River have been reduced by impoundments over the years. Constructed in 1898, Calallen Diversion Dam was the first impoundment on the lower Nueces River tidal segment developed for surface water storage (Norwine et al. 2005 as cited by Hill et al. 2011). Raised several times over the years, this small dam prevents Nueces Bay saltwater from entering Calallen Pool. In 1929, La Fruta Dam was constructed approximately 56 river kilometers upstream of Calallen Dam, creating a storage capacity of 55,000 acre-feet (ac-ft; Cunningham 1999 as cited by Hill et al. 2011). In 1958, the Wesley Seale Dam replaced the La Fruta Dam, creating Lake Corpus Christi, with a storage capacity of 257,260 ac-ft (Hill et al. 2011). In 1982, Choke Canyon Reservoir was constructed approximately 80 river kilometers upstream of Lake Corpus Christi on the Frio River with a storage capacity of 695,271 ac-ft (Corpus Christi Water Department Lake Corpus Christi and Choke Canyon Reservoir 2011 as cited by Hill et al. 2011). Combined, these reservoirs help to provide a reliable water supply for human uses, but they also increase evaporative losses and decrease the frequency of high flow pulses (Hill et al. 2011; Asquith et al. 1997).

1.4 Purpose of this Study

The purpose of this study is to provide information and guidance to the BBASC to better understand how nutrients impact the ecological health of Nueces Bay and how these dynamics may have changed since pre-development times. For this study, nutrient loadings (i.e., sources and sinks) for Nueces Bay are evaluated in the context of system nutrient budgets for pre-and post-development conditions.[2] Nutrient components considered in these budgets include local watershed inputs, groundwater inputs, municipal and industrial point source discharges, tidal exchanges, wet deposition, dry deposition, burial, and biochemical reactions such as denitrification.

This report includes quantitative estimates of each of the components of the nutrient budget under average conditions. Estimated changes from pre- to post-development conditions are highlighted and discussed. Insights drawn from this evaluation provide the BBASC with a better understanding of the historical and current influence of nutrients on ecological health and productivity. This understanding can be used to help guide recommendations for changes to the freshwater inflow

[2] Pre- and Post-development are defined identically as in the *2015 Watershed Study—Nueces Watershed Pre- and Post-Development Nutrient Budgets* (HDR 2015). In the HDR report, which estimated nutrient concentrations and loads throughout the Nueces River watershed, the year 1986 was used as the dividing year between pre- and post-development due to the construction and subsequent filling of Choke Canyon Reservoir.

standards, understand benefits associated with discharge of municipal wastewater treatment plant (WWTP) effluent, prioritize SB 3 strategies, and evaluate other management options related to nutrients. Given the BBASC's desire to understand pre-development conditions and the inherent limitations in pre-development data, an alternative, paleoecological approach for understanding the pre-development ecology of Nueces Bay is investigated. Findings and possible recommendations for future work are provided.

1.5 Report Organization

The report is organized as follows:

- Section 2 describes the development of conceptual site models, including determination of the limiting nutrient for Nueces Bay and review of macro-detritus literature.
- Section 3 documents the nutrient loadings estimated for each component of the nutrient budget for pre-and post-development conditions.
- Section 4 describes the investigation of the utility of paleoecological reconstruction for assessing pre-development conditions.
- Section 5 provides study conclusions and recommendations for future work.
- Section 6 provides all citations.
- Appendix A presents reviewer comments on the draft version of this report dated June 2017.

2 Conceptual Site Model Development

A nutrient-focused conceptual site model (CSM) is a conceptual framework for understanding and prioritizing nutrient sources and sinks. A CSM for a waterbody can be communicated graphically with "in" and "out" arrows depicting sources and sinks of nutrients.

Figure 2-1 provides an initial representation of a nutrient CSM for Nueces Bay. The focus is on nitrogen (N) because it is the limiting nutrient for Nueces Bay (Section 2.1); total nitrogen (TN) is used because it encompasses the bioavailable forms of N. At the request of the BBASC, literature on macro-detritus is also reviewed (Section 2.2).

2.1 Determination of the Limiting Nutrient

Plant and algae productivity (sometimes collectively referred to as "primary productivity") is limited by the availability of nutrients, typically N, phosphorus (P), and occasionally silica (Si) and trace metals. In general, freshwater systems are predominately P limited whereas saltwater systems are predominately N limited. Estuaries and bays have been observed to shift between N, P, or Si limitation depending on environmental conditions; however, they may be limited by an individual nutrient more often than others (USEPA 2001a). While a waterbody may be characterized as being limited by a nutrient, it does not mean the system is always deficient in that nutrient. Primary productivity is also mediated by factors such as light intensity, pH, salinity, and temperature (Kirk 1994). Limiting nutrient classification is based solely on which nutrient has the lowest ambient concentration, relative to physiological requirements and other nutrients.[3]

One common method for assessing the limiting nutrient is measuring the N to P ratio (N:P) in the water column. On average, marine phytoplankton use N and P at an approximate molar ratio of 16:1 (USEPA 2001a; Sterner and Elser 2002; Redfield et al. 1963), meaning that they require 16 mols of N to 1 mol of P for growth. Lower ratios indicate that N is the limiting nutrient, while higher ratios indicate a relative abundance of N and a limitation in P. Similarly, Boynton et al. (1982) examined N:P ratios from many estuaries and proposed that molar ratios less than 10 suggest N limitation and ratios greater than 20 suggest P limitation.

A long-term nutrient study of Rincon Bayou between 1995 and 1999 found that a majority of N:P ratios were below 5 (USBR 2000). The ratio only exceeded a value of 15 in 1% of 493 samples at eight stations. These results indicate an abundance of P relative to N. Bioassays conducted in the same study showed additions of P rarely enhanced growth of phytoplankton, but additions of N did. While these results do not confirm that Nueces Bay is also limited by N, they do suggest that water flowing from the bayou into Nueces Bay is low in N relative to P.

[3] Because the physiological requirement for N is greater than that for P, N may be the limiting nutrient, even when its ambient concentration exceeds the concentration of P.

Ward (2003a) analyzed the Corpus Christi Bay National Estuary Program (CCBNEP) historical water quality database and found the average 1990 to 2002 N:P ratio to range between 1 and 2 across nine regional bays; the ratio was 2.2 for Nueces Bay.[4] From these ratios, Ward concluded that P was in excess and N limited productivity in the region.

Several studies in the Nueces Estuary have also found that N measurements are more often below the detection limit than P measurements and thus the authors have inferred that N is more often limiting than P (Brock 2001; TPWD 2002).

Si has been suggested to be a jointly limiting nutrient in some Texas and Louisiana coastal systems (USEPA 2001a). Si is an important nutrient for diatoms, a major group of algae (D'Elia et al. 1983; Conley and Malone 1992). The source of Si to water systems is primarily from weathering and erosion of rocks in upland areas (USEPA 2001). Alterations of waterways and the construction of artificial lakes and reservoirs have been suggested to reduce the Si input into coastal areas (Officer and Ryther 1980 as cited in USEPA 2001). Si limitation can be determined using a biomass ratio in N:Si:P of 16:16:1 (Redfield et al. 1963; Conley et al. 1993). Si:N and Si:P ratios calculated from data (Montagna et al. 2009 as cited in BBEST 2011; Dunton et al. 2011 as cited in BBEST 2011) indicate Si is in abundance relative to N and P in Nueces Bay and therefore is unlikely to be the limiting nutrient. Based on this evidence that N is the most commonly limiting nutrient in Nueces Bay, the nutrient budget will be developed for N.

2.2 Review of Macro-detritus Literature

Macro-detritus is large organic matter that can degrade and provide nutrients for aquatic organisms.[5] It originates from terrestrial sources (e.g., leaf-litter and fallen trees) and aquatic sources (e.g., dead aquatic plants and organisms). Terrestrial macro-detritus is an external source that provides new nutrient inputs into a watershed and is the focus of the BBASC (2012). In general, terrestrial woody vegetation is high in carbon and low in nutrients (Wetzel 2001). Those portions of terrestrial vegetation that are relatively high in nutrients (e.g., leaves) tend to decompose rapidly, releasing organic and inorganic nutrients in dissolved form (Wetzel 2001).

Terrestrial detritus is introduced to the watershed by trees and plants along the banks of rivers. Under low flow conditions, leaf litter and woody debris are typically degraded into finer particulate matter before they reach estuaries and bays (Vannote et al. 1980). However, macro-detritus may reach estuaries and bays during high flow events that flush trapped debris downstream.

Efforts to find literature quantifying macro-detritus input to Nueces Bay were not fruitful (similarly, HDR [2015] was not able to find data quantifying macro-detritus input to Nueces Bay from the

[4] Calculations in Ward (2003a) were based on available N and P, as opposed to total.
[5] One can think of macro-detritus as organic matter that is not collected in water sampling bottles during routine monitoring events.

Nueces River). While the lack of TN data from macro-detritus prohibited its evaluation as a riverine source in the N budget developed for Nueces Bay, terrestrial macro-detritus may be important to the ecology of Nueces Bay. A study on diets of juvenile brown shrimp in the Rincon Bayou found shrimp near the freshwater entrance of the Nueces River had a significant proportion of their diets attributed to terrestrial detritus and/or riverine phytoplankton (Riera et al. 2000), indicating terrestrial detritus is a food source for organisms in some portions of Nueces Bay.

3 Quantification of Sources and Sinks

Based on an initial literature review of site-specific studies and previous budgets in the Coastal Bend region (Brock 2001; Breier et al. 2004; Yoon and Benner 1992; Whitledge 1989; Ward 2000a-e), the following sources and sinks may be important processes for a N nutrient budget for Nueces Bay and are therefore included in the CSM:

- Sources
  - Gaged streams
  - Ungaged watersheds
  - WWTPs
  - Other return flows
  - Wet deposition (precipitation)
  - Dry deposition
  - Nitrogen fixation
  - Groundwater discharge
- Sinks
  - Diversions
  - Denitrification
  - Nitrogen burial
- Source or sink
  - Tidal exchange with Corpus Christi Bay

Nutrient loads for each of these processes under average conditions are estimated based on data, literature (including local studies), and professional judgment and are expressed in units of mass per time (e.g., million grams (g) per year). This section describes each source and sink and the methods used to quantify each pre-development and post-development load.

3.1 Gaged Streams

Gaged inflow load is the nutrient load from watersheds calculated using measured streamflow combined with instream nutrient concentrations. For Nueces Bay, the only gaged inflow is the Nueces River. In 2015, HDR completed pre- and post-development nutrient loads for the Nueces River for the TWDB and Nueces BBASC (HDR 2015). In those calculations, loadings were estimated using simple linear regression analysis for TN as far downstream as the Nueces River at Mathis gage (Figure 1-1). For this study, to capitalize on the recent HDR work, the pre- and post-development values for the Nueces River were either taken directly from or calculated using values presented in HDR 2015.

Although pre-development loads at Mathis were not provided in HDR 2015 due to lack of total Kjeldahl nitrogen (TKN) data during the pre-development period, Tables 8-4 and 8-5 of HDR 2015 provide the pre-development load at the Nueces River near Three Rivers gage location ("Three Rivers," which is located upstream of Mathis[6]) and the percent change in load between Three Rivers and Mathis for the post-development period, respectively (Figure 1-1). Assuming the pre-development percent change in load between the Three Rivers and Mathis stations was the same as for the post-development period, a pre-development value was estimated by multiplying the pre-development load at Three Rivers (2,167,000 pounds per year [lbs/yr] under average[7] conditions) by the post-development percent change in load between Three Rivers and Mathis (-52.1% under average conditions). This results in an estimated pre-development load of 1,038,000 lbs/yr (471 million g N per year [mil g N/yr]) at Mathis.

The post-development value for TN load under average[8] conditions of 269,000 lbs/yr (122 mil g N/yr) was obtained directly from Table 8-4 of HDR 2015 for the Nueces River at Mathis.

The post-development value is lower than pre-development value due to a combination of lower flows and lower concentrations post-development. Neither flows nor concentrations at Mathis were provided in Table 8-4 of HDR 2015, but they could be back-calculated from values in that table. For comparison to loads calculated at gages within the Nueces basin, the table reports loads for U.S. Environmental Protection Agency (USEPA) regional reference conditions.[9] Using the Sub-ecoregion 34 loads reported on Table 8-4 of HDR 2015 and the constant Sub-ecoregion TN concentration of 0.86 milligrams per liter (mg/L) used in those load calculations, a pre-development average flow of 1,093 ac-ft per day (ac-ft/d) [551 cubic feet per second (cfs)] and post-development flow of 565 ac-ft/d (285 cfs) at Mathis were back-calculated for a flow reduction of nearly 50%. In turn, dividing the pre- and post-development loads at Mathis by these flows resulted in TN concentrations of 0.96 and 0.48 mg/L, respectively, for a concentration reduction of 50%.

3.2 Ungaged Watersheds

Ungaged inflow nutrient load was determined using flow from ungaged watersheds combined with runoff nutrient concentrations. Ungaged watersheds include those adjacent to the northern shore of Nueces Bay and feeding into the Nueces River between Mathis and Nueces Bay, including the tidal segment of the Nueces River (Figure 3-1). Watershed #22013 drains to the Corpus Christi Ship Channel and, therefore, was excluded from the calculations of watersheds draining into Nueces Bay.

---

[6] Lake Corpus Christi is located between the Three Rivers and Mathis gages.

[7] For pre-development, the average flow year was determined to be 1974 for the Nueces River near Mathis (HDR 2015). Geometric average flow was used because it more closely resembles the median flow than the arithmetic average flow (HDR 2015).

[8] For post-development, the average flow year was determined to be 1993 for the Nueces River near Mathis (HDR 2015). Geometric average flow was used because it more closely resembles the median flow than the arithmetic average flow (HDR 2015).

[9] The USEPA's ecoregional nutrient criteria for the Western Gulf Coastal Plain, specifically Sub-region 34 of Ecoregion X, were used by HDR for comparison to annual loads calculated from Nueces River data. These criteria represent water quality reference (i.e., pristine or minimally impacted) conditions for the watershed.

Flows for the ungaged watersheds were obtained from the Texas Rainfall-Runoff (TxRR) model, as provided by TWDB (Fernando 2017a). This model, which uses precipitation data to estimate runoff, was developed and is maintained by TWDB to provide flow inputs to TxBLEND, a hydrodynamic and salinity model for the bays and estuaries of Texas. TxRR simulated runoff for ungaged watersheds is also used as a component in the coastal hydrology dataset that TWDB maintains. The ungaged watersheds that flow to Nueces Bay are TxRR watersheds #21010, 22012, and 20005[10] (Figure 3-1). Hydrological data from TWDB are available starting from 1941.[11,12] For each watershed, average flows under pre-development and post-development conditions were calculated from 1941 to 1985 and 1986 to 2015, respectively.

Runoff concentrations for the ungaged watersheds were calculated using median TN values for each land use category for the CCBNEP Study area (Baird et al. 1996) and weighting the TN concentration by the approximate proportions of land use categories in watersheds #21010, 22012, and 20005 from the 2011 National Land Cover Database (Homer et al 2015; Figure 3-2). Land use in these watersheds was categorized into Industrial, Rangeland, and Undeveloped/Open, with TN in runoff concentrations of 1.26, 0.7, and 1.5 mg/L, respectively (Baird et al. 1996). Based on this approach, the land use-weighted TN concentrations were estimated to be 1.1, 1.3, and 1.5 mg/L for watersheds #21010, 22012, and 20005, respectively.

To determine the ungaged watershed loads, the TxRR flow estimates were multiplied by the land use-weighted TN concentrations. This resulted in load estimates of 82 mil g N/yr and 66 mil g N/yr under pre- and post-development conditions, respectively (Table 3-1). As shown in Table 3-1, the decline in TN loading from pre- to post-development is solely due to the decline in flow from the watershed between Mathis and Calallen Dam (#21010). In this calculation, TN concentrations were assumed to be the same under pre- and post-development conditions due to lack of land use and runoff data for the pre-development period; differences in runoff concentrations may have occurred between the pre- and post-development periods.

[10] Fifty percent of TxRR watershed #20005 was estimated to drain into Nueces Bay (TWDB 2011a).
[11] Ungaged flows were provided by TWDB starting with 1941. Flows before 1977 are from a water yield model; since 1977, TWDB has used the TxRR model to estimate daily stream flows in ungaged watersheds (TWDB 2011a). Due to a reduction in ungaged watershed area between the water yield and TxRR models (TWDB 2011a), ungaged flows from 1941 to 1976 were adjusted by the ratio of surface areas for each watershed (TWDB 2011a).
[12] TWDB disclaimer (Fernando 2017a): *The TxRR model simulations from 1941–1977 for ungaged watersheds draining to the Nueces estuary have not been verified. The simulations are being provided at the request of Anchor QEA. The TWDB makes no warranty, either expressed or implied, or assumes any legal liability or responsibility for the validity of the simulations for the 1941–1977 time period and its merchantability or fitness for any specific application*.

Table 3-1
Nitrogen Loadings for Ungaged Watersheds

TxRR Watershed	Watershed Description	Average Flow (ac-ft/d)		TN (mg/L)	TN Load[a] (mil g N/yr)	
		Pre-development	Post-development		Pre-development	Post-development
21010	Mathis to Calallen Dam	137.1 (69.1 cfs)	96.6 (48.7 cfs)	1.1	67.9	47.8
22012	Calallen Dam to Nueces Bay	7.5 (3.8 cfs)	8.7 (4.4 cfs)	1.3	4.4	5.1
20005[b]	Adjacent to northern shore of Nueces Bay	14.7 (7.4 cfs)	19.8 (10.0 cfs)	1.5	9.9	13.4
				Total	82.2	66.3

Notes:
a. Nitrogen load was calculated as the product of the average flow from the TxRR model (pre-development: 1977 to 1985; post-development: 1986 to 2015) and estimated land use-weighted TN concentrations of 1.1, 1.3, and 1.5 mg/L for watersheds #21010, 22012, and 20005, respectively.
b. Fifty percent of TxRR watershed #20005 was estimated to drain into Nueces Bay (TWDB 2011b).

3.3 Wastewater Treatment Plants

Effluents from WWTPs serve as point sources to a waterbody. Domestic and industrial WWTPs discharging to Nueces Bay and its watersheds that are not accounted for in Section 3.1 (Gaged Streams) and Section 3.2 (Ungaged Watersheds) are discussed in this subsection. Other return flows, such as from power plants, are discussed in Section 3.5.

Texas Pollutant Discharge Elimination System (TPDES)[13] permittee information was compiled from online searches of the Permit Compliance System and Integrated Compliance Information System databases (USEPA 2016) and a review of industrial and municipal permitted outfalls provided in a map (TCEQ 2016). It was assumed that effluent from dischargers in the watershed of Nueces Bay upstream of Nueces delta and downstream of Mathis would be attenuated and accounted for in the N loadings for the ungaged watershed (Section 3.2). Permittees that discharge to Nueces Bay and were not likely to introduce additional nutrients to the water being used were included under Section 3.5 (Other Return Flows); no TN data were available for these permittees. Based on discharge data, the permittees found to be the main contributors of point source nutrient loadings to Nueces Bay are the City of Corpus Christi Allison WWTP and City of Portland WWTP (Table 3-2; Figure 3-3).

[13] The State of Texas has the authority to administer the National Pollutant Discharge Elimination System (NPDES) in Texas. NPDES is a federal regulatory program to control discharges of pollutants to surface waters of the United States.

Table 3-2
Main TPDES Permittees Discharging Nitrogen to Nueces Bay

TPDES Permit Number	NPDES Permit Number	Permittee	Category	Original Permit Issue Date	Permitted Flow (ac-ft/d)	Nitrogen Data Available?
WQ0010401-006	TX0047082 and TXS000601	City of Corpus Christi – (Allison WWTP)	Sewage systems	8/27/1974	15.3 (5 MGD)	Yes
WQ0010478-001	TX0055433	City of Portland	Sewage systems	8/29/1974	7.7 (2.5 MGD)	No

Notes:
Other permittees discharge to Nueces Bay, but they were excluded because of low flow and/or lack of N data.
MGD: million gallons per day

Pacheco et al. (1990) reported annual total flow and pollutant load estimates for major and significant minor permittees for Nueces Bay for 1987.[14] Instead of using the Pacheco et al. pollutant load directly since they assumed typical pollutant concentrations of 11.2 mg/L for TN,[15] the pre-development N loads were recalculated using the Discharge Monitoring Report (DMR)-based flows from Pacheco et al. 1990 and the TN concentration estimated from recent DMR records (see post-development below). This assumption is reasonable given that no treatment process changes have occurred at Allison WWTP since the facility was built (Corn 2017). The pre-development loads for Allison WWTP and City of Portland WWTP were estimated to be 10.6 and 7.6 mil g N/yr, respectively, and totaled 18.2 mil g N/yr together (Table 3-3).

Table 3-3
Pollutant Load Estimates for Major WWTPs Pre-development

Permittee	Flow[a] (ac-ft/d)	TN[b] (mg/L)	TN Load (mil g N/yr)
City of Corpus Christi – Allison WWTP	6.8 (2.2 MGD)	3.5	10.6
City of Portland	4.9 (1.6 MGD)		7.6
		Total	18.2

Notes:
a. Flows reported by Pacheco et al. (1990) are for 1987.
b. Data (average of DMR records from 1999 to 2013; see post-development below) were used instead of the typical pollutant concentration of 11.2 mg/L assumed by Pacheco et al. 1990.

[14] This was assumed to be close enough to represent pre-1986 conditions.
[15] This TN concentration of 11.2 mg/L used by Pacheco et al. (1990) was drawn from a USEPA effluent guidelines document and was not based on any site-specific data.

For post-development N loads, all available DMR information was used in the calculations (USEPA 2016). For Allison WWTP, based on a flow of 6.4 ac-ft/d (2.1 million gallons per day [MGD; the average of available DMR records (1995 to 2013)]) and a TN concentration of 3.5 mg/L (the average of available DMR records [1995 to 2015]), the N loading to Nueces Bay was estimated to be 10.2 mil g N/yr. For City of Portland WWTP, TN data were not available. Assuming the Allison WWTP TN concentration of 3.5 mg/L is a reasonable approximation for the City of Portland WWTP and using an average City of Portland flow of 5.2 ac-ft/d (1.7 MGD) from available DMR records (2002 to 2016), the TN loading from the City of Portland WWTP to Nueces Bay was calculated to be 8.2 mil g N/yr. The calculated total load for the two permittees (18.4 mil g N/yr, Table 3-4) is similar to the pre-development load. At permitted flow levels, the total load would be 36.3 mil g N/yr.

Table 3-4
Pollutant Load Estimates for Major WWTPs Post-development

Permittee	Flow (ac-ft/d)	TN (mg/L)	TN Load (mil g N/yr)
City of Corpus Christi – Allison WWTP	6.4 (2.1 MGD)[a]	3.5 [b]	10.2
City of Portland	5.2 (1.7 MGD)[c]	3.5 [d]	8.2
		Total	18.4

Notes:
a. Average of all available DMR records (1995 to 2013)
b. Average of all available DMR records (1995 to 2015)
c. Average of all available DMR records (2002 to 2016)
d. The same concentration as Allison WWTP effluent is assumed since no TN data are available.

3.4 Diversions

Most notably from Calallen Diversion Dam, water diversions occur within the Nueces River basin to meet municipal and industrial needs. Since this water contains N, diversions result in the removal of N from the inflows to Nueces Bay and therefore is a sink in the CSM. Some of the diverted water may re-enter Nueces Bay through return flows (Section 3.5) or exit the Nueces Bay system through loss or by being returned to a different basin (e.g., Corpus Christi Bay).

TN removal from diversions was determined as the product of diversion flow rate and TN concentration. Based on data from TCEQ's water availability division, daily diversion data for the ungaged watersheds that flow to Nueces Bay were provided by TWDB from 1941 to 2014 (Fernando 2017a); methodologies for the derivation of diversion rates are described in TWDB (2011a, 2011b). Average diversions under pre- and post-development conditions were calculated from 1941 to 1985 and 1986 to 2015, respectively. TN concentrations of 0.96 and 0.48 mg/L for the pre- and post-development periods, respectively, were back-calculated from the TN loads and flows at Mathis, which were computed from values in HDR 2015 (Section 3.1). The resulting TN loads are -75 and -70 mil g N/yr under pre- and post-development conditions, respectively (Table 3-5).

Table 3-5
Estimated Nitrogen Load Removed Due to Diversions

Time Period	Diversions[a]		TN[b] (mg/L)	TN Load (mil g N/yr)
	Dates	Average Rate (ac-ft/d)		
Pre-development	1941-1985	-173.4 (-87.4 cfs)	0.96	-74.9
Post-development	1986-2014	-324.3 (-163.5 cfs)	0.48	-70.1

Notes:
a. Daily diversion rates were provided by TWDB (Fernando 2017a).
b. Back-calculated from N load and flow values at Mathis, as calculated from values in HDR 2015

3.5 Other Return Flows

Diversions occur within the Nueces River basin to meet municipal and industrial needs (Section 3.4). Some of this water re-enters the Nueces Bay watershed as return flows whereas some may exit the watershed through loss or as return flows to a different basin (e.g., Corpus Christi Bay). Because the water returned contains N, return flows result in the addition of N to the system and therefore are a source in the CSM.

The TN load from return flows was determined as the product of return flow rate and TN concentration. Based on data from TCEQ's water quality division and USEPA's discharge elimination system database, daily return flows from 1941 to 2014 were provided by TWDB (Fernando 2017a); methodologies for the derivation of return flows are described in TWDB (2011a, 2011b). Average return flows under pre-development and post-development conditions were calculated from 1941 to 1985 and 1986 to 2015, respectively. Because return flows and associated TN loads from the two main WWTPs—Allison and City of Portland WWTPs—have been quantified separately (Section 3.3), these average return flows were then reduced by the average flows of the two WWTPs. Because N concentration is not measured in many of the return flows and the water users (e.g., electric service providers) would likely not affect N concentrations in the diverted water, the same pre- and post-development TN concentrations that were applied to diversions were assumed for the return flows (Section 3.4). This resulted in load estimates of 38 and 73 mil g N/yr under pre- and post-development conditions, respectively (Table 3-6).

Table 3-6
Estimated Nitrogen Load Due to Return Flows Other than Allison and City of Portland WWTPs

Time Period	Returns[a] Dates	Returns[a] Average Rate (ac-ft/d)	Return Flow Minus WWTP Flows (cfs)	TN[b] (mg/L)	TN Load (mil g N/yr)
Pre-development	1941-1985	93.6 (47.2 cfs)	87.3 (44.0 cfs)	0.96	37.7
Post-development	1986-2014	342.3 (172.6 cfs)	337.0 (169.9 cfs)	0.48	72.8

Notes:
a. Daily return flow rates were provided by TWDB (Fernando 2017a).
b. Back-calculated from N load and flow values at Mathis, as calculated from values in HDR 2015

3.6 Wet and Dry Deposition

Atmospheric deposition is the process by which dissolved and particulate nutrients enter a waterbody at the water's surface either by rainfall (wet deposition) or particulate matter (dry deposition). N in atmospheric deposition originates from human sources such as transportation, agriculture, and industrial emissions as well as natural sources such as soil, vegetation, and wildfire (WSDOE 2017).

Wade and Sweet (2008) conducted a long-term study of atmospheric deposition in the Coastal Bend region. The study included a sampling station at Whites Point along the northern coast of Nueces Bay; air and rainwater were sampled weekly from June 1997 to August 1999 and analyzed for a suite of parameters, including inorganic N (i.e., total ammonia, as nitrogen [NH_3] plus nitrate [NO_3]).

For this N budget, post-development wet and dry deposition load estimates for Nueces Bay were based on annual TN deposition rates reported at Whites Point by Wade and Sweet (2008). The annual average deposition rate from Whites Point in 1998 was used because that year had the most complete record of sampling. Because organic N was not measured, it was calculated as 19% of TN, similar to the approach used by Wade and Sweet, which in turn was based on an earlier U.S. Geological Survey (USGS) study of atmospheric deposition in the Coastal Bend region (Ockerman and Livingston 1999). The deposition rates, per unit surface area, reported by Wade and Sweet were multiplied by the surface area of Nueces Bay to obtain the TN loads per year to the bay. The resulting TN loads calculated for wet and dry deposition to Nueces Bay were 27 and 34 mil g N/yr, respectively.

Atmospheric deposition has also been studied at other sites nearby. Wade and Sweet (2008) reported wet deposition from Texas A&M University, Corpus Christi (TAMUCC) campus, a National Atmospheric Deposition Program (NADP) site at Beeville, Texas, and two sites operated by the USGS in San Patricio County and Kleberg County (Ockerman and Livingston 1999). Wade and Sweet (2008) found average yearly wet N deposition to be consistent across the region. Castro et al. (2003) reported annual wet deposition loads for several Texas estuaries, including Corpus Christi Bay. Rates were reasonably similar to the rates found in Wade and Sweet (2008) when normalized by estuary surface areas. Dry deposition sampling was limited to the Whites Point and TAMUCC sites (Wade and Sweet 2008). The TAMUCC site consistently reported higher dry deposition rates than those at the Whites Point site, suggesting that dry deposition loads may be more spatially variable than wet deposition.

Studies measuring wet or dry N deposition on the coast of Nueces Bay during the pre-development period were not found. However, wet N deposition was measured at a USGS NADP site located 38 miles inland at Beeville, Texas, between 1984 and 2015 (NADP 2017). Annual TN wet deposition loads at this site showed no trend, which suggests no meaningful change in rates between pre- and post-development periods. Additionally, Asquith et al. (1997) did not identify a trend in annual precipitation amounts at three regional sites (1968 to 1993 data). Therefore, the pre-development TN loads for wet and dry deposition were assumed to be the same as those for the post-development period.

3.7 Nitrogen Fixation

N fixation is the process where nitrogen gas (N_2) from the atmosphere is converted into NH_3, which is subsequently incorporated into cellular N. This introduces new bioavailable N into the waterbody. In aquatic systems, this process is mediated by blue-green algae either in the water column as plankton or in benthic algal mats. The contribution to N fixation by planktonic algae in the water column was suggested to be minimal in most estuaries (Howarth et al. 1988). Therefore, literature reviewed for this report focused primarily on benthic N fixation.

Gardner et al. (2006) studied benthic N fixation in several Texas bays and estuaries, including five locations in the Nueces Estuary: one at the Nueces River mouth, one in upper Corpus Christi Bay, and three in southeastern Corpus Christi Bay. Sediment cores were collected at each site for continuous-flow incubation experiments where nutrient and gas fluxes were measured. Due to the limited locations and dates of data (i.e., cores were collected during the summer of 2001 for the Nueces River and upper Corpus Christi Bay sites and during the spring and summer of 2002 and 2003 for the three southeastern Corpus Christi Bay sites), the average of these data was calculated, resulting in a N fixation rate of 2.35 g N per square meter per year (g N/m^2/yr). When scaled to the surface area of Nueces Bay, this rate equates to 167 mil g N/yr. Due to lack of data during the pre-development period, the N fixation rate was assumed to be the same for both the pre- and post-development periods.

N fixation rates were found to have high variability. Gardner et al. (2006) sampled the Nueces Estuary sites during only the spring and summer and thus it is unclear if these data are representative of an average annual rate; even the rates measured during these two seasons varied widely among the Nueces Estuary sites, with some cores exhibiting no N fixation. Gardner et al. (2006) did measure N fixation during other seasons in neighboring estuaries, although the results are variable and the data are not sufficiently comprehensive to support a seasonal analysis. Bruesewitz et al. (2013) examined seasonal N fixation rates in nearby Copano Bay and found high variability and no significant differences between seasons. Howarth et al. (1988) reported a typical range for organic-rich estuarine sediments of 0.4 to 1.6 g $N/m^2/yr$, which is somewhat lower than the average for the Nueces Estuary as reported by Gardner et al. (2006).

3.8 Groundwater Discharge

Submarine groundwater discharge transports dissolved nutrients into a waterbody via subsurface flow. NO_3 is the primary form of N in groundwater systems (CWS-UCD 2012). Dissolved NO_3 in groundwater systems originates from fertilizers, atmospheric deposition of N compounds, septic systems, and animal manure. NO_3 that leaches into the groundwater table may persist and accumulate over many years (Nolan et al. 1998).

Breier et al. (2004) estimated the groundwater NO_3 load to Nueces Bay by estimating groundwater discharge through the use of measured radium isotopes as a tracer and applying average NO_3 concentrations from regional well samples. Surface water was collected for radium and nutrient analysis in April and July of 2002. Just prior to the July sampling event, an unusually large storm caused massive flooding in the system. These two events represented the driest and wettest rainfall conditions the watershed would likely experience over a span of years. A subset of ten stations was also sampled twice during May 2003 to measure variations in radium and nutrients due to tidal cycles. Using the radium isotope measurements, Breier et al. (2004) estimated groundwater discharge to be 6 to 16 million cubic meters per month (161 to 426 ac-ft/d; 81 to 215 cfs). The study used a regional groundwater N concentration of 2.56 mg/L N as NO_3 based on 274 samples from 176 wells sampled between 1950 and 2001 as obtained from the TWDB groundwater database. This results in a range of 180 to 480 million g NO_3 per year (mil g NO_3/yr) of NO_3 load to Nueces Bay via groundwater. For this report, a value of 74.5 mil g N/yr was used for groundwater N load, which is the average of the range reported by Breier et al. (2004), after converting from g NO_3 to g N. Since NO_3 is only a component of TN, the TN load from groundwater may be higher.

Data from the TWDB groundwater database were examined to compare potential changes in pre- and post-development groundwater NO_3 concentrations (TWDB 2017). Average NO_3 concentrations in Nueces and San Patricio county wells between 1970 to 1984 and 1985 to 2015 were similar, implying that groundwater concentrations have not changed appreciably between the pre- and post-development periods. In the absence of groundwater discharge studies during the pre-development period, and considering the similar NO_3 concentrations in the pre-development and post-development periods, the pre-development groundwater NO_3 load was assumed to be equal to the post-development load.

Later work by Breier and Edmonds (2007) suggested that brackish groundwater discharge and leakage from oil-field brine from submerged petroleum wells and pipelines are potentially major sources of N to Nueces Bay.[16] A follow-up study, however, found no evidence of oil-field brine leakage but did not rule out the possibility of its existence and impact (Breier et al. 2010). While both the 2004 and 2007 studies used the same dataset, groundwater discharge loads from Breier et al. (2004) were used instead of those in Breier and Edmonds (2007) because the primary focus of the former study was on quantifying groundwater discharge and nutrients in the groundwater whereas the focus of the latter study was on investigating an additional source of radium.

More recent studies of groundwater nutrient load to Nueces Estuary have been conducted by Dr. Dorina Murgulet at TAMUCC. The results have yet to be published, but a draft publication is anticipated to be available during the summer of 2017. Dr. Murgulet has conducted similar work for Corpus Christi Bay and the upper Laguna Madre (Murgulet et al. 2015).

3.9 Tidal Exchange with Corpus Christi Bay

Tidal exchange is the process by which tides exchange water, in this case, between Corpus Christi Bay and Nueces Bay. With this exchange, there is an import and export of N. During flood tide, water from Corpus Christi Bay enters Nueces Bay, bringing in N associated with Corpus Christi Bay water and mixing with water in Nueces Bay. During ebb tide, newly mixed water from Nueces Bay exits, carrying along N. During this back-and-forth exchange, mixing occurs between Nueces Bay water and Corpus Christi Bay water; the mixing can be considered water entrainment. Therefore, the TN load associated with tidal exchange can be calculated as the product of the average tidal exchange between Nueces Bay and Corpus Christi Bay, water column TN concentration differences between Corpus Christi Bay and Nueces Bay, and a water entrainment rate (Equation 1).

[16] Using the data from the Breier et al. (2004) study but for only the May 2003 sampling period, Breier and Edmonds (2007) hypothesized that groundwater alone unlikely supplied the high levels of radium activities observed in the measurements. Based on a different set of assumptions than those used in the 2004 study, they proposed an input of 19 mil g N/yr from groundwater if groundwater is the only contributor to the excess radium and 132 mil g N/yr if oil-field brine was the only contributor.

Equation 1

$$L = V_{exchange} \times C_{diff} \times E \times Conv$$

where:

L	=	TN load (million g N per year)
$V_{exchange}$	=	average tidal exchange between Corpus Christi Bay and Nueces Bay (acre-feet per day)
C_{diff}	=	TN concentration difference between Corpus Christi Bay and Nueces Bay (mg/L)
E	=	water entrainment rate (%)
$Conv$	=	conversion factor for units (2.22)

This sub-section describes the two-step process for calculating TN load due to tidal exchange: 1) estimation of the rate of water entrainment; and 2) calculation of the tidal exchange rate of TN. Pre- and post-development values were based on the availability of N data to quantify these conditions.

3.9.1 Estimation of Water Entrainment Rate

Brock (1998) estimated a water entrainment rate between Matagorda Bay and the Gulf of Mexico by iteratively applying a salt-balance model and comparing the results to observed salinity changes. His model was adapted for the Nueces Bay calculations in this report (Equation 2).

Equation 2 (based on Brock 1998)

$$S_{nb,new} = \frac{(V_{nb} \times S_{nb}) + (Q_i \times E \times S_{ccb}) - (Q_o \times E \times S_{nb}) - (R \times S_{nb})}{V_{nb}}$$

where:

$S_{nb,new}$	=	salinity of Nueces Bay (parts per thousand [ppt])
V_{nb}	=	volume of Nueces Bay (ac-ft)
S_{nb}	=	salinity of Nueces Bay on previous day (ppt)
S_{ccb}	=	salinity of Corpus Christi Bay (ppt)
Q_i	=	total volume of flood tide per day from Corpus Christi Bay to Nueces Bay (ac-ft)
Q_o	=	total volume of ebb tide per day from Nueces Bay to Corpus Christi Bay (ac-ft)
E	=	water entrainment rate (%)
R	=	volume of freshwater inflow (ac-ft)

Values for variables in Equation 2 were based on input to and output from the TxBLEND model, a hydrodynamic and salinity transport model for Texas bays and estuaries.[17] The TxBLEND simulation was driven by a revised[18] version of the Alternate Hydrology dataset (TWDB 2011b). TWDB provided TxBLEND model output of daily salinities for Nueces Bay (S_{nb}) and Corpus Christi Bay (S_{ccb}), daily volumes of Nueces Bay (V_{nb}), and daily sums of hourly positive and negative flow volumes,[19] respectively (Figure 2-1; Fernando 2017c). The salinities used in Equation 2 were those for the location Mid Nueces and average of salinities at the North CCBay and Upper CCBay locations (Figure 3-4). Since the daily sums of hourly increasing (positive) flow volumes include freshwater inflows, the total volume of flood tide per day (Q_i) was isolated by subtracting half the daily volume of freshwater inflow from the daily sum of positive flow volumes, assuming flood tide occurs half of each day. Likewise, the total volume of ebb tide per day (Q_o) was isolated by subtracting half the daily volume of freshwater inflow from the daily sum of negative flow volumes (which include freshwater inflows), assuming ebb tide occurs half of each day. The volume of freshwater inflow in Equation 2 was calculated as the sum of daily Nueces River inflow based on data at the Calallen gage, inflow from ungaged watersheds (50% of #20005, 20% of #21010, and 100% of #22012),

[17] Hydrodynamic predictions in TxBLEND are based, in part, on wind. Accordingly, the positive and negative flow volumes (and subsequent flood and ebb tide volumes) incorporate the effects of wind.

[18] The revised version included 1) a reduction to the contribution of return flows from watershed #21010 because some of the return flows would be captured by the streamflow gage at Calallen and 2) one diversion in watershed #20005 (Fernando 2017d).

[19] Flow volumes were not a direct output from the TxBLEND model. Water surface elevation at several Nueces Bay grid points were used to calculate hourly differentials in the total volume of Nueces Bay. These hourly differentials were used to calculate the positive (i.e., into Nueces Bay) and negative (i.e., out of Nueces Bay) flow volumes.

returns flows (13% of #20005, 20% of #21010, and 100% of #22012), and precipitation over Nueces Bay (watershed #24820) minus diversion[20] and evaporation over Nueces Bay.[21] All freshwater inflow components were provided by TWDB (Fernando 2017a, b, and e).

Equation 2 can be used to estimate the water entrainment rate (*E*) by fitting the salinity values predicted by the equation to TxBLEND-predicted salinities. This approach is most applicable when salinity changes at a relatively steady rate over a few weeks. Accordingly, TxBLEND-predicted salinities for Nueces Bay and Corpus Christi Bay were reviewed to find time periods when salinities in Nueces Bay and Corpus Christi Bay are very different and Nueces Bay salinity is exhibiting a smooth increase (e.g., after a storm event). These periods are useful because they more clearly show the impacts of tidal exchange on salinity—Nueces Bay starts with low salinity (i.e., its waters are fresh) and then gradually becomes more saline as salt water from Corpus Christi Bay enters and mixes. The following three time periods were selected for evaluation:

1. July 17, 1994 to August 3, 1994[22]
2. December 12, 1998 to January 2, 1999
3. August 3, 2004 to October 8, 2004

Figure 3-5 shows the Nueces Bay salinities predicted by TxBLEND and those calculated by Equation 2 using four example entrainment rates (5, 10, 15, and 20%). For each of the three time periods, the Solver tool in Microsoft Excel was subsequently used to calculate the best fit entrainment rate by minimizing the sum of the square of the errors between calculated salinities and TxBLEND-predicted salinities. The best fit entrainment rates were 13, 6, and 9% for the three time periods, respectively. Calculated salinities using the best fit entrainment rates are shown as squares on Figure 3-5. The average of the three best fit rates, 9%, was carried forward in the tidal exchange loading calculation (Section 3.9.2). While entrainment rates are site-specific and based on hydrodynamics in the vicinity of the water exchange location, this 9% rate is reasonable compared to the value of 5% for the Nueces Estuary estimated by Brock (2001) and rates on the order of 10% for other Texas bays (Brock 1998).

The same entrainment rate of 9% was assumed for pre-development and post-development since no TxBLEND outputs are available prior to 1987 for the Nueces Bay. This assumption is reasonable because the entrainment rate is largely regulated by flood and ebb tides. Relative to the uncertainties in this calculation, the flood and ebb tides have not changed appreciably.

[20] The diversion is from watershed #20005 (Fernando 2017d).

[21] The temporal resolution of diversion, return flow, and evaporation data is monthly. Therefore, the monthly values were divided evenly over the number of days in each month (Fernando 2017a).

[22] As a frame of reference, the averages of volume of Nueces Bay (V_{nb}), total volume of flood tide per day (Q_i), total volume of ebb tide per day (Q_o), and volume of freshwater inflow per day (*R*) were 49,085, 8,392, 7,970, and -324 ac-ft, respectively, for this time period.

3.9.2 Calculation of Nitrogen Loading Due to Tidal Exchange

Equation 1 was used to calculate the TN load entering and exiting Nueces Bay. Average volumes of flood and ebb tides were calculated from Q_i and Q_o (Section 3.9.1) from TxBLEND output from 1990 to 2014. TN concentrations were calculated from surface water data from three stations in Nueces Bay and one station in Corpus Christi Bay monitored as part of the TCEQ's Surface Water Quality Monitoring (SWQM) program (TCEQ 2017). The water entrainment rate was calculated using a salt-balance model (Section 3.9.1).

TN is the sum of nitrate plus nitrite (NO_{23}), NH_3, and organic N (Equation 3). TKN is the sum of NH_3 and organic N and thus TN can also be calculated as the sum of NO_{23} and TKN. Because neither organic N nor TKN were reported during the pre-development period, a ratio[23] of organic N to NH_3 was calculated using post-development data. The average[24] ratio was applied to NH_3 data measured during the pre-development period to estimate organic N. Finally, TN for the pre-development period was calculated as the sum of NO_{23}, NH_3, and estimated organic N concentrations (Table 3-7).

Equation 3

$$\mathrm{TN} = \mathrm{NO}_{23} + \mathrm{NH}_3 + \mathrm{OrgN}$$

$$\mathrm{TN} = \mathrm{NO}_{23} + \mathrm{TKN}$$

$$\mathrm{TN} = \mathrm{NO}_{23} + \mathrm{NH}_3 + \mathrm{NH}_3 \times \mathrm{average}\left(\frac{\mathrm{OrgN}}{\mathrm{NH}_3}\right)$$

where:

TN	=	total nitrogen (mg/L as N)
NO_{23}	=	nitrate plus nitrite (mg/L as N)
NH_3	=	total ammonia nitrogen (mg/L as N)
OrgN	=	organic nitrogen (mg/L as N)
TKN	=	total Kjeldahl nitrogen (mg/L as N)

[23] A similar ratio was calculated using post-development organic N to NO_{23}. Both this ratio and the organic N:NH_3 ratio were then used to estimate TN for the post-development period so that estimated TN could be compared to measured TN. A comparison (i.e., mean squared error) of the estimated and measured TN values for the post-development period indicated a better fit using the organic N to NH_3 ratio.

[24] The average ratio excluded non-detect values of NH_3.

Table 3-7
Pre-development Nitrogen Concentrations Calculated Using Organic N to NH_3 Ratios at Select SWQM Stations in Nueces Bay and Corpus Christi Bay

SWQM Station	SWQM Description	Organic N:NH_3[b]			Calculated TN for Pre-development Period[c] (mg/L)		
		Average	Years	Count	Average	Years	Count
Nueces Bay[a]							
13422	Nueces Bay near south shore	27.5	1994 – 2016	20	1.9	1976 – 1985	26
13425	Nueces Bay near Whites Point	19.3	1993 – 2015	30	n/a	No N data prior to 1991	0
Corpus Christi Bay							
13407	Corpus Christi Bay at CM62	26.7	1993 – 2010	11	1.1	1974 – 1985	26

Notes:

a. SWQM Station 13423 (Nueces Bay near north shore) was also considered, but excluded due to limited dates with N data (count = 6).

b. The calculation of the average ratio excluded non-detect values of NH_3. Fifty-three, 43, and 57 non-detect values of NH_3 were excluded for SWQM stations 13422, 13425, and 13407, respectively. If they were included in the calculation at the provided result value in the SWQM data file, the average ratios would be 39.0, 42.6, and 32.2 for the three stations. The calculated TN concentrations would be 2.6 mg/L for SWQM station 13422 and 1.2 mg/L for SWQM station 13407.

c. TN was calculated as the sum of NO_{23}, NH_3, and the product of NH_3 times the average organic N:NH_3 ratio.

Data source: TCEQ 2017

For the post-development period, TN concentrations were calculated as the average of the sum of NO_{23} and TKN data in surface water from three stations in Nueces Bay and one station in Corpus Christi Bay (Table 3-8). These average TN concentrations in Nueces Bay and Corpus Christi Bay are similar to the values reported by Ward (2003a): 1.03 and 0.66[25] mg/L, respectively, as calculated from average TKN and NO_{23}.

Table 3-8
Nitrogen Concentrations Measured at Select SWQM Stations in Nueces Bay and Corpus Christi Bay

SWQM Station	SWQM Description	Years of Available Data	Count	Average TN[b] (mg/L)
Nueces Bay[a]				
13422	Nueces Bay near south shore	1993 – 2016	73	0.88
13425	Nueces Bay near Whites Point	1993 – 2015	73	1.10
			Average	0.99

[25] For the western half of Corpus Christi Bay

SWQM Station	SWQM Description	Years of Available Data	Count	Average TN[b] (mg/L)
Corpus Christi Bay				
13407	Corpus Christi Bay at CM62	1993 – 2015	68	0.61

Notes:
a. SWQM Station 13423 (Nueces Bay near north shore) was also considered, but excluded due to limited dates with N data (count = 6).
b. TN was calculated as the sum of NO_{23} and TKN. Non-detect values were set to half the reported values prior to summation.
Data source: TCEQ 2017

Table 3-9 summarizes the tidal exchange load calculations pre- and post-development, where the only difference in the calculation is the difference in TN concentrations. The net TN load is -350 and -166 mil g N/yr for pre- and post-development respectively, indicating a loss of TN from Nueces Bay due to tidal exchange with Corpus Christi Bay during both periods and a decline in loss rate post-development.

Table 3-9
Estimated Nitrogen Load Due to Tidal Exchange

Time Period	Average Volume Exchange[a] (ac-ft/d)	Water Entrainment Rate[b] (%)	Difference in TN Concentration between Corpus Christi Bay and Nueces Bay (mg/L)	TN Load (mil g N/yr)
Pre-development [c]	10,807	9	-0.8 (1.1 – 1.9)	-350
Post-development [d]			-0.38 (0.61 – 0.99)	-166

Notes:
a. Average volumes were calculated for January 1, 1990, through December 31, 2014, because the TxBLEND output from 1987 through 1989 were not recommended for use (Fernando 2017d).
b. See Section 3.9.1.
c. See Table 3-7 for pre-development TN concentrations.
d. See Table 3-8 for post-development TN concentrations.

The pre-development TN concentrations for Nueces Bay and Corpus Christi Bay are uncertain due to the lack of organic N data, which necessitated the use of ratios of paired TKN and NH_3 data from the post-development period for calculating TN during pre-development. Prior to 1986, a single measurement of TN was reported in the SWQM datasets for Nueces Bay (and none for Corpus Christi Bay)—a value of 0.4 mg/L at SWQM station 13420 (Nueces Bay at US 181) on December 10, 1969. This is 21% of the estimated TN concentration calculated for the pre-development period for Nueces Bay (Table 3-7); however, it is only a single data point and therefore not deemed as usable as the organic N:NH_3 ratio approach.

While a trend analysis was not in the scope of work for this project, the results from previous studies of water quality trends in the Coastal Bend bays by Ward (2003a) and Montagna and Palmer (2012) qualitatively support a temporal decline in TN in Nueces Bay and are mixed as to the decline in TN in Corpus Christi Bay. For Nueces Bay, Ward (2003a) reports a decline in TKN (i.e., given current trends, TKN will halve in 48 years) and a slower rate of increase in NO_{23} over time (i.e., NO_{23} would double in 89 years); the combination of these rates suggests a TN decline over time, given the higher concentrations of TKN relative to NO_{23} in Nueces Bay. Likewise, Montagna and Palmer (2012) describe the TKN temporal trend as a "probable decrease" and "no change" for NO_{23}. For the western half of Corpus Christi Bay, Ward (2003a) reports declines in both TKN and NO_{23} over time. In contrast, Montagna and Palmer (2012) describe the temporal trends in TKN as "no change" and in NO_{23} as a "probable increase" for the northern part of Corpus Christi Bay.

3.10 Denitrification

Denitrification is the process by which NO_3 is converted to N_2, which then exits the waterbody. Typically, this process is performed by bacteria under anoxic (very low oxygen) conditions such as those found in sediments. The denitrification rate typically increases with increases in nitrate, increases with increases in organic carbon loading, increases as water column and sediment dissolved oxygen decreases, and increases with temperature (Di Toro 2011; Wetzel 2001).

Yoon and Benner (1992) measured denitrification rates at several stations in two south Texas estuaries, the Nueces Estuary and the Guadalupe Estuary. Two of these stations were within Nueces Bay. Sediment cores were collected from Nueces Bay in August 1988 and January and May 1989 and transferred to the laboratory, where N_2 production in sealed incubation chambers was directly measured. The average[26] denitrification rate for the Nueces Bay stations was 11.0 g $N/m^2/yr$ (44.7 μmol $N_2/m^2/h$). This rate, scaled to the surface area of Nueces Bay, results in a loss of 776 mil g N/yr from the system. This rate was used for both the pre- and post-development periods in the absence of pre-development studies on denitrification.

Denitrification rates were found to have high variability; this is unsurprising because the bacteria that facilitate denitrification and the conditions suitable for denitrification can be expected to be both spatially and temporally variable. The standard deviations reported by Yoon and Benner (1992) from five measurements in replicate cores ranged from 7 to 71% of the average denitrification rate per sampling event per Nueces Bay station. Other studies in the Coastal Bend region have also found variable results. Gardner et al. 2006 sampled within the Nueces Estuary (five locations: one at the Nueces River mouth, one in upper Corpus Christi Bay, and three in southeastern Corpus Christi Bay)

[26] Of the two stations (A and B), station A was sampled in the summer of 1988 and winter and spring of 1989 while station B was only sampled in the summer of 1988. The average value was derived by first averaging the summer rates of stations A and B then averaging with the winter and spring rates of station A.

and reported a mean rate nearly half the rate calculated from data from Yoon and Benner (1992).[27] Additionally, a study in Copano Bay by Bruesewitz et al. (2013) found average denitrification rates from four sampling events ranging from 2.4 to 70.8 g N/m^2/yr, with the average rate nearly three times the rate calculated from data from Yoon and Benner (1992). The high rates reported by Bruesewitz et al. (2013) are likely influenced by one sampling event that occurred several weeks after a large storm event that flushed organic matter into the system. The variability between studies may be due to sensitivity to environmental conditions. A study that measured denitrification in nearby Baffin Bay and the Laguna Madre found that the denitrification rate appeared to be limited by organic matter supply to the sediment and did not seem to be influenced by temperature fluctuations (An and Gardner 2000), although other references do indicate a dependence on temperature (Di Toro 2011).

3.11 Nitrogen Burial

N burial occurs when deposition to the sediment bed causes deeper layers to no longer be accessible for uptake by algae and plants. The depth at which inaccessibility occurs is typically below the top 10 centimeters (cm) of sediment, in which benthic biota are active (McCall and Tevesz 1982; Kristensen 2005; Boudreau 1998).

Equation 4

$$\mathrm{B} = \frac{S}{\rho} \times \mathrm{C}$$

where:

B	=	mass of N buried (g N per m^2 per year)
S	=	sediment accumulation rate (g sediment per cm^2 per year)
ρ	=	sediment dry density (g/cm^3)
C	=	TN content at 10 cm depth (g N per m^2 per cm)

Sediment burial was calculated using a sediment accumulation rate, sediment dry density, and mass of N that moves at that rate below a 10-cm depth threshold (Equation 4). The values used to calculate N burial were obtained from several literature sources. A sediment accumulation rate (*S*) of 0.39 g/cm^2/yr was calculated as the average of the mean accumulation rates from cores collected at two Nueces Bay sites, as reported in Santschi and Yeager (2004). A sediment dry density (*ρ*) value of 1.2 g/cm^3 reported by Hill et al. (2014) was used. Brock (2001) calculated a TN content (*C*) of

[27] Yoon and Benner 1992 was used instead of Gardner et al. 2006 for the denitrification rate for this report because Yoon and Benner sampled more locations within Nueces Bay whereas the only Nueces Bay location sampled by Gardner et al. was at the Nueces River mouth.

4.6 g N/m^2/cm using a sediment N content of 0.08% dry weight (Montagna 1991) and a sediment-water content of 65%. Using these values, a nitrogen burial rate of 1.5 g N/m^2/yr was calculated. Scaled to the surface area of Nueces Bay, N burial results in a loss of 106 mil g N/yr from the system.

Uncertainty exists in the N burial rate estimate. The estimate assumes that the identified sediment accumulation rate, TN content, and sediment density are representative of the system. Some spatial variability can be expected and has been observed. For example, the mean sediment accumulation rates were shown to decline with distance from the Nueces River mouth (Santschi and Yeager 2004); however, overlap in the error bars and the limited number of samples confound any explicit quantification of spatial variability. Hill et al. (2014) estimated sediment accumulation rates from 0.28 g/cm^2/yr to 0.72 g/cm^2/yr in Nueces Bay, but had difficulty in definitively identifying such rates because of the confounding effects of anthropogenic activity.

Sediment accumulation rates from Santschi and Yeager (2004) were determined by radionuclide dating. This method considers long-term sediment accumulation and therefore does not distinguish between pre- and post-development periods. Accordingly, the rate of N burial was assumed to be equal for both pre- and post-development.

3.12 Summary of Nutrient Balance

Table 3-10 and Figure 3-6 summarize the TN loads quantified under average conditions during the pre- and post-development periods for each CSM component. Across both the pre- and post-development periods, the dominant processes contributing N to Nueces Bay appear to be gaged streams and nitrogen fixation; for loss of N from Nueces Bay, denitrification and tidal exchange appear to be the most important. The least important sources of N to the water column are WWTPs and wet and dry deposition. The least important sink is diversions.

Table 3-10
Summary of Nitrogen Budget for Nueces Bay Under Average Conditions

CSM Component	TN Load (mil g N/yr)		
	Pre-development	Post-development	Pre- Minus Post-development
Gaged Streams[a]	471	122	349
Ungaged Watersheds	82	66	16
WWTPs	18	18	0
Diversions	-75	-70	-5
Other Return Flows[b]	38	73	-35
Wet Deposition	27	27	0
Dry Deposition	34	34	0
Nitrogen Fixation	167	167	0
Groundwater Discharge	75[c]	75[c]	0

CSM Component	TN Load (mil g N/yr)		
	Pre-development	Post-development	Pre- Minus Post-development
Tidal Exchange	-350	-166	-184
Denitrification	-776	-776	0
Nitrogen Burial	-106	-106	0
Total	-395	-536	141

Notes:
a. This load represents the N load at Nueces River at Mathis.
b. These values exclude loads under the WWTP CSM component.
c. The groundwater value is for NO_3. TN load may be higher.
Positive and negative values indicate sources to and sinks from the water column, respectively.

The totals on Table 3-10 indicate that estimated sources and sinks are out of balance (i.e., sum of sources and sinks is not equal to zero). This is expected because of uncertainty due to limited data, spatial and temporal variability that are not fully defined by the data, and possibility of sources or sinks that were not quantified in this effort. In his N balance of the Nueces Estuary, Brock (2001) also generated a net negative balance.

3.12.1 Uncertainty

The following subsections describe uncertainty for the four CSM components with the highest N loads.

3.12.1.1 Denitrification

Denitrification rates were quantified in laboratory experiments using sediment cores collected from two stations in Nueces Bay in August 1988 and January and May 1989 (Yoon and Benner 1992) and applying the denitrification rates to the surface area of Nueces Bay. Denitrification rates can differ spatially and temporally because conditions suitable for denitrifying bacteria vary. The average rates at the two stations from cores collected in August had a relative percent difference of 33%. The average denitrification rates at the same station from cores collected in January, May, and August were within a factor of 6 of each other. Moreover, even denitrification measurements for replicate cores can vary significantly; the standard deviations from five measurements in replicate cores ranged from 7 to 71% of the average denitrification rate per sampling event per Nueces Bay station.

Denitrification rates were also found to vary in nearby coastal locations. In the same study used for the Nueces Bay denitrification rates herein (Yoon and Benner 1992), denitrification rates were also found to vary widely for stations in Corpus Christi Bay and San Antonio Bay. Gardner et al 2006 reported a mean rate about half the Nueces Bay rate from Yoon and Benner (1992) for sites, including Corpus Christi Bay, whereas Bruesewitz et al. (2013) found varying rates in Copano Bay, with an average rate nearly three times the Nueces Bay rate from Yoon and Benner (1992).

3.12.1.2 Gaged Streams

TN loads for gaged streams were either taken directly from or calculated using values presented in HDR 2015; these loads had been estimated using linear regression analysis on paired flow and concentration data as far downstream as the Nueces River at Mathis. Pre-development loads at Mathis were not provided in HDR 2015 due to lack of TKN data during the pre-development period and therefore were calculated using loads at Three Rivers and assuming the pre-development change in load between the Three Rivers and Mathis stations was the same as for the post-development period. Each of these pieces carries some uncertainty.

In this CSM, the data at Mathis represent the "gaged stream" component, and the contribution from the downstream watershed is accounted for in ungaged watershed #21010 as part of the "ungaged watersheds" component.[28] Channel losses for the gaged stream component from Mathis to Nueces Bay are not accounted for in the loading estimate because of limited data; therefore, the estimated gaged stream load may be higher than the actual load.

3.12.1.3 Tidal Exchange

TN, particularly for Nueces Bay, for the pre-development period is uncertain. Because organic N was not measured during the pre-development period, it was estimated using ratios of organic N to NH_3 data during the post-development period and NH_3 data from the pre-development period. TN was then computed as the sum of the calculated organic N concentration and NO_{23} and NH_3 data from the pre-development period. The average TN was 1.9 mg/L for Nueces Bay for the pre-development period, which may be high as Ward (2003a) reported concentrations for TKN of 1.04 mg/L and NO_{23} of 0.049 mg/L, which when summed, gives a TN concentration of 1.089 mg/L for the period of record.[29] Including non-detect NH_3 concentrations in the calculation of organic N resulted in an even higher average TN concentration of 2.6 mg/L (Tables 3-7 and 3-9). Uncertainty in TN concentrations can have a large impact on the TN load calculated for tidal exchange (Equation 1).

3.12.1.4 Nitrogen Fixation

N fixation was quantified in laboratory experiments using sediment cores and overlying water collected from five Nueces Estuary sites in spring 2003 and summer of 2001 and 2002 (Gardner et al. 2006) and applying the N fixation rates to the surface area of Nueces Bay. These rates can differ spatially and temporally because conditions suitable for N-fixing benthic algae vary. During the two seasons in which cores were collected, the N fixation rates varied widely among the Nueces Estuary sites, with some cores exhibiting no N fixation. It is unknown if an average of the rates from the spring and summer sampling would be representative of average conditions throughout the year, as the study did not measure N fixation in fall or winter. In addition, N fixation that may occur in the

---

[28] Ideally, the gaged stream loads would have been determined at Calallen Dam, but limited data prevented the development of suitable linear regressions.

[29] The years included in the period of record are not specifically defined in Ward 2003a.

Nueces Delta, e.g., in algal mats, and subsequently wash downstream into Nueces Bay could not be estimated and was not included.

4 Investigation of Paleoecological Reconstruction for Assessing Pre-development Conditions

4.1 Background

A foundational precept of the Texas SB 3 Environmental Flows is the identification of an "environmental flow regime," which is defined as "a schedule of flow quantities that … are shown to be adequate to support a sound ecological environment" (BBEST 2011). In the same report, the BBEST members agreed "that the sound ecological environment … depends on … [the waterbody's] historical conditions." Furthermore, the BBEST "reached consensus that the Nueces Bay and Delta region is an unsound ecological environment." This information implies that the BBEST concluded that Nueces Bay and Delta had diverged importantly, and negatively, from their historical condition. This information also implies that achievement of a sound ecological environment in the future, if possible, would be predicated on moving the system back toward a more natural, historical condition.[30] Given the lack of data and overall uncertainty of the "pre-development" N budget, a different approach to better understand historical conditions may be useful. One such approach is through a paleoecological reconstruction using preserved markers of ecological condition, as can be analyzed in sediment cores.[31] This review is based on published literature, with a focus on estuarine studies. The Nueces Estuary Advisory Council (NEAC) is fortunate to have as a resource Erin Hill (TAMUCC and NEAC member) and Mark Besonen (TAMUCC), two researchers who are familiar with most of the concepts described herein and who can provide additional guidance to the NEAC and BBASC.

4.2 Introduction to Paleoecological Concepts

Due to the absence of extensive monitoring data, substantial uncertainty exists regarding nutrient loads and the productivity of Nueces Bay under pre-development conditions. One approach to fill this gap is with paleoecological reconstruction, an investigation to aid in the reconstruction of past environments in depositional waterbodies. In essence, markers of ecological condition (e.g., diatoms, which are a group of algal species that are often well preserved in sediments) are obtained from sediment cores, which can be dated using lead 210 (Pb-210) or other radioisotopes. Because diatoms have been shown to correlate well with salinity (Gaiser et al. 2004; Underwood et al. 1998) and

[30] It is recognized that many human actions cannot, or will not, be reversed and that restoration of the original historical condition of Nueces Bay and the Delta is not realistic. However, management actions that move the system back towards the historical condition would appear to be advantageous, given the opinions expressed by the BBEST (i.e., constructive management of a complex system such as the Nueces may be promoted by the identification of a target, based on historical conditions, even if all stakeholders understand that a reversal of many human influences is impossible).

[31] The term "paleo" evokes a distant past, but in the current context, this method can be used to evaluate estuarine conditions in the recent past, e.g., in the early 1800s shortly before significant human activities. This time period is termed "historical" in this section. An understanding of earlier conditions, e.g., hundreds to thousands of years before present, is theoretically possible as well, but probably of little interest to the NEAC for the evaluation of environmental flow standards.

nutrients (Tropea et al. 2011), the paleoecological reconstruction could be used to estimate historical salinity and nutrient conditions (Wachnicka et al. 2013).

Paleoecological reconstruction require two fundamental aspects of sedimentary record investigation: 1) development of a sediment chronology (dating); and 2) evaluation of proxies of environmental conditions.

4.3 Development of Sediment Chronology

Chronological reconstruction establishes time horizons within the sediment column, on the order of years. Sediment cores are obtained from the field and examined in the laboratory for markers of time, including anthropogenic radionuclides (e.g., Cesium-137 from nuclear weapons testing), natural radioactive decay, pollen, contaminants, fertilizer residues, and depositional patterns influenced by land development, drought, or tropical storms. Because time markers are often uncertain, generally, at least two different dating methods are used to increase the confidence in the chronology.

Similar investigations have been undertaken in Nueces Bay and other Texas coastal bays. Recently, Hill et al. (2014) obtained sediment cores from Nueces Bay to investigate historical metals contamination (Figure 4-1). Although some cores were challenging to age-date, useful information on deposition was obtained (left panel of Figure 4-1). More importantly, a paleoecological investigation for the BBASC would not need highly resolved age-dating; it would be sufficient to simply identify strata that are clearly pre-development and to evaluate diatoms and other markers in those strata.

4.4 Evaluation of Proxies of Environmental Conditions

An environmental proxy is a remnant from the past that is indicative of certain historical ecologic and climatic conditions. Preserved minerology, pollen, shells, organic chemicals, and stable isotopes can be used as proxies of environmental conditions, including redox state (oxic versus anoxic conditions), nutrient levels, trophic status, and salinity. To date, proxies for hydrologic, nutrient loadings, and upland influences have not been a focus of study in Nueces Bay. Elsewhere, investigators have developed and used paleoecological reconstructions to evaluate the effects of long-term anthropogenic impacts in marsh, estuarine, and coastal ecosystems, including the U.S. Gulf of Mexico and Atlantic Ocean coastlines. Several examples from these studies that may have application to Nueces Bay are discussed below.

4.4.1 Diatoms and Foraminifera as Proxies for Salinity and Trophic State

Diatoms are a diverse and globally distributed group of single-celled algae characterized by their silica frustules, or shells (Figure 4-2). The frustules are taxonomically distinct down to the species level, and they are well-preserved in most sediments. Species of diatoms can be indicators of salinity, nutrient availability, and turbidity (Brush and Davis 1984; Parsons et al. 1999; Potapova 2011).

Contemporary studies of diatom taxa across salinity gradients (0 to 37 ppt) in South Florida coastal ecosystems illustrate the fidelity of this indicator (Gaiser 2009; Nodine and Gaiser 2014). Diatom species are characterized by their habitat preference: benthic diatoms inhabit surface sediment, periphyton diatoms predominantly inhabit the blades of submerged aquatic vegetation (SAV), and pelagic diatoms inhabit the water column. As turbidity increases, indicative of greater input of riverine sediments and nutrients, estuarine productivity shifts from the sediment surface and SAV to water column algae. Several studies document ecosystem changes on decadal to century timescales using diatoms as paleoecological indicators for U.S. Atlantic coastal estuaries (Chesapeake Bay: Brush and Davis 1984; Cooper and Brush 1993; North Carolina: Cooper et al. 2004).

A history of water quality in the Neuse and Pamlico estuaries of North Carolina was studied through sediment stratigraphic analysis (Cooper et al. 2004). Chronologies were developed using carbon-14, Pb-210, Cesium-137 (Cs-137), and pollen data (e.g., patterns in the pine-to-ragweed pollen ratio, which can be used as a marker of deforestation). Census and historical records were reviewed for the counties within the watersheds of these estuaries to augment and inform the sediment chronologies. Cores of 100 to 150 cm in length were dated to the mid 1600s. Prior to the 20th century, diatom diversity was relatively stable. Following this, diatom diversity declined with increasing human activities in the watersheds (Figure 4-3; left panel). A similar trend was observed in the ratio of centric to pennate diatoms (Figure 4-3; right panel). Centric diatoms are circular in shape, relatively small, and typically water column forms. Pennate diatoms are large, elliptical in shape, and typically benthic (inhabiting the sediment surface) or periphytic (occurring on SAV blades; Figure 4-2). Shifts in algal and plant production from the benthos to the water column are indicative of increased nutrient and sediment supply from the adjacent watershed. Estimates of sedimentation rate and the concentrations of organic carbon, biogenic silica (from diatom frustules), and P were used to estimate net fluxes from the water column to the sediment over time, which all showed large increases after 1950.

Similar to diatoms, foraminifera are a group of diverse and globally distributed single-celled organisms that create a calcium carbonate shell, which is preserved in sediments. Foraminifera are predominantly marine organisms, with species-specific preferences for salinity and for benthic or planktonic habitats. Foraminifera taxonomic assemblages have been evaluated in dated core sections from Florida Bay and indicate that fluctuations in salinity regimes between marine salinities (30 to 35 ppt and estuarine salinities (less than 20 ppt) over the past century, with a trend of increasing salinity in recent decades (Brewster-Wingard et al. 1997). Foraminifera are currently being investigated as an indicator of salinity in Texas bays (Besonen 2017).

4.4.2 Molluscan Proxy for Salinity

Freshwater flows to the Florida Everglades and Florida Bay have been highly modified and reduced over the past century with similar effects on salinity, including hypersalinity, as experienced in Texas bays. A number of studies have examined the sediment record for evidence of salinity-related changes, including pre-alteration conditions. Molluscan (i.e., clams, oysters, and snails) remains have been evaluated as a proxy for salinity and models have been developed to estimate impacts of managed freshwater flows on salinity in Florida Bay (Marshall et al. 2009; Wingard and Hudley 2012; Marshall and Wingard 2014). The molluscan dataset for five sites (cores) in Florida Bay comprises approximately 70 taxa (most identified down to species) in assemblages with relative abundance characterized by modern salinity records for each of the five sites. Assemblages of these same taxa at intervals within dated sediment cores are evaluated to provide an estimate of salinity during the time periods of the core interval. Core intervals were dated using a combination of Pb-210, Cs-137, radium, and pollen data. Taxonomic data were recorded in 2-cm intervals. Shifts in taxonomic abundance show fluctuations over the past century, with an increasing trend in salinity during recent decades. Marshall and Wingard have extended the use of these molluscan-derived paleosalinity datasets by coupling them with climatic-hydrologic regression models of upland stage and flow data with salinity to derive estimates of historical flows (Marshall and Wingard 2009, 2012). These models are being used to evaluate impacts of managed freshwater flows in the Florida Everglades to salinities in Florida Bay (Marshall and Wingard 2014).

4.5 Summary and Recommendations

Sedimentological studies for the Nueces estuarine complex (lower river, delta, and bay) have been conducted for contemporary (decadal scale) and Holocene epochs (covering the past 10,000 years) (Hill et al. 2014; Ricklis and Cox 1998). The Holocene estuary and coastline were far different than conditions today, evidenced by dense shell deposits and middens (anthropogenic in origin) of clams and oysters (Ricklis and Cox 1998). Recent sediments show patterns of contamination associated with human activities (Hill et al. 2014). Most of the recent sediment column (represented by the top tens of cm) have been largely disturbed (mixed) through human activities; deeper sediments, representing several decades to centuries before present, remain undisturbed and amenable to paleoecologic investigation.

There have been extensive investigations of benthic community structure and productivity in relation to the temporal and spatial characteristics of freshwater inflows to Texas estuaries. Freshwater inflows affect both nutrient delivery and the variability and gradients in estuarine salinities, which in turn impact the productivity and diversity of algae and benthic organisms (Palmer et al. 2011). Based on the flora and faunal responses to salinity and nutrients during modern times, the proxies described above should be useful for determining historical conditions in Nueces Bay. Diatom remains should provide a good proxy for salinity and nutrient conditions. As for benthic organisms, much of the modern studies in Texas bays include both soft-bodied organisms (e.g., polychaete worms) and shelled mollusks (see, for example, Kim and Montagna 2010; Montagna and Palmer 2011, and references therein). A historical proxy can only rely upon the remains of shelled organisms.

The successful application of molluscan-based proxies from subtropical Gulf of Mexico estuaries that have similar species composition to Texas estuaries suggests that this would be a useful approach to providing another means to assess historical conditions in Nueces Bay.

A paleoecological investigation can provide insight into the historical nutrient status of Nueces Bay, based on the review of prior studies and of relevant methodologies provided in this report, which can be summarized as follows

- Historical conditions were different from contemporary conditions.
- Contemporary conditions were declared not a sound ecological environment by the BBEST.
- Useful sediment chronologies, to the level of resolution required by a paleoecological reconstruction, are likely possible.
- By using one or more ecological proxies (e.g., diatom, foraminifera, and molluscan assemblages), along with hydrological data and models, developing a reasonable picture of historical nutrient and salinity regimes in Nueces Bay may be attainable.

A key decision point of the BBEST and BBASC is therefore whether this type of information would be useful to guide management decisions. Opinions will likely vary. Some may value a greater understanding of historical conditions and will support acquiring and using that information to guide management decisions. Others may feel that understanding historical conditions is of little practical relevance and that scientific funds are better spent on other priorities. The BBASC may wish to schedule a dedicated and facilitated discussion on this issue prior to selecting priorities for future work.

5 Conclusions and Recommendations

Following the quantification of nutrient loadings for each component of the CSM, numerical values were posted and arrow sizes were adjusted on the CSM graphic to represent relative magnitudes of N loadings for the pre- and post-development periods (Figure 5-1). This section summarizes the conclusions from this work and provides recommendations for future work.

5.1 Conclusions

Through the development of the CSM for N, the limiting nutrient for Nueces Bay, the following conclusions can be made regarding the importance of processes contributing to the gain or loss of N to Nueces Bay during average conditions:

- Sources
  - The gaged streams component is an important input of N to Nueces Bay. The N load from the Nueces River appears to have declined by 75% between the pre- and post-development periods due to a combination of reduction in flow and N concentration. Given the relative lack of pre-development data, both the pre-development load and the estimated decline can be considered to have relatively high overall uncertainty. The estimate of post-development load is also somewhat uncertain, particularly due to the uncertainty in TN concentrations across a range of flows, but may be improved in the future as a result of an ongoing effort by the USGS (e.g., the BBASC and TWDB-funded effort entitled "Nutrient and sediment monitoring of Nueces River inputs to Nueces Bay"). N fixation appears to be a moderate source of N to Nueces Bay. N fixation rates, however, varied widely among the Nueces Estuary sites, with some sediment cores exhibiting no N fixation.
- Sinks
  - Denitrification appears to be the most important process for the loss of N from Nueces Bay. The rates, however, were found to be highly variable, with studies from nearby bays also reporting widely varying rates. Based on the age (primarily 1980s) and variability of the available data, this component can be considered to have relatively high overall uncertainty.
  - Tidal exchange appears to be a moderate sink of N from Nueces Bay. However, uncertainty—particularly in TN concentrations during the pre-development period—is relatively high because the magnitude of this sink is dependent on relatively small differences in water column TN concentrations between Nueces Bay and Corpus Christi Bay.

The paleoecological evaluation suggests that a paleoecological reconstruction may provide a reasonable picture of historical nutrient and ecological conditions;[32] however, it is up to the BBASC and NEAC to decide how, or whether, to prioritize such an effort.

5.2 Recommended Future Work

A nutrient budget offers insight into the important components that contribute to the gain or loss of nutrients to and from a waterbody, which in turn impacts ecological health and productivity. It can help identify primary sources so that management decisions can be optimized to address these sources. A nutrient budget cannot, however, quantify the degree to which primary productivity is limited by nutrients, nor predict the response of the system to various management decisions. In addition, due to limited data, components of this CSM were quantified for average conditions on an annual basis and therefore cannot be used to evaluate N loads during shorter timeframes (e.g., seasonal) or under extreme conditions (e.g., during high flow events). These more complicated questions are appropriately addressed by building a numerical (computer) model that includes hydrodynamics and water quality. In light of these limitations, opportunities for future work are provided below.

5.2.1 Enhancements to the Nitrogen Budget

The CSM is a living framework. Incorporation of more recent and future data collection will refine the understanding of N sources and sinks to Nueces Bay.

The USGS is (as of summer 2017) performing a hydrology, sediment, and nutrient reconnaissance study for the NEAC in the lower reaches of the Nueces River (USGS 2016). One goal of this effort is to better characterize flow and nutrients entering Nueces Bay. Given the uncertainty in the N loads quantified herein, additional data would be welcome and could be used in the future to update the riverine loads estimated in this report (Section 3.1).

As mentioned in Section 3.7, more recent studies of groundwater nutrient load to Nueces Estuary have been conducted by Dr. Murgulet at TAMUCC. The results have yet to be published, but a draft publication is anticipated to be available during the summer of 2017.

Of the nitrogen budget components, the largest sink is denitrification. The estimate used in the budget is based on a 1992 publication, which used data from 1988 and 1989. Updated estimates, particularly using an experimental design intended to represent spatial and annual variability, would improve the estimate of this component of the budget. Additionally, anaerobic ammonium oxidation (referred to as Anammox, in which ammonia and nitrite are transformed into N_2) is a potential sink of

[32] Such a reconstruction cannot be used to confidently estimate individual sources and sinks, but can inform an understanding of nutrient concentrations and ecological conditions.

N, occurring under low oxygen conditions. This mechanism was not considered due to lack of data, but could be included in the future should local or regional data be made available.

5.2.2 Importance of Nitrogen to a Sound Ecological Environment

Recent reductions in freshwater inflows have led to a concern that nutrient loads have also been reduced. The N budget corroborates this concern by indicating that riverine inputs of N are significant and have declined since the construction of Choke Canyon Reservoir. Based on this information, several additional questions are worth evaluating, including:

- Has the reduction in N load led to a reduction in N concentrations in Nueces Bay? Previous studies suggest that N concentrations in Nueces Bay have declined (Montagna and Palmer 2012; Ward 2003a), and this nutrient budget is based on data that suggest a decline (Section 3.9.2).
- What effect has the likely reduction in N concentrations had on primary productivity in Nueces Bay? Previous studies suggest that algal biomass (as represented by chlorophyll-a concentrations) have decreased over time (Montagna and Palmer [2012] report a "probable decrease" in chlorophyll-a, and Ward (2003a) reports a declining trend).
- Is the current level of primary productivity in Nueces Bay adequate to support a sound ecological environment? This question can be informed by studies on nearby systems, the history of Nueces Bay, temporal trends, and other scientific investigations.
- If primary productivity in Nueces Bay is inadequate, is N limitation the primary controlling factor, or are other factors (e.g., light limitations due to turbidity) more important? This question may be addressed by a combination of the following:
  - A comparison of water column N concentrations to algal physiological requirements
  - Bottle dosing studies (e.g., USBR 2000)
  - Water quality modeling, which can estimate nutrient and light limitations over time and space

These concepts are encapsulated in Figure 5-2. It is recommended that the BBASC and NEAC consider these questions and undertake a dedicated and facilitated discussion to establish consensus on these issues, where possible. This will help to define future priorities related to nutrient concentrations. If additional scientific investigations are desired, a numerical hydrodynamic and water quality model is recommended, as this provides the best framework for quantifying 1) sources and sinks of N; 2) N concentrations; 3) limitations to primary productivity (N and light); and 4) expected responses of the system to proposed management decisions.

5.2.3 Deliberation on Historical Conditions

The BBASC and NEAC should explicitly discuss the value of a better understanding of historical conditions, e.g., through a paleoecological approach, and base scientific investigation priorities on the outcome of this discussion.

5.2.4 Revisions to Freshwater Inflow Standards

The primary goal of the TWDB-funded SB 3 studies is to better understand, and potentially recommend changes to, the instream flow and freshwater inflow standards. This study has concluded that N is the limiting nutrient for primary productivity in Nueces Bay and that the available data suggest that reductions in N loads from the Nueces River have occurred since the construction of Choke Canyon Reservoir. There is no strong evidence that other sources of N to Nueces Bay have counterbalanced these reductions; accordingly, it is likely that Nueces Bay currently receives less N than prior to the construction of Choke Canyon Reservoir. These observations could be interpreted as a rationale for increasing the freshwater inflow standards; however, the effects of increasing freshwater inflows,[33] and N loads, are not quantifiable at this time because the degree to which N availability actually limits primary productivity, in both space and time, is unclear. If further scientific investigations are deemed valuable, then the development and calibration of a hydrodynamic and water quality model should be a key topic of discussion.

5.2.5 Discharge of WWTP Effluent into Nueces Delta

As part of a demonstration project, the Allison WWTP discharge was temporarily routed to the Nueces Delta (Dunton and Hill 2006). Following a series of scientific investigations, the authors concluded:

- "There were no measurable negative effects of the demonstration project on the ecology of the local ecosystem."
- "diversion of effluent from the Allison Plant appears to have significantly reduced the frequency of recorded hypoxic events in the Nueces River"
- There was evidence for ecosystem benefits; however, quantification of these was confounded by large storm events.

Results from this study's N budget do not contradict the conclusions of Dunton and Hill (2006), and the available evidence further reinforces the expectation that the Nueces Delta is N limited (Section 2.1). Accordingly, it is recommended that diversion of WWTP effluent into the Nueces Delta receive serious consideration, should the opportunity arrive in the future.

[33] This text equates increasing the freshwater inflow standards with ultimately increasing the freshwater inflow to Nueces Bay; however, it is recognized that the standards do not apply to existing water rights and therefore any changes to the standards would only affect the permit conditions imposed on new water rights.

6 References

An, S.A., and W.S. Gardner, 2000. *Nitrogen Cycling in Laguna Madre and Baffin Bay*. Prepared for Texas Water Development Board. July 2000.

Asquith, W.H., J.G. Mosier, and P.W Bush, 1997. *Status, Trends and Changes in Freshwater Inflows to Bay Systems in the Corpus Christi Bay National Estuary Program Study Area*. CCBNEP-17. September 1997.

Baird, C., M. Jennings, D. Ockerman, and T. Dybala, 1996. *Characterization of Nonpoint Sources and Loadings to Corpus Christi Bay National Estuary Program Study Area*. CCBNEP-05. January 1996.

BBASC (Nueces River and Corpus Christi and Baffin Bays Basin and Bay Area Stakeholders Committee), 2012. *Work Plan for Adaptive Management.* Final Submission to the Environmental Flows Advisory Group and Texas Commission on Environmental Quality. November 2012.

BBEST (Nueces River and Corpus Christi and Baffin Bay Basin and Bay Expert Science Team), 2011. *Environmental Flows Recommendations Report*. Final Submission to the Environmental Flows Advisory Group, Nueces River and Corpus Christi and Baffin Bays Basin and Bay Area Stakeholders Committee, and Texas Commission on Environmental Quality. October 2011.

Besonen, M., 2017. Personal communication with Dan Opdyke and Mark Meyers. April 28, 2017.

Boudreau, B.P., 1998. Mean mixed depth of sediments: The wherefore and the why. *Limnology and Oceanography* 43(3):524-526.

Boynton, W.R., W.M. Kemp, and C.W. Keefe, 1982. A comparative analysis of nutrients and other factors influencing estuarine phytoplankton production. In: *Estuarine Comparisons*, edited by V. Kennedy. San Diego: Academic Press, 69-90.

Breier, J.A., and H.N. Edmonds, 2007. High 226Ra and 228Ra activities in Nueces Bay, Texas indicate large submarine saline discharges. *Marine Chemistry* 103:131-145.

Breier, J.A., H.N. Edmonds, and T.A. Villareal, 2004. *Submarine Groundwater Discharge and Associated Nutrient Fluxes to the Corpus Christi Bay System*. January 2004.

Breier, J.A., C.F. Breier, and H.N. Edmonds, 2010. Seasonal dynamics of dissolved Ra isotopes in the semi-arid bays of south Texas. *Marine Chemistry* 122:39-50.

Brewster-Wingard, G.L., S.E. Ishman, D.A. Willard, L.E. Edwards, and C.W. Holmes, 1997. *Preliminary paleontologic report on cores 19A and 19B from Russell Bank, Everglades National Park, Florida Bay*. U.S. Geological Survey Open-File Report 97-460.

Brock, D.A., 1998. Salinity Recovery in Texas Bays. *Texas J. Sci.* 50(1):17-34.

Brock, D.A., 2001. Nitrogen Budget for Low and High Freshwater Inflows, Nueces Estuary, Texas. *Estuaries* 24(4):509-521.

Bruesewitz, D.A., W.S. Gardner, R.F. Mooney, L. Pollard, and E.J. Buskey, 2013. Estuarine ecosystem function response to flood and drought in a shallow, semiarid estuary: Nitrogen cycling and ecosystem metabolism. *Limnology Oceanography* 58(6):2293-2309.

Brush, G.S., and F.W. Davis, 1984. Stratigraphic Evidence of Human Disturbance in an Estuary. *Quaternary Research* 22:91-108.

Castro, M.S., C.T. Driscoll, T.E. Jordan, W.G. Reay, and W.R. Boynton, 2003. Sources of Nitrogen to Estuaries in the United States. *Estuaries* 26(3):803-814.

Conley, D.J., C.L. Shelske, and E.F. Stoermer, 1993. Modification of the biogeochemical cycle of silica with eutrophication. *Mar. Ecol. Progr. Ser.* 101:179-192.

Conley, D.J., and T.C. Malone, 1992. Annual cycle of dissolved silicate in Chesapeake Bay: implications for the production and fate of phytoplankton biomass. *Mar. Ecol. Progres. Ser.* 81:121-128.

Cooper, S.R., and G.S. Brush, 1993. A 2,500-Year History of Anoxia and Eutrophication in Chesapeake Bay. *Estuaries* 16(3B):617-626.

Cooper, S.R., S.K. McGlothlin, M. Madritch, and D.L. Jones, 2004. Paleoecological Evidence of Human Impacts on the Neuse and Pamlico Estuaries of North Carolina, USA. *Estuaries* 27(4):617-633.

Corn, R., 2017. Regarding: Allison WWTP. Email to R. Mooney. April 5, 2017.

Corpus Christi Water Department Lake Corpus Christi and Choke Canyon Reservoir [Internet], 2011. Corpus Christi (TX): City of Corpus Christi. Available from: http://cctexas.com/water/resources/lakecorpuschristichokecanyon.html.

Cunningham, A.M., 1999. *Corpus Christi water supply: documented history 1852–1997*. 2nd ed. Corpus Christi(TX): Texas A&M University–Corpus Christi. 588 p.

CWS-UCD (Center for Watershed Science University of California Davis), 2012. *Nitrogen Sources and Loading to Groundwater Technical Report 2*. Prepared for California State Water Resources Control Board. July 2012.

D'Elia, C.F., D.M. Nelson, and W.R. Boynton, 1983. Chesapeake Bay nutrient and plankton dynamics. III. The annual cycle of dissolved silica. *Geochim. et Cosmochim. Acta* 47:1945-1955.

Di Toro, D.M., 2001. *Sediment Flux Modeling*. John Wiley & Sons Publishing.

Dunton, K.H., and E. M. Hill, 2006. *Concluding Report. Allison Wastewater Treatment Plant Effluent Diversion Demonstration Project*. Volume I: Executive Summary. University of Texas - Marine Science Institute Port Aransas, Texas and Texas A&M University - Corpus Christi, Center for Coastal Studies, Corpus Christi, Texas.

Dunton, K.H., S.V. Schonberg, K. Jackson, J. Stachelek, and M.K. Rasser, 2011. The Rincon Bayou Diversion Project Database: Vegetation and Water Column Monitoring, 2001-2010. (Database) University of Texas Marine Science Institute, Port Aransas, Texas.

Fernando, N., 2017a. Regarding: Nueces Bay nutrient budget – request for ungaged flow estimates from TxRR model. Email to E. Chen. January 13, 2017.

Fernando, N., 2017b. Regarding: Nueces Bay nutrient budget – request for ungaged flow estimates from TxRR model. Email to E. Chen. April 7, 2017.

Fernando, N., 2017c. Regarding: Nueces Bay nutrient budget – request for ungaged flow estimates from TxRR model. Email to E. Chen. April 11, 2017.

Fernando, N., 2017d. Regarding: Nueces Bay nutrient budget – request for ungaged flow estimates from TxRR model. Email to E. Chen. April 17, 2017.

Fernando, N., 2017e. Regarding: Nueces Bay nutrient budget – request for ungaged flow estimates from TxRR model. Email to E. Chen. April 20, 2017.

Gaiser, E, 2009. Periphyton as an indicator of restoration in the Everglades. *Ecological Indicators* 9(6):S37-S45.

Gaiser, E., A. Wachnicka, P. Ruiz, F. Tobias, and M. Ross, 2004. Diatom Indicators of Ecosystem Change in Subtropical Coastal Wetlands. *Estuarine Indicators*. Boca Raton, Florida: CRC Press.

Garder, W.S., M.J. McCarty, S. An, and D. Sobolev, 2006. Nitrogen fixation and dissimilatory nitrate reduction to ammonium (DNRA) support nitrogen dynamics in Texas estuaries. *Limnology Oceanography* 51(1, part 2):558-568.

HDR, 2015. *Nueces BBASC Work Plan Study No. 3: Nueces Watershed Pre-and Post-Development Nutrient Budgets*. Prepared for Texas Water Development Board. August 2015.

Hill, E.M., M. Besonen, B. Nicolau, and P. Tissot, 2014. *Nueces Bay Zinc in Sediment Profiling Assessment*. Prepared for Coastal Bend Bays and Estuary Program. January 2014.

Hill, E.M., B.A. Nicolau, and P.V. Zimba, 2011. History of Water and Habitat Improvement in the Nueces Estuary, Texas, USA. *Texas Water Journal* 2(1):97-111.

Homer, C.G., J.A. Dewitz, L. Yang, S. Jin, P. Danielson, G. Xian, J. Coulston, N.D. Herold, J.D. Wickham, and K. Megown, 2015. Completion of the 2011 National Land Cover Database for the conterminous United States-Representing a decade of land cover change information. *Photogrammetric Engineering and Remote Sensing* 81(5):345-354.

Howarth, R.W., R. Marino, J. Lane, and J.J. Cole, 1988. Nitrogen fixation in freshwater, estuarine, and marine ecosystems. 1. Rates and importance. *Limnology and Oceanography* 33:669-687.

Kirk, J.T.O., 1994. *Light & Photosynthesis in Aquatic Systems*. Second edition. Cambridge, United Kingdom: Cambridge University Press

Kim, H-C, and P.A. Montagna, 2010. *Effect of Climatic Variability on Freshwater Inflow, Benthic Communities, and Secondary Production in Texas Lagoonal Estuaries*. Prepared for the Texas Water Development Board, Contract Number 08-483-0791.

Kristensen, E., 2005. Interactions Between Macro- and Micro-organisms in Marine Sediments. *Coastal and Estuarine Studies*. American Geophysical Union. Volume 60, pp. 7-29.

Marshall, F.E., G.L. Wingard, and P. Pitts, 2009. A simulation of Historic Hydrology and Salinity in Everglades National Park: Coupling Paleoecologic Assemblage Data with Regression Models. *Estuaries and Coasts* 32:37-53.

Marshall, F.E., and G.L. Wingard, 2012. *Florida Bay Salinity and Everglades Wetlands Hydrology Circa 1900 CE: a compilation of paleoecology-based statistical modeling analyses (ver. 1.1, August 2014)*: U.S. Geological Survey Open-File Report 2012–1054, 32 p. (Revised 2014; supersedes ver. 1.0 released in 2012.)

Marshall, F.E., and G.L. Wingard, 2014. Estimates of Natural Salinity and Hydrology in a Subtropical Estuarine Ecosystem: Implications for Greater Everglades Restoration. *Estuaries and Coasts* 37:1449-1466.

Matsumoto, J., 2017. Regarding: Nueces Bay nutrient budget – request for ungaged flow estimates from TxRR model. Email to E. Chen. January 26, 2017.

Mims, C., 2015. Letter to Troy Fraser, Environmental Flows Advisory Group; Jim Keffer, Environmental Flows Advisory Group; and Richard Hyde, TCEQ. Regarding: Request for Amendment of the

Nueces River and Corpus Christi and Baffin Bays Basin and Bay Area Stakeholder Committees' Work Plan for Adaptive Management dated November 2012. November 16, 2015.

McCall, P.L., and M.J.S. Tevesz, 1982. The effects of benthos on physical properties of freshwater sediments. In *Animal-Sediment Relations: The Biogenic Alterations of Sediments*, edited by P.L. McCall and M.J.S. Tevesz. New York: Plenum Press, 105-176.

Montagna, P., 1991. *Predicting long-term effects of freshwater inflow on macrobenthos in the Lavaca-Colorado and Guadalupe estuaries*. Prepared for Texas Water Development Board. TR/91-004. October 1991.

Montagna, P.A., E.M. Hill, and B. Moulton, 2009. P. Role of science-based and adaptive management in allocating environmental flows to the Nueces Estuary, Texas, USA. In *Ecosystems and Sustainable Development VII*, edited by C.A. Brebbia and E. Tiezzi. United Kingdom: WIT Press, 559-570.

Montagna, P.A., and T.A. Palmer, 2011. *Effect of Freshwater Inflow on Macrobenthos Productivity in the Guadalupe Estuary*. Prepared for the Texas Water Development Board, Contract Number 104831133. December 2011.

Montagna, P.A., and T.A. Palmer, 2012. *Water and Sediment Quality Status and Trends in the Coastal Bend Phase 2: Data Analysis*. Prepared for Coastal Bend Bays and Estuaries Program. Project Number – 1206. August 2012.

Murgulet, D., M.S. Wetz, A. Douglas, W. McBee, N. Spalt, and K. Linares, 2015. *Evaluating Groundwater Inflow and Nutrient Transport to Texas Coastal Embayments. Final Report*. Prepared for Texas General Land Office. August 2015.

NADP (National Atmospheric Deposition Program), 2017. NTN Site TX03. Cited March 7, 2017. Available from: http://nadp.isws.illinois.edu/data/sites/siteDetails.aspx?net=NTN&id=TX03.

Nodine, E.R, and E.E. Gaiser, 2014. Distribution of Diatoms along Environmental Gradients in the Charlotte Harbor, Florida (USA), Estuary and Its Watershed: Implications for Bioassessment of Salinity and Nutrient Concentrations. *Estuaries and Coasts* 37:864-879.

Nolan, B.T., B.C. Ruddy, K.J. Hitt, and D.R. Helsel, 1998. A National Look at Nitrate Contamination of Ground Water. *Water Conditioning and Purification* 39(12): 76-79.

Norwine J., J.R. Giardino, S. Krishnamurthy, and L. Sayavedra, 2005. *Water for Texas.* Texas A&M University Agriculture Series. College Station (TX): Texas A&M University Press. 154 p.

Ockerman, D.J., and C.W. Livingston, 1999. *Nitrogen Concentrations and Deposition in Rainfall at Two Sites in the Coastal Bend Area, South Texas, 1996-1998*. USGS Fact Sheet FS-146-99. U.S. Geological Survey.

Officer, C.B., and J.H. Ryther. 1980. The possible importance of silica in marine eutrophication. *Mar. Ecol. Prog. Ser.* 3:83-91.

Pacheco, P.A., D.R.G. Farrow, T. Manuelides, S.O. Rohmann, M. Katz, and J. McLeod, 1990. *Point Source Discharges in Coastal Areas of Texas – A Summary by Estuarine Watershed for 1987. DRAFT*. May 1990.

Palmer, T.A., P.A. Montagna, J. Beseres-Pollack, R.D. Kalke, and H.R. DeYoe, 2011. The role of freshwater inflows in lagoons, rivers, and bays. *Hydrobiologia* 667:49-67.

Parsons, M.L., Q. Dortch, R.E. Turner, and N.N. Rabalais, 1999. Salinity history of coastal marshes reconstructed from diatom remains. *Estuaries* 22(4):1078-1089.

Potapova, M., 2011. Patterns of diatom distribution in relation to salinity. In: *The Diatom World*. Edited by J. Seckbach and P. Kociolek. Dordrecht: Springer, 313-332

Redfield, A.C., B.H. Ketchum, and F.A. Richards, 1963. The influence of organisms on the composition of sea- water. In: *The Sea, Vol. 2. The Composition of Sea-Water. Comparative and Descriptive Oceanography*, edited by M.N. Hill. New York: Interscience, 26-77.

Riera P., P.A. Montagna, R.D. Kalke, and P. Richard, 2000. Utilization of estuarine organic matter during growth and migration by juvenile brown shrimp Penaeus aztecus in a South Texas estuary. *Mar. Ecol. Progr. Ser.* 199:205-216.

Ricklis, R.A. and K.A. Cox, 1998. Holocene climatic and environmental change in the Texas Coastal Zone: some geoarchaeological and ecofatual indicators. *Plains Anthropologist* 43(164):125-136.

Santschi, P.H. and K.M. Yeager, 2004. *Quantification of Terrestrial and Marine Sediment Sources to a Managed Fluvial, Deltaic and Estuarine System: The Nueces-Corpus Christi Estuary, Texas*. Prepared for Texas Water Development Board. December 2004.

Sterner, R.W., and J.J. Elser, 2002. *Ecological stoichiometry: The biology of elements from molecules to the biosphere*. Princeton: Princeton University Press.

TCEQ (Texas Commission on Environmental Quality), 2016. Download TCEQ GIS Data. Published: September 27, 2016. Cited: December 21, 2016. Available from: https://www.tceq.texas.gov/gis/download-tceq-gis-data/

TCEQ, 2017. Surface Water Quality Web Reporting Tool. Cited: April 7, 2017. Available from: https://www80.tceq.texas.gov/SwqmisPublic/public/default.htm

TPWD (Texas Parks and Wildlife Department), 2002. *Freshwater Inflow Recommendations for the Nueces Estuary*. September 2002.

TWDB (Texas Water Development Board), 2011a. *Coastal Hydrology for the Nueces Estuary: Hydrology for Version #TWDB201101 with Updates to Diversion and Return Data for 2000-2009*. Bay & Estuary Program. Surface Water Resources Division. July 2011.

TWDB, 2011b. *Comparison of Two Hydrology Datasets, as Applied to the TxBLEND Model, on Salinity Condition in Nueces Bay*. Bay & Estuary Program. Surface Water Resources Division. July 2011.

TWDB, 2017. Groundwater Database Reports, Cited: March 23, 2017. Available from: http://www.twdb.texas.gov/groundwater/data/gwdbrpt.asp.

Tropea, A.E., A.M. Paterson, W. Keller, and J.P. Smol, 2011. Diatoms as indicators of long-term nutrient enrichment in metal-contaminated urban lakes from Sudbury, Ontario. *Lake and Reservoir Management* 27(1):48-60.

Underwood, G., J. Phillips, and K. Saunders, 1998. Distribution of estuarine benthic diatom species along salinity and nutrient gradients. *European Journal of Phycology* 33(2):173-183.

USBR (United States Department of the Interior Bureau of Reclamation), 2000. *Rincon Bayou Demonstration Project Concluding Report*. In cooperation with University of Texas Marine Science Institute. September 2000.

USEPA (U.S. Environmental Protection Agency), 2001a. *The nutrient criteria technical manual: Estuarine and coastal waters*. Office of Water. EPA-822-B-01-003. October 2001.

USEPA, 2001b. *Ambient water quality criteria recommendations – Rivers and streams in nutrient ecoregion X*. Office of Water. EPA 822-B-01-016. December 2001.

USEPA, 2016. Envirofacts. Updated: March 28, 2016. Cited: December 21, 2016. Available from: https://www3.epa.gov/enviro/facts/pcs-icis/search.html

USEPA, 2017. National Primary Drinking Water Regulations. Updated: March 21, 2017. Cited: June 6, 2017. Available from: https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations

USGS (U.S. Geological Survey), 2001. *Water Budget for the Nueces Estuary, Texas, May-October 1998*. USGS Fact Sheet 081-01. December 2001.

USGS, 2016. *An Evaluation of the Variability of Sediment and Nutrient Loading into Texas Bays and Estuaries from Riverine Systems: Focus on Nueces River and Nueces Bay System*. Nueces Estuary Advisory Council (NEAC) Project Update. October 2016.

Vannote, R.L, G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing, 1980. The River Continuum Concept. *Canadian Journal of Fisheries and Aquatic Sciences* 37(1):130-137.

Wachnicka, A., E. Gaiser, L. Wingard, H. Briceno, and P. Harlem, 2013. Impact of Late Holocene climate variability and anthropogenic activities on Biscayne Bay (Florida, U.S.A.): Evidence from diatoms. *Palaeogeography, Palaeoclimatology, Palaeoecology* 371(2013):80–92.

Wade, T.L., and S.T. Sweet, 2008. *Final Report Coastal Bend Bays and Estuaries Program (CBBEP): Atmospheric Deposition Study*. Prepared for Coastal Bend Bays and Estuary Program. March 2008.

Ward, G.H., 2003a. *Distribution of Nutrients in the Coastal Bend Bays in Space and Time*. Prepared for Texas General Land Office. March 2003.

Ward, G.H., 2003b. *Summary of Data Base for Nutrients and Related Parameters for Coastal Bend Bays*. Prepared for Texas General Land Office. April 2003.

Ward, G.H., 2003c. *Assignment of Corpus Christi Bay Eutrophic Status by National Ocean Service*. Prepared for Texas General Land Office. May 2003.

Ward, G.H., 2003d. *Review of Estimated Nitrogen Loads from Coastal Bend Bays Watersheds*. Prepared for Texas General Land Office. July 2003. Revised October 2003.

Ward, G.H., 2003e. *Eutrophication State of Corpus Christi Bay: Executive Summary*. Prepared for Texas General Land Office. August 2003. Revised October 2003.

Wetzel, R.G., 2001. *Limnology: lake and river ecosystems*. San Diego: Gulf Professional Publishing.

Whitledge, T.E., 1989. *Data Synthesis and Analysis Nitrogen Processes Study (NIPS). Nutrient Distributions and Dynamics in Lavaca, San Antonio and Nueces/Corpus Christi Bays in Relation to Freshwater Inflow. Part I: Results and Discussion. Final Report*. Prepared for TWDB Bays and Estuaries Program Environmental Systems Section. December 1989.

Wingard, G.L., and J.W. Hudley, 2012. Application of a weighted-averaging method for determining paleosalinity: a tool for restoration of South Florida's Everglades. *Estuaries and Coasts* 35:262-280.

WSDOE (Washington State Department of Ecology), 2017. Nitrogen from Atmospheric Deposition. Cited: May 23, 2017. Available from: http://www.ecy.wa.gov/programs/eap/Nitrogen/Nitrogen Atmosphere.html.

Yoon, W. B., and R. Benner, 1992. Denitrification and oxygen consumption in sediments of two south Texas estuaries. *Marine Ecology Progress Series 90*:157-167.

Figures

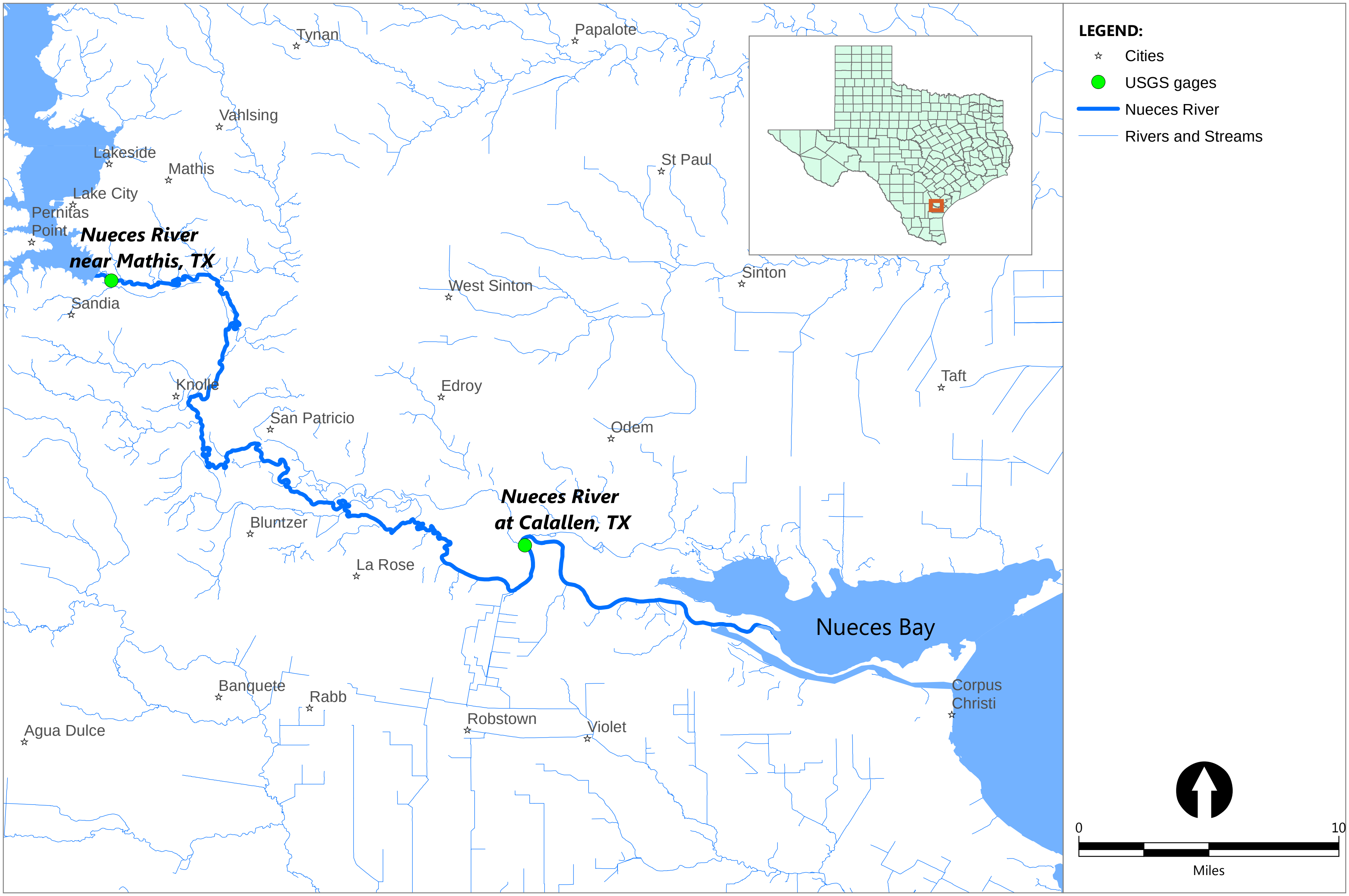


Figure 1-1
Study Area
Nutrient Budget for Nueces Bay
Texas Water Development Board

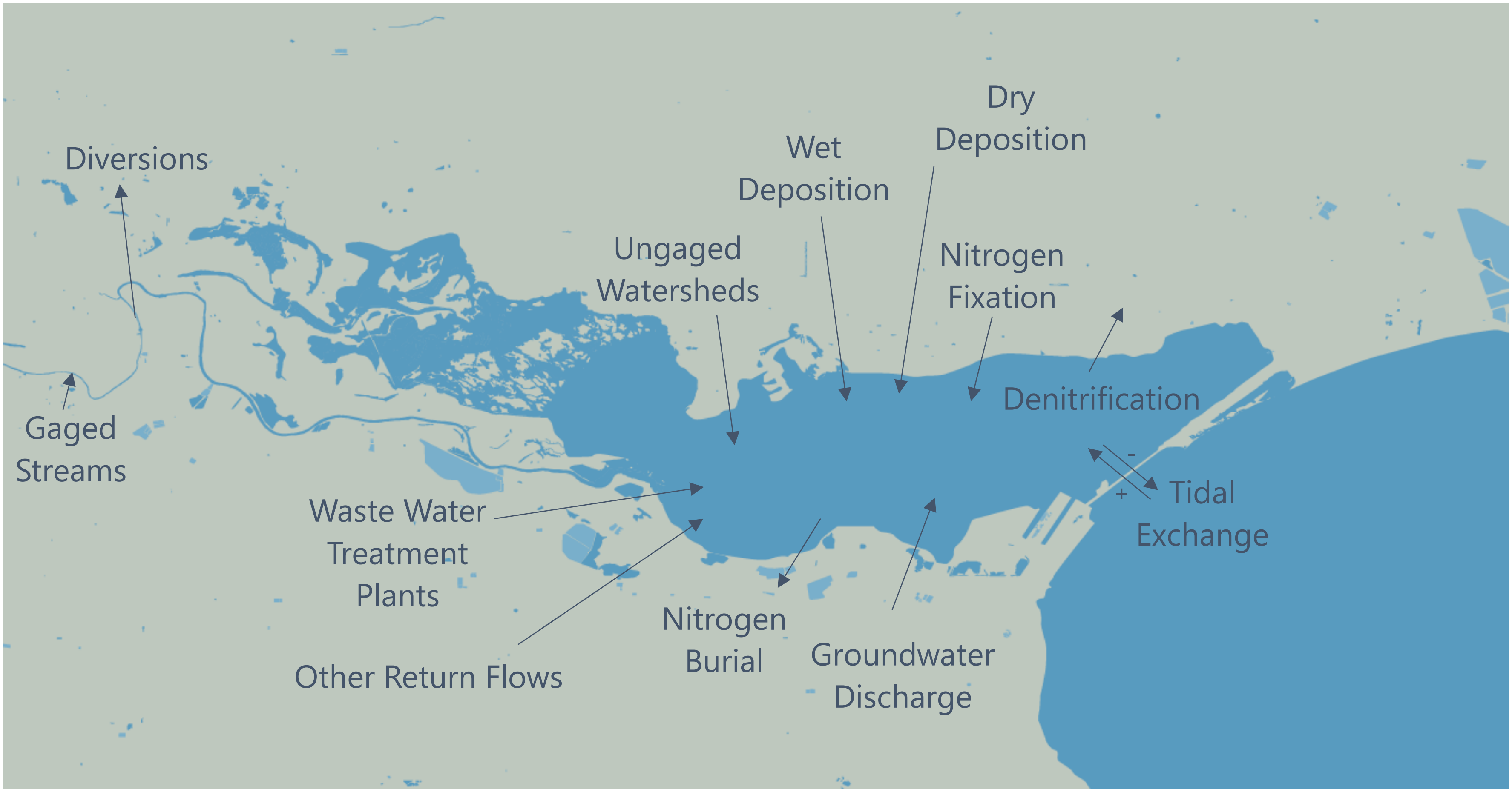
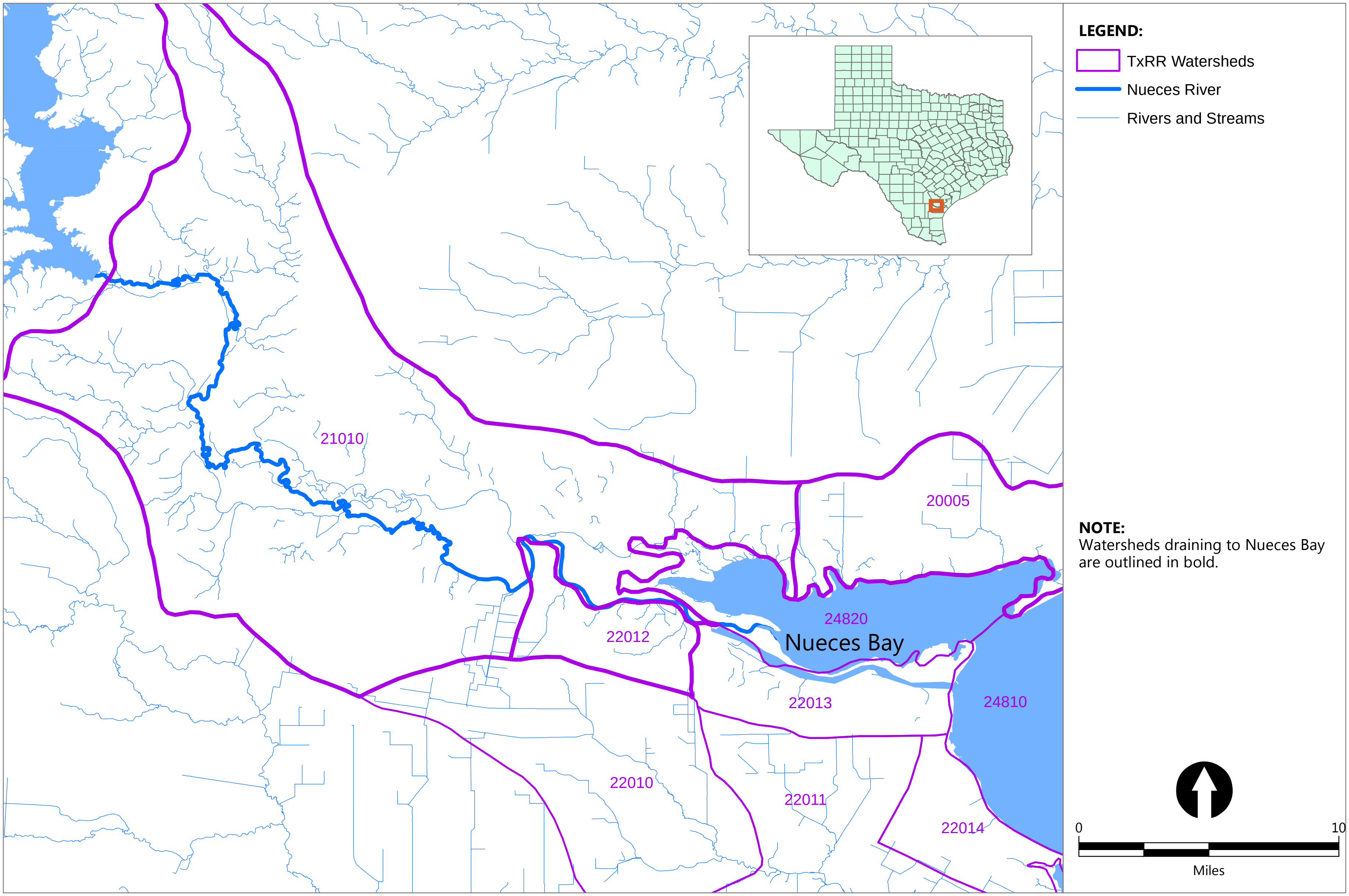
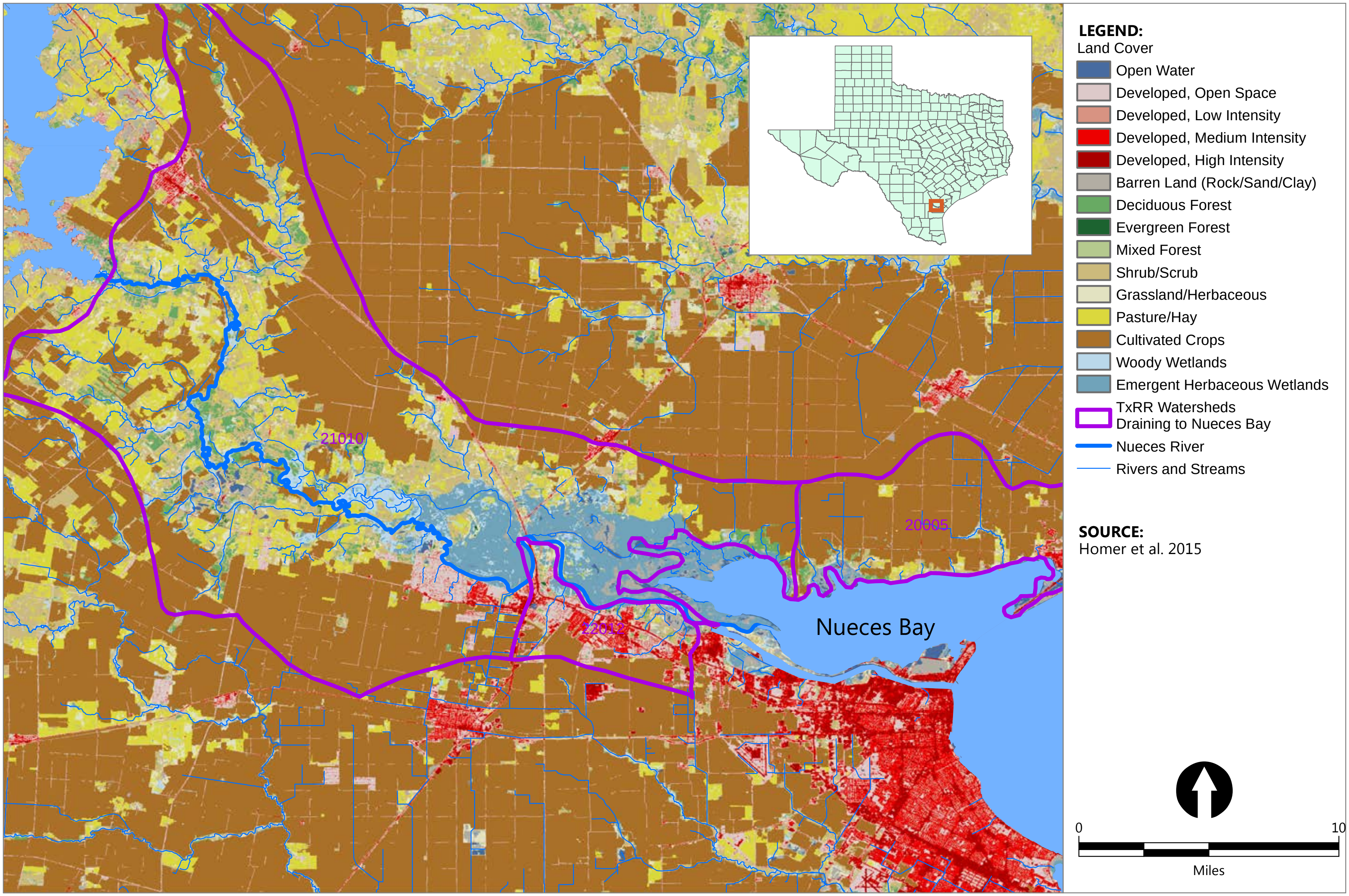


Figure 2-1
Initial Conceptual Site Model for Nitrogen in Nueces Bay
Nutrient Budget for Nueces Bay
Texas Water Development Board



ANCHOR QEA

Figure 3-1
TxRR Watersheds
Nutrient Budget for Nueces Bay
Texas Water Development Board



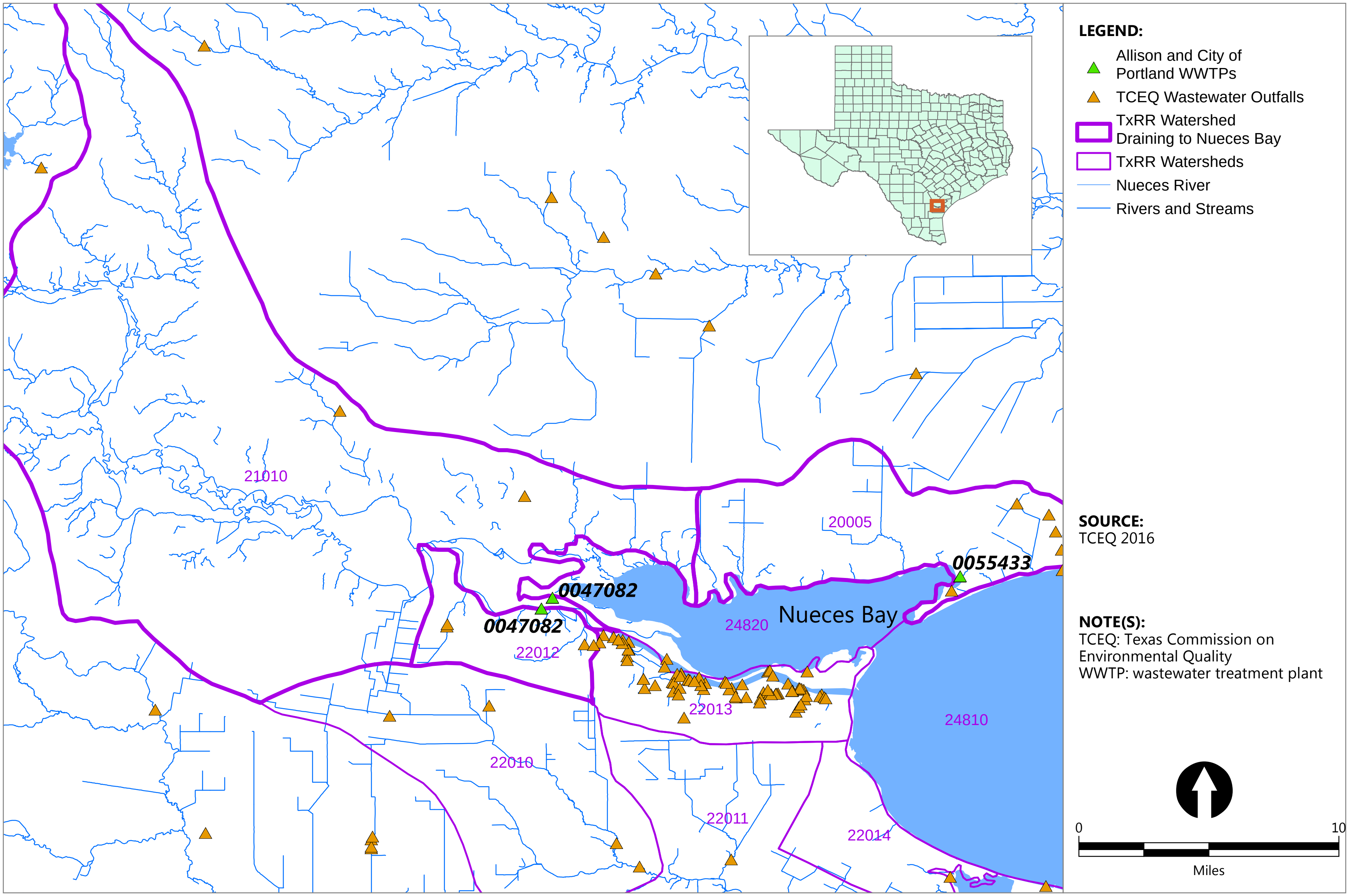
ANCHOR QEA

Figure 3-2

Land Cover from 2011 National Land Cover Database

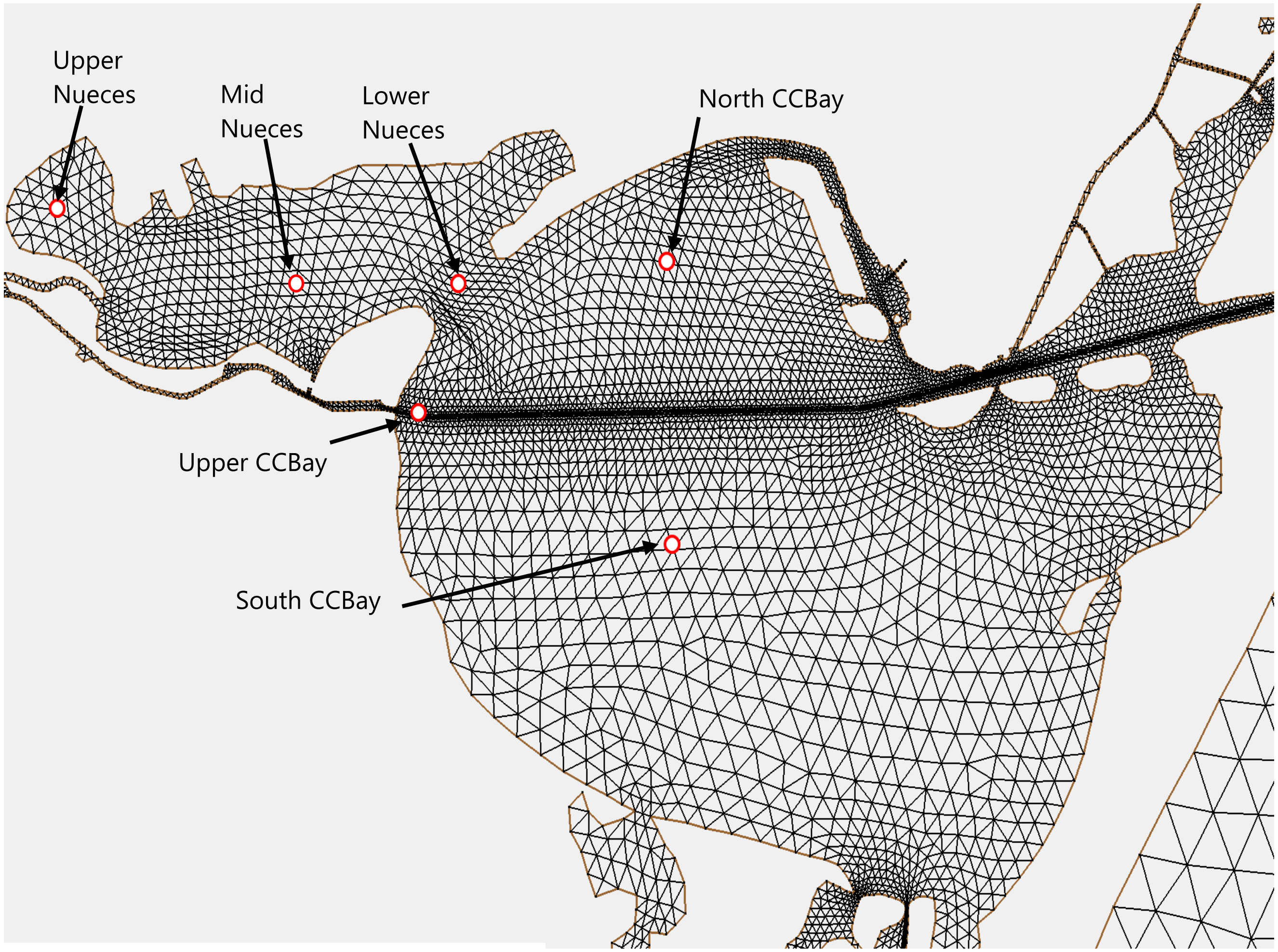
Nutrient Budget for Nueces Bay

Texas Water Development Board



ANCHOR QEA

Figure 3-3
Wastewater Outfalls
Nutrient Budget for Nueces Bay
Texas Water Development Board

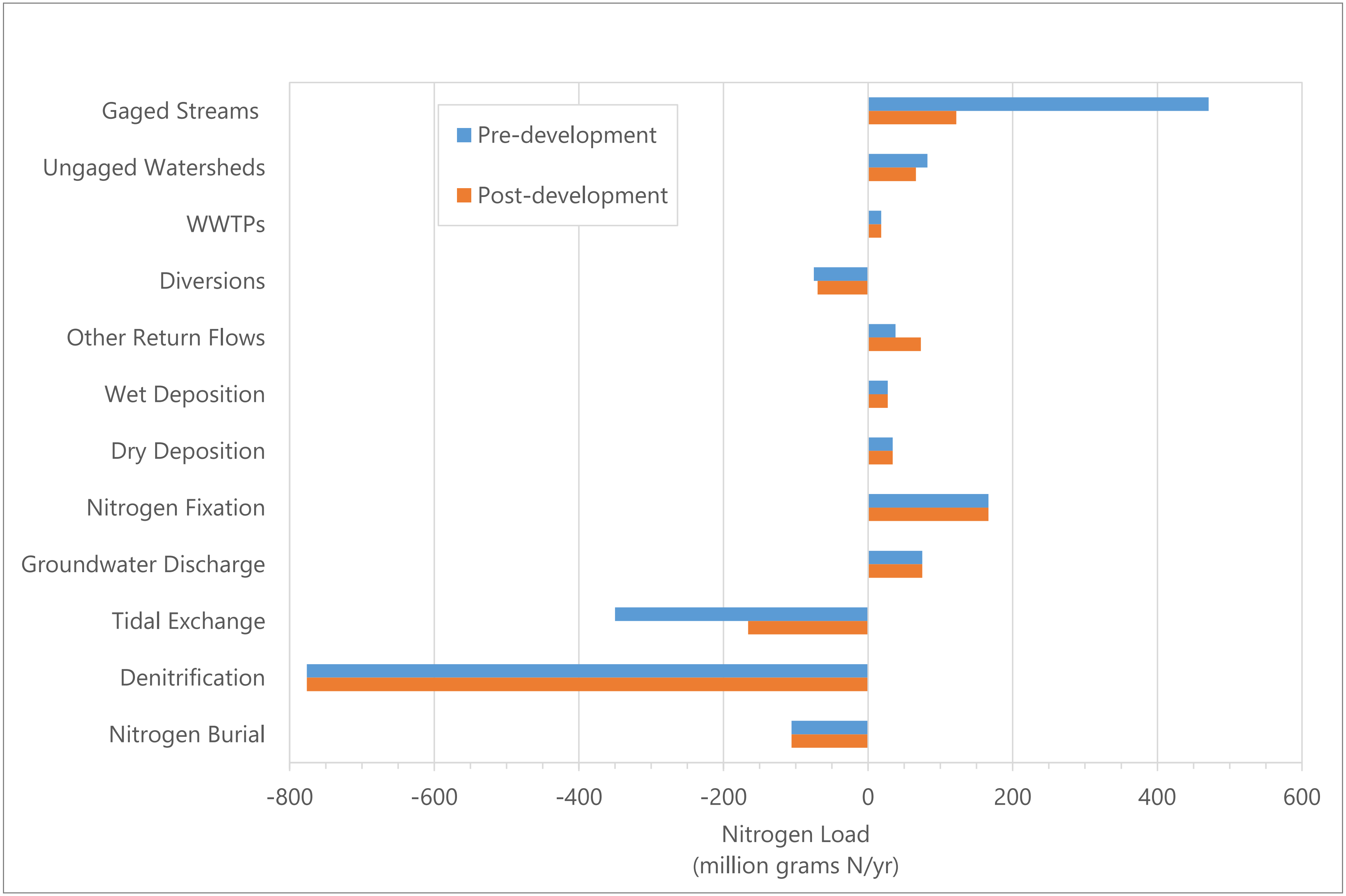


Source: Matsumoto 2017

Anchor QEA

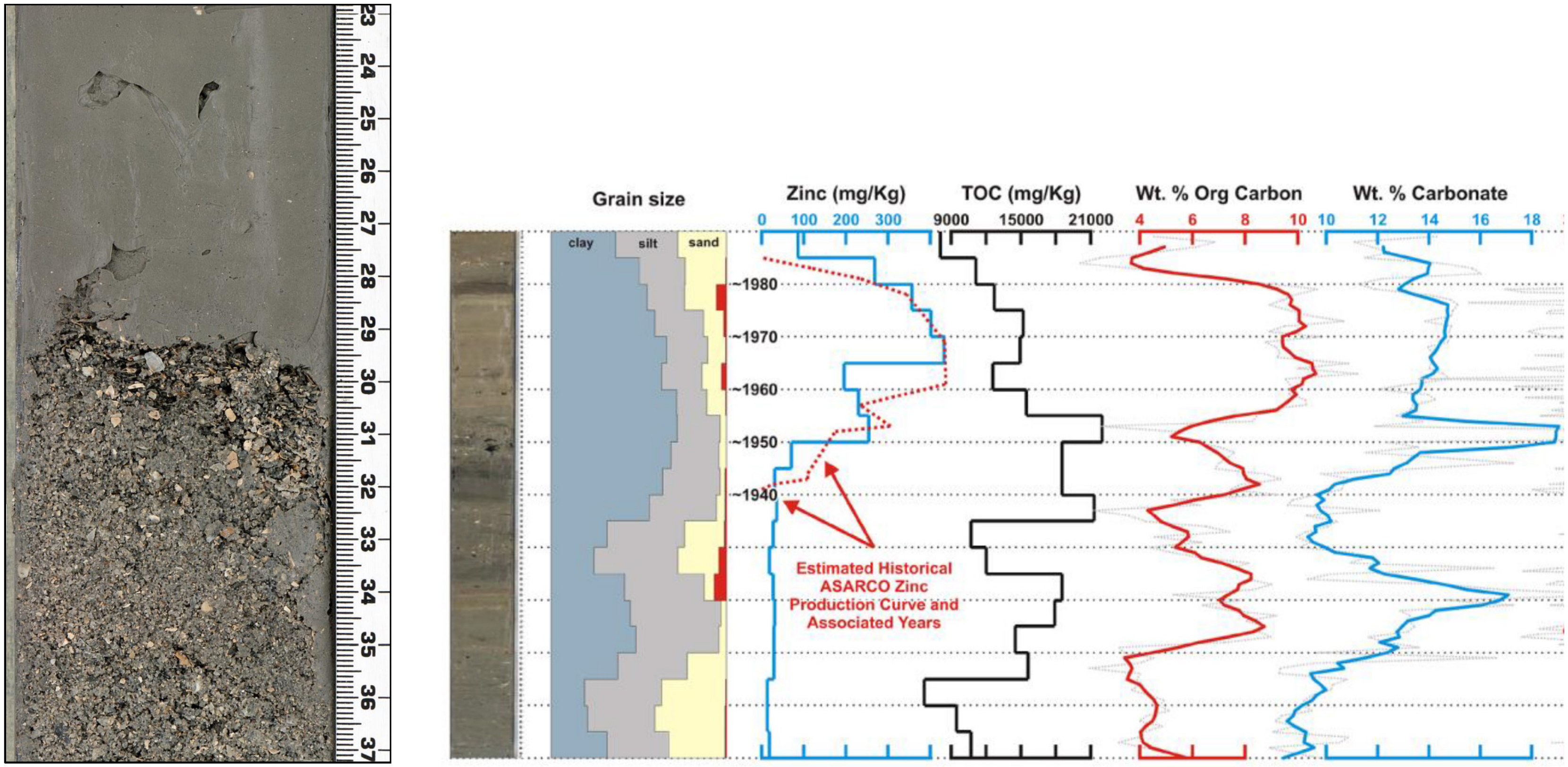
Figure 3-4
Locations of TxBLEND Salinity Output Provided by Texas Water Development Board

Figure 3-5
Calculated Salinities Using Various Water Entrainment Rates for Nueces Bay



ANCHOR QEA

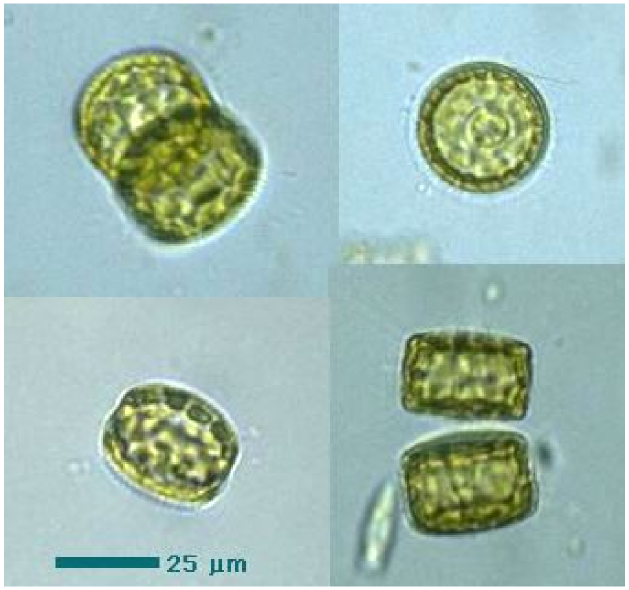
Figure 3-6
Summary of Nitrogen Budget for Nueces Bay Under Average Conditions



Left Panel: Section of core from Nueces Bay (Station 18619) showing an abrupt transition from surface muds to shell hash (at 130 cm). Information from this location suggests that dredging and subsequent infilling are responsible for the surface mud layer.

Right Panel: Photograph and interpretation of a core from Nueces Bay (Station 21484) showing sedimentological features and human contaminants (zinc) with chronological information form radioisotopic data (not shown). Next to the photograph, gray dashed lines represent 10 cm intervals.

(Images and interpretation from Hill et al. 2014)



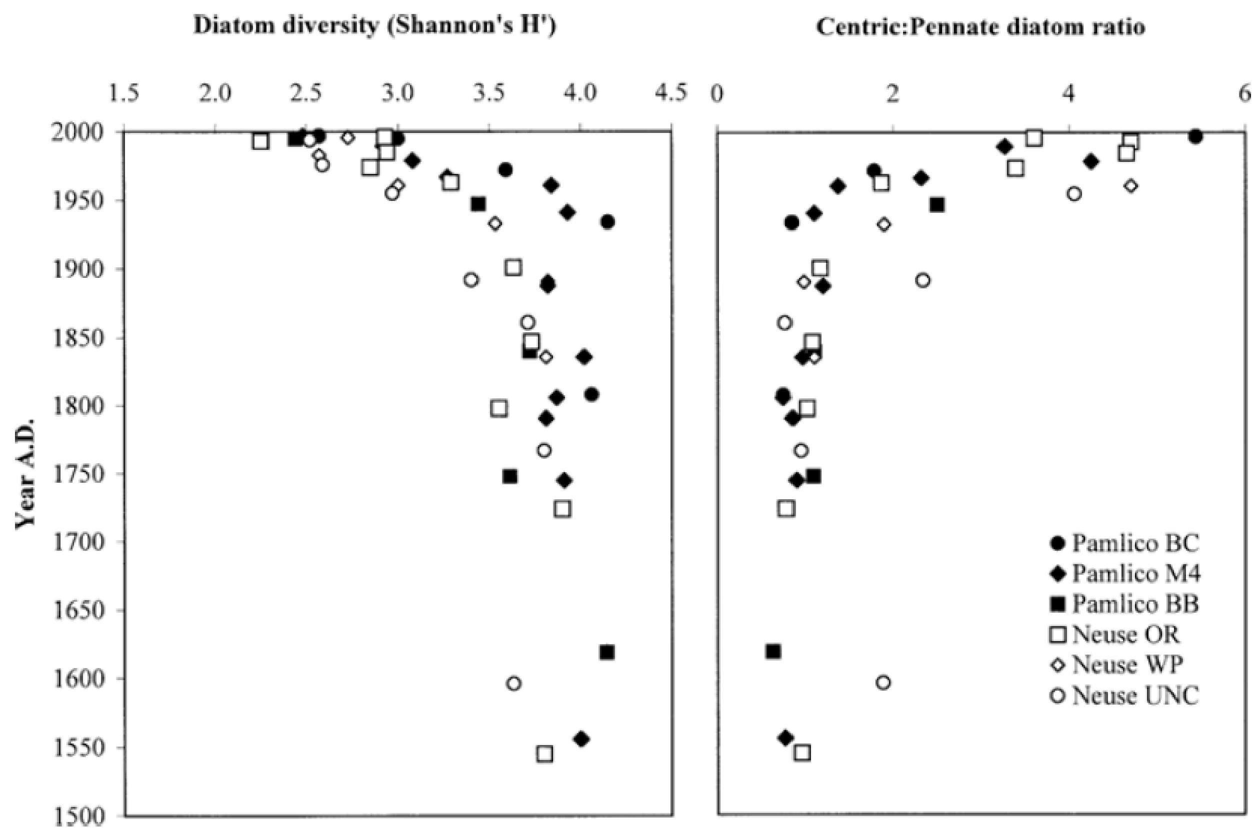
A. *Cyclotella* sp., a centric diatom

B. *Navicula* sp., a pennate diatom

Centric diatoms typically inhabit the water column, whereas pennate forms are benthic (living in the sediment) or periphytic (living on plants).

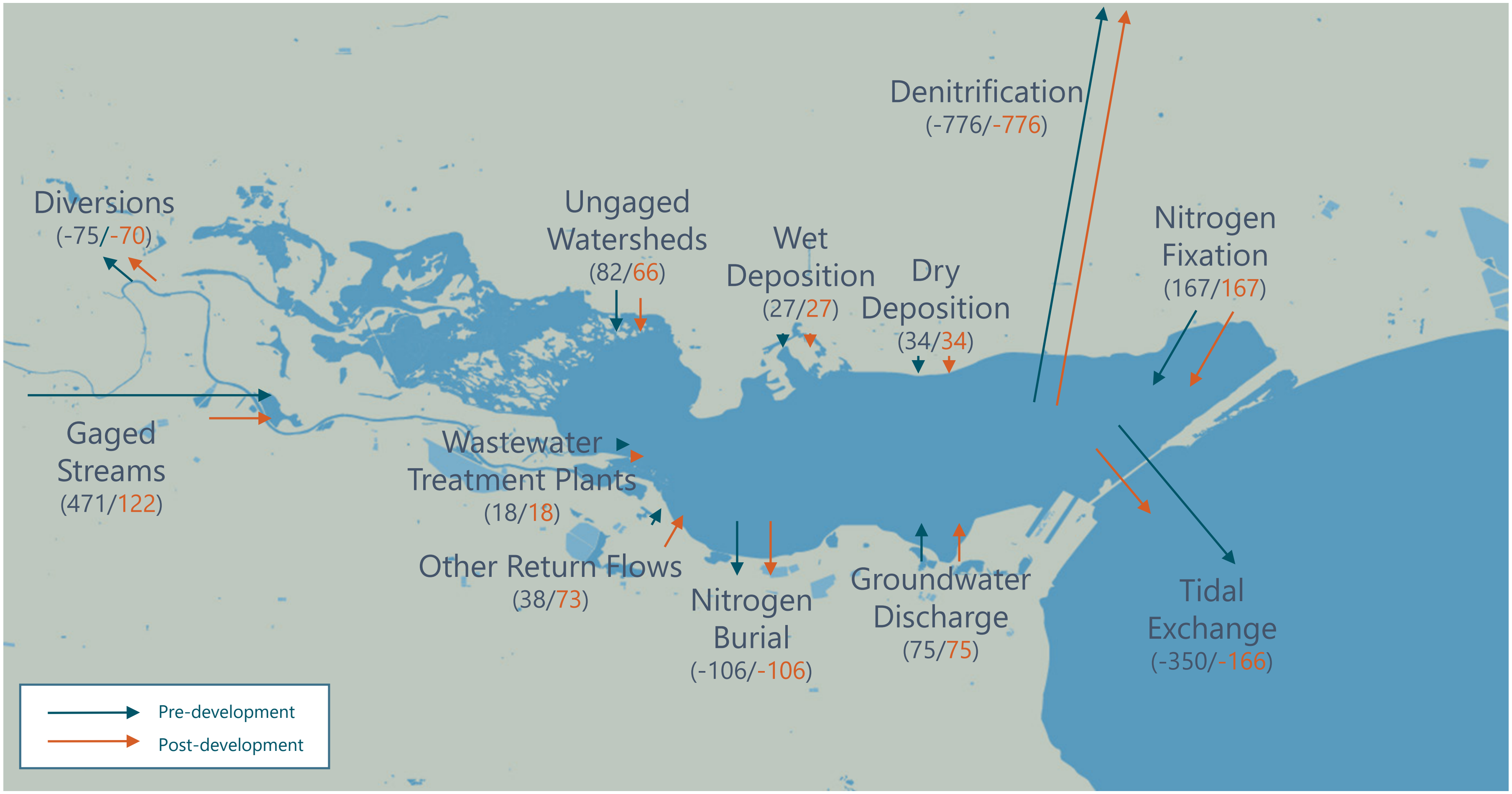
(images from Protist Information Server: http://protist.i.hosei.ac.jp)

Figure 4-2
Examples of (A) Centric and (B) Pennate Diatoms



Source: Cooper et al. 2004

Figure 4-3
Trends in Diatom Taxonomic Diversity and the Ratio of Centric to Pennate Diatom Forms in Sediment Cores from the Neuse and Pamlico (North Carolina) Estuaries



Numbers in parentheses indicate estimated TN load during average conditions for pre-/post-development periods (million g N/yr).

The arrows are to scale: ⟶ = 100 million g N/yr

The loads for Gaged Streams were calculated for Nueces River at Mathis.

ANCHOR QEA

Figure 5-1
Conceptual Site Model with Estimated Nitrogen Loadings Under Average Conditions
Nutrient Budget for Nueces Bay
Texas Water Development Board

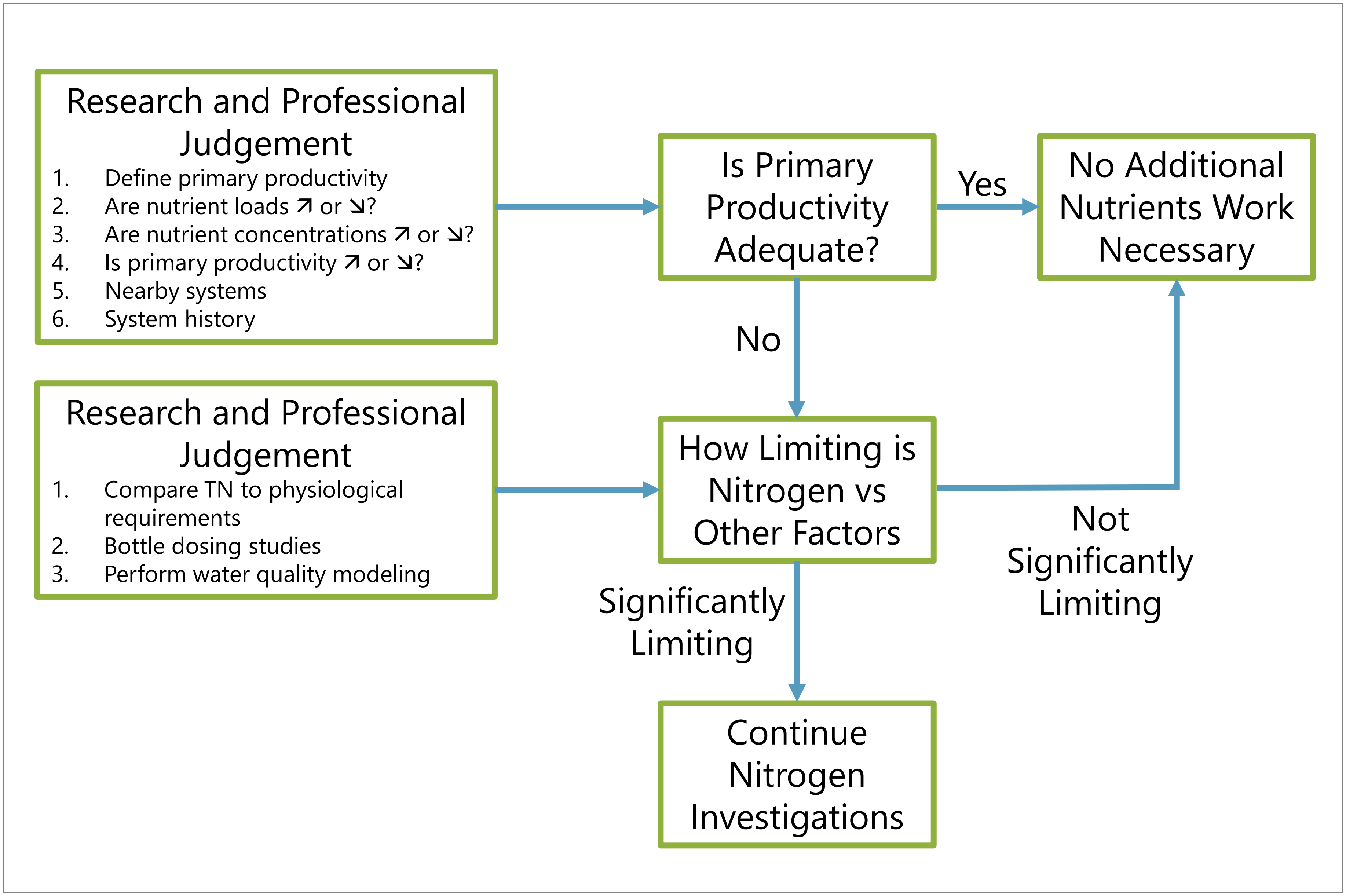


Figure 5-2
Discussion Flow Chart for Possible Future Work

Appendix A
Draft Report Comments

Texas Water Development Board

P.O. Box 13231, 1700 N. Congress Ave.
Austin, TX 78711-3231, www.twdb.texas.gov
Phone (512) 463-7847, Fax (512) 475-2053

Ms. Elaine B. Darby
Anchor QEA, LLC
901 S. Mopac Expressway
Barton Oaks Plaza V, Suite 150
Austin, Texas 78746

RE: BBASC Contract with ANCHOR QEA; Contract No. 1600012015, Draft Comments on Draft Report Entitled **"Nutrient Budget for Nueces Bay"**

Dear Ms. Darby:

Staff members of the Texas Water Development Board (TWDB) have completed a review of the draft report prepared under the above-referenced contract. ATTACHMENT 1 provides the comments resulting from this review. As stated in the TWDB contract, Anchor QEA (ANCHOR) will consider revising the final report in response to comments from the Executive Administrator and other reviewers. In addition, ANCHOR will include a copy of the Executive Administrator's draft report comments in the Final Report.

The TWDB looks forward to receiving one (1) electronic copy of the entire Final Report in Portable Document Format (PDF) and six (6) bound double-sided copies. **Please further note, that in compliance with Texas Administrative Code Chapters 206 and 213 (related to Accessibility and Usability of State Web Sites), the digital copy of the final report must comply with the requirements and standards specified in statute. For more information, visit http://www.sos.state.tx.us/tac/index.shtml.** If you have any questions on accessibility, please contact David Carter with the Contract Administration Division at 512-936-6079 or David.Carter@twdb.texas.gov.

ANCHOR shall also submit one (1) electronic copy of any computer programs or models, and, if applicable, an operations manual developed under the terms of this Contract.

Please feel free to contact Ms. Caimee Schoenbaechler of our Surface Water Resources staff at 512-463-3128 or Caimee.schoenbaechler@twdb.texas.gov if you have any questions or need any further information.

Sincerely,

Robert E. Mace, Ph.D., P.G.
Deputy Executive Administrator
Water Science and Conservation

Date: 8/4/17

Attachment

c w/o att.: Ms. Caimee Schoenbaechler, Surface Water Resources

Attachment 1
Anchor QEA
"Nutrient Budget for Nueces Bay"
Contract No. 1600012015
TWDB Comments to Draft Report

REQUIRED CHANGES

General Draft Final Report Comments:

The goal of this study was to quantify the primary components of the nutrient budget for Nueces Bay during pre-development and post-development conditions and to investigate the feasibility of a paleo-ecological approach for assessing pre-development nutrient conditions. The draft report is well-written, adequately meets the objectives identified in the scope of work, and provides stakeholders with useful recommendations for future study.

Several reviewers commented that the simplified conceptual model used in the report does not reflect the current state of knowledge regarding the complexity of transformations that occur during nitrogen cycling and regeneration. Processes such as anaerobic ammonium oxidation (anammox) as a parallel process to denitrification and dissimilatory nitrate reduction to ammonium (DNRA) should be considered. The role of organic nitrogen is becoming increasingly obvious, yet largely unaccounted for in conceptual models of nutrient cycling in Texas estuaries. Additionally, reviewers request that the authors address the spatial and temporal variability of physical-chemical parameters (e.g., salinity, temperature, dissolved oxygen, etc.), especially as related to episodic events, that drive various nutrient cycling processes and provide a discussion of how assumptions of constant rates should be interpreted.

Despite these concerns, the methodology is sufficient to make global estimates (except for some assumptions about the pre-development period) and the report conclusions are likely correct. For the authors' consideration, reviewers have provided additional references and a summary on the state of the science of nutrient cycling processes in south Texas estuaries at the end of this review.

1. Please add the following statement to the cover page of the final report:

   PURSUANT TO HOUSE BILL 1 AS APPROVED BY THE 84TH TEXAS LEGISLATURE, THIS STUDY REPORT WAS FUNDED FOR THE PURPOSE OF STUDYING ENVIRONMENTAL FLOW NEEDS FOR TEXAS RIVERS AND ESTUARIES AS PART OF THE ADAPTIVE MANAGEMENT PHASE OF THE SENATE BILL 3 PROCESS FOR ENVIRONMENTAL FLOWS ESTABLISHED BY THE 80TH TEXAS LEGISLATURE. THE VIEWS AND CONCLUSIONS EXPRESSED HEREIN ARE THOSE OF THE AUTHOR(S) AND DO NOT NECESSARILY REFLECT THE VIEWS OF THE TEXAS WATER DEVELOPMENT BOARD.

2. Please add the TWDB Contract #1600012015 to the front cover of the report.

3. Please convert the units of volume, weight, and mass used in the report to a consistent standard, or consolidate the number of units used for uniformity. Consider replacing usage of cubic feet per second with acre-feet per time unit, which is commonly used for quantifying inflow volumes to estuaries. The usage of other large volume units, such as millions of gallons, can also be converted to acre-feet to create uniformity in the report. For small volumes, please also convert to a consistent standard such as milligrams per liter.

Specific Draft Final Report Comments:

1. Page 2, Section 1.3, last sentence: The statement, *"Combined, these reservoirs help to provide a reliable water supply for human uses, but they also increase evaporative losses and decrease the frequency of high flow pulses."* is an observation that is not substantiated with an appropriate citation. Please remove the statement or provide a backing citation(s).

2. Page 4, Section 2.1, first paragraph, last sentence: Please include reference citation(s) for the following sentence, or remove it (the latter would be reasonable because the evidence is discussed on the next page in the report): *"Many lines of evidence suggest that Nueces Bay is predominantly N limited on yearly time scales."*

3. Page 7, Section 3.1: The "change in load" comparison between Three Rivers and Mathis is unclear. Please provide additional clarification and specify if the "difference in load" is meant rather than "change in load."

4. Page 8, Section 3.1, foot notes 7 and 8: Please define *"year of geometric average flow."*

5. Page 8, Section 3.2, first paragraph: Please clarify that sub-watershed #22013 drains to the Corpus Christi Ship Channel and thus was excluded from the calculations of watersheds draining into Nueces Bay.

6. Page 9, Section 3.2, second paragraph: Please add the statement, *"TxRR simulated runoff for ungauged watersheds is also used as a component in the coastal hydrology dataset that TWDB maintains."* Also, please provide more details on land use categories and their associated median TN values in the three sub-watersheds studied. Provide a brief description of what land use categories have a higher/lower TN.

7. Page 9, Section 3.2, third paragraph, last sentence: Please clarify the following statement "As shown in Table 3-1, the decline in TN loading from pre- to post-development is mainly due to the decline in flow from the watershed between Mathis and Calallen Dam" to reflect the fact that the decline is *solely* due to the

decline in flow given that the same TN concentration was used for both pre- and post-development in this study. As related to the data in Table 3-1, please consider that one would expect land use (and hence TN) to change between pre- and post-development periods, so the use of a common TN value (which is determined from land use data) for both periods could be an unlikely assumption. Additionally, please clarify how the TN load is calculated in Table 3-1 or make an appropriate correction, as the TN load reported in Table 3-1 can't be replicated by multiplying 'Average Flow' by the 'TN concentration.'

8. Pages 12 – 13, Sections 3.4 and 3.5: Please provide additional documentation (other than personal communication) for how diversion and return flow rates were derived. The methodologies described in TWDB technical notes can be referenced (TWDB 2011a and 2011b).

9. Page 13, Section 3.6: Please carefully consider and provide an expanded discussion of the assumption that wet and dry deposition of N is the same in the pre- and post-development periods. For example, consider that all forms of bioreactive N have increased over time, particularly with increased fertilizer use. National estimates may be available in the Millennium Ecosystem Assessment reports, or in EPA and TCEQ data sets. On a related note, please also carefully consider the interpretation of concentration trends over time (as in section 3.9.2) because the flux is quantified as concentration multiplied by flows minus losses in the system. Thus, one can still have lower concentrations of N in the pre-development period but the higher flows loaded more than in the post-development period.

10. Page 15, Section 3.8, second paragraph: Please cite a reference to the TWDB groundwater database.

11. Page 16, Section 3.8, fourth paragraph: Please provide additional details of the studies conducted by Dorina Murgulet (at TAMUCC) or omit this paragraph.

12. Page 18, Section 3.9.1: First paragraph, second sentence: Please provide a brief description of the "revised version of the Alternate Hydrology dataset." Also, please modify the statement to, "The TxBLEND simulation was driven by inputs from a revised version of the Alternate Hydrology dataset." Or, "A revised version of the Alternate Hydrology dataset (TWDB 2011b) was used as an input to drive the TxBLEND simulation."

13. Page 18, Section 3.9.1: Please describe how the positive and negative flow volumes were calculated and clarify that those volumes were not a direct output from the TxBLEND model. Water surface elevation at several Nueces Bay grid points was used to calculate hourly differentials in the total volume of Nueces Bay, which was in turn used to calculate the positive and negative flow volumes.

14. Page 18, Section 3.9.1: Please define what "positive and negative flow volumes" means in terms of in/out of Nueces Bay and describe the tidal exchange cross section (or by referencing Figure 2-1). Adding a "+" and "–" to the tidal exchange arrows in Figure 2-1 and referencing the figure in this section will suffice.

15. Page 18, Section 3.9.1: Please provide additional clarification describing why half of the inflows were subtracted from the positive and negative flow volumes. For example: "...to isolate the tidal exchange process from all other sources/sinks..."

16. Page 18, Section 3.9.1: Please consider providing a quantitative description of V_{nb}, Q_i, Q_o, and R with common units to give an idea of the magnitude of each value and how they compare to each other.

17. Page 19, Section 3.9.1, last paragraph: a) Please add "for the Nueces Bay" after the first sentence that ends with "prior to 1987" and b) Please provide a justification or citation for the statement *"The entrainment rate is unlikely to have changed meaningfully over time."* Also, please define *"meaningfully"* as used in this statement.

18. Page 20, Section 3.9.2: To estimate pre-development organic N, the study uses a ratio of NH_3:organic N from existing data. However, the footnote (#19), indicates that the ratio was not used when NH_4 was below detection limits. Please provide a discussion on the fraction of the NH_3 values out of the entire dataset that were below detection limits. If those values constitute a large fraction of samples (>5-10% of samples), please discuss the implications or potential bias for the estimates of organic N.

19. Page 25, Section 3.12, last paragraph: Please make the correction in the following sentence, "The totals on Table 3-1..." to refer to Table 3-10.

20. Page 34, Section 5.1, first paragraph: Please clarify whether a paleo-proxy approach will provide actual nutrient concentrations that can be used to constrain pre-development load estimates, in regards to the statement that "... a paleoecological reconstruction may provide a reasonable picture of historical nutrient and ecological conditions..."

Figures and Tables Comments:

1. All Figures: Please adopt a standardized, consistent format for the report figures by ensuring that figure titles, captions, and references have similar fonts, font size, and location. For example, the references for Figure 3-4, 4-1, and 4-3 differ in format: "Source: Matsumoto 2017" (font size 14), "(Images and interpretation from Hill et al. 2014)" (font size 12), and "Source: Cooper et al. 2004" (font size 12) respectively. Additionally, please remove file paths and internal documentation from the images for the final report. The clarity of the map figures

could be improved by using a transparency setting on the base maps and using larger symbols and font sizes for features being displayed.

2. Figure 3-6: Per the Contract Exhibit D, please include this figure at a higher resolution if possible. The TWDB author guidelines request graphics be included at a resolution of 300 dots per inch (dpi) or greater.

3. Figure 4-3: Per the Contract Exhibit D, please include this figure at a higher resolution if possible.

SUGGESTED CHANGES

Specific Draft Final Report Comments:

1. Please consider adding an abstract to the report, including a description of the motivation for the study (i.e., questions or hypotheses), findings, and significance of findings.

2. Consider including a graphic, or supplementary aid, to visualize unit quantities used in the report to aid in the understanding of the amounts of an acre-foot of water, million gallons of water, million pounds of N, or 1 mg of N in a liter. Also, see general comment #4.

3. Section 2 and 3: Please consider adding discussion or acknowledgement of anaerobic ammonium oxidation (Anammox) processes (NH_4 + NO_2 transformed to N_2) as a parallel process to denitrification (NO2 transformed to N2) and dissimilatory nitrate reduction to ammonium (DNRA; NO_3 reduction to NH_4) processes in the conceptual model and equations.

4. Page 2, Section 1.4: Please consider that this study does not "...provide information and guidance to the BBASC to better understand how nutrients impact the ecological health of Nueces Bay..." This would require additional field, experimental, and modeling studies on phytoplankton, macroalgal, and/or seagrass response to nutrient inputs. Please consider rewriting this to more accurately reflect what was done in the study.

5. Page 4, Section 2.1, last sentence: In regards to the following sentence, please consider that since the water is moving so slowly, low N could also mean it is taken up more rapidly than P. *"While these results do not confirm that Nueces Bay is also limited by N, they do suggest that water flowing from the bayou into Nueces Bay is low in N relative to P."*

6. Page 5, Section 2.2: Consider that dissolved organic nitrogen (DON) and particulate organic nitrogen (PON) are implicitly identified as sources of "macro-detritus." Although macro-detritus data was not available, it is not uncommon to

use other data (e.g., TOC, TN, POC/PN) as a proxy. The algal component of the particulate matter can be estimated, thus allowing for separation of the detrital fraction. TCEQ's Surface Water Quality Monitoring (SWQM) data has TOC data from the Nueces River and Bay. Please also consider the following sources of information related to macro-detritus: Terry Whitledge (1989) made many measurements in the late 1980's for the TWDB (i.e., Nitrogen Processes Study), also summarized in Longley et al. 1994. Recently, Bhanu Paudel published a dissertation and other papers on this topic as well (Paudel, 2014; Paudel and Montagna, 2014; Paudel et al., 2017), and Dr. Michael Wetz is another source to consult regarding of this kind of data. Ona related note, Dr. Evan Turner also published a dissertation on modeling nutrient dynamics in Texas estuaries (Turner, 2014; Turner et al., 2014).

7. Page 7, Section 3: Please consider acknowledging additional sources of nutrients, such as from sediment porewater flux (i.e., not deeper groundwater), algal exudation of DON, fish excretion and/or movement of nekton biomass into and out of Nueces Bay.

8. Pages 7-8, Section 3.1, second paragraph: Please consider adding an explanation that Lake Corpus Christi is located between the Three Rivers and Mathis gauges.

9. Page 8, Section 3.1: Please consider comparing the estimated TN concentrations to SWQM data to increase confidence levels in the estimates provided in this study. Please also discuss the notion that the TN concentration at the Mathis Nueces River site, which was higher in the post-development period and lower in the pre-development period, contrasts with what is known about the effects of development on waterbody nutrient concentrations.

10. Page 10, Section 3.3: Please consider contacting the Portland Waste Water Treatment Plant operators for access to data, as they may be required to sample N in their discharge.

11. Page 19, Section 3.9.1, second paragraph: Please consider describing the 'best fit' rate in the body of the manuscript in equation form.

12. Page 19, Section 3.9.2: The exchange between Nueces and Corpus Christi Bay assumes that tides are the dominant influence. Please discuss whether winds were accounted for. Consider mentioning that wind is an input driving the TXBLEND model simulations. Also, please consider that NO_x usually refers to nitrous oxides in gaseous form in the atmosphere, and Nitrite + Nitrate is usually referred to as NO_{2+3} or NO_{23}.

13. Page 23, Section 3.10: Please carefully consider the implications of using a common denitrification value, as Gardner et al. 2006 demonstrated that sediments can vary between being a source or sink of N depending on the balance between dissimilatory nitrate reduction to ammonium (DNRA) and

denitrification. Also, please consider revising Section 3.10 to give a more in-depth account of the many ways N_2 is formed.

14. Page 26, Section 3.12.1.1: Please consider that denitrification and nitrogen cycling in general seems to vary according to the availability of N and environmental conditions. As noted above, DNRA should be mentioned because Gardner et al. (2006) has shown it to be high at times and as such, nitrate would be kept in the pool of available N.

15. Page 27, Section 3.12.1.3: Please consider and mention in this section that wind forcing can often dominate over tidal forcing.

16. Pages 33-34, Sections 5.1, 5.2: Please consider that the limited availability of riverine TN data that is used to estimate TN loadings (although USGS is addressing this), as well as limited nitrogen fixation and denitrification rate measurements (including direction of net sediment fluxes), among others, imposes significant error bars on the nitrogen budget in this study. In addition, this study as well as proposed paleo-ecological studies will not provide a much-needed understanding of how nutrients affect the ecological health of Nueces Bay in *modern* conditions. Given these constraints, it could be reasonably argued that the paleo-ecological approach should be given low priority compared to future studies that address these other needs (such as studies advocated in bullet 4 on page 35).

17. Page 36, Section 5.2.5: Please consider an expanded description of the history, goals, objectives, and outcomes of the demonstration project for those readers who may not be as familiar with the project.

Figures and Tables Comments:

1. Please consider embedding the figures within the text rather than forcing the reader to flip back and forth between the text and figures.

2. Page 25, Table 3-10: Please consider adding a third column showing the difference between pre- and post-development TN load.

3. Figure 3-4: Please consider placing the citation such that the white text-box is not overlaid onto the image (i.e. see the general comment about figure citation and formatting).

4. Figure 3-5: Please consider including descriptive figure captions for this figure and/or subfigures.

5. Figure 5-1: Please consider increasing the font size of the figure annotations and arrows. Consider increasing the resolution of the base map to remove what appears to be image artifacts. Additionally, it may be helpful to highlight those

sources/sinks that have changed since pre-development versus those that are constant.

OTHER SUGGESTED CONSIDERATIONS:

Please consider the information provided in the expert summary below on the state of the science regarding nutrient cycling in south Texas estuaries. Additional references are also listed.

Background statement

It appears that excellent progress has been made on this report. Reviewers appreciate the consideration of biogeochemical process rates and believe that they, and the meteorological factors controlling them, are undoubtedly among the most dominant factors controlling the dynamics of nutrient budgets in the region. Reviewers list various sources of data (see references below; contact TWDB for acquisition) for the Nueces Estuary and related systems that may add to the authors' current data sources. In general, shallow, warm eutrophic systems worldwide are dominated by internal cycling processes (see Gardner et al. 2017 and King et al. 2017 for information and conceptual model for systems that support harmful algal blooms). Similar things occur in estuarine systems except that DNRA becomes a very important source of ammonium under some conditions) and can affect biogeochemical dynamics dramatically. For example, Gardner's back-of-the envelop cycling rates for the Nueces Estuary exceed the riverine input rates as a source for microbial populations by about five to one (unpublished comparison). Depending on meteorological or other environmental conditions, internal recycling becomes the dominant process in most south Texas estuaries (represented by the National Estuarine Research Reserve [NERR] site), especially during low flow, as Bruesewitz et al. (2013, 2015) discusses from different perspectives in recent NERR papers.

Why can we not get accurate estimations of nutrient dynamics from NH4+ and organic matter concentrations?

Reviewers believe that one reason for this is because the nitrogen and labile organic material are recycled so rapidly that one cannot measure them except by measuring rates (Gardner et al. 2017). Specifically, they are taken up as rapidly as they are produced, and the amounts measured simply represent the instantaneous difference between the two processes at the time they are measured and are ***much lower*** on average than the amounts recycled. Therefore, the data from the different sources are so scattered, even though averages often agree with each other within an order of magnitude or so, as the authors have mentioned. Most of the measured "**organic matter content**" is the amount that is left over rather than the amount of "**labile organic matter**" produced by photosynthesis. Much of the N-containing labile organic matter is removed very rapidly (within hours) by animal and microbial consumption after it is produced (Gardner et al. 2017; i.e., "If someone can eat it, it will not be there," as once mentioned by David Menzel). Although simplified here, reviewers believe that these concepts are critical but very difficult for most readers (including scientists) to understand unless put in terms of a concept like Biological

Oxygen Demand (BOD) regarding carbon removal via respiration. That is why reviewers emphasize the concept of Biological Community Ammonium Demand (CBAD) as applied to ammonium dynamics in the conceptual model (Gardner et al. 2017).

Importance of presence or absence of episodic events

Unfortunately, rates of the different processes are also difficult to estimate in south Texas models unless one evaluates the effects of episodic events, which are extensive in the region (as shown by Paul Montagna and colleagues). Unraveling these issues is helped by the Bruesewitz papers, which were funded by Dr. Ed Buskey's EPA-GOMA proposal of a few years back. Also, the effort to examine process rates as related to other factors in the NERR system is actively continuing with Amber Hardison, Jim McClelland, Zhanfei Liu and other colleagues from TAMU-CC.

Dissimilatory nitrate reduction to ammonium (DNRA)

Reviewers believe that DNRA is a critical factor in south Texas systems. For example, it may be a major factor in maintaining Brown Tide in Texas estuaries, as they depend on reduced N (ammonium or possibly organic N) but do not respond to oxidized forms as an N source (Hudson Deyoe results). Unfortunately, reviewers were not funded to investigate that specific question several years ago. $^{15}NH_4^+$ was regenerated rapidly from added 15N nitrate (i.e. DNRA evidence) in previous studies of Texas salt marshes in papers by Lee and Dunton (contact Dunton for literature). Large amounts of N were regenerated as ammonium by DNRA, especially under warm eutrophic saline systems (see An and McCarthy papers for south Texas, in addition to Gardner 2006, and Florida Bay results based on a hypothesis developed from work in south Texas (Gardner and McCarthy 2009). Reviewers do have a large additional data set including DNRA for south Texas estuaries for a study that the National Science Foundation supported a few years ago, but reviewers have not yet found time yet to interpret the data for publication, except for as included in Fennel et al. 2008. However, the reviewers can easily supply raw data to anyone interested.

Reference list to consider:

An, S., & Gardner, W. S. (2002). Dissimilatory nitrate reduction to ammonium (DNRA) as a nitrogen link, versus denitrification as a sink in a shallow estuary (Laguna Madre/Baffin Bay, Texas). Marine Ecology Progress Series, 237, 41-50.

An, S., Gardner, W. S., & Kana, T. (2001). Simultaneous measurement of denitrification and nitrogen fixation using isotope pairing with membrane inlet mass spectrometry analysis. *Applied and environmental microbiology*, *67*(3), 1171-1178.

Bruesewitz, D. A., Gardner, W. S., Mooney, R. F., & Buskey, E. J. (2015). Seasonal Water Column NH4+ Cycling Along a Semi-Arid Sub-Tropical River–Estuary Continuum: Responses to Episodic Events and Drought Conditions. *Ecosystems*, *18*(5), 792-812.

Bruesewitz, D. A., Gardner, W. S., Mooney, R. F., Pollard, L., & Buskey, E. J. (2013). Estuarine ecosystem function response to flood and drought in a shallow, semiarid estuary: Nitrogen cycling and ecosystem metabolism. *Limnology and Oceanography*, *58*(6), 2293-2309.

Fennel, K., Brady, D., DiToro, D., Fulweiler, R. W., Gardner, W. S., Giblin, A., ... & Tobias, C. (2009). Modeling denitrification in aquatic sediments. *Biogeochemistry, 93*(1-2), 159-178.

Gardner, W.S., Newell, S.E., McCarthy, M.J., Hoffman, D.K., Lu, K., Lavrentyev, P.J., Hellweger, F.L., Wilhelm, S.W., Liu, Z., Bruesewitz, D.A. and Paerl, H.W. (2017). Community Biological Ammonium Demand (CBAD): A Conceptual Model for Cyanobacteria Blooms in Eutrophic Lakes. *Environmental Science & Technology.*

Gardner, W. S., Newell, S. E., McCarthy, M. J., Hoffman, D. K., Lu, K., Lavrentyev, P. J., ... & Paerl, H. W. (2017). Community Biological Ammonium Demand (CBAD): A Conceptual Model for Cyanobacteria Blooms in Eutrophic Lakes. *Environmental Science & Technology.*

Gardner, W. S., & McCarthy, M. J. (2009). Nitrogen dynamics at the sediment–water interface in shallow, sub-tropical Florida Bay: why denitrification efficiency may decrease with increased eutrophication. *Biogeochemistry, 95*(2-3), 185-198.

Gardner, W. S., McCarthy, M. J., An, S., Sobolev, D., Sell, K. S., & Brock, D. (2006). Nitrogen fixation and dissimilatory nitrate reduction to ammonium (DNRA) support nitrogen dynamics in Texas estuaries. *Limnology and Oceanography, 51*(1part2), 558-568.

King, M.D., Bryant, R.B., Saporito, L.S., Buda, A.R., Allen, A.L., Hughes, L.A., Hashem, F.M., Kleinman, P.J. and May, E.B. (2017). Urea Release by Intermittently Saturated Sediments from a Coastal Agricultural Landscape. *Journal of Environmental Quality, 46*(2), pp.302-310.

Longley, W. L. (1994). *Freshwater inflows to Texas bays and estuaries: ecological relationships and methods for determination of needs*. Texas Water Development Board and Texas Parks and Wildlife Department.

McCarthy, M. J., Gardner, W. S., Lavrentyev, P. J., Jochem, F. J., & Williams, C. J. (2009). Water column nitrogen cycling and microbial plankton in Florida Bay. *Contributions in Marine Science, 38*, 49-62.

McCarthy, M. J., McNeal, K. S., Morse, J. W., & Gardner, W. S. (2008). Bottom-water hypoxia effects on sediment–water interface nitrogen transformations in a seasonally hypoxic, shallow bay (Corpus Christi Bay, TX, USA). *Estuaries and Coasts, 31*(3), 521-531.

Paudel, B., Montagna, P. A., Besonen, M., & Adams, L. (2017). Inorganic nitrogen release from sediment slurry of riverine and estuarine ecosystems located at different river regimes. *Marine and Freshwater Research, 68*(7), 1282-1291.

Paudel, B. (2014). *Interactions Between Suspended Sediments, Nutrients and Freshwater Inflow in Texas Estuaries* (Doctoral dissertation Texas A&M University-Corpus Christi).

Paudel, B., & Montagna, P. A. (2014). Modeling inorganic nutrient distributions among hydrologic gradients using multivariate approaches. *Ecological informatics, 24*, 35-46.

Scott, J. T., McCarthy, M. J., Gardner, W. S., & Doyle, R. D. (2008). Denitrification, dissimilatory nitrate reduction to ammonium, and nitrogen fixation along a nitrate concentration gradient in a created freshwater wetland. *Biogeochemistry, 87*(1), 99-111.

Turner, E. L. (2014). *Modeling nutrient dynamics in coastal lagoons* (Doctoral dissertation, Texas A&M University-Corpus Christi).

Turner, E. L., Bruesewitz, D. A., Mooney, R. F., Montagna, P. A., McClelland, J. W., Sadovski, A., & Buskey, E. J. (2014). Comparing performance of five nutrient phytoplankton zooplankton (NPZ) models in coastal lagoons. *Ecological modelling, 277*, 13-26.).

Whitledge, T. E. (1989). *Data Synthesis and Analysis Nitrogen Processes Study (NIPS) Nutrient Distributions and Dynamics in Lavaca, San Antonio and Nueces/Corpus Christi Bays in Relation to Freshwater Inflow Part I: Results and Discussion.* TR/89-007. University of Texas, Port Aransas.