Texas Water Resources Institute
Annual Technical Report
FY 2006

Introduction

The Texas Water Resources Institute (TWRI), a unit of the Texas Agricultural Experiment Station and Texas Cooperative Extension, and member of the National Institutes for Water Resources, provides leadership in working to stimulate priority research and Extension educational programs in water resources.

TWRI thrives on collaborations and partnerships currently managing more than 70 projects, involving more than 125 faculty members from across the state and collaborates with more than 100 faculty members from other universities and research institutions. In fiscal year 2006, the TWRI obtained more than $10.2 million in funding.

The institute maintains joint or collaborative projects with 15 Texas universities and 3 in other states; 11 federal agencies; 5 state agencies; 6 consulting engineering firms; 30 water districts; 6 river authorities; 5 water utility providers; several commodity and environmental organizations; and others.

TWRI works closely with agencies and stakeholders to provide research-derived, science-based information to help answer diverse water questions and also to produce communications to convey critical information and to gain visibility for its cooperative programs.

Research Program

The Texas Water Resources Institute (TWRI) funded 10 research projects for 2006-07 conducted by graduate students and researchers at Texas A&M University (7 projects), Texas Tech University (1), West Texas A&M University (1), and the University of Texas at Austin (1).

David Barre, of Texas A&M University Rangeland Ecology and Management Department, evaluated the effects of clearing brush on deep drainage of soil chloride.

Yongxia Cai in the department of agricultural economics at Texas A&M University studied the impacts of interbasin transfers in Texas.

In the department of range, wildlife and fisheries at Texas Tech University, Bassil El-Masri estimated water quality parameters for Lake Kemp using remotely sensed data.

Texas A&M University graduate student in the department of Civil Engineering, Mohammad Islam, developed an observation and assessment system for the coastal margin of Corpus Christi Bay to monitor water quality.

Andrew Karvonen, an architectural graduate student at University of Texas in Austin, conducted a socio-technical case study of sustainable stormwater management for the city of Austin, Texas.

Texas A&M University graduate student, Megan Meier, evaluated urban streams in Central Texas following restoration.

Awra Rabie, Texas A&M University student in the Chemical Engineering Department, evaluated the management and optimization of the use and discharge of water in industrial facilities.

Debabrata Sahoo, a student in the Biological and Agricultural Engineering Department at Texas A&M University, modeled the effect of urbanization and optimized land use for environmental flows in estuaries.

West Texas A&M University Student, Robert Taylor, conducted a pricing model to assess the effects of groundwater availability on land valuation.

A Texas A&M University Student in the Civil Engineering Department, Dongsuk Han, evaluated arsenic removal by novel nanoporous adsorbents.

Bridging the Gap Between Plankton Dynamics and Spatial Variability in Water Quality in the Guadalupe Estuary (Texas): The Importance of Freshwater Pulses

Basic Information

Title:	Bridging the Gap Between Plankton Dynamics and Spatial Variability in Water Quality in the Guadalupe Estuary (Texas): The Importance of Freshwater Pulses
Project Number:	2003TX112G
Start Date:	9/1/2003
End Date:	8/31/2006
Funding Source:	104G
Congressional District:	8
Research Category:	None
Focus Category:	Ecology, Water Quality, Water Quantity
Descriptors:	None
Principal Investigators:	Stephen Edward Davis, Daniel L. Roelke

Publication

1. Davis, S.E.. Understanding the importance of pulsed events in Gulf Coast estuaries. April 20, 2005 Marine Biology Departmental Seminar at Texas A&M University at Galveston, Galveston, TX.
2. Roelke, D.L. 2006. Large-scale disturbances and the predictability of complex aquatic ecosystems. US EPA, Western Ecology Division, Corvallis, Oregon. March 22.
3. Roelke, D.L. 2005. Regional species richness and supersaturation: The role of migration and disturbance of chaotic communities. University of Oklahoma Seminar Series, OK, USA. October 12.
4. Roelke, D.L. 2005. Water issues and research needs in Texas. Brazos Chapter, Texas Master Naturalists, Bryan, TX, USA. November 3.
5. Davis, S., D. Roelke, G. Gable, H-P. Li, C. Miller. 2005. Physical, chemical, and biological responses to inflow events in Galveston and San Antonio Bays (TX): Bay-wide characterizations. Estuarine Research Federation. Norfolk, VA, USA. October 16-21.
6. Davis, S.E., D. Roelke, J. Pinckney. 2005. Use of high resolution spatial mapping to estimate plankton response to freshwater inflows entering Galveston Bay: Importance of watershed development and ecosystem health. Galveston Bay Estuarine Program meeting. Houston, TX. November 15.
7. Davis, S.E., D. Roelke, D. Slack. 2005. Physical, Chemical, and Biological Responses to Inflow Events in the San Antonio Bay System. Environmental Flows Conference, Texas State University, San Marcos, TX. Oct 31 - Nov 1.
8. Davis, S.E., D. Roelke, et al. Determining the importance of freshwater inflows to ecological structure and function in the bays and marshes of the Guadalupe Estuary (TX). April 1, 2005 at the Gulf Estuarine Research Society Meeting, Pensacola, FL.
9. Gable, G., D. Roelke, S. Davis, H-P. Li., K.-J. Liu, C. Miller. 2006. Spatial and Temporal Trends in Physiochemical Water Parameters, Productivity, and Planktonic Community in Mesquite Bay, Texas: Preliminary Data. TAMU, Student Research Week, College Station, TX, USA. April 1.
10. Li, H.-P., D.L. Roelke, S. Davis, C. Miller, G. Gable, J.V. Montoya, L. Romero. 2005. Biological response during a wet year in San Antonio Bay, TX: Fixed station data. TX Sea Grant Researcher Conference. College Station, TX. October 5.
11. Li, H.-P., D. Roelke, S. Davis, C. Miller, G. Gable, K.-J. Liu, J. V. Montoya, L. Romero. 2006. Freshwater inflow affect in San Antonio Bay, Texas: Preliminary Data. Environmental Protection Agency, Bandera, TX, USA. April 12-14.
12. Miller, C.M., D.L. Roelke, S.E. Davis. 2005. Hydrologic connectivity of saltwater ponds adjacent to Sundown Bay, Aransas National Wildlife Refuge, TX. TAMU Student Research Symposium, Texas A&M University. College Station, TX. April 23.
13. Roelke, D., S. Davis, H-P. Li, C. Miller, G. Gable, J.V. Montoya, L. Romero. 2005. Biological response during a wet year in San Antonio Bay, TX: Fixed station data. Estuarine Research Federation. Norfolk, VA, USA. October 16-21.

Bridging the Gap Between Plankton Dynamics and Spatial Variability in Water Quality in the GuadalupeEstuary (Texas): *The Importance of Freshwater Pulses*

Project Number
2003TX112G

Final Report
September 1, 2003 through August 31, 2006

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Effective Date: June 6, 2007

Project Overview

As decisions regarding freshwater diversions to meet human needs are made, an understanding of the downstream ecological effects is needed. In fact, the primary challenge for water resource managers in coastal states like Texas is to determine how to meet human demands for freshwater, yet maintain critical inflows of freshwater to our nation's estuaries. Therefore, as part of the LGWSP, GBRA, SARA, and SAWS are supporting ongoing ecological and statistical studies of the Guadalupe Estuary by scientists from Texas A&M University and the University of Texas. These studies aim to promote an understanding of the impact of a reduction in freshwater inputs from the Guadalupe River on the marsh ecosystem along the Blackjack Peninsula and commercially important species in the bays (Figure 1).

Section 11.147 (a) of the Texas Water Code defines "beneficial inflows" as those that provide a "salinity, nutrient, and sediment loading regime adequate to maintain an ecologically sound environment in the receiving bay and estuary system that is necessary for the maintenance of productivity of economically important and ecologically characteristic sport or commercial fish and shellfish species and estuarine life upon which such fish and shellfish are dependent." Pulich *et al.* (1998) reported freshwater inflow recommendations for the Guadalupe Estuary based on Texas Estuarine Mathematical Programming (TXEMP) and recommended 1.15 million acre-ft/yr as the "Maximum Harvest (MaxH) target value to fulfill the biological needs of the Guadalupe Estuary System on a seasonal basis." In particular, Pulich *et al*. (1998) found that densities of key harvested species, including both finfish and shellfish, were positively related to inflows that would produce maximum salinity areas of the bay between 5‰ and 20‰. Critical conditions for estuarine health are related to inflows during the wetter months of May and June. Low values of inflows during the drier months (e.g. August) are typical and can be tolerated if adequate inflows occur in earlier months (Pulich *et al*. 1998).

This was a three-year study centered on the San Antonio Bay Estuary (Figure 1) that sought to characterize and map water quality and quantify water column productivity across the entire estuary during different inflow conditions a minimum of 12 times per year (i.e. monthly). Our study also sought to provide a continuous record of materials loading into the bay from the Guadalupe River. This work and all sample analyses have been conducted at Texas A&M University. The synthesis of information collected from this study and concurrent studies in the Galveston Bay Estuary (by Davis and Roelke) will help to provide a more comprehensive understanding of the relationships between the nature (i.e. frequency, magnitude, and mode) of pulsed inflow events and estuarine ecosystem health along the Texas Gulf Coast, thus allowing state water managers to optimize diversions of freshwater (for municipal, agricultural, and industrial uses) while minimizing impact to estuarine ecosystem health. Our results showed strong relationships between nutrient concentrations and location along the estuarine gradient. We also found clear correlations among river inflow and CDOM—an indication of a river source of organic matter possibly fueling net ecosystem production in the upper estuary.

Project objectives, tasks, and schedule of deliverables are described as follows:

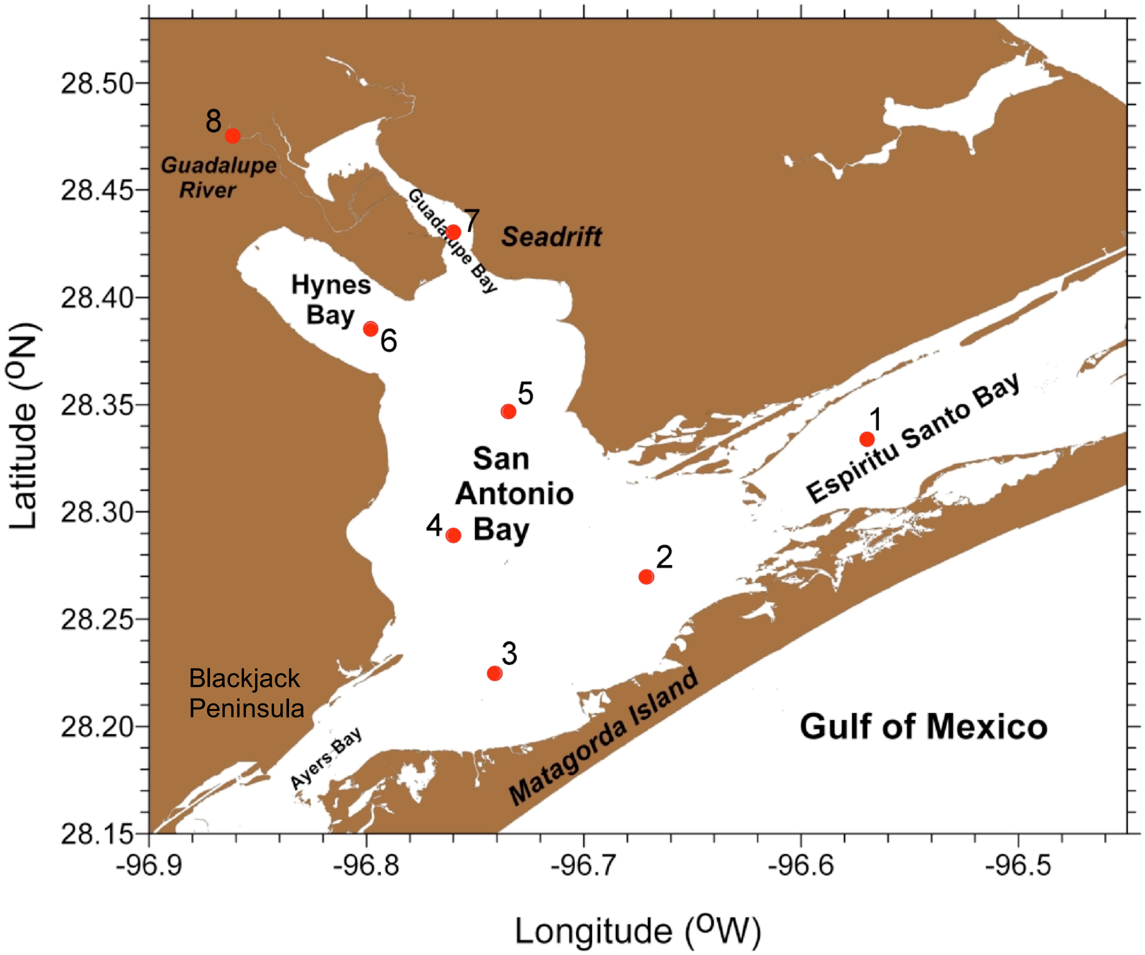

Figure 1: Map of San Antonio Bay/Guadalupe River Estuary and identification of fixed sampling stations.

<u>Objective</u>**:** To collect data on nutrient loading into the San Antonio Bay (i.e., Guadalupe River) Estuary from Guadalupe River and conduct monthly samplings for bay-wide water quality mapping, water column productivity, and plankton community composition.

Task 1	Establish refrigerated water sampler at USGS gauge at Tivoli, TX along the lower Guadalupe River. Run sampling program that will collect tri-daily, composite water samples. These samples will be retrieved every two weeks, processed, and taken to the laboratory for nutrient analyses.
Task 2	Conduct monthly Dataflow runs and measurements of water quality and water column productivity at fixed stations along estuarine salinity axis.
Task 3	Acquire daily flow and stage data from USGS gauge at Tivoli, TX along the lower Guadalupe River and hourly water level and meteorological data from TCOON stations across the estuary.

<u>Progress Report on Program Element 1:</u> The timeline deviated from our original plan as a result of logistical problems encountered with sampling equipment. We finally achieved a successful sampling program along the lower Guadalupe River (Station 8; Figure 1) beginning in late 2005. The site is located near Tivoli, TX and is stationed at the Guadalupe-Blanco River Authority's (GBRA) saltwater barrier site—less than 15 miles from the river's outflow point into Guadalupe Bay (Figure 1). Although there is a USGS gage at the Tivoli, TX site, it only provides reliable measures of gage height (i.e., stage). Discharge values above about 3000 cfs at this site result in over-bank flooding. Since values above this threshold are quite common, we used a combination of discharge values from the San Antonio River (at Goliad, TX), Guadalupe River (at Victoria, TX) and Coleto Creek (near Victoria, TX) to estimate discharge into the estuary. Resource managers at GBRA estimate that this estimate represents approximately 70% of channelized flow into the estuary (Tommy Hill, GBRA personal communication).

With the assistance of staff from GBRA, we installed a refrigerated automated sampler at this site as part of this project. The sampler is programmable and requires a continuous supply of AC electricity. This power was provided by GBRA at no cost to the project and the sampler was secured to anchors set into the concrete bridge at this site. Typically, we programmed the sampler to collect composited samples over a 3-day period of time. The sampling and analysis of nutrients on those samples has continued since the conclusion of this project. In this report, we cover all samples analyzed through August 2006 (Figure 2). However, this Guadalupe River sampling site will continue to operate beyond this project, as long as funds can be secured to maintain its operation. We ran into several equipment-related problems along the way the resulted in several large gaps in the data set. The problems were related to defects in the water detection system in the sampler. Although the problems were corrected at no charge to the project, many of the problems took weeks to months to correct.

Guadalupe River sample data from this period indicates positive correlation between flow magnitude and concentration for most all parameters measured (Figure 2). We saw record inflows prior to the beginning of our field data collection (in late 2004) and most constituents were declining towards the end of this massive pulse. However, smaller, but significant pulses later in the study resulted in noticeable increases in concentrations of most nutrients—especially nitrogen and TSS. DOC and TSS concentrations are reflective of particulate and organic matter loadings to the estuary and often increase under high flows. Concentrations of TN and TP are oftentimes associated with these organic and inorganic constituents and show similar patterns relative to flow magnitude. In terms of dissolved inorganic nitrogen and phosphorus, phosphate, ammonium, and nitrate + nitrite were sensitive to flow magnitude in the Guadalupe River (see fixed station nutrients in appendix). However, a longer, continuous record is needed in order to understand the seasonal dynamics as well as response to flow conditions exhibited by these water column constituents.

We conducted nineteen, monthly Dataflow samplings as a result of USGS/NIWR project funding (**Table 1**). Due to equipment problems, we did not start Dataflow sampling till January 2005. During each of these samplings, we stopped at all fixed stations to collect water samples for nutrient analysis, TSS, HPLC pigments, and chlorophyll *a*. We also conducted light/dark bottle incubations for measurements of water column productivity.

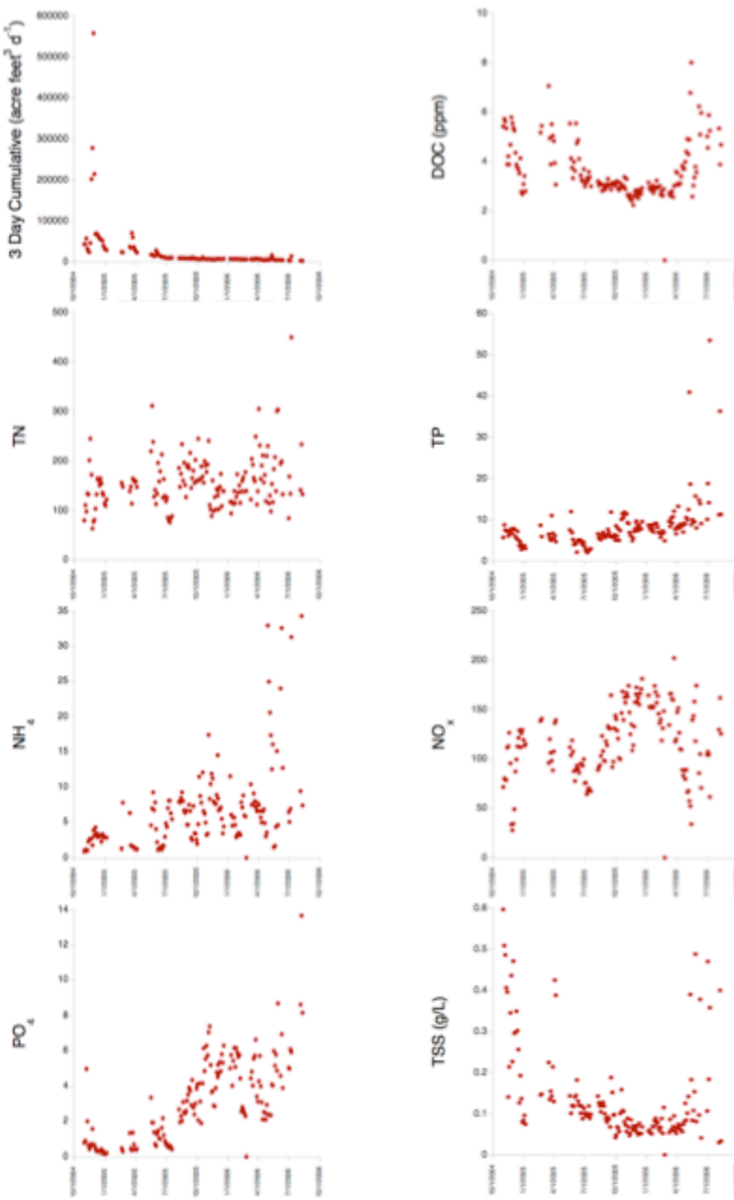

Figure 2: Combined river discharge estimate (upper left) and constituent concentrations (µM unless indicated otherwise) measured at Station 8 throughout the project duration.

Table 1: List of Dataflow sampling dates and parameters measured in San Antonio Bay. *The September 2005 sampling was delayed as a result of Hurricane Rita.

Dates	**Parameters**
January 25, 2005	transmissivity, chl *a*, DOM, temperature, PAR
February 28, 2005	transmissivity, chl *a*, DOM, temperature, PAR
March 29, 2005	transmissivity, chl *a*, DOM, temperature, salinity/conductivity, PAR
April 26, 2005	transmissivity, chl *a*, DOM, temperature, salinity/conductivity, PAR
May 24, 2005	transmissivity, chl *a*, DOM, temperature, salinity/conductivity, PAR
June 24, 2005	transmissivity, chl *a*, DOM, temperature, salinity/conductivity, PAR
July 24, 2005	transmissivity, chl *a*, DOM, temperature, salinity/conductivity, PAR
August 29, 2005	transmissivity, chl *a*, DOM, temperature, salinity/conductivity, PAR
October 4, 2005*	transmissivity, chl *a*, DOM, temperature, salinity/conductivity, PAR
October 27, 2005	transmissivity, chl *a*, DOM, temperature, salinity/conductivity, PAR
November 19, 20, 2005	transmissivity, chl *a*, DOM, temperature, salinity/conductivity, PAR
December 20, 2005	transmissivity, chl *a*, DOM, temperature, salinity/conductivity, PAR
January 26, 2006	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
February 22, 2006	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
April 21, 2006	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
May 22, 2006	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
June 23, 2006	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
July 30, 2006	transmissivity, chl *a*, DOM, temperature, salinity/conductivity
August 28, 2006	transmissivity, chl *a*, DOM, temperature, salinity/conductivity

In addition to the station (#8) at the Guadalupe River's saltwater barrier, seven fixed stations were selected to represent the range of salinity/inflow conditions across San Antonio Bay (Figure 1; Table 2). Station 1 was located nearest the Gulf of Mexico in Espiritu Santo Bay and represented our saline end-member. Stations 2 and 3 were located in lower San Antonio Bay. Stations 4 and 5 represented mid-estuary sites. Station 6 was in Hynes Bay and Station 7 represented the freshwater end-member near the mouth of the Guadalupe River (Figure 1; Table 2).

Table 2: Latitude and longitude of fixed sampling stations in San Antonio Bay.

Station	**Latitude**	**Longitude**
1	28°19.00'	93°36.00'
2	28°16.00'	96°41.00'
3	28°14.00'	96°44.00'
4	28°18.00'	96°45.00'
5	28°21.00'	96°44.00'
6	28°23.00'	96°48.00'
7	28°26.00'	96°46.00'

Inflows to the estuary varied considerably over the course of the study. At the beginning of 2005, inflows were high and tapered off through the summer (Figure 2). The drought continued through 2005 and was followed by a series of smaller pulses in early 2006. Low inflows then prevailed for the remainder of the study. Winds in this system are predominantly out of the SE and E—especially during the summer months and represent a significant force in estuarine hydrodynamics.

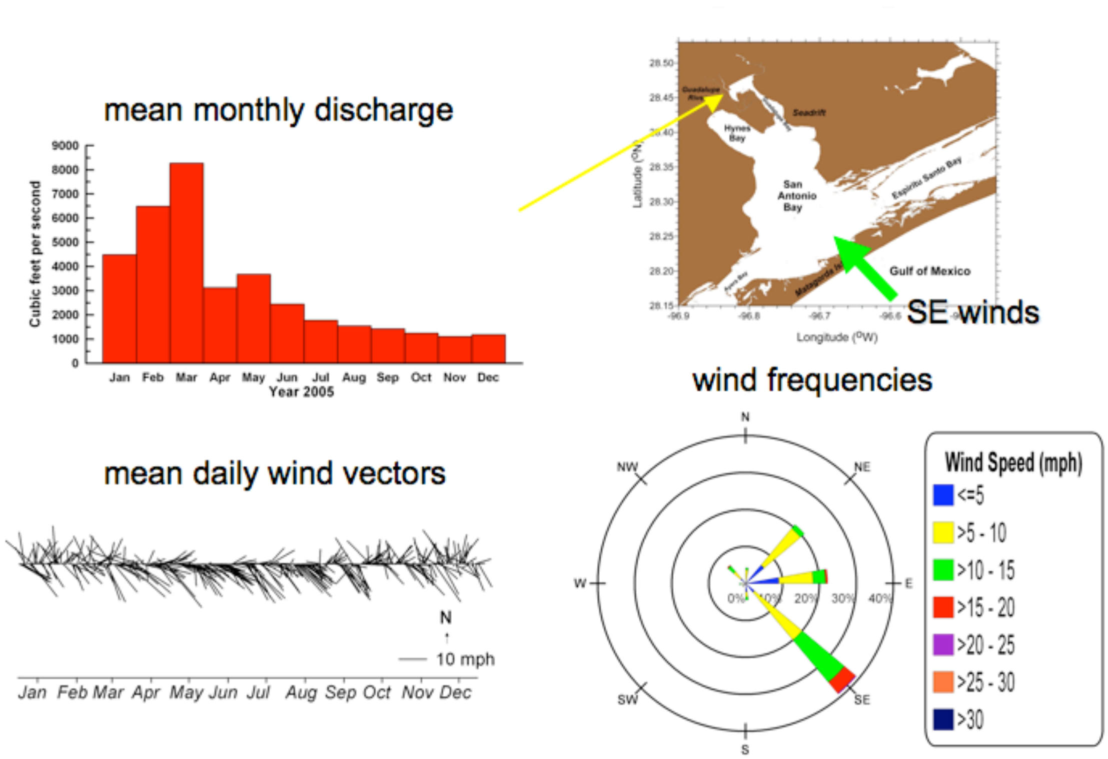

Figure 2: Plots of combined river discharge for 2005 and wind direction, speed (both on lower left) and frequency (lower right) relative to the body of the San Antonio Bay estuary (upper right). Discharge data from USGS and wind data from TX Coastal Ocean Observation Network (http://lighthouse.tamucc.edu/TCOON/HomePage).

Water quality data from the fixed bay stations reflected the relative importance of Gulf of Mexico (GOM) versus river influence (see fixed station data in appendix). Salinity was always lowest in the upper estuary, especially at Station 7 near the Guadalupe River outfall. This was followed by Stations 6, 5, 4, 3, and 2. Station 1 always had the highest salinity. Light attenuation across stations was similar, although Station 1 typically had the lowest attenuation. This site was most influenced by relatively clear GOM waters, but also showed a strong influence of wind mixing. Throughout the bay, light attenuation was largely driven by wind forcing and river inflows.

In general, concentrations of dissolved inorganic nitrogen and phosphorus were lowest in the lower estuarine areas (see fixed station data in appendix). This represents the relative paucity of nutrients in the GOM relative to river sources. Concentrations near the river mouths tended to be highest during high inflow periods.

Concentrations of total nitrogen and total phosphorus showed a similar spatial pattern of river influence and disproportionately higher concentrations near the mouth of the river. However, these constituents were more conservative across the estuarine salinity axis than dissolved inorganic N and P concentrations. This is likely due to the fact that TN and TP concentrations across the bay are likely affected by wind-driven re-suspension. Gross productivity in the water column at these fixed stations often exceeded respiration, resulting in consistent, positive net productivity. Overall, rates of these water column processes indicated more of a seasonal than inflow-related pattern (see fixed station data in appendix).

Obviously, salinity within the estuary is strongly controlled by the relative contributions of river inflow and exchanges with the Gulf of Mexico. We found strong relationships between river discharge and salinity at each site (see plots of concentration vs. salinity in appendix). As expected, this relationship was weakest at Station 1 and only existed as a result of a few high inflows measured early in 2005. Turbidity, DO, and [DOC] were less related to river inflow and were more variable as a result of seasonal variations in wind and temperature. DOC data were lacking for many samplings, but there was evidence of an inverse relationship with inflow. An opposite trend was observed with Dataflow (described below), as CDOM concentrations were positively correlated with river inflows. [TN] and [TP] also were not clearly related to river inflows from the Guadalupe. Despite the lack of a clear trend, the highest concentrations of TN and NH_4^+ measured corresponded with lower inflows, indicating a benthic source of these constituents during periods of high residence times. Likewise, phosphate was typically highest at each fixed station during the lower inflow periods, suggesting a periodic release of this constituent from the sediments. On the other hand, nitrate + nitrite concentrations were positively correlated with river inflows at some sites (especially Stations 4-6; see appendix).

Overall, we found molar ratios of TN:TP were highest in the lower reaches of the estuary and lowest in the mid-upper estuary. However, Station 7 ratios were also high. Given that the rivers seem to represent a significant supply of inorganic N to these areas of the bay, high inflow periods may result in greater productivity in the upper bay. In looking at the spatial patterns of nutrients relative to water column processes, our results are inconclusive in supporting this (see fixed station data and contour plots of nutrients in appendix). Perhaps further work looking at the direct effects of nutrient enrichment on water column processes and benthic exchanges would clarify this.

Dataflow samplings were conducted monthly and required a minimum of 1 day to complete. The technique involved pumping water on board a moving boat and deposited into a de-bubbling reservoir. This water was then pumped into a series of water quality sensors that were connected in-line via tubing. Water quality data were then harvested from these sensors at a fixed time interval (approximately every 4 seconds) and linked with a set of GPS coordinates and stored in a data logger (see Dataflow maps for all samplings and parameters in appendix).

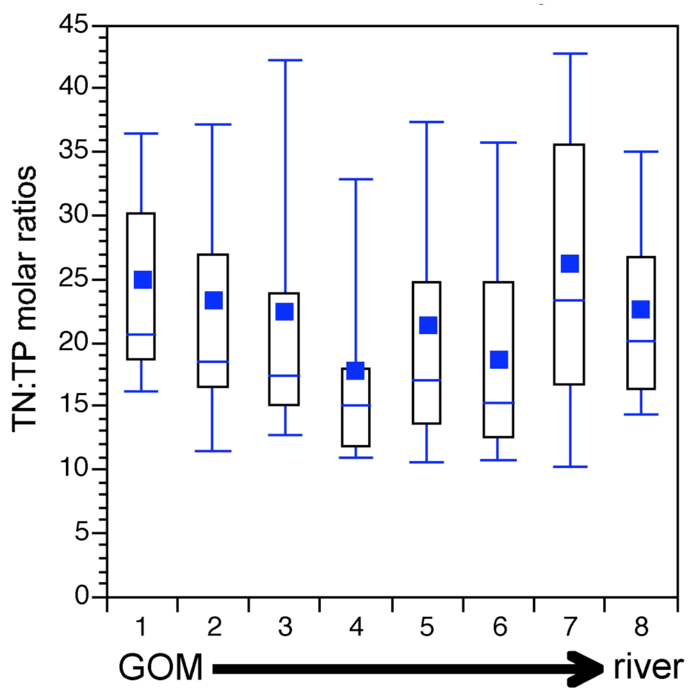

Figure 3: Box plot of molar TN:TP ratios across the salinity gradient of the Guadalupe Estuary throughout the duration of sampling. The boxes in each represent the inter-quartile range of each distribution. The middle line is the mean and the blue square represents the statistical mean. Whiskers indicate the 10th and 90th percentiles.

Dataflow maps were generated for each sampling described in Table 1 (see appendix). These maps provide a powerful illustration of the influence of river inflow relative to marine exchange and even serve to identify general circulation/exchange patterns. They can also help identify areas of management concern (areas of wetland loss, urban development, pollutant loading, etc.). In each map, the transect sampled is indicated by the dashed line.

Program Element 2: Data Analysis

<u>Objective</u>**:** Establish the link between riverine inflows and spatial patterns in water quality and fixed station data.

Task 1 — Analyze spatial patterns in water quality parameters using Dataflow information. These data will be synthesized as Surfer-based contour plots (i.e. maps) of bay-wide water quality.

Task 2 — Link temporal patterns in inflows and loadings to spatial patterns in estuary-wide water quality and water column productivity through multivariate statistical analyses.

<u>Progress Report on Program Element 2:</u> Although we have estimates of discharge available to us from USGS' Guadalupe River site, the difficulties in sample collection at the SW Barrier site have precluded us from calculating loadings for the period of this study. Still, we have continued to archive data and analyze the link between estimated inflows and patterns we observed throughout the bay during each of our monthly samplings.

Many of these patterns were described in the previous section of this report. However, further analysis of Dataflow data collected in the Galveston Bay and San Antonio Bay estuaries indicates similar trends between river inflows and the loading of dissolved organic matter (Figures 4 and 5). Moving from a period of high inflow to low inflow in each system during 2005 shows the similar spatial patterns for CDOM and conductivity in each estuary (Figure 4 and 5). The statistical distributions for each are quite different though. Likely a result of its smaller size and reduced connection to the Gulf of Mexico, San Antonio Bay had smaller, tighter distributions of CDOM relative to Galveston Bay. For conductivity, distributions were tighter during periods of high inflow in San Antonio Bay relative to Galveston Bay. However, there appeared to be a shift in the distributions as flows decreased in these systems. These patterns reflect differential responses to similar climatic patterns and likely reflect the relative connectivity to the marine end-member and the amount of freshwater inflow relative to estuarine volume. As for relationships among all Dataflow parameters, we saw several instances of correlation among Dataflow parameters—especially between CDOM and conductivity (Figure 6).

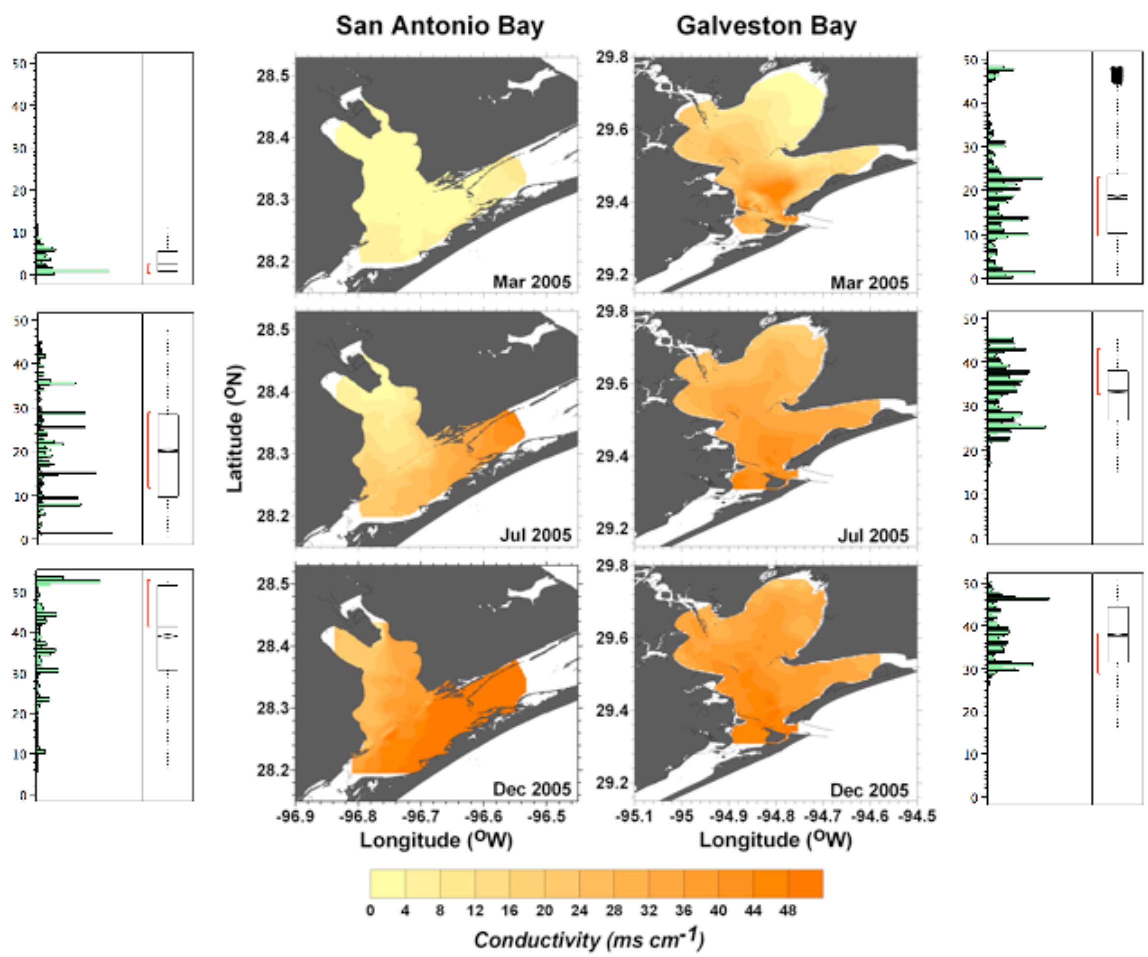

Figure 4: Spatial and Statistical patterns of conductivity in San Antonio and Galveston Bays during the same monthly samplings that went from a period of high inflow (March 2005) to a period of extended low inflow (December 2005).

We used non-metric multi-dimensional scaling to assess the role of estuarine flushing, location along the estuarine gradient, and pulsed nature of inflows on the relationships among fixed station data. PC-ORD 4.25 (MjM Software, Gleneden Beach, OR) was used to run NMS ordination analyses for these data. Dividing the site-specific data by flushing rate (both week^{-1} and month^{-1}) resulted in no distinct separation of clusters except at the highest flushing rate (see NMS results in appendix). This same analysis with two levels of pulsing ("after pulsed inflow" and "not after pulsed inflow") resulted in similar clustering and pulsing during a dry year also indicated some clustering more towards the "no pulse" cluster. However, it should be noted that much of this was driven by differences in site-specific differences in salinity/conductivity, which was the most robust indicator of inflow. And as expected, this pattern was most noticeable at stations nearest the river mouth, where the greatest inflows occurred.

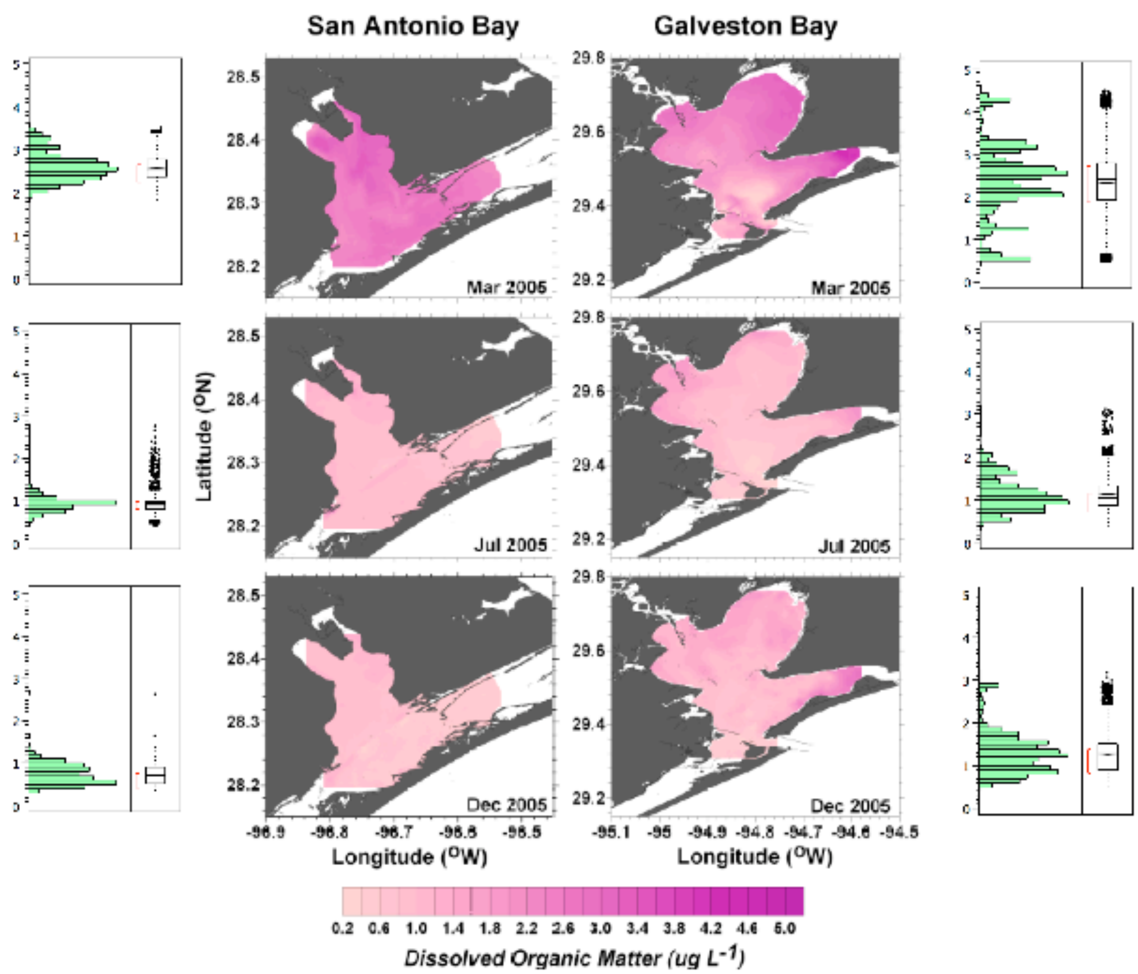

Figure 5: Spatial and statistical patterns of CDOM in San Antonio and Galveston Bays during the same monthly samplings that went from a period of high inflow (March 2005) to a period of extended low inflow (December 2005). CDOM patterns were directly related to river inflows in most all samplings.

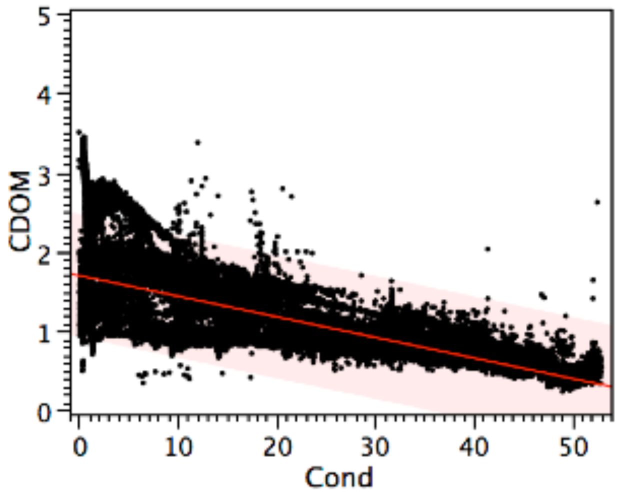

Figure 6: Scatter plot with best fit line showing the relationship between CDOM and conductivity observed across all monthly Dataflow samplings in San Antonio Bay.

CDOM = 1.7009766 - 0.0258825 Cond
RSquare Adj = 0.499

Project Impact

This projected supported three graduate students throughout its duration (George Gable, M.S.; Hsiu-Ping Li, Ph.D.; and Carrie Miller, M.S.). Both Carrie and George completed their M.S. degrees in summer 2007 and have publications that are being submitted for review at this time. Hsiu-Ping will finish her dissertation in late 2008 and will also be submitting portions of her dissertation for publication soon. The project also produced 15 presentations, and several other manuscripts that are in preparation. It is also led to sources of additional funding for the Guadalupe and Galveston Bay Estuarine systems that will generate many more peer-reviewed publications and presentations.

As a result of this project, researchers imported a technology from Florida, i.e., Dataflow, that invloves ship-board, flow-through sensors. The technique is relatively inexpensive, rapid and reliable, and invloves the collection of GPS-linked data points collected while the ship runs tight transects across the bay. This technology provides scientists an alternative to remote sensing for data collection in shallow water environments. In addition, this technology is much more accurate and reliable than remote sensing because of the uncertainties associated with remote sensing algorithms targeting shallow type II waters.

Researchers developed a web-based data access system were users can quickly view monthly data being collected in San Antonio Bay, which includes fixed station data and high-resolution spatial maps of the entire bay stsrem (see above for parameters measured). The link for access to these data can be found by visiting the following site: (http://www.wfsc.tamu.edu/roelkelab/SABproj.htm). This service will provide resource managers, scientists, and lay people quick access to system-wide parameters of San Antonio, such as salinity, productivity, etc. This information will be useful to diverse stakeholders in the region, which include commercial and recreational fisherman.

INVITED SEMINARS

Davis, S.E. Understanding the importance of pulsed events in Gulf Coast estuaries. April 20, 2005 Marine Biology Departmental Seminar at **Texas A&M University at Galveston**, Galveston, TX.

Roelke, D.L. 2006. Large-scale disturbances and the predictability of complex aquatic ecosystems. **US EPA, Western Ecology Division**, Corvallis, Oregon. March 22.

Roelke, D.L. 2005. Regional species richness and supersaturation: The role of migration and disturbance of chaotic communities. **University of Oklahoma Seminar Series**, OK, USA. October 12.

Roelke, D.L. 2005. Water issues and research needs in Texas. **Brazos Chapter, Texas Master Naturalists**, Bryan, TX, USA. November 3.

Davis, S.E. 2005. Physical, chemical, and biological responses to inflow events in Galveston and San Antonio Bays (TX). **Environmental Flows Conference: "Flows for the Future" meeting**, San Marcos, TX.

Davis, S.E. 2005. Use of high-resolution spatial mapping to estimate plankton response to freshwater inflows entering Galveston Bay: Importance of watershed development and ecosystem health**. Monitoring & Research Subcommittee of the Galveston Bay Estuary Program**, Houston, TX

Davis, S.E. 2006. Use of high-resolution spatial mapping to estimate plankton response to freshwater inflows entering Galveston Bay: Importance of watershed development and ecosystem health II. **Monitoring & Research Subcommittee of the Galveston Bay Estuary Program**, Houston, TX

CONTRIBUTED TALKS

Davis, S., D. Roelke, G. Gable, H-P. Li, C. Miller. 2005. Physical, chemical, and biological responses to inflow events in Galveston and San Antonio Bays (TX): Bay-wide characterizations. **Estuarine Research Federation**. Norfolk, VA, USA. October 16-21.

Davis, S.E., D. Roelke, D. Slack. 2005. Physical, Chemical, and Biological Responses to Inflow Events in the San Antonio Bay System. **Environmental Flows Conference**, Texas State University, San Marcos, TX. Oct 31 - Nov 1.

Davis, S.E., D. Roelke, et al. Determining the importance of freshwater inflows to ecological structure and function in the bays and marshes of the Guadalupe Estuary (TX). April 1, 2005 at the **Gulf Estuarine Research Society Meeting**, Pensacola, FL.

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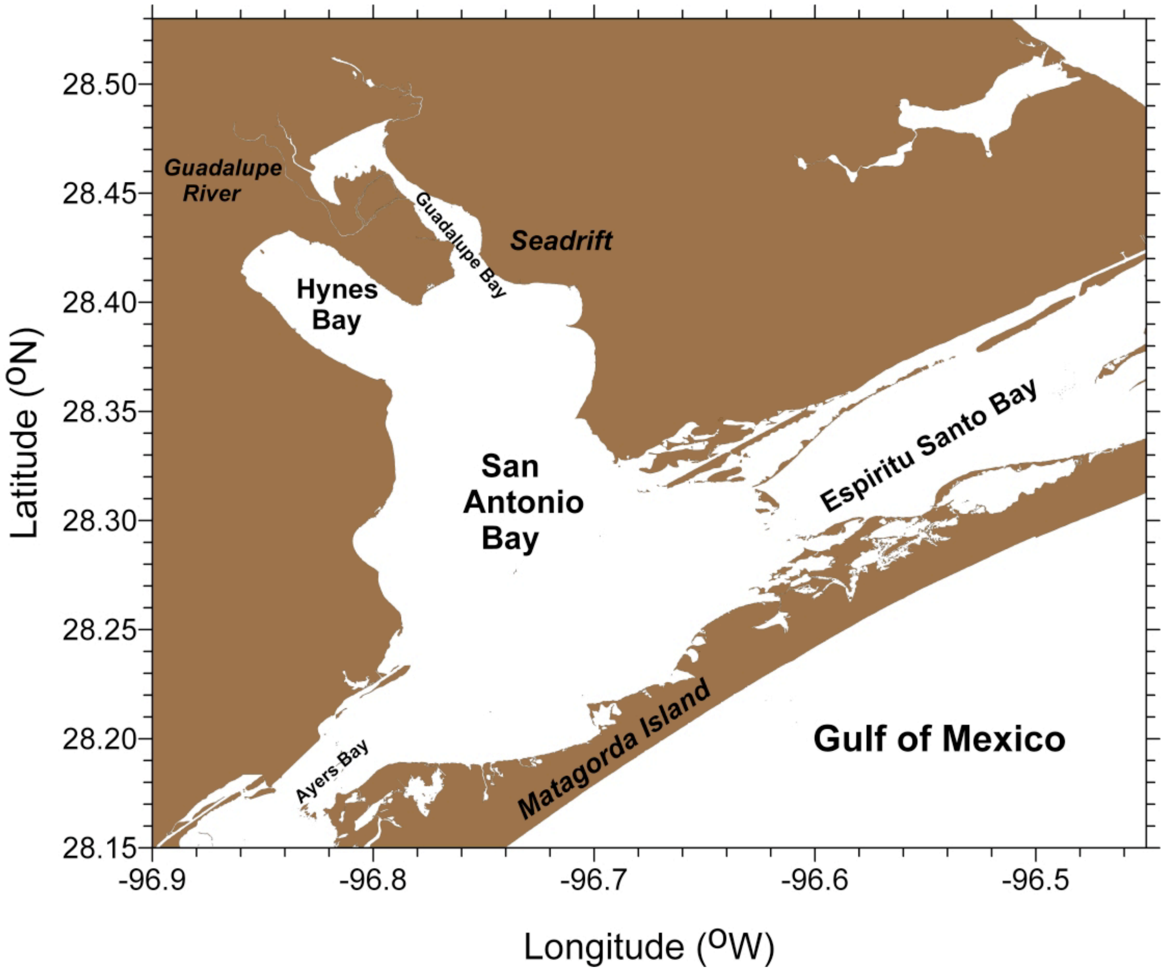
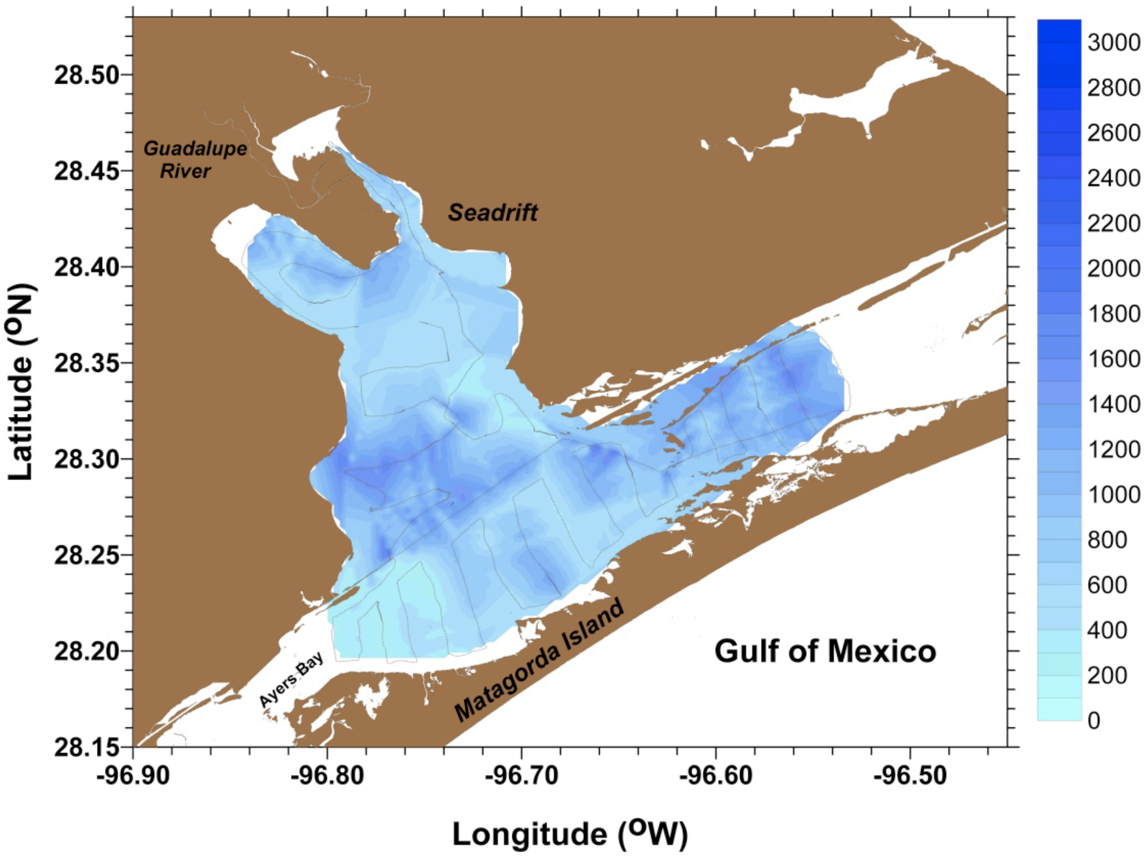
Dataflow Maps from Guadalupe River Estuary



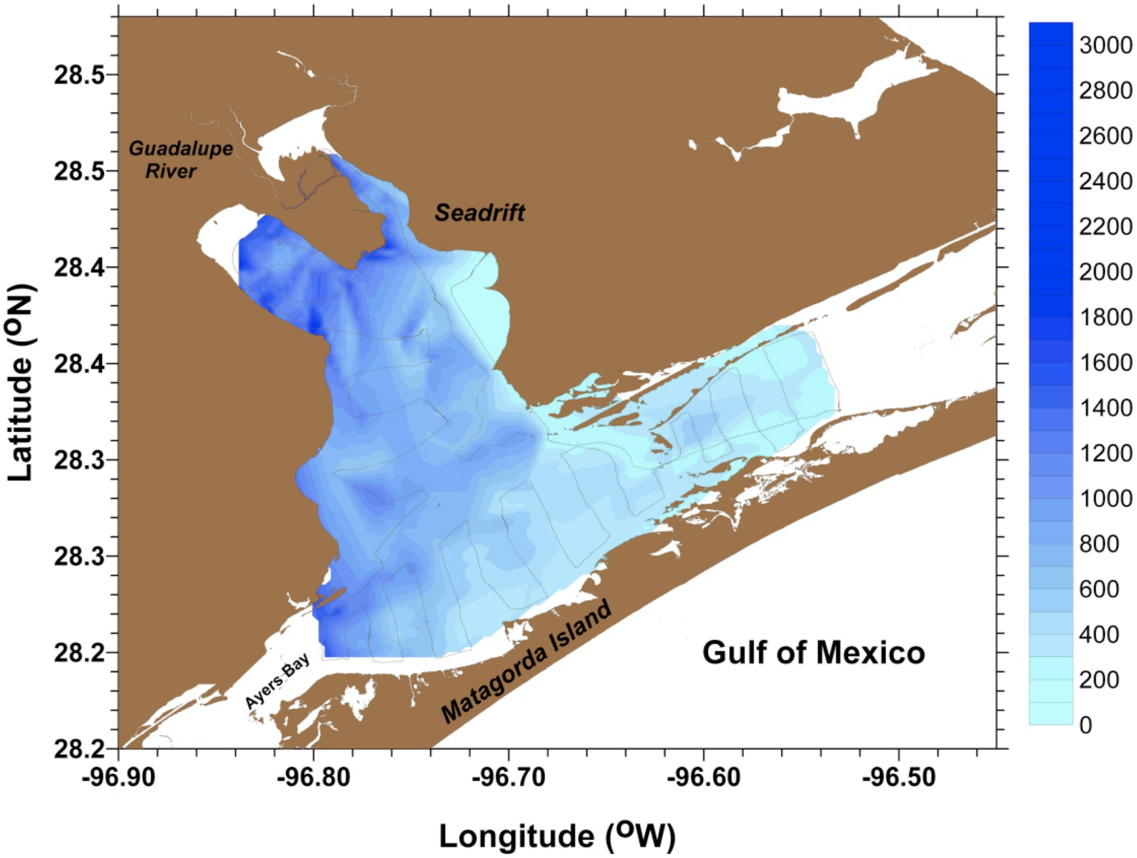
San Antonio Bay, January 05

PAR (umol m^{-2} sec^{-1})



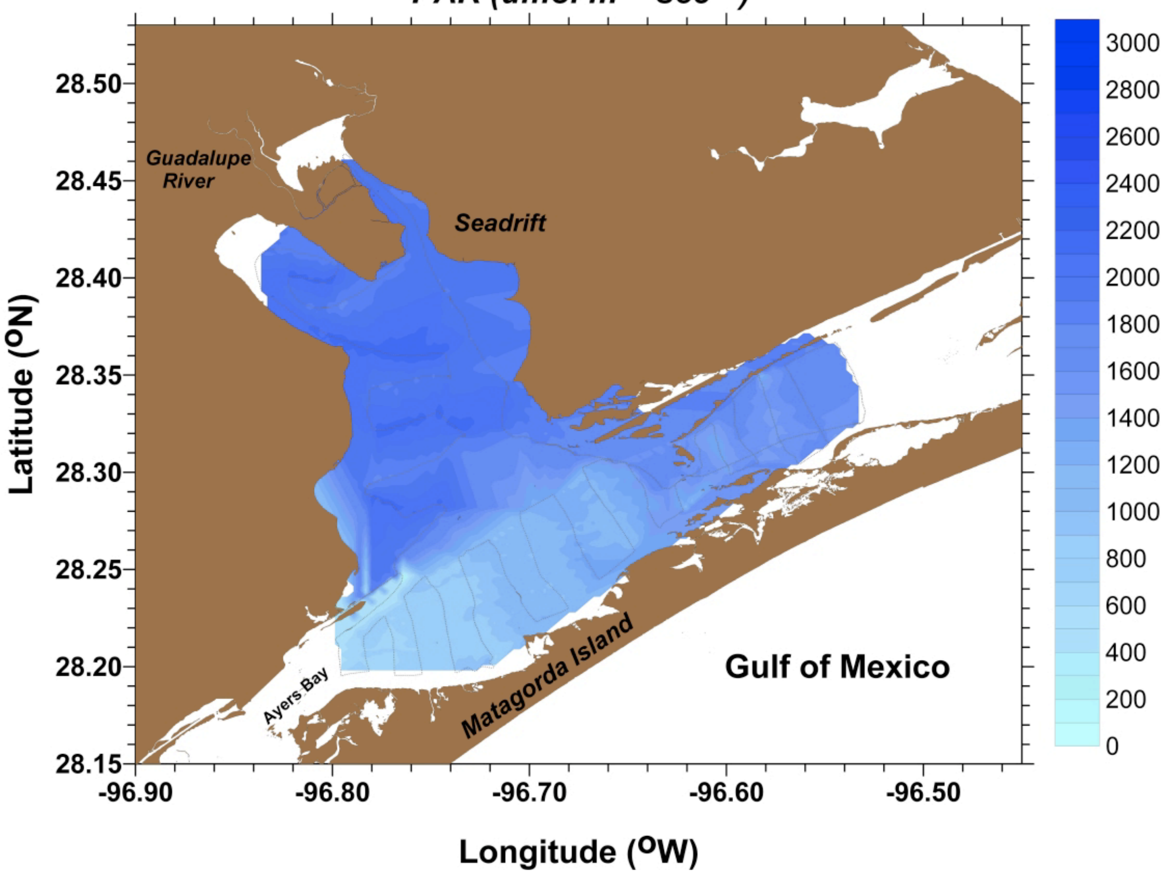
San Antonio Bay, February 05

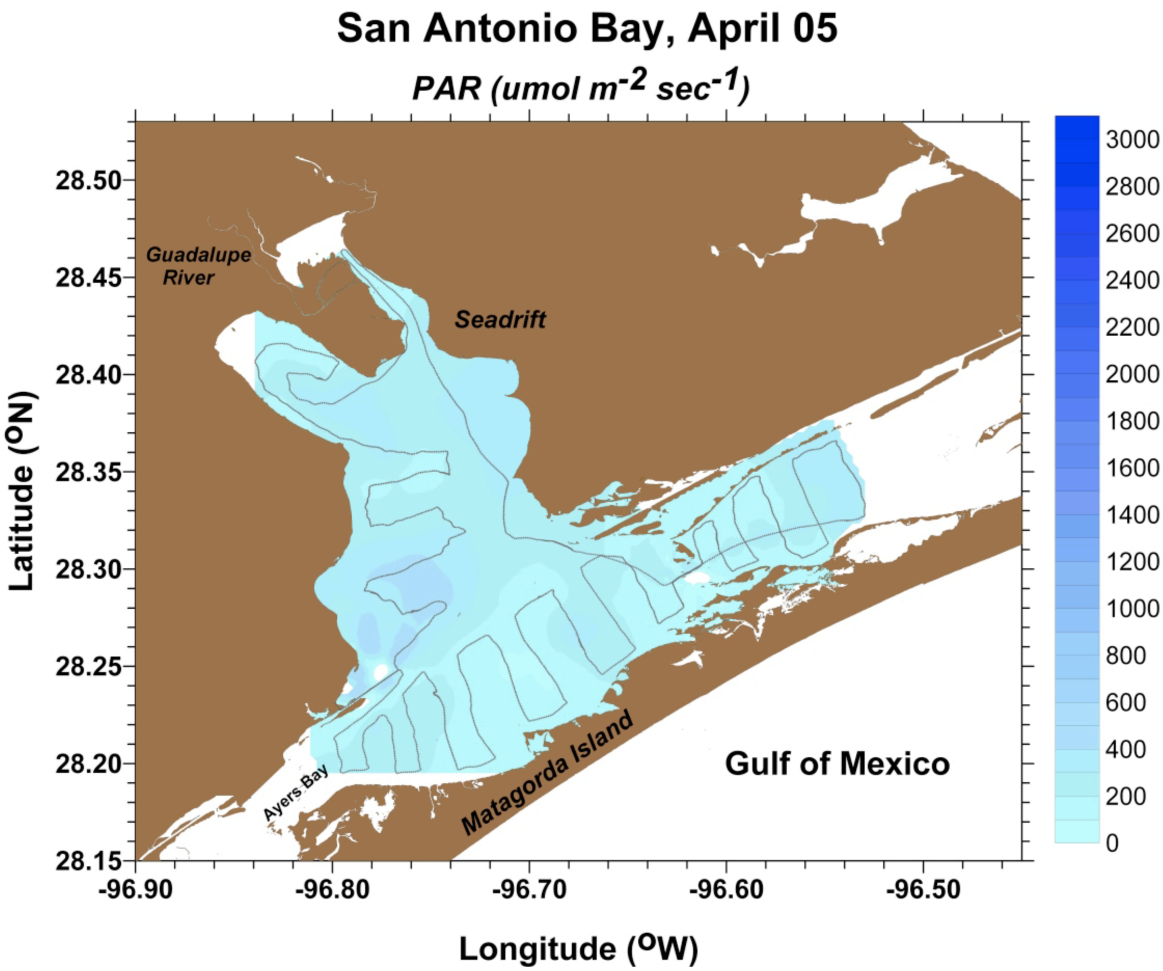
PAR (umol m^{-2} sec^{-1})



San Antonio Bay, March 05

PAR (umol m^{-2} sec^{-1})




San Antonio Bay, April 05
PAR (umol m-2 sec-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3000
2800
2600
2400
2200
2000
1800
1600
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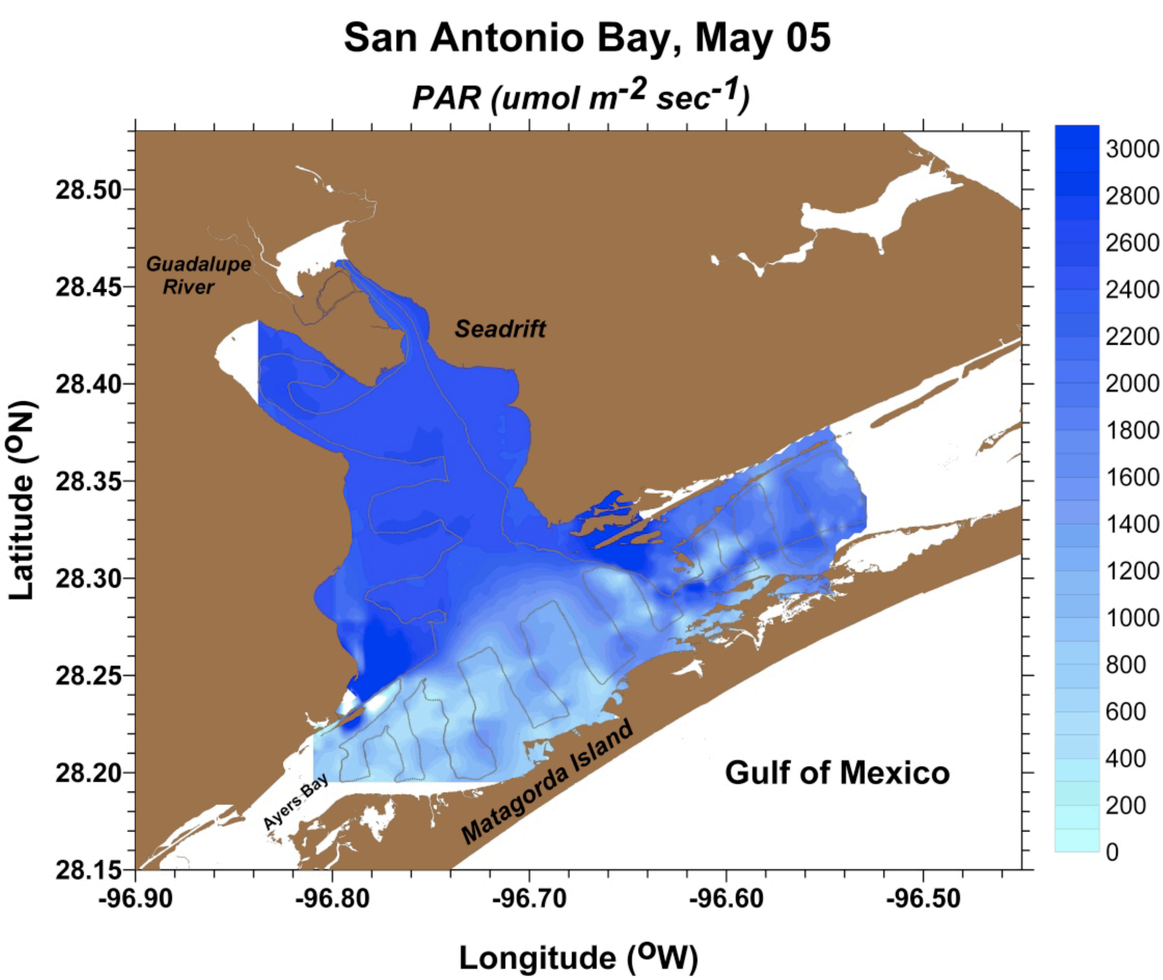
800
600
400
200
0


San Antonio Bay, May 05
PAR (umol m-2 sec-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
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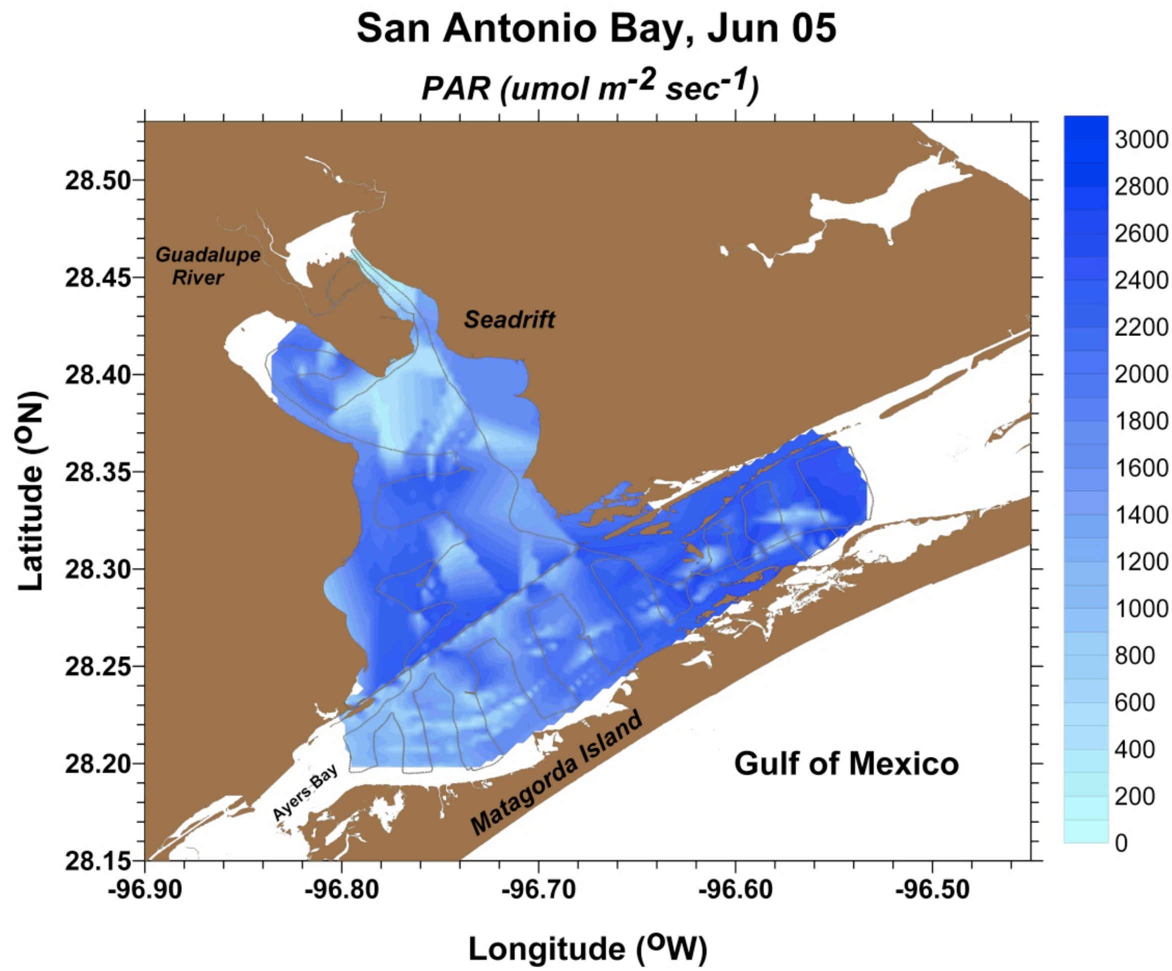
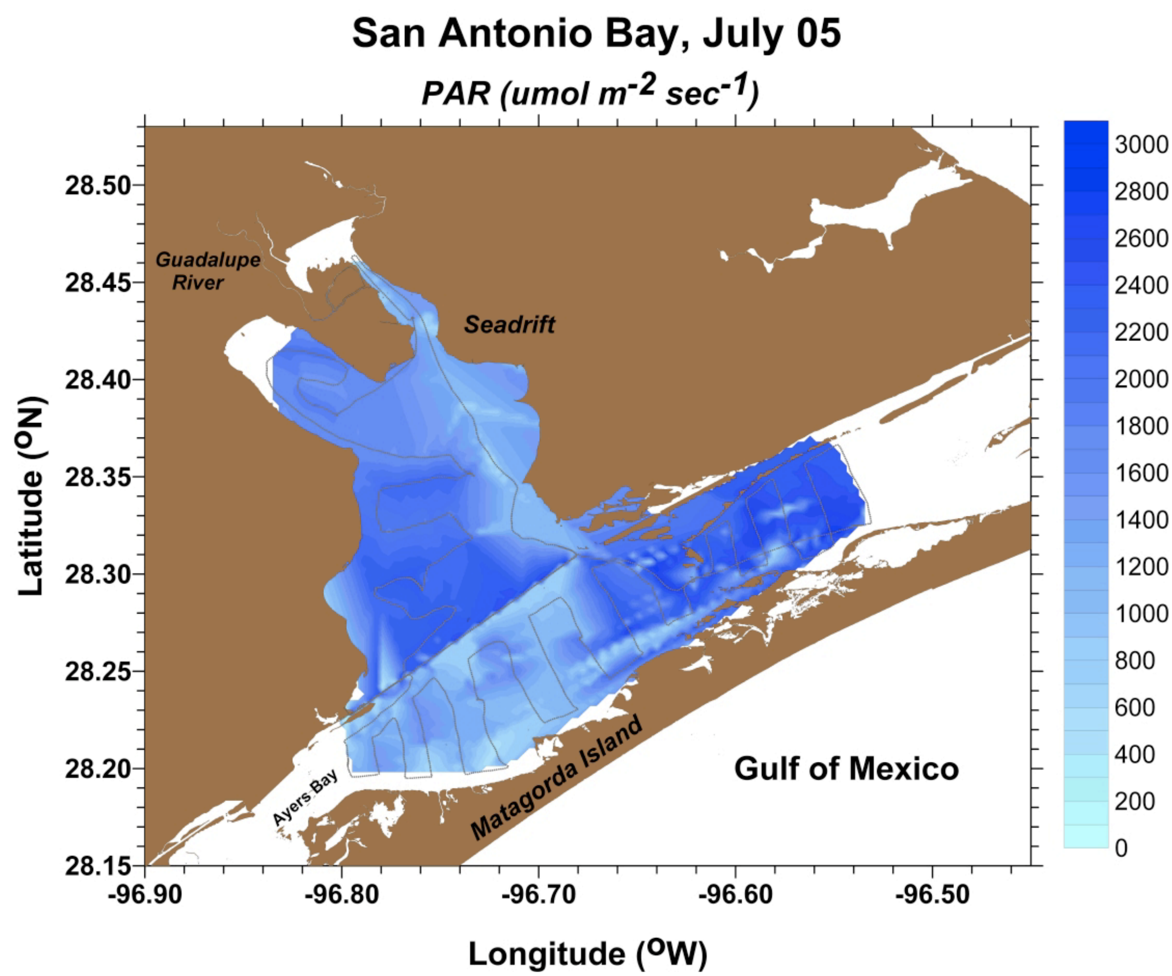
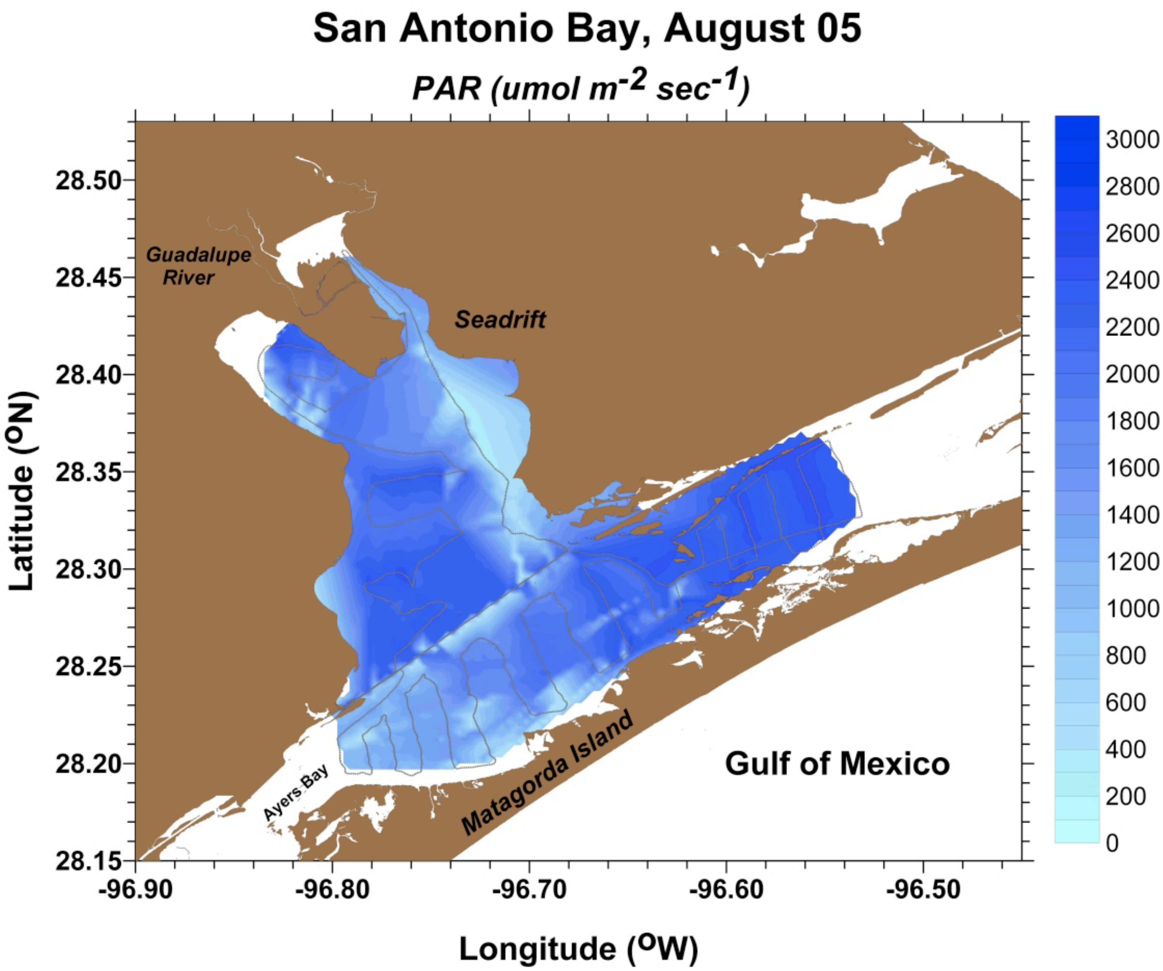
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0


San Antonio Bay, Jun 05
PAR (umol m-2 sec-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0


San Antonio Bay, July 05
PAR (umol m-2 sec-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0


San Antonio Bay, August 05
PAR (umol m-2 sec-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3000
2800
2600
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2200
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600
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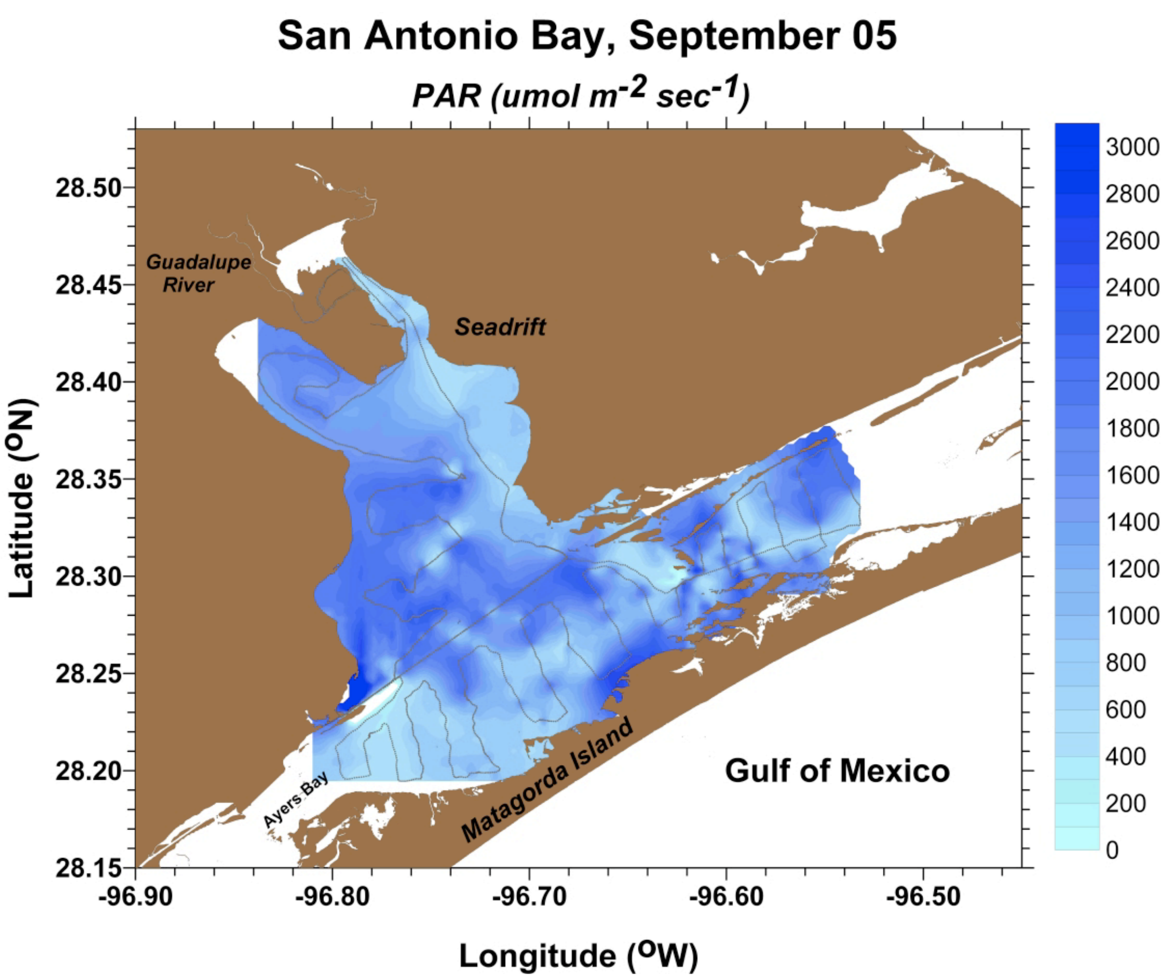
200
0


San Antonio Bay, September 05
PAR (umol m-2 sec-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3000
2800
2600
2400
2200
2000
1800
1600
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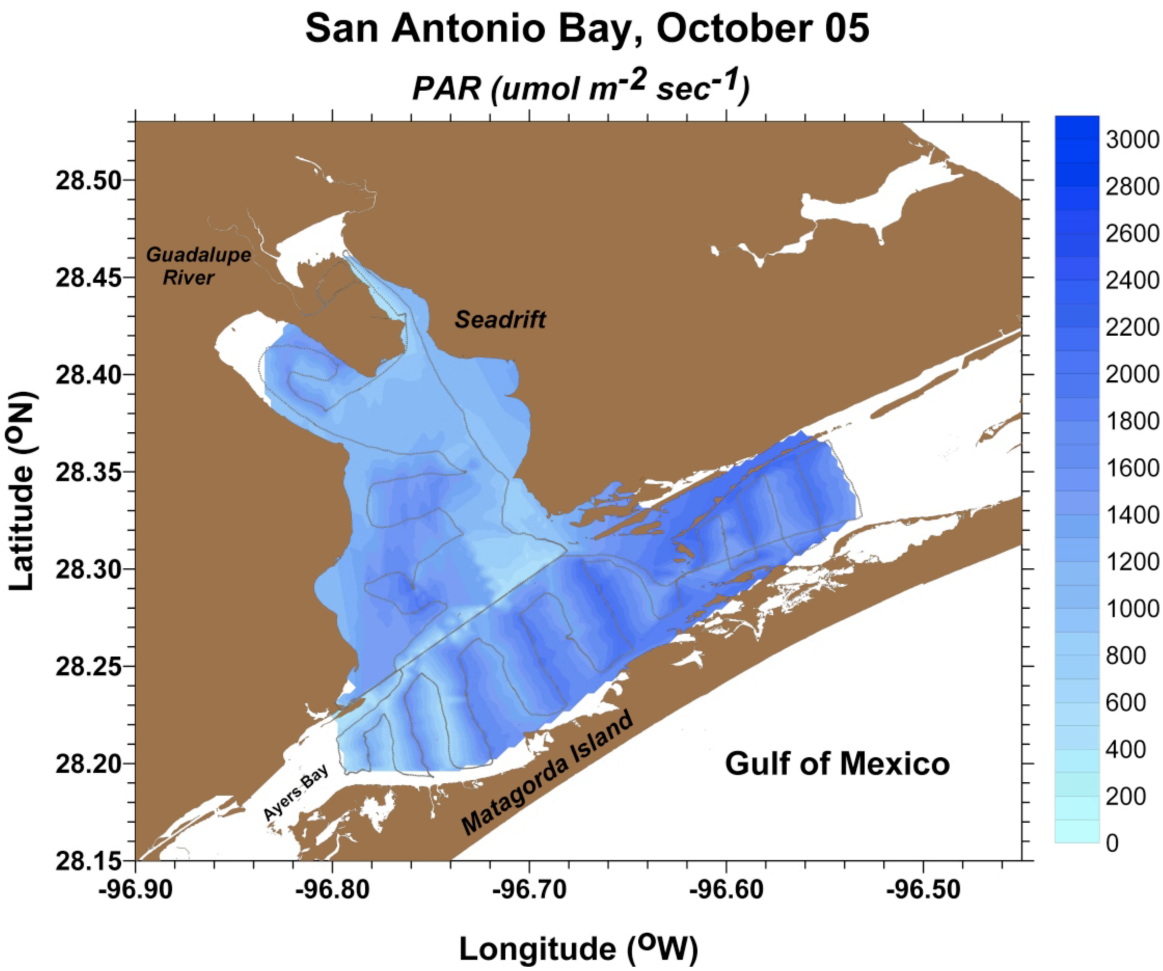
600
400
200
0



San Antonio Bay, October 05
PAR (umol m-2 sec-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3000
2800
2600
2400
2200
2000
1800
1600
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600
400
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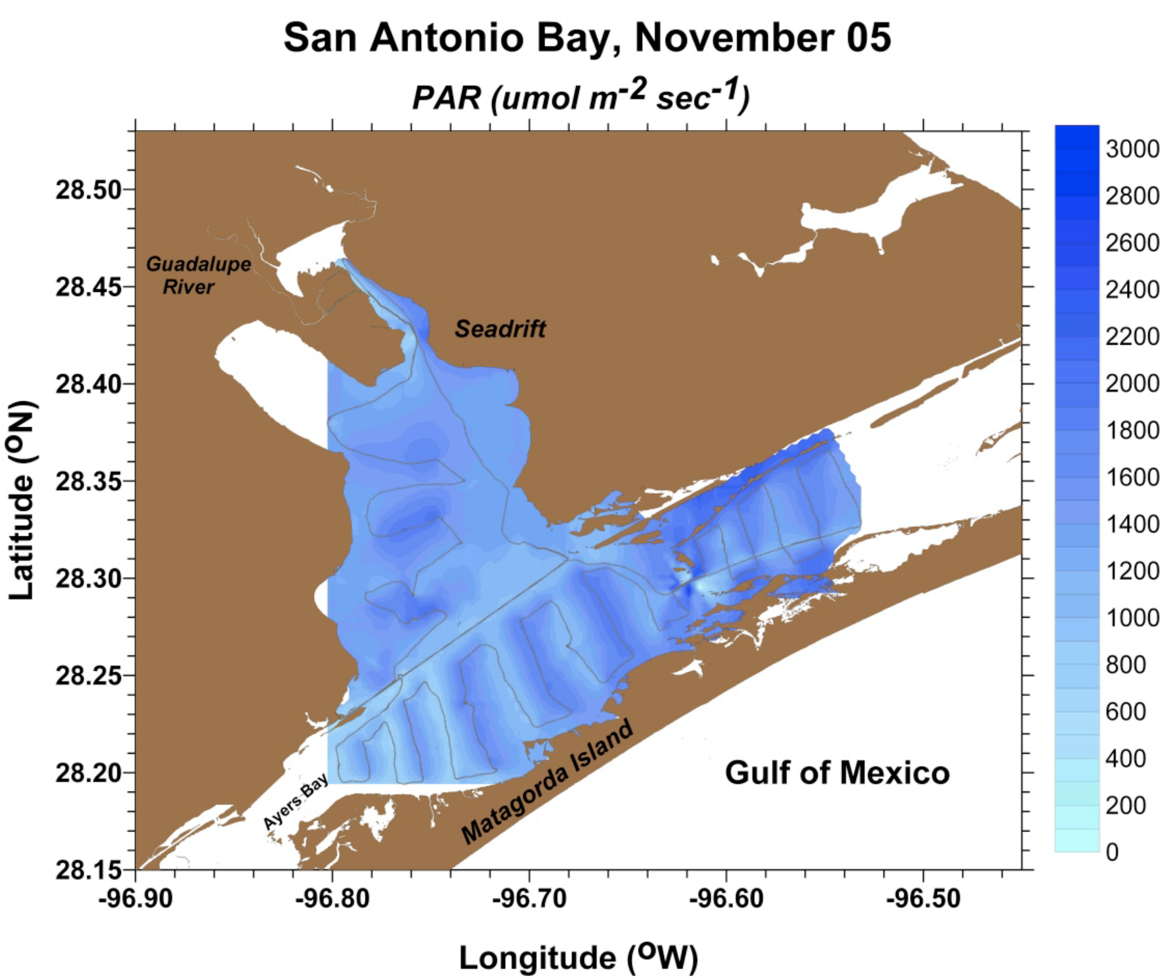
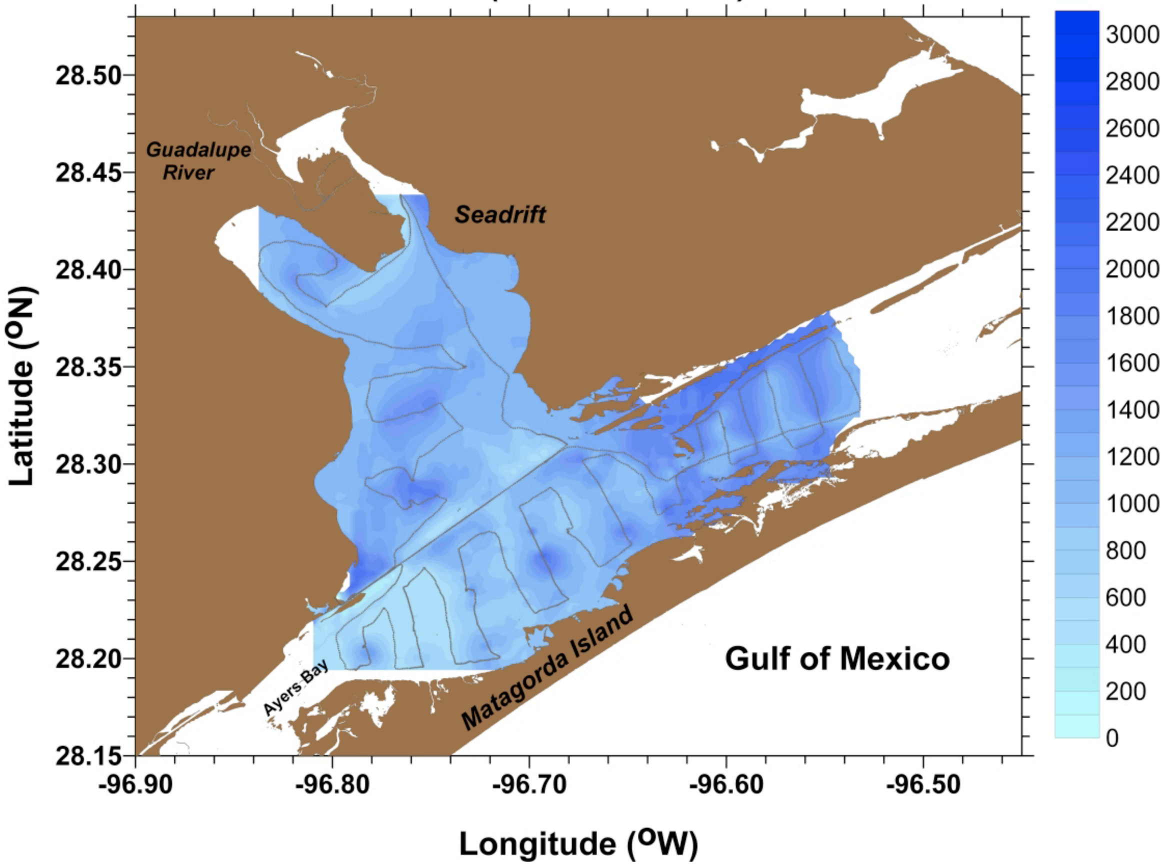


San Antonio Bay, November 05
PAR (umol m-2 sec-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0

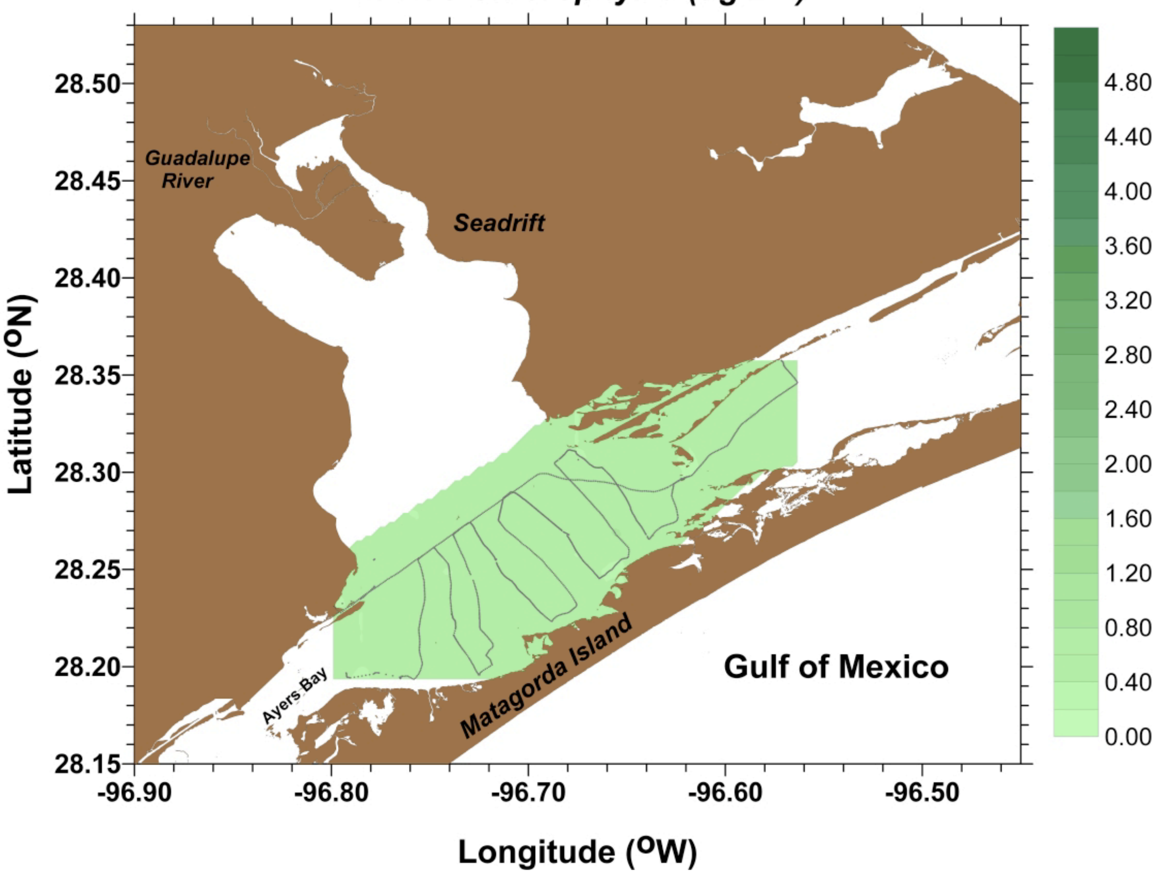
San Antonio Bay, December 05

PAR (umol m^{-2} sec^{-1})



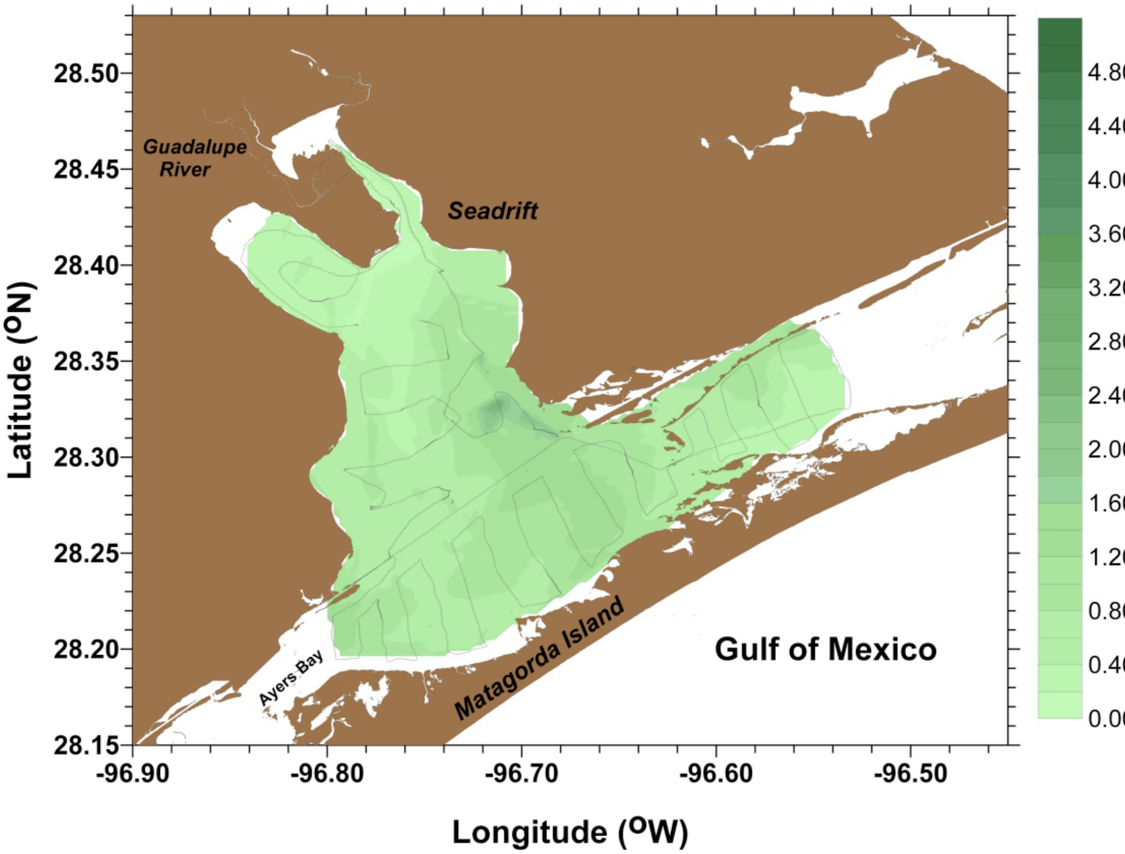
San Antonio Bay, Oct 04

In vivo Chlorophyll a (ug L^{-1})



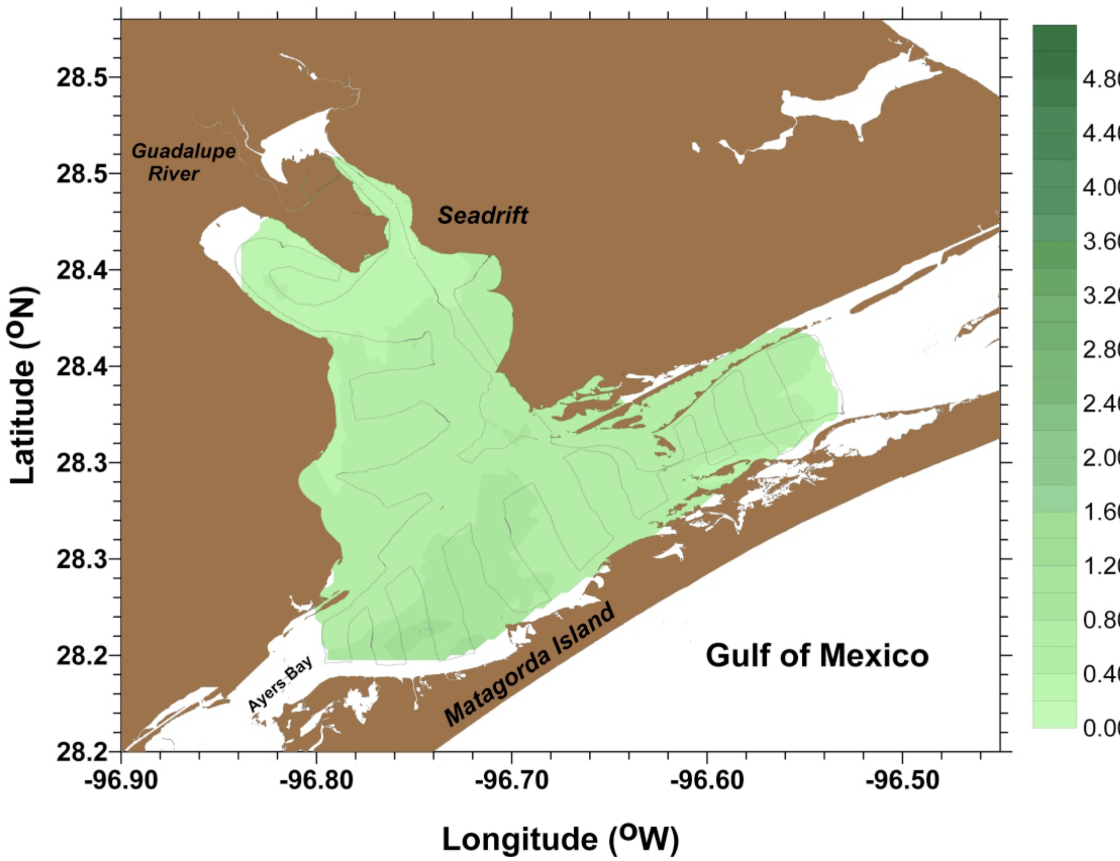
San Antonio Bay, January 05

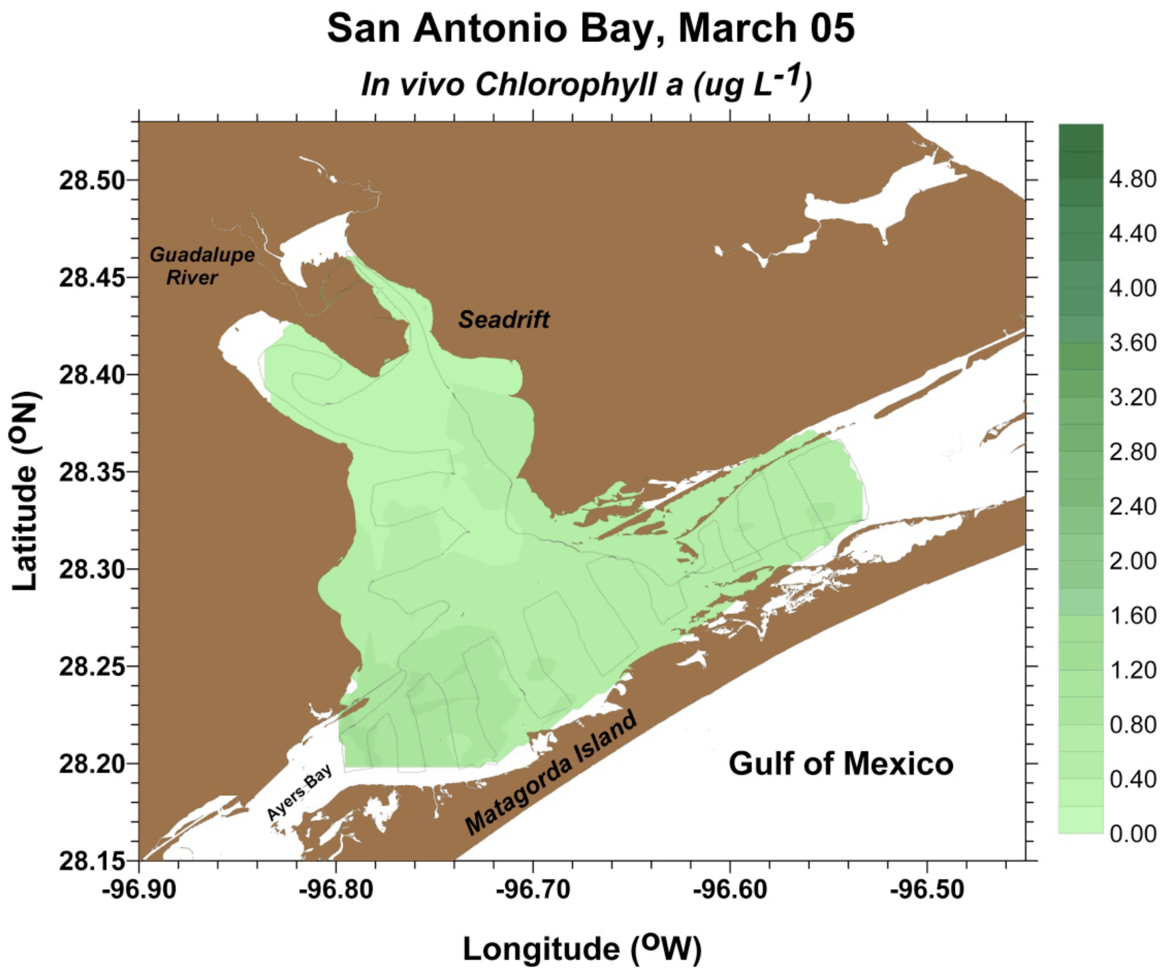
In vivo Chlorophyll a (ug L^{-1})

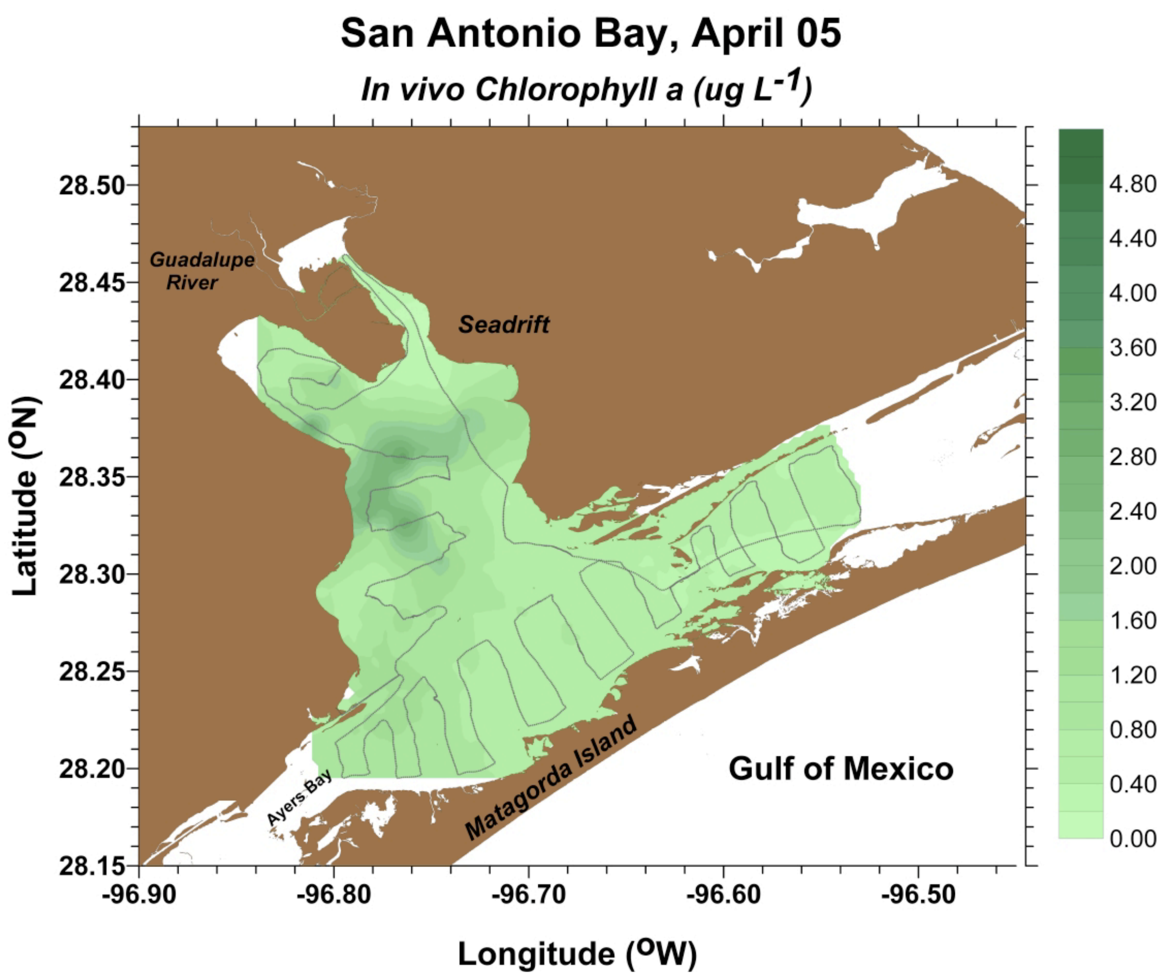


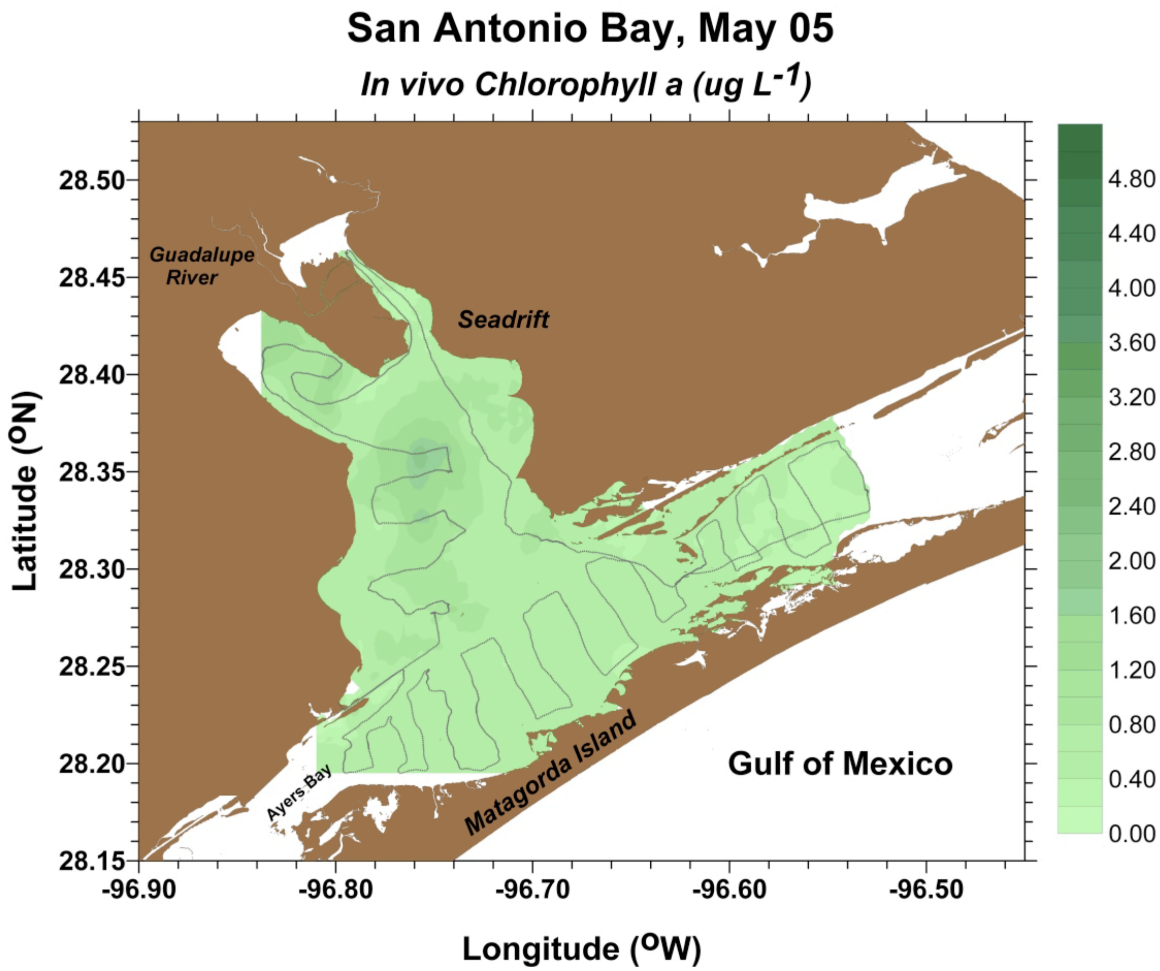
San Antonio Bay, February 05

In vivo Chlorophyll a (ug L^{-1})




San Antonio Bay, March 05
In vivo Chlorophyll a (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00


San Antonio Bay, April 05
In vivo Chlorophyll a (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00


San Antonio Bay, May 05
In vivo Chlorophyll a (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
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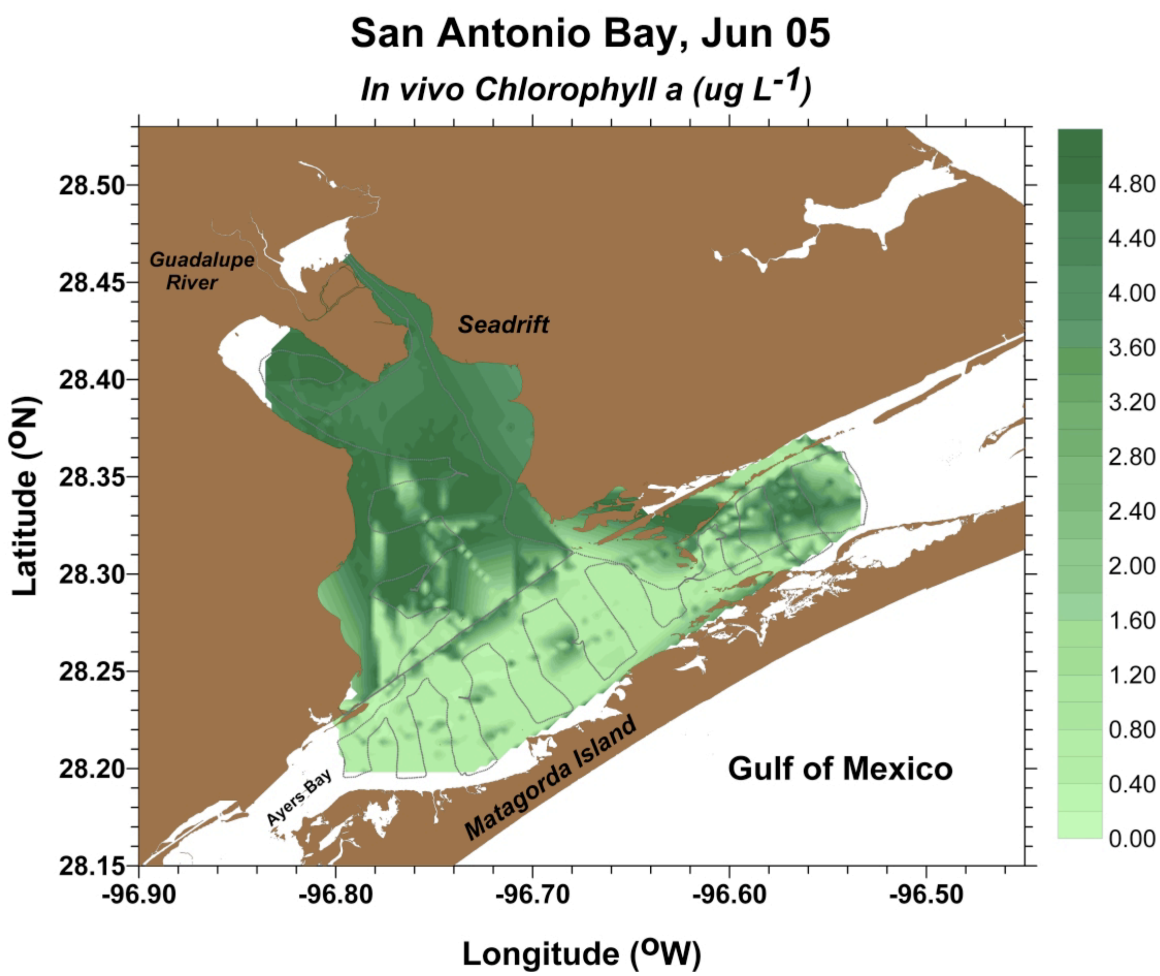
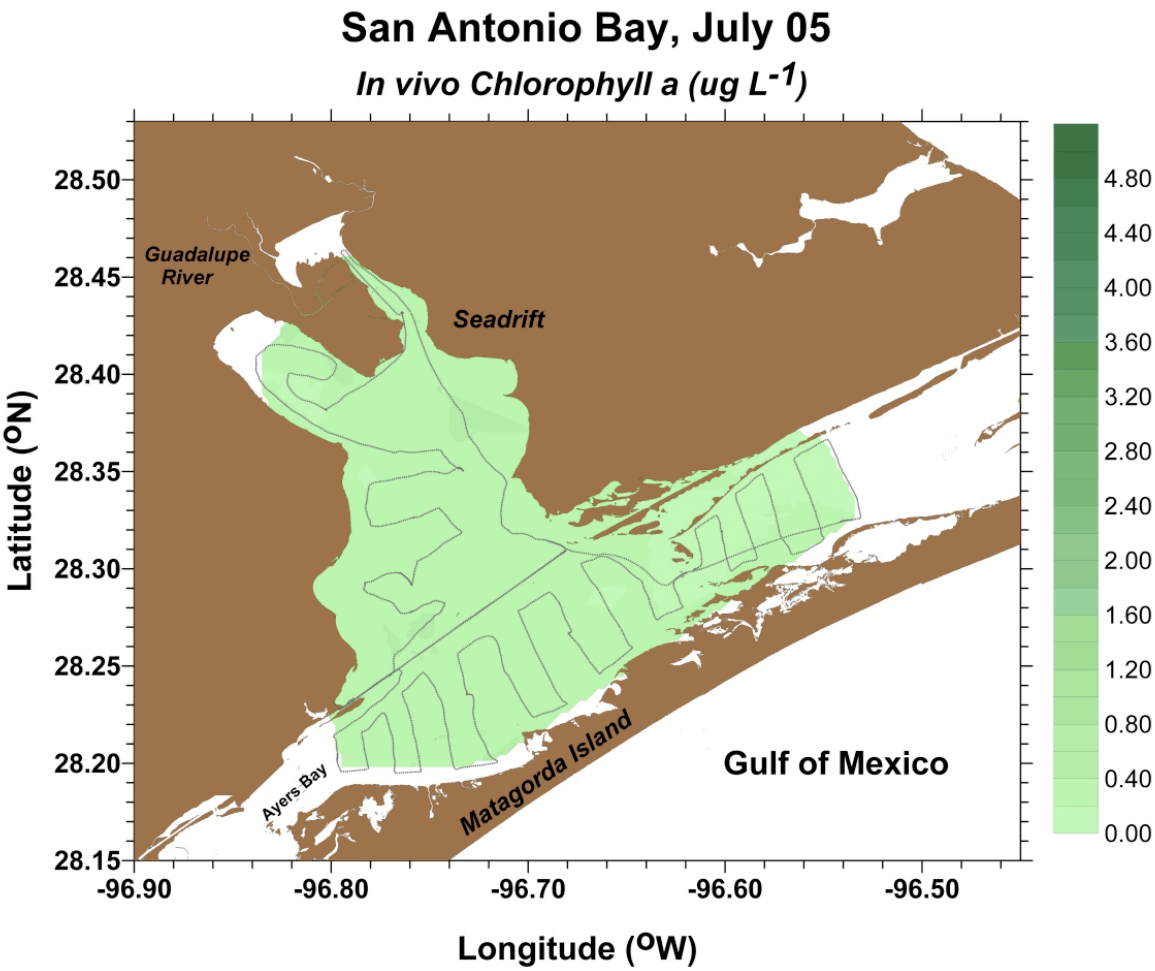
0.40
0.00


San Antonio Bay, Jun 05
In vivo Chlorophyll a (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00


San Antonio Bay, July 05
In vivo Chlorophyll a (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
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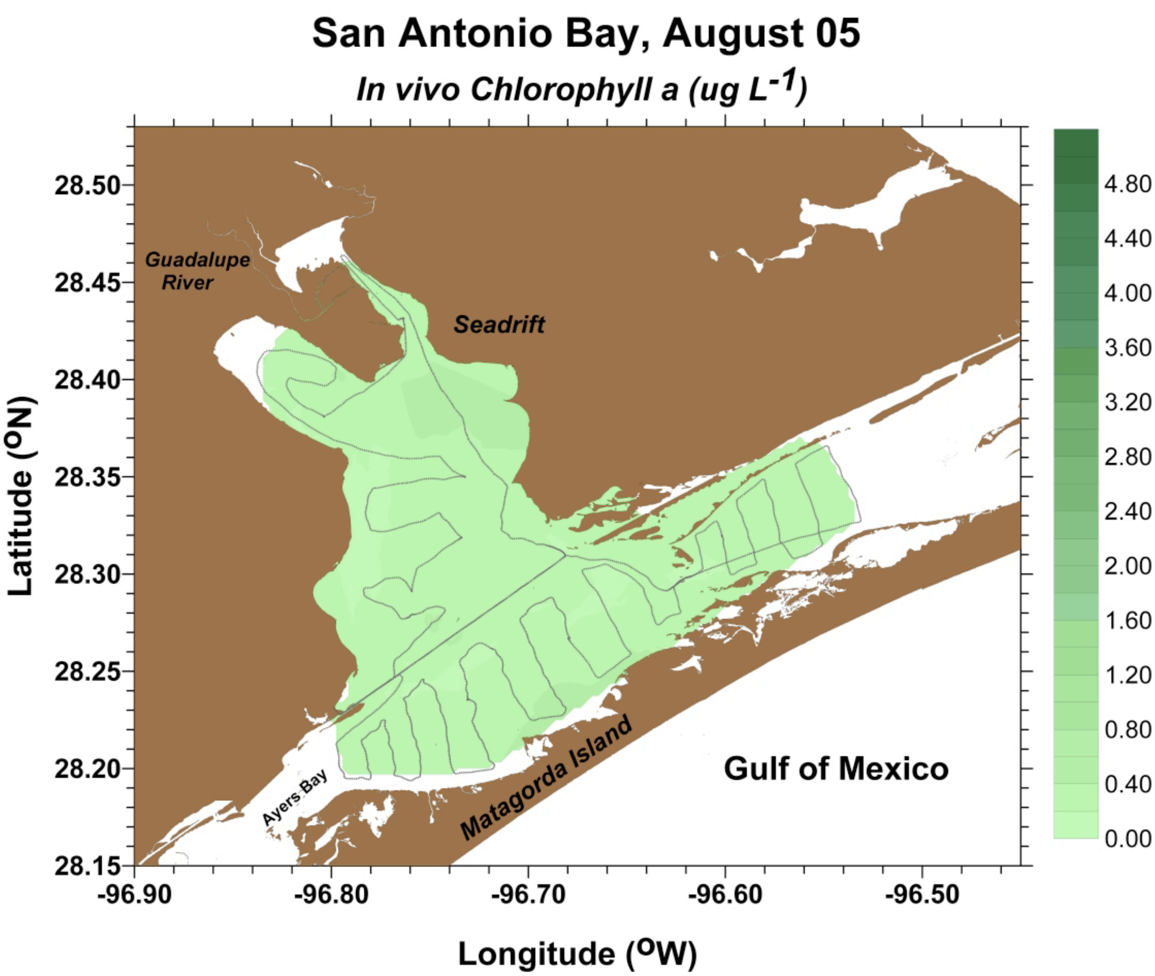
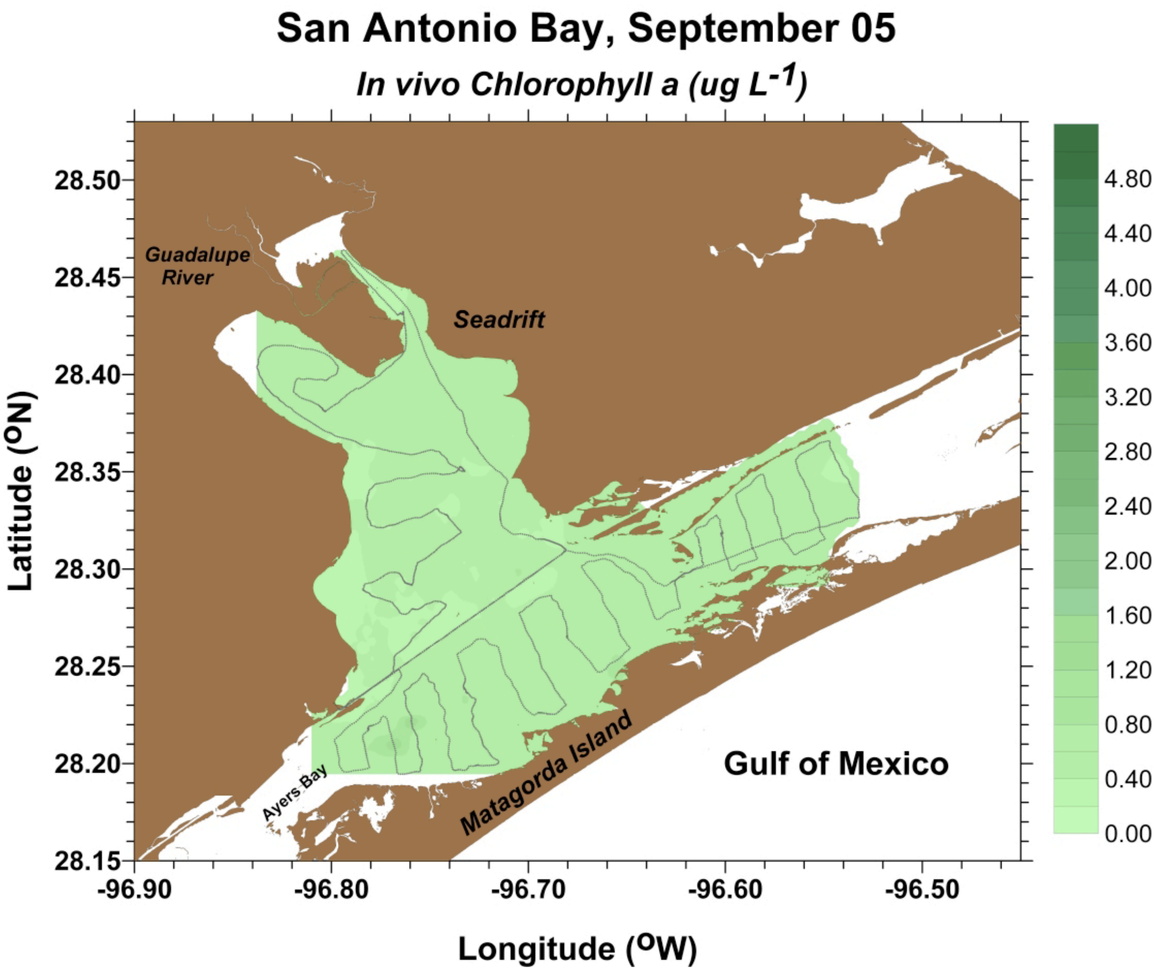
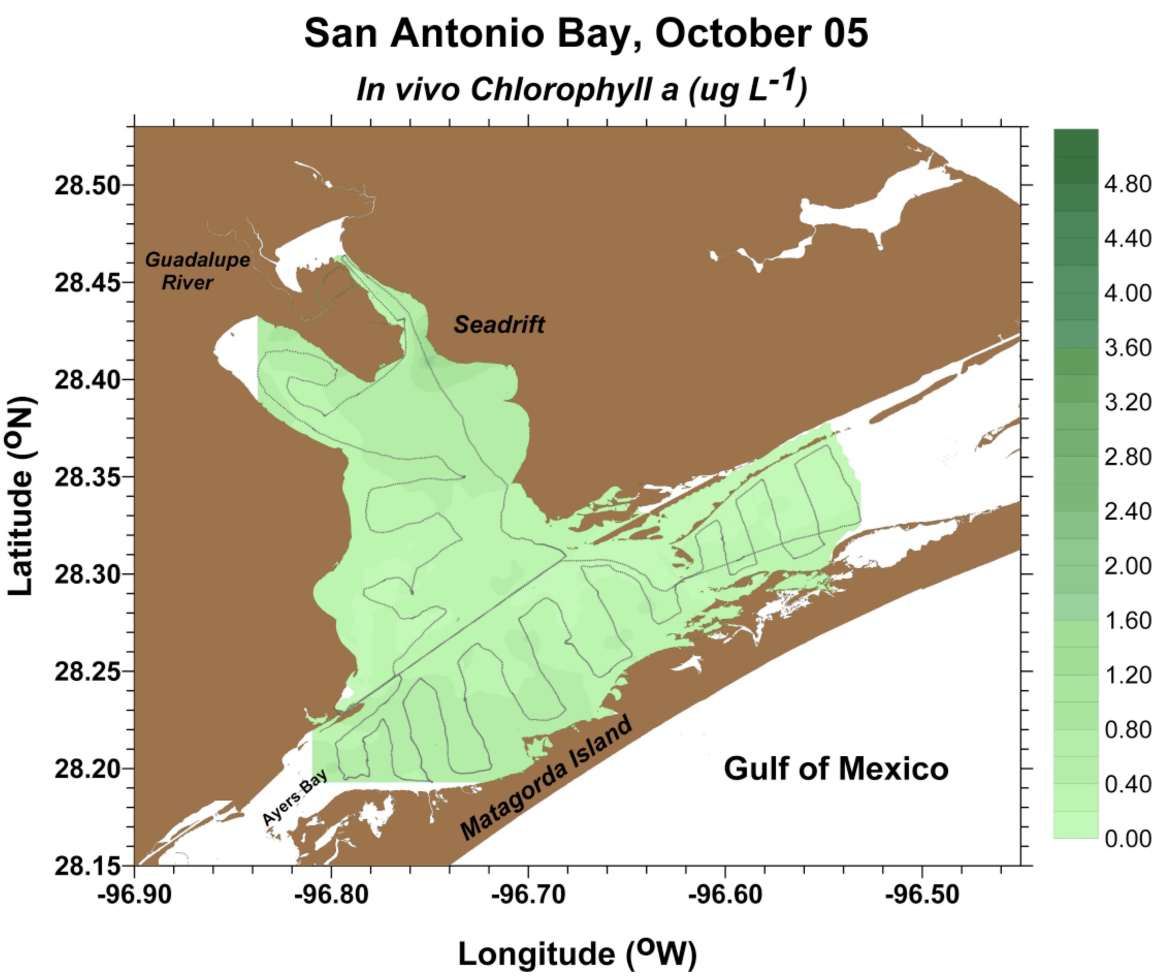
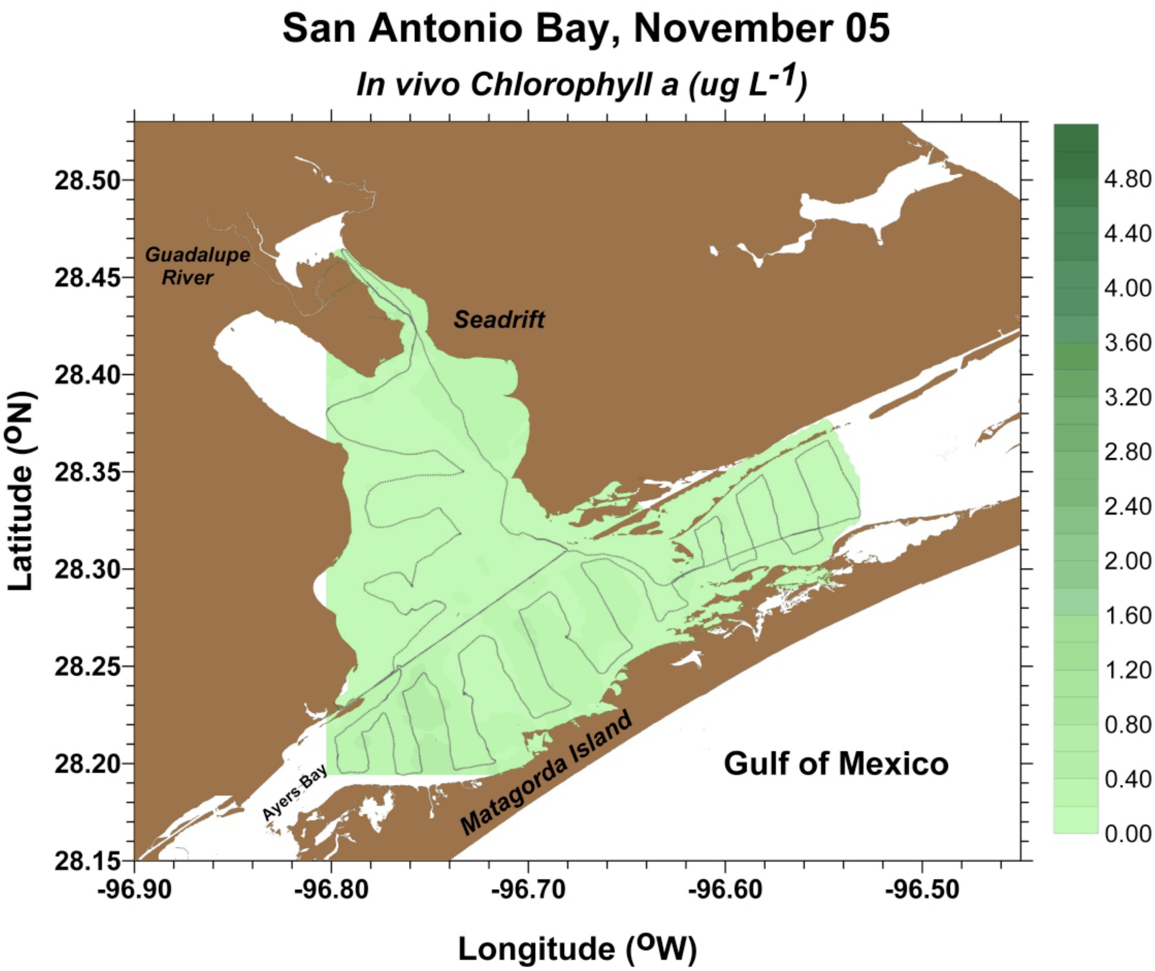
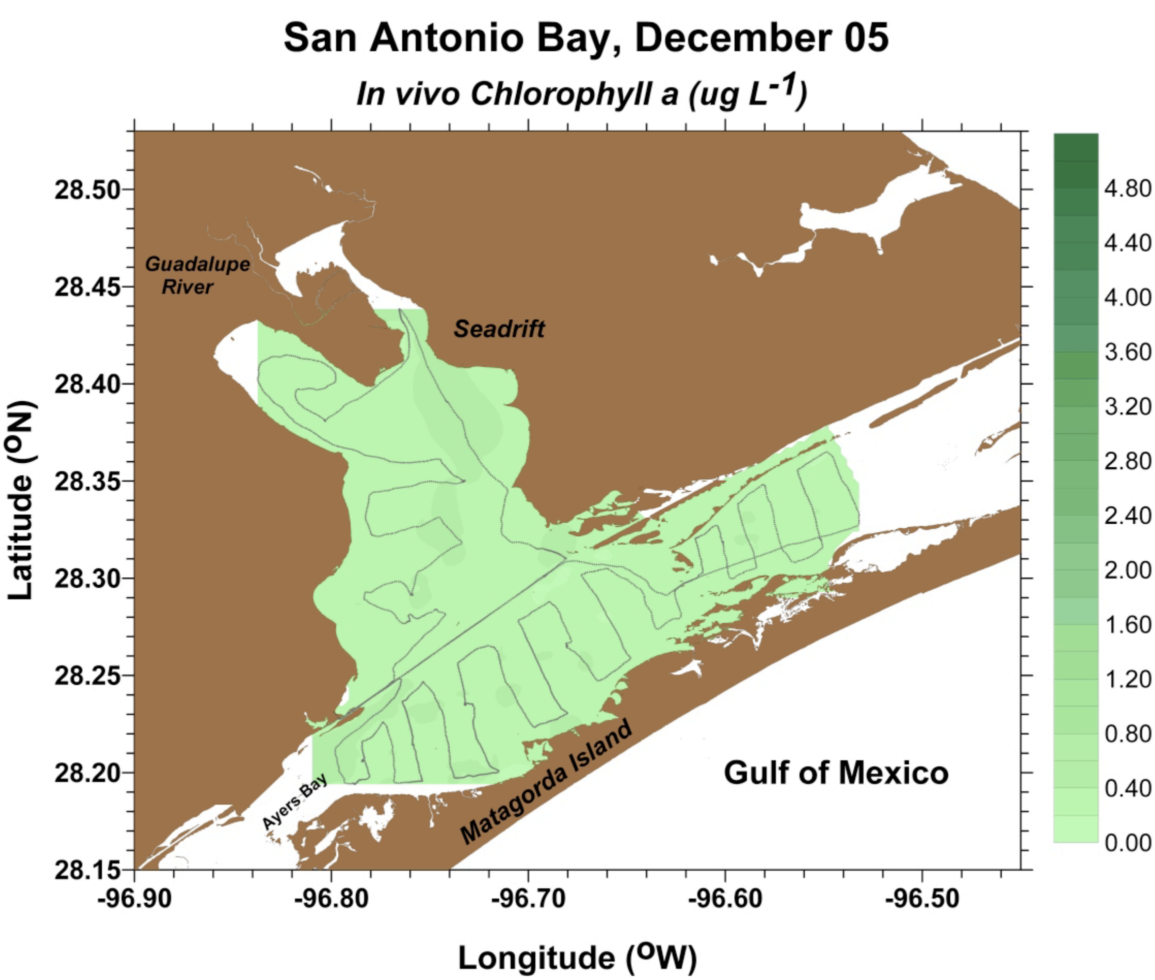
0.00

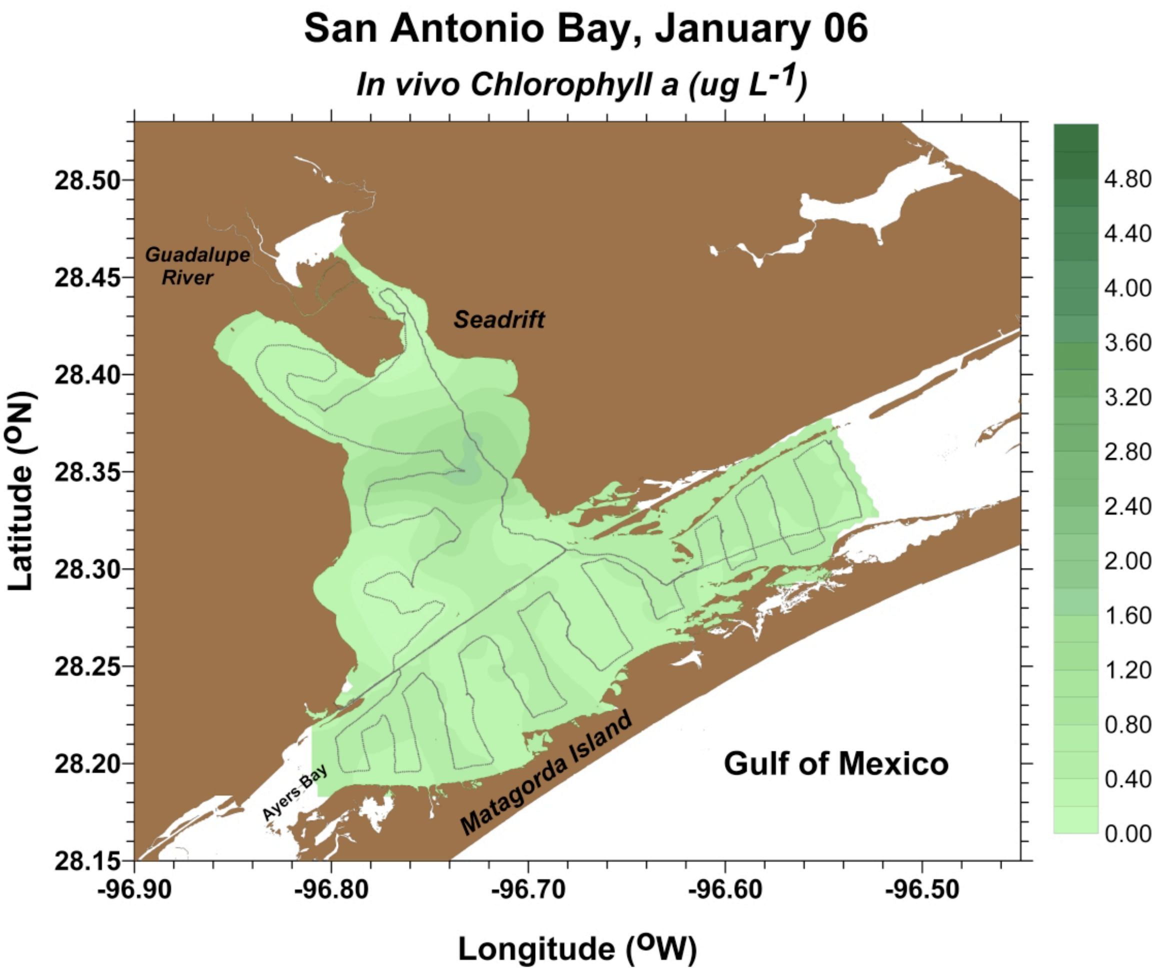

San Antonio Bay, August 05
In vivo Chlorophyll a (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00

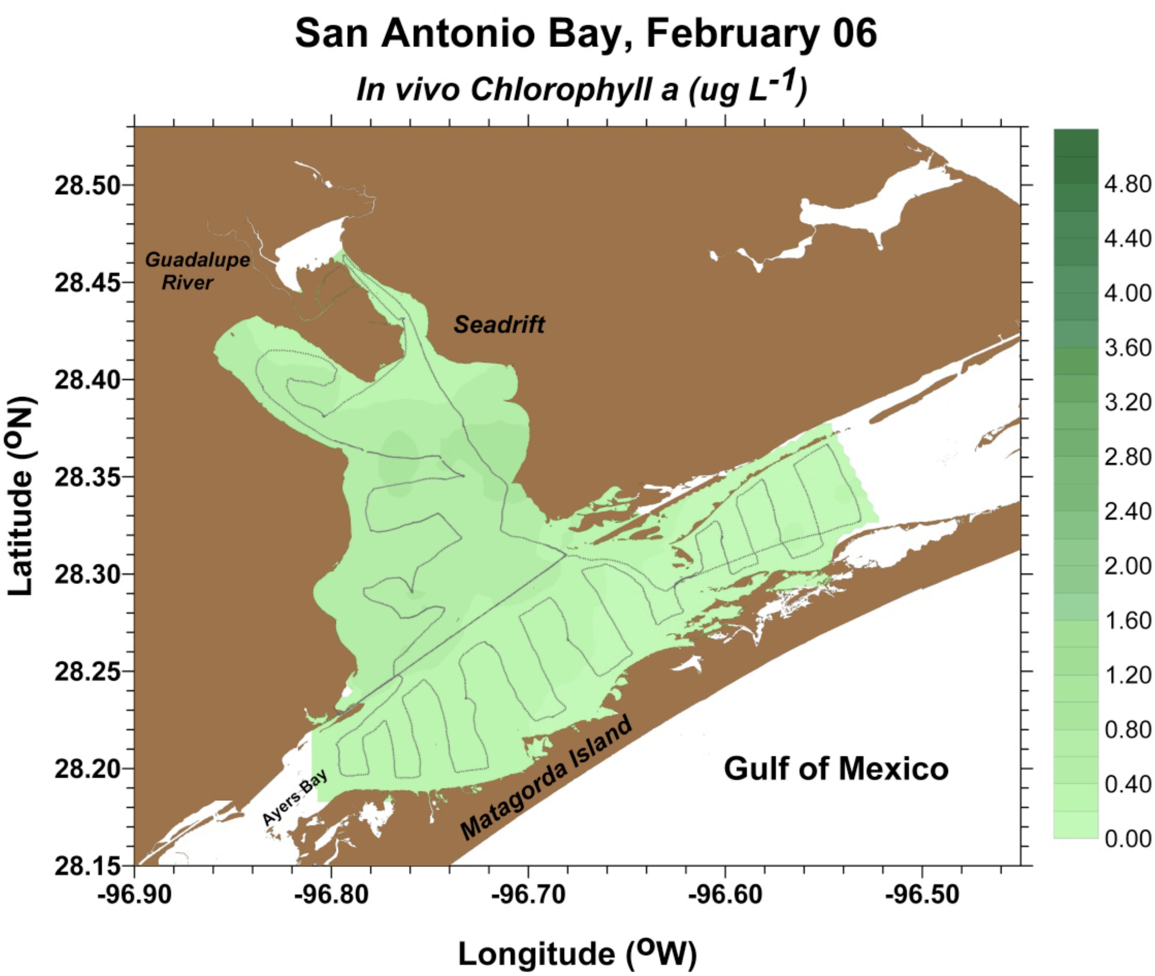

San Antonio Bay, September 05
In vivo Chlorophyll a (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
Longitude (oW)
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00

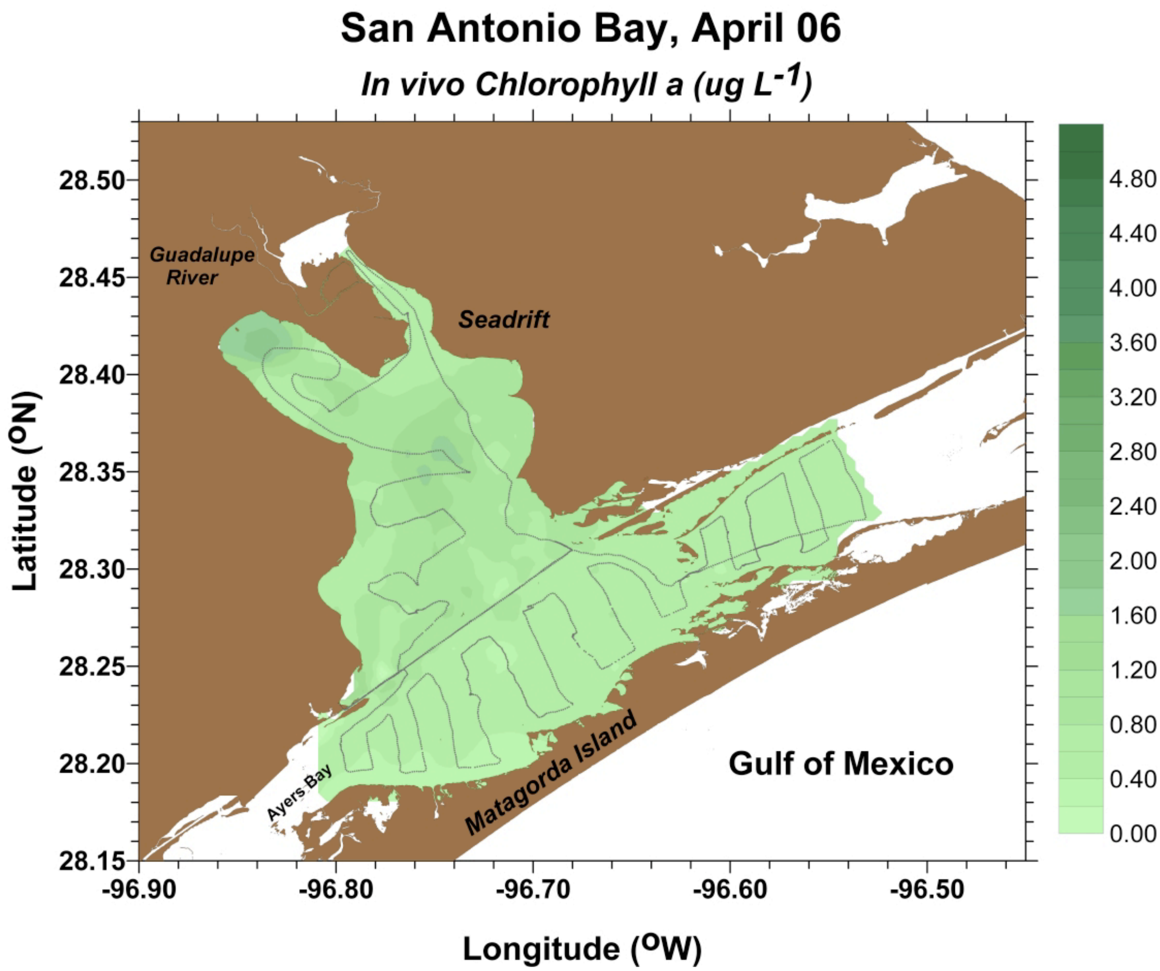

San Antonio Bay, October 05
In vivo Chlorophyll a (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
Longitude (oW)
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00

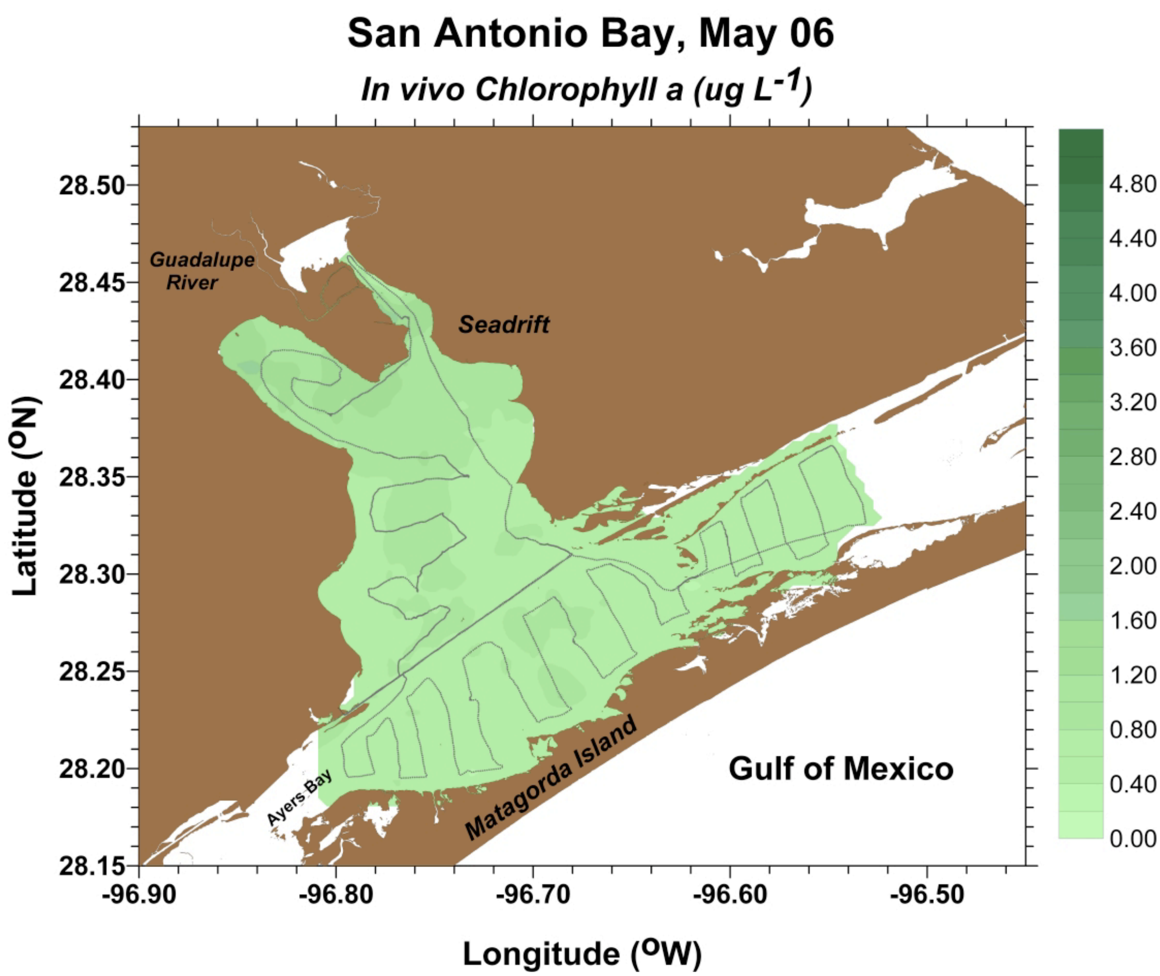

San Antonio Bay, November 05
In vivo Chlorophyll a (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00

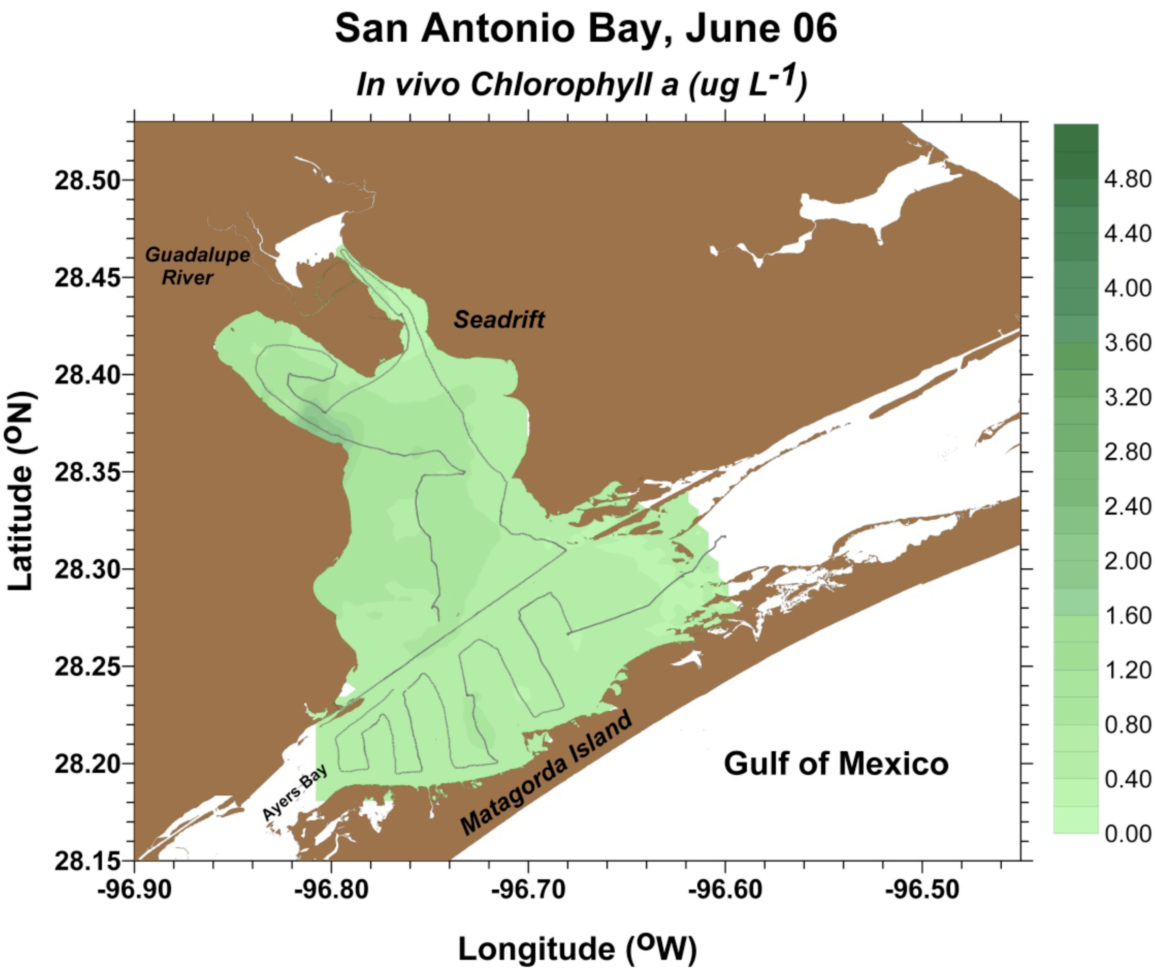

San Antonio Bay, December 05
In vivo Chlorophyll a (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00

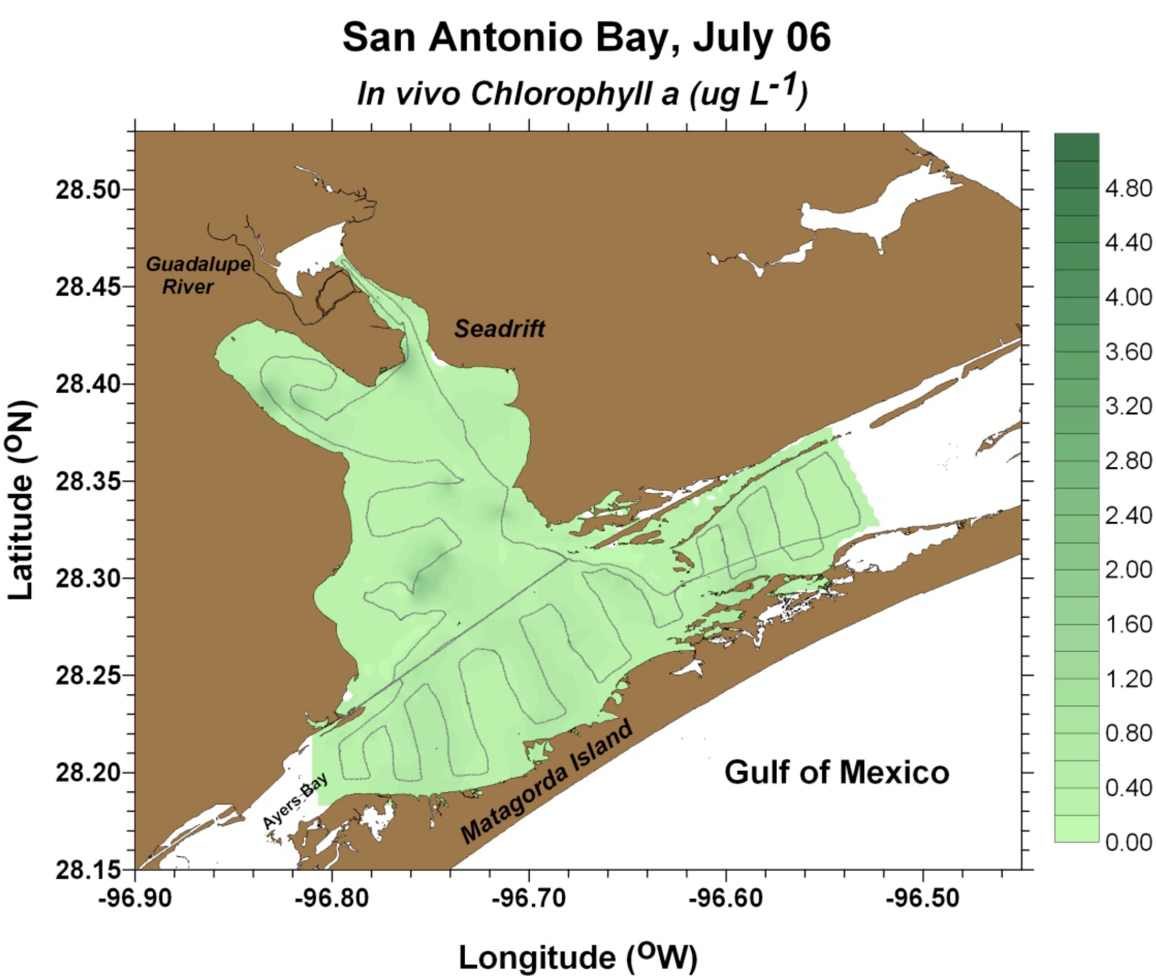

San Antonio Bay, January 06
In vivo Chlorophyll a (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00

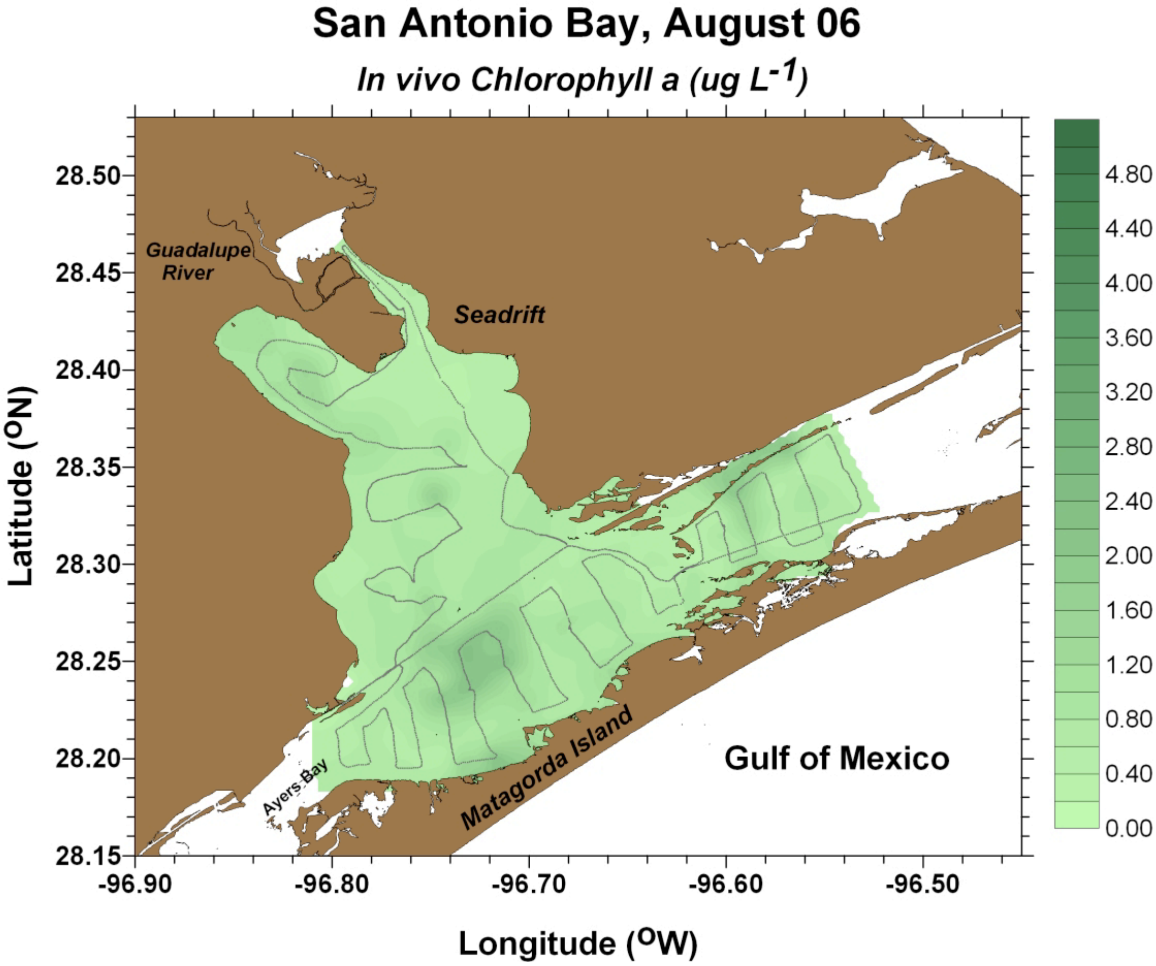

San Antonio Bay, February 06
In vivo Chlorophyll a (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00

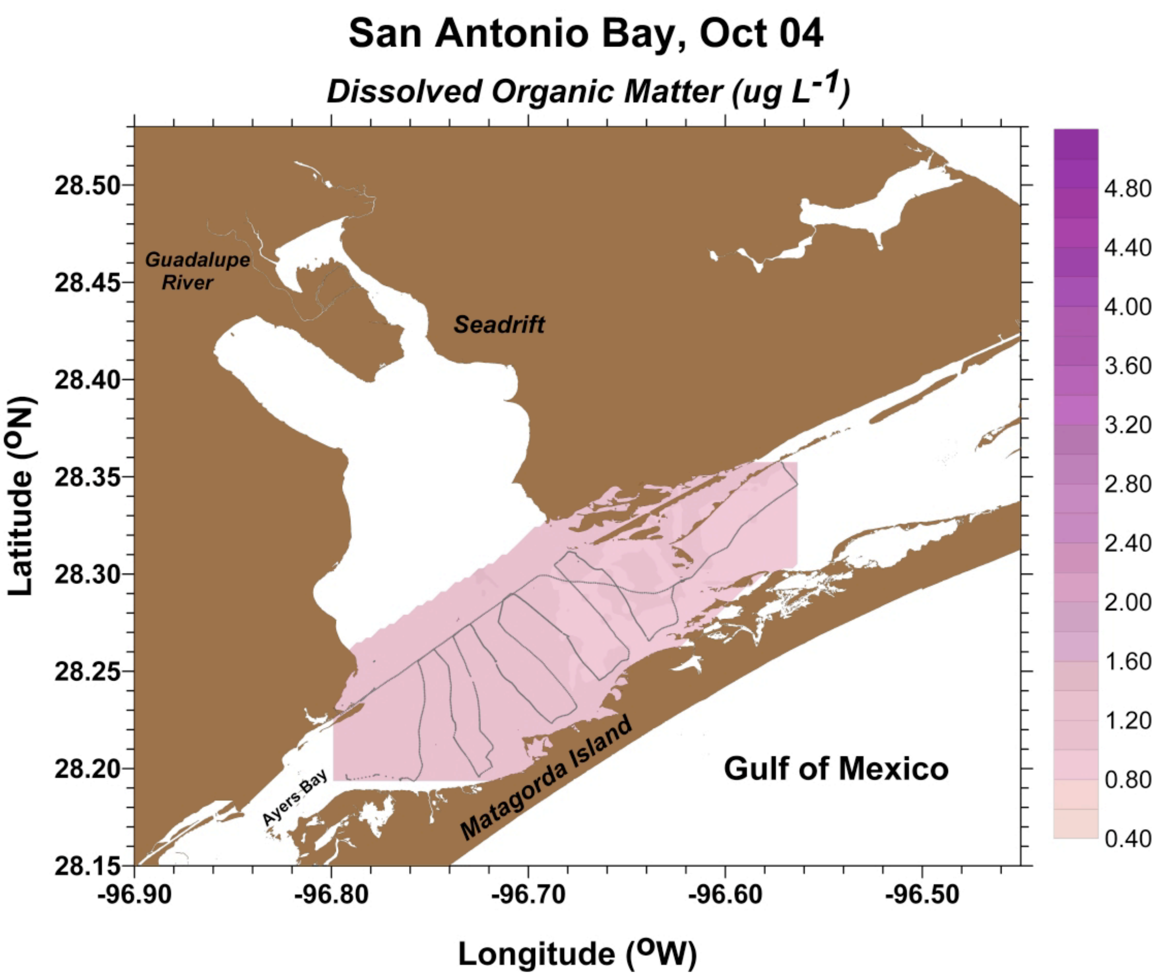

San Antonio Bay, April 06
In vivo Chlorophyll a (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00

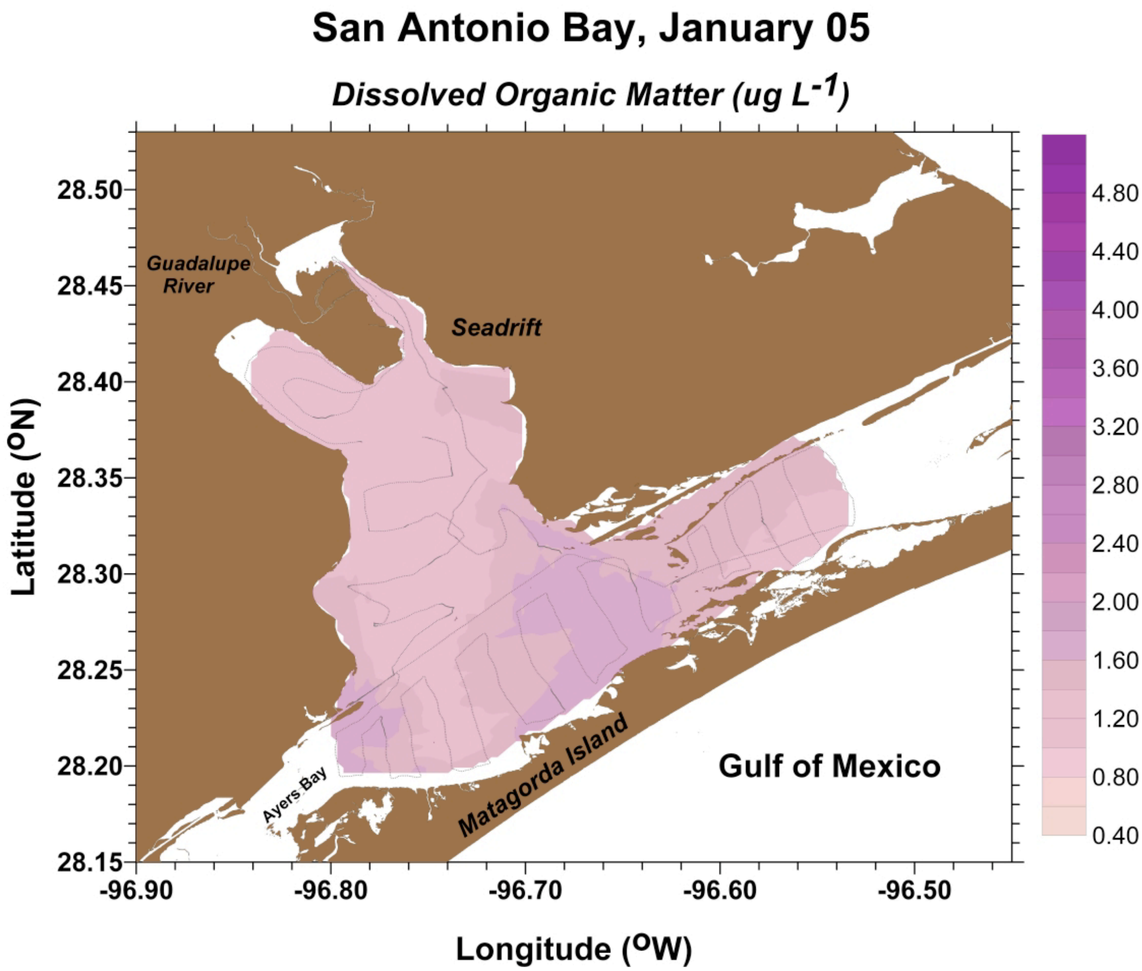

San Antonio Bay, May 06
In vivo Chlorophyll a (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00

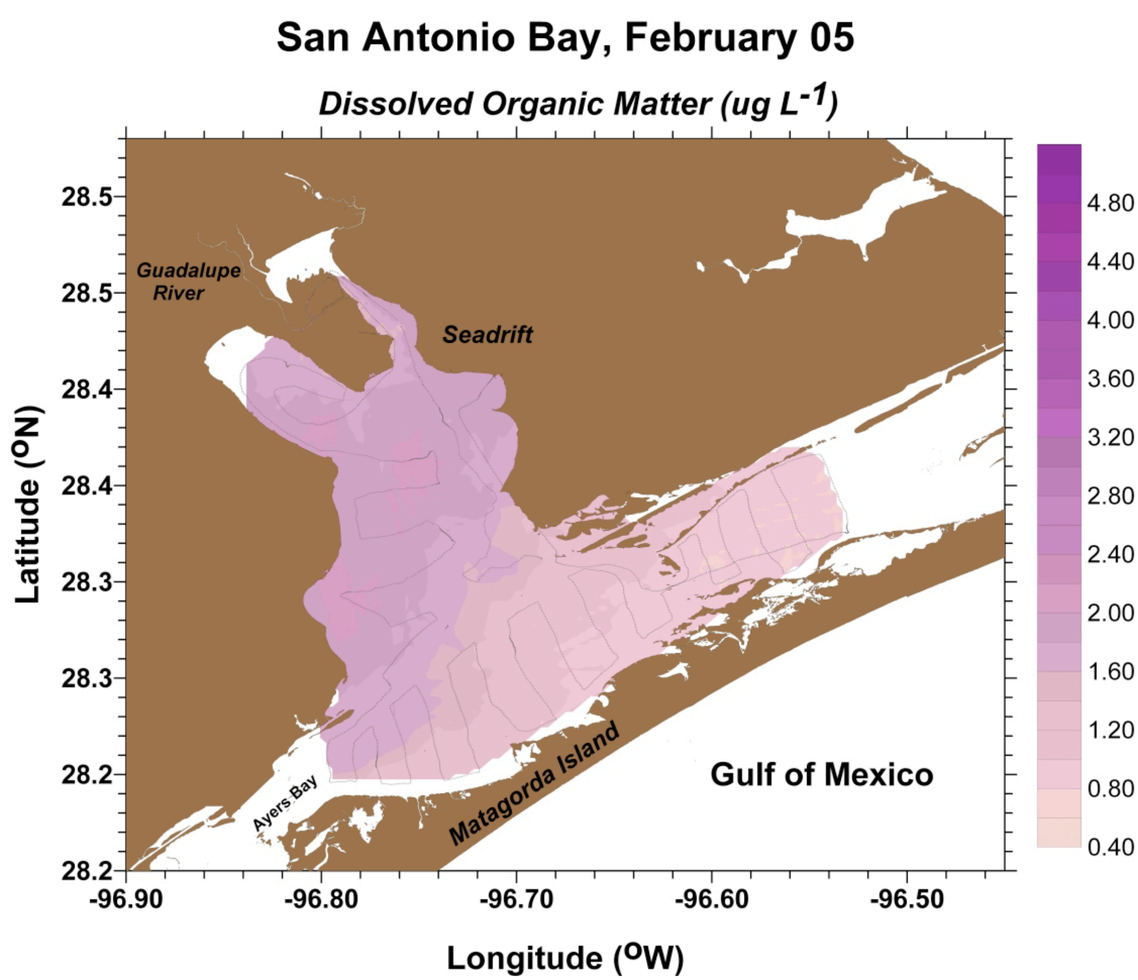

San Antonio Bay, June 06
In vivo Chlorophyll a (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00


San Antonio Bay, July 06
In vivo Chlorophyll a (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00


San Antonio Bay, August 06
In vivo Chlorophyll a (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40
0.00

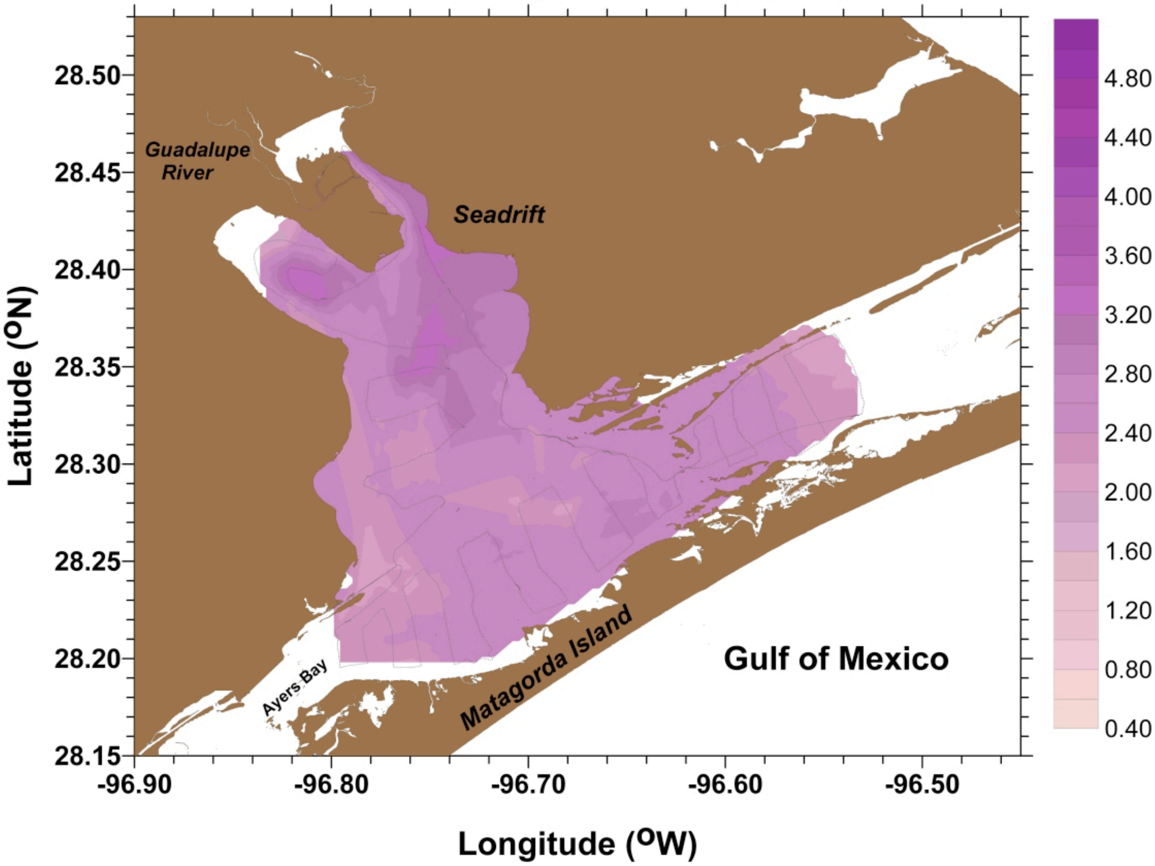

San Antonio Bay, Oct 04
Dissolved Organic Matter (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40


San Antonio Bay, January 05
Dissolved Organic Matter (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40


San Antonio Bay, February 05
Dissolved Organic Matter (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.5
28.5
28.4
28.4
28.3
28.3
28.2
28.2
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40

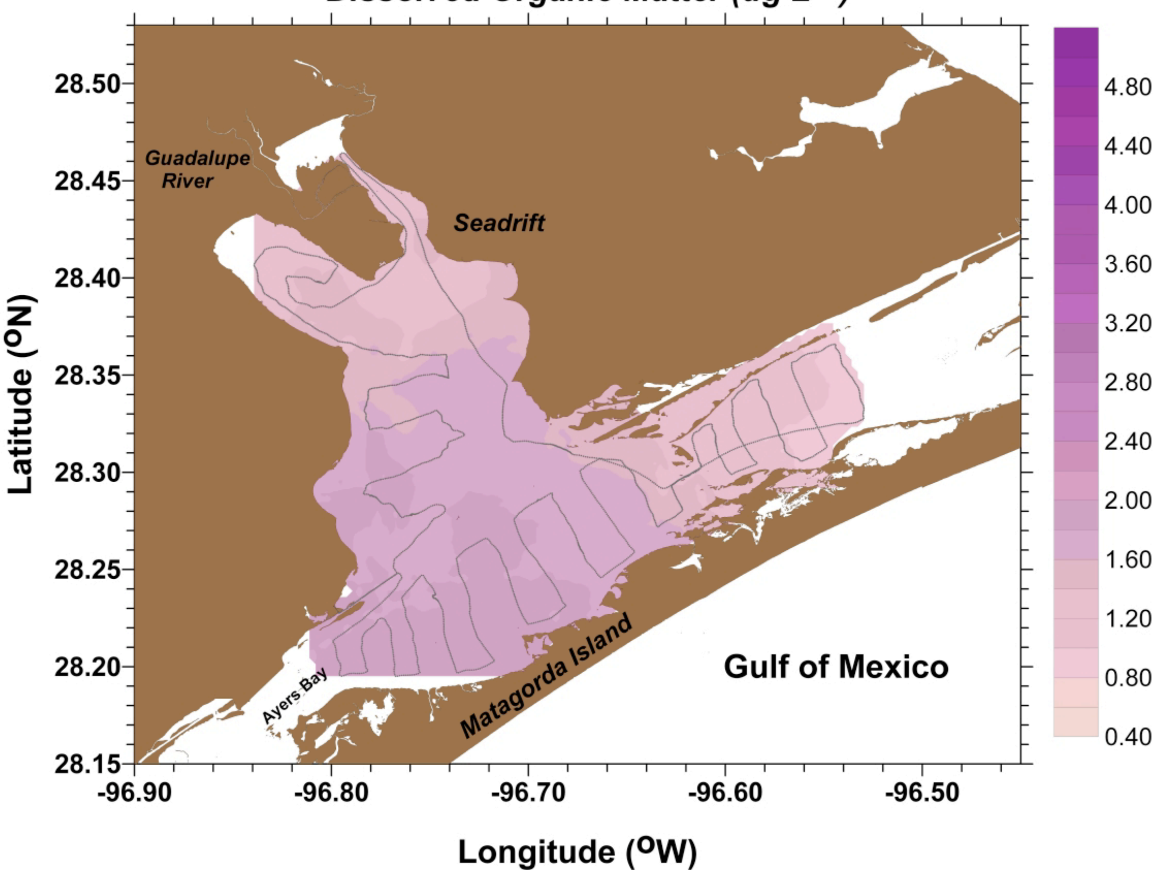
San Antonio Bay, March 05

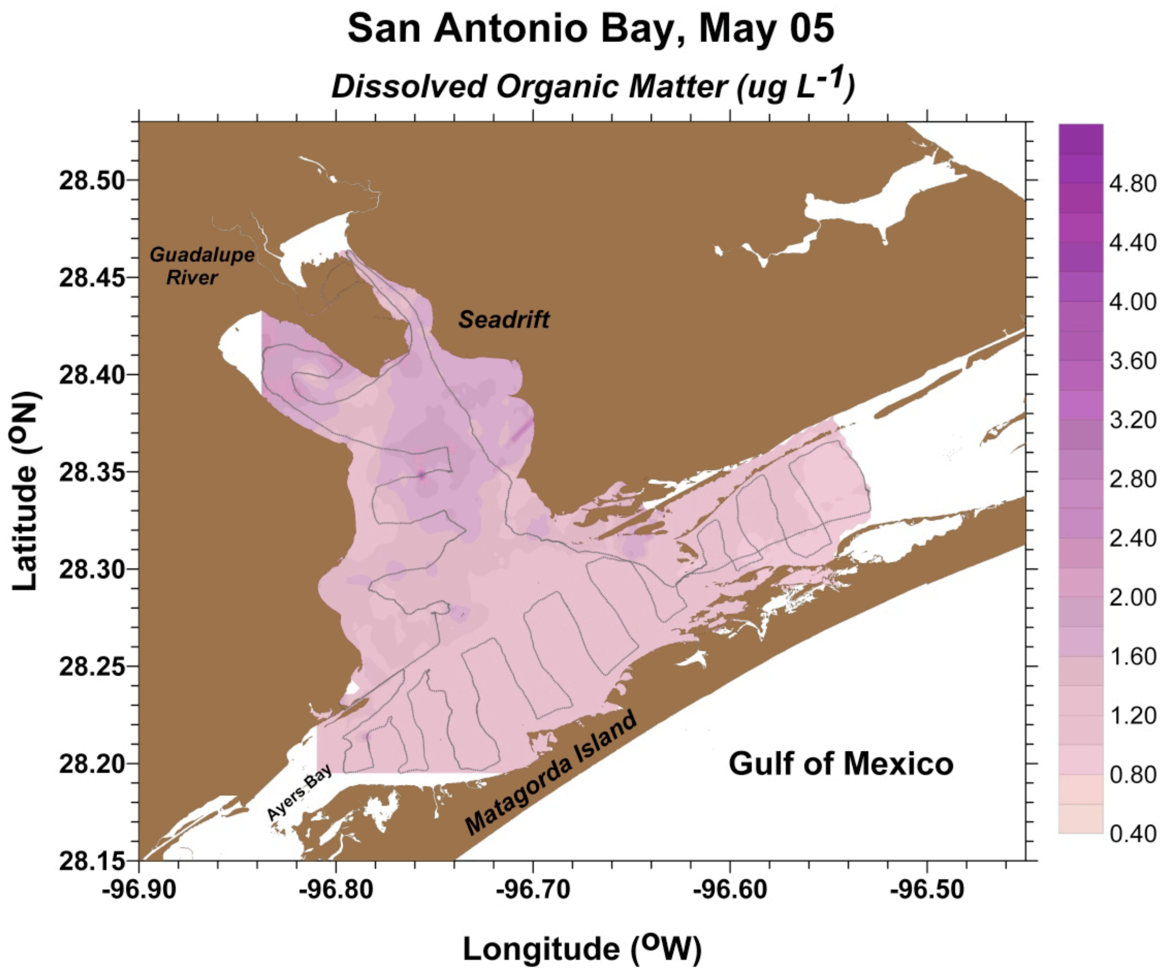
Dissolved Organic Matter (ug L^{-1})

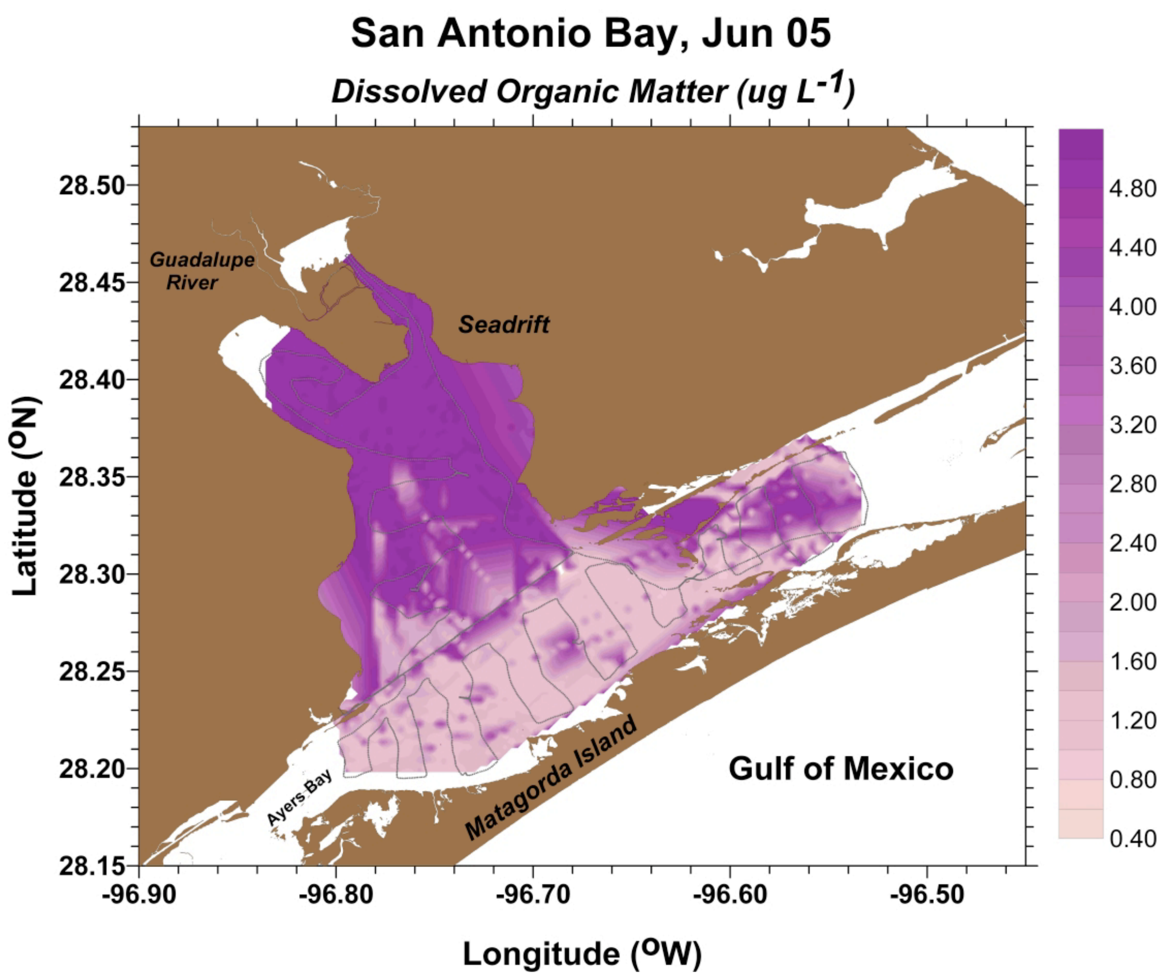


San Antonio Bay, April 05

Dissolved Organic Matter (ug L^{-1})

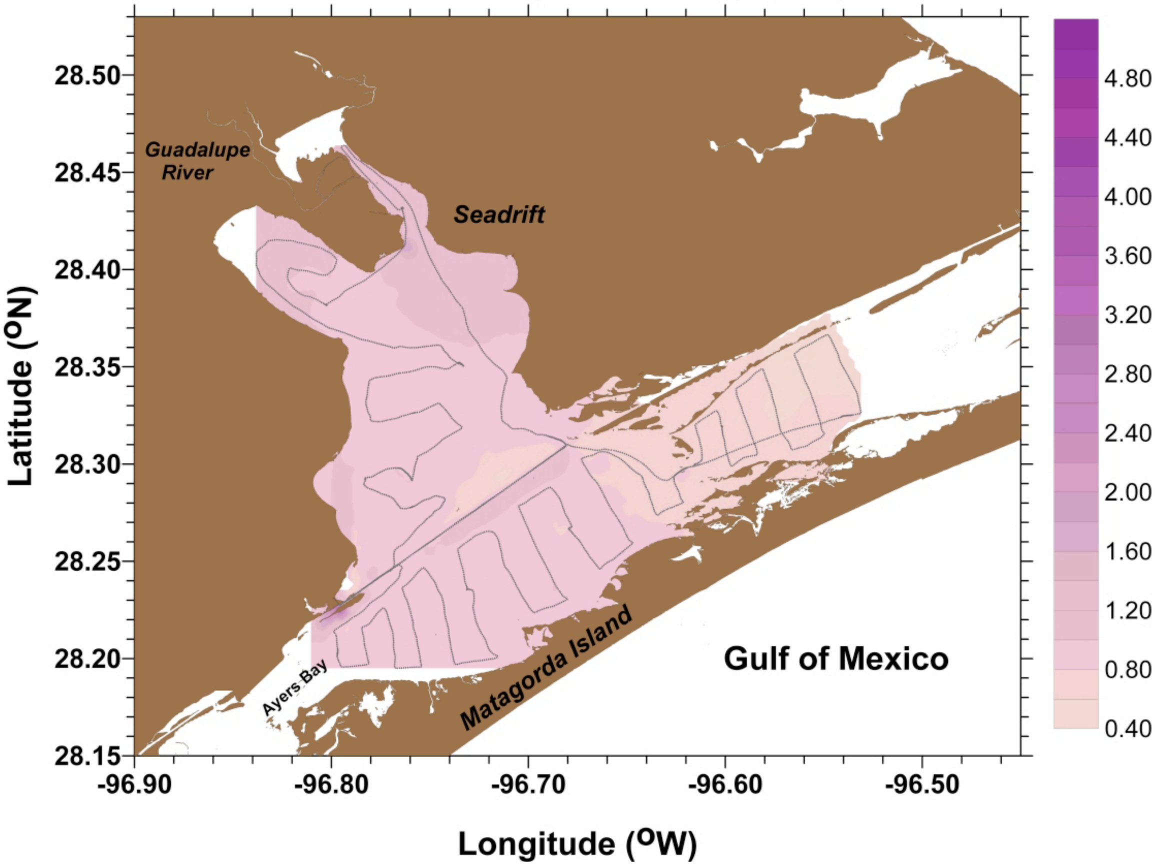



San Antonio Bay, May 05
Dissolved Organic Matter (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40


San Antonio Bay, Jun 05
Dissolved Organic Matter (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
4.80
4.40
4.00
3.60
3.20
2.80
2.40
2.00
1.60
1.20
0.80
0.40

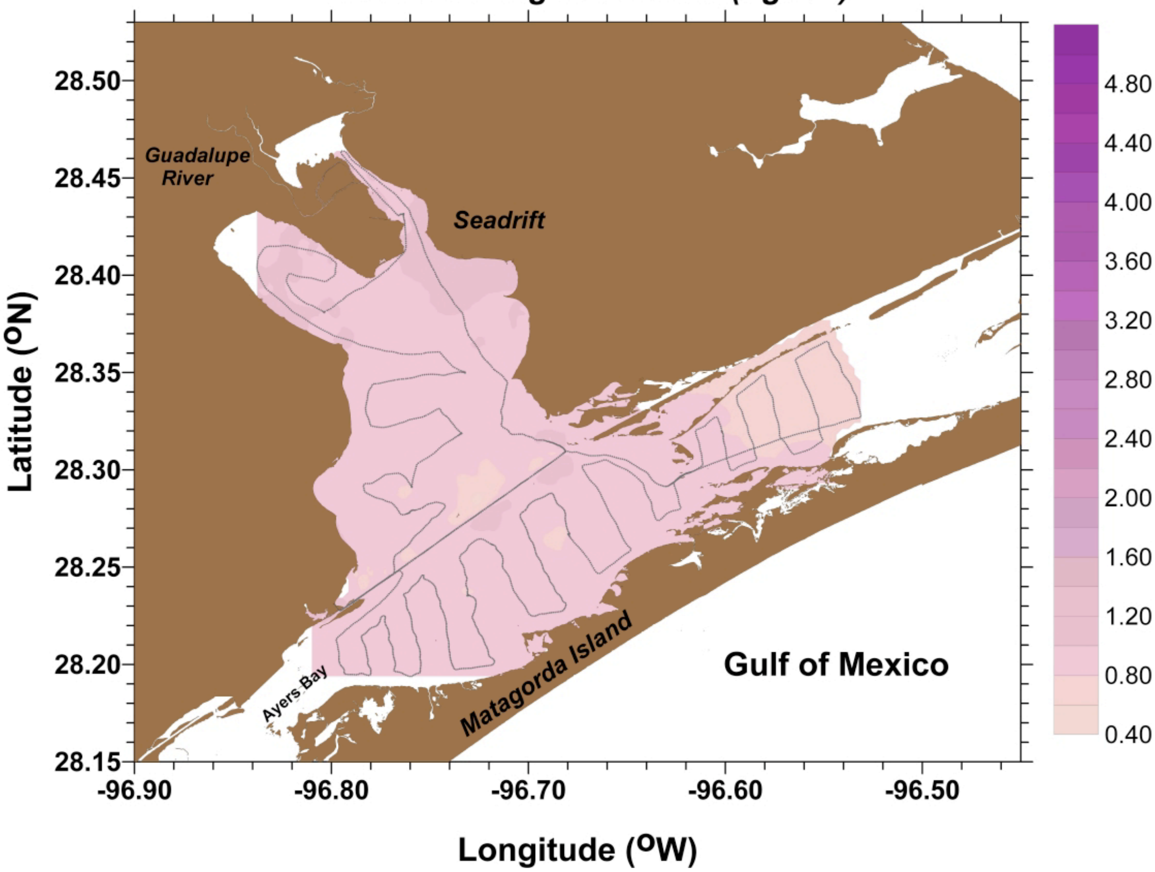
San Antonio Bay, July 05

Dissolved Organic Matter (ug L-1)



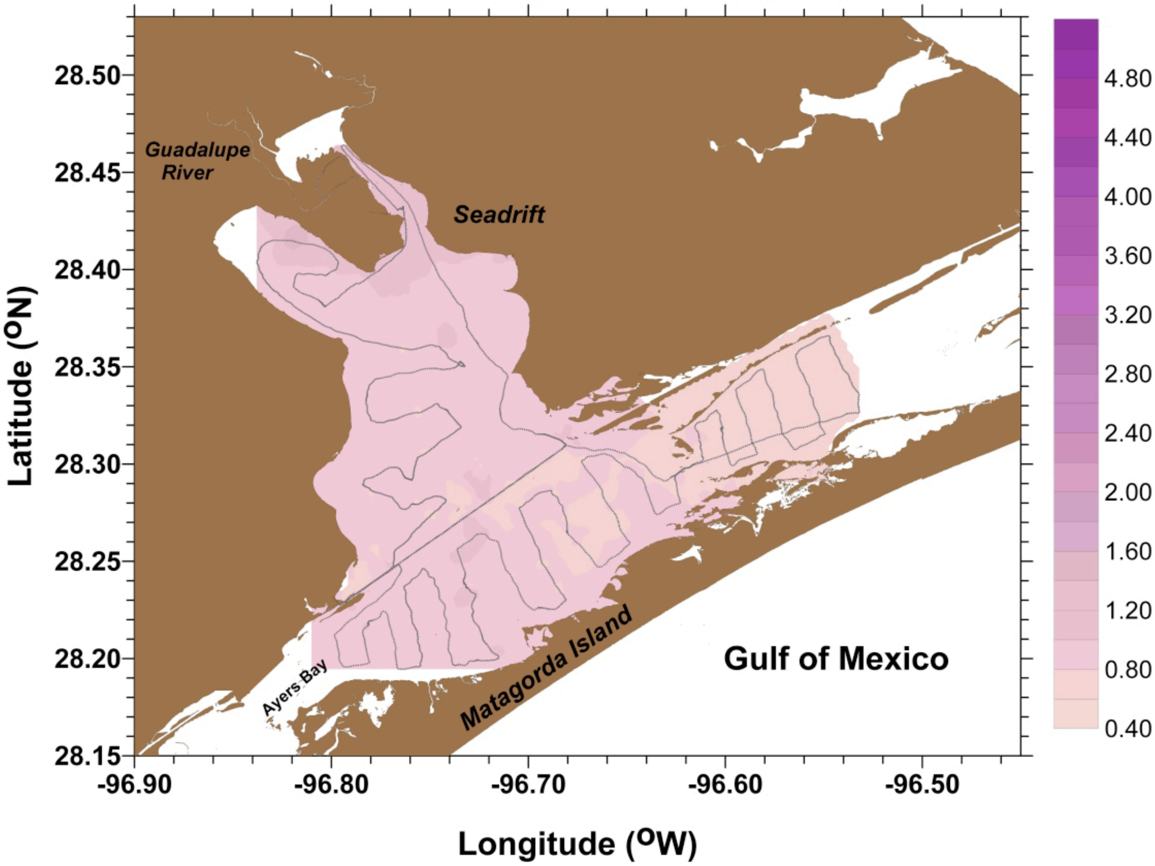
San Antonio Bay, August 05

Dissolved Organic Matter (ug L-1)



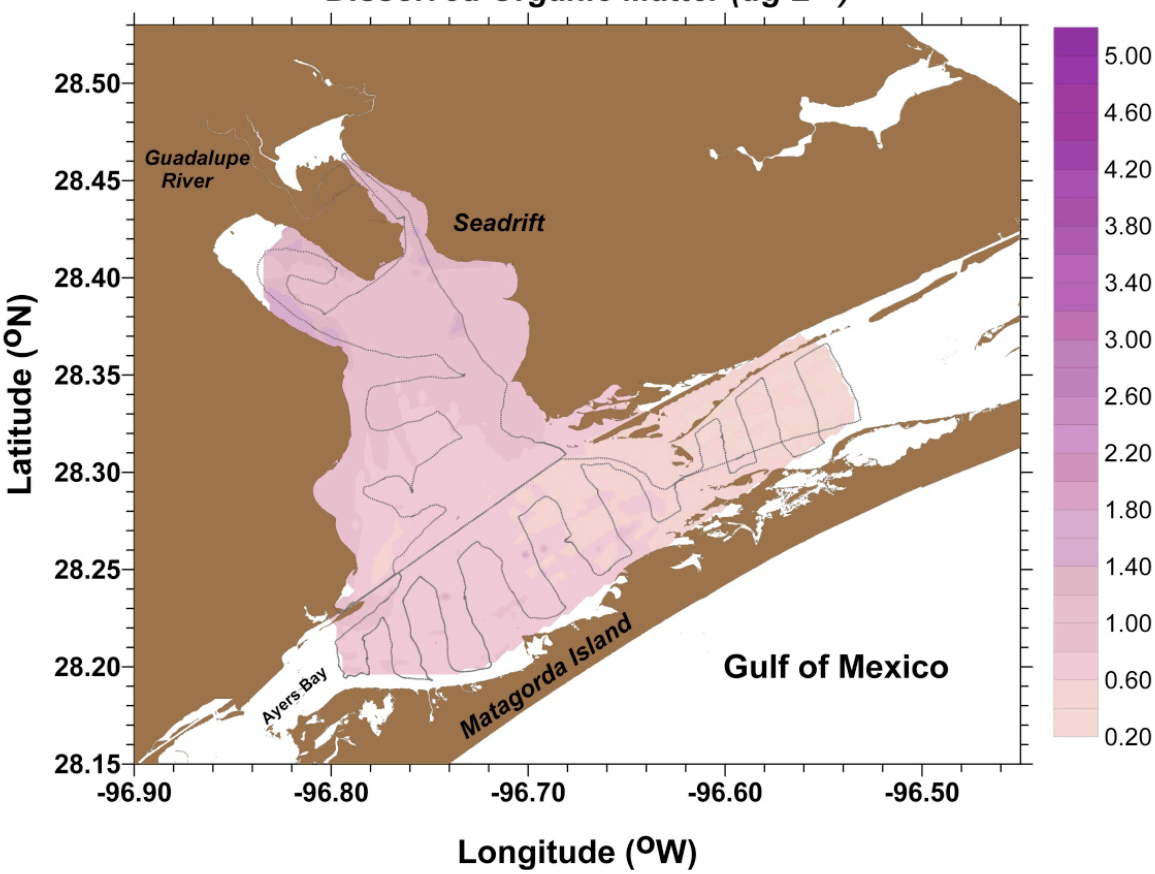
San Antonio Bay, September 05

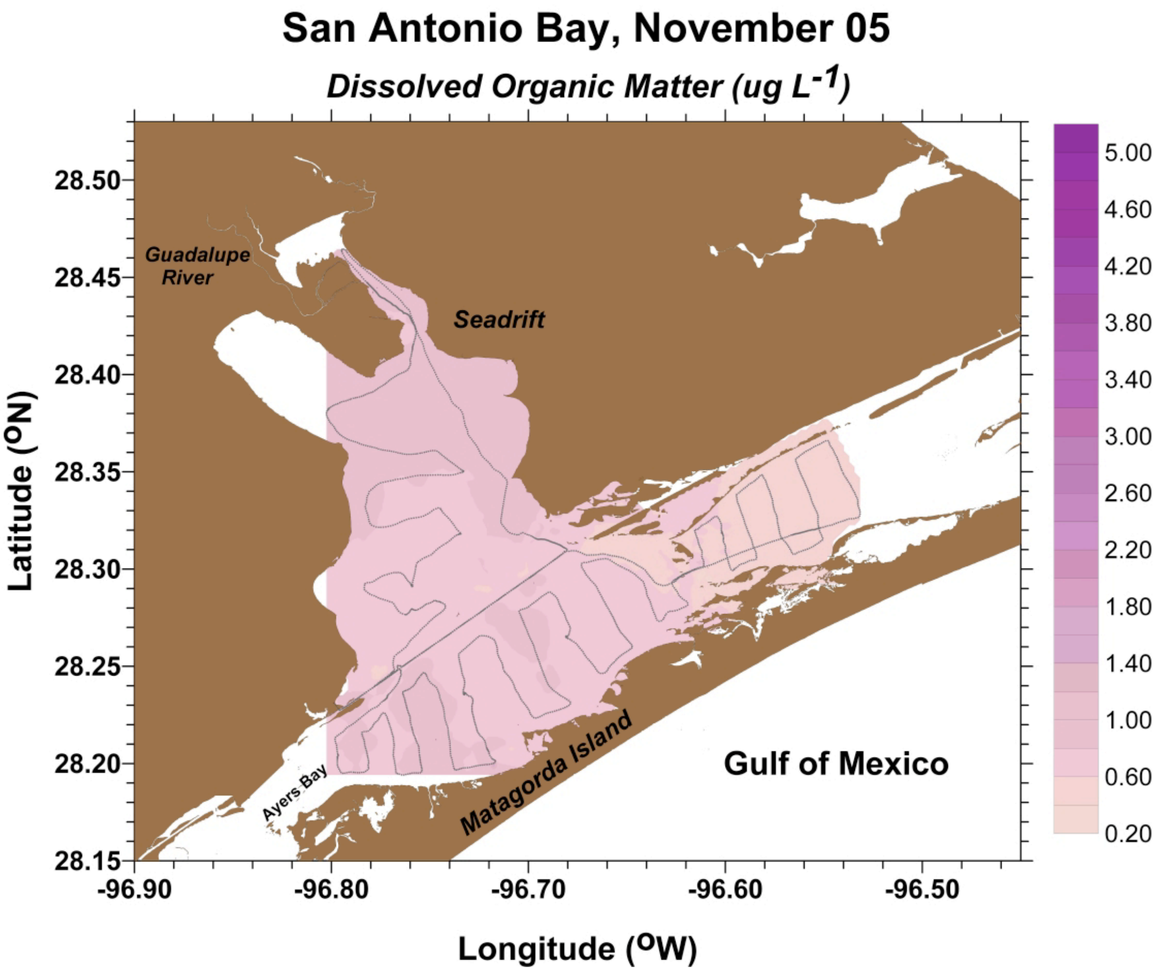
Dissolved Organic Matter (ug L^{-1})

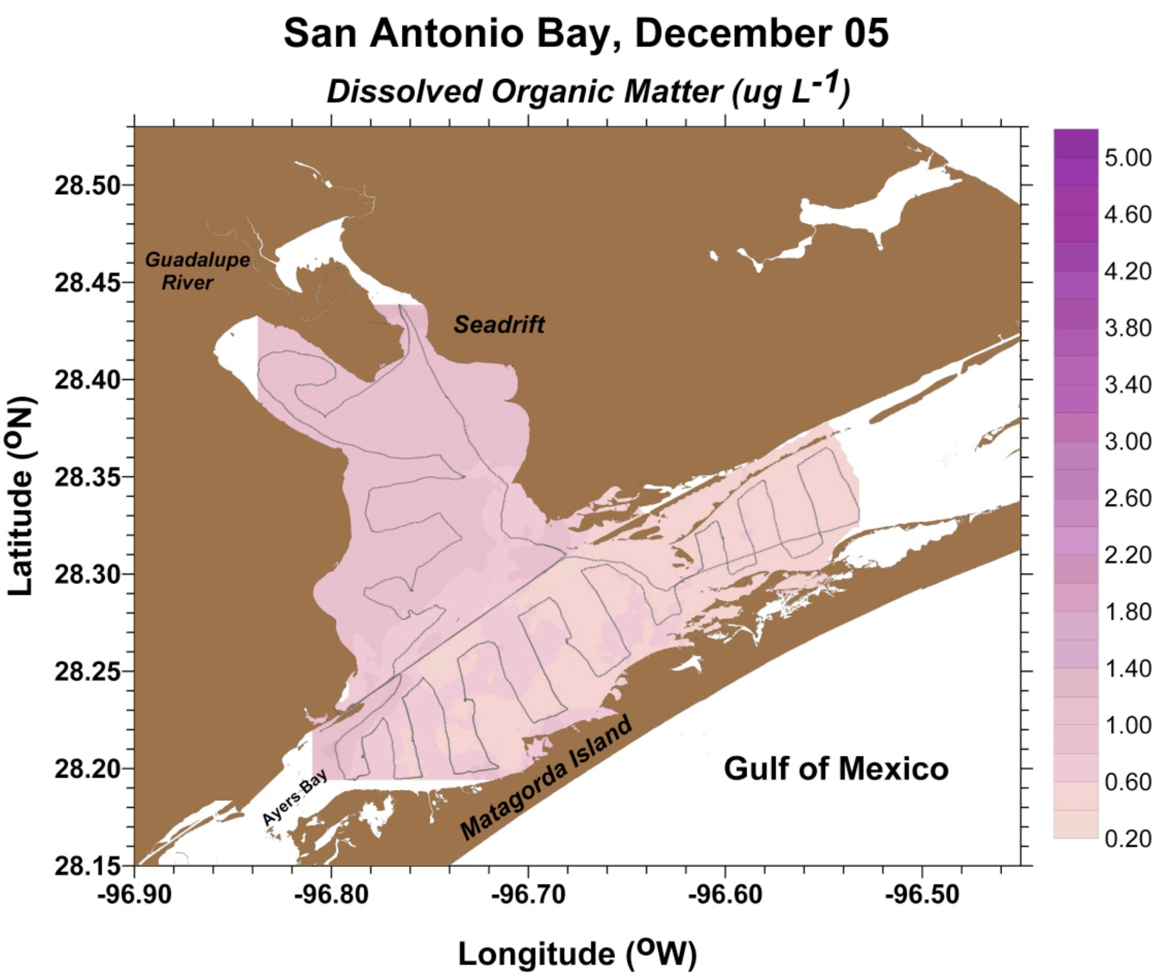


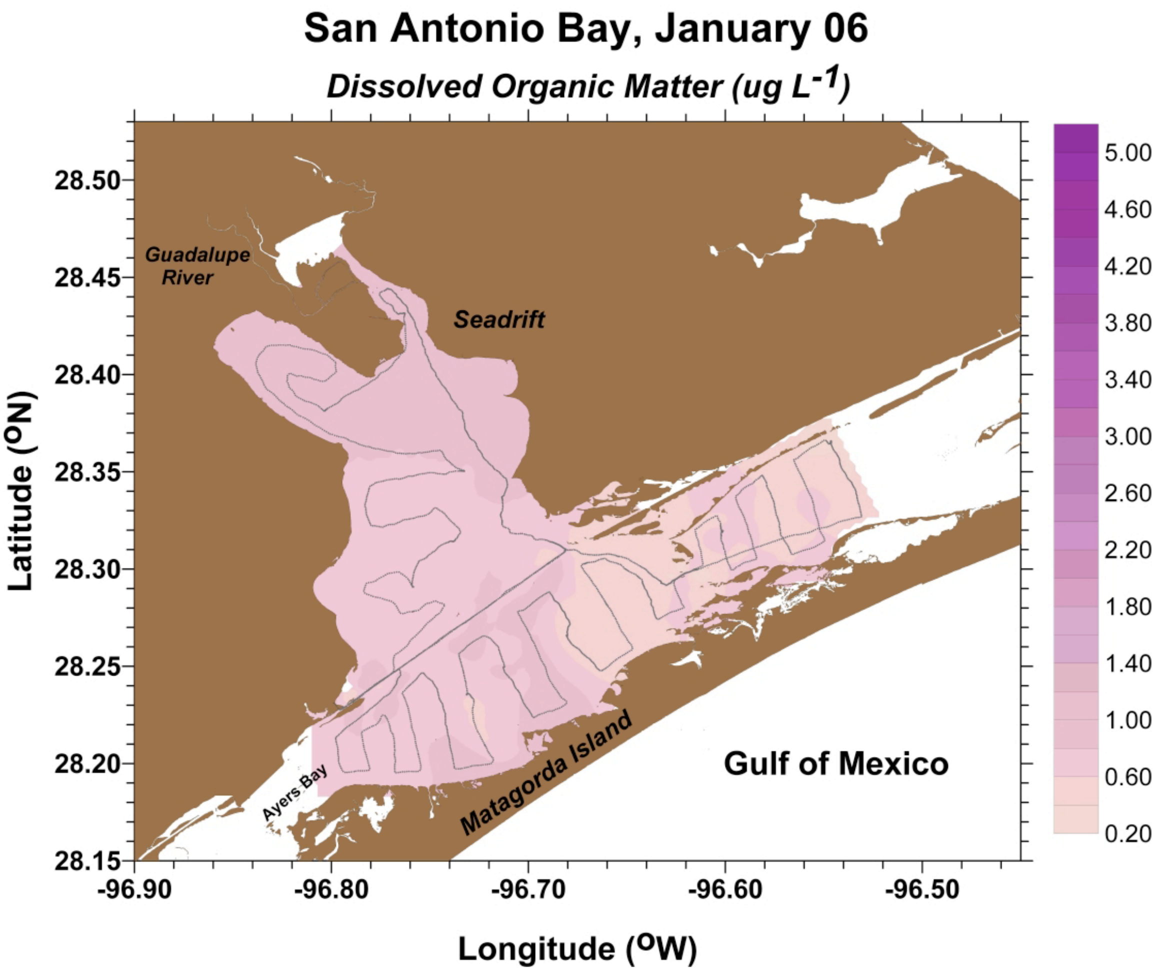
San Antonio Bay, October 05

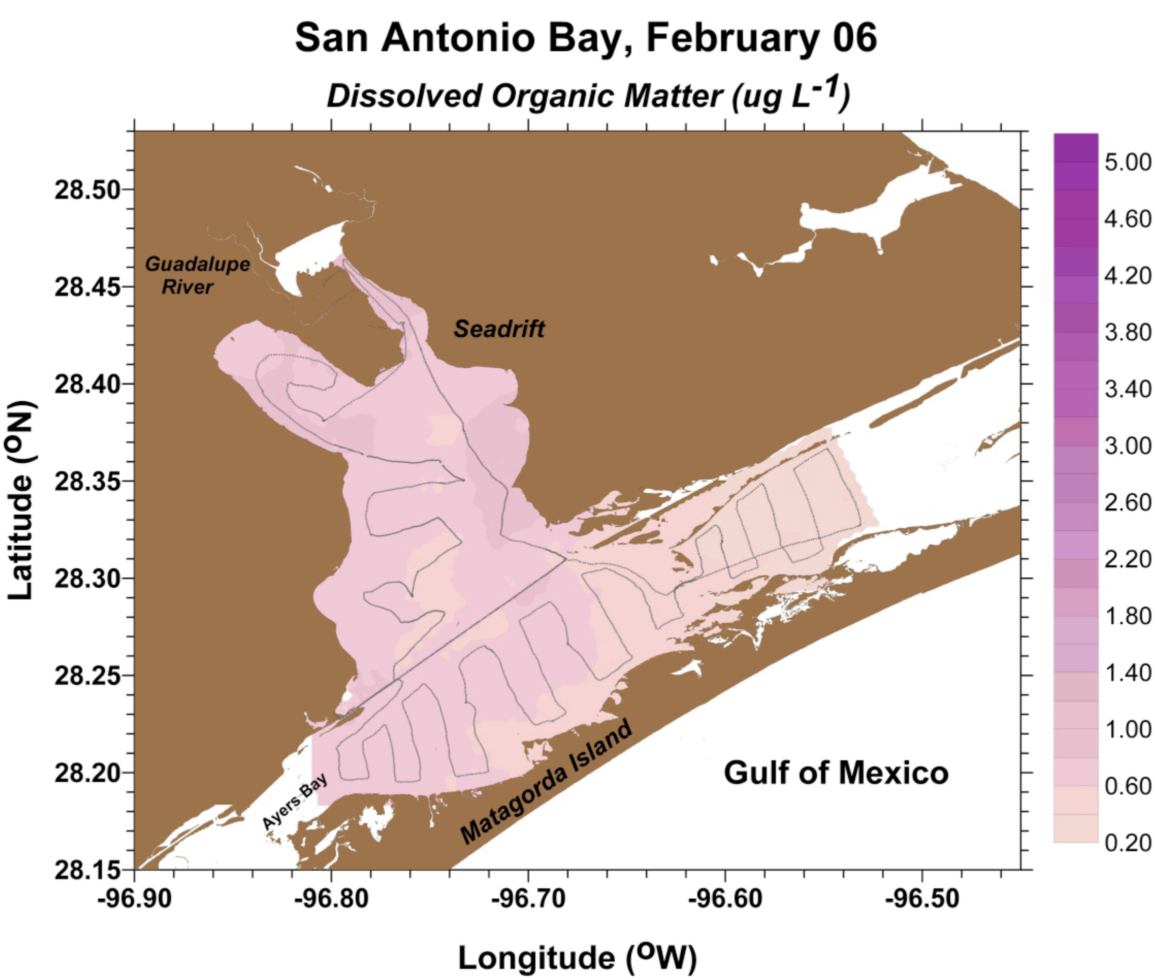
Dissolved Organic Matter (ug L^{-1})




San Antonio Bay, November 05
Dissolved Organic Matter (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
5.00
4.60
4.20
3.80
3.40
3.00
2.60
2.20
1.80
1.40
1.00
0.60
0.20

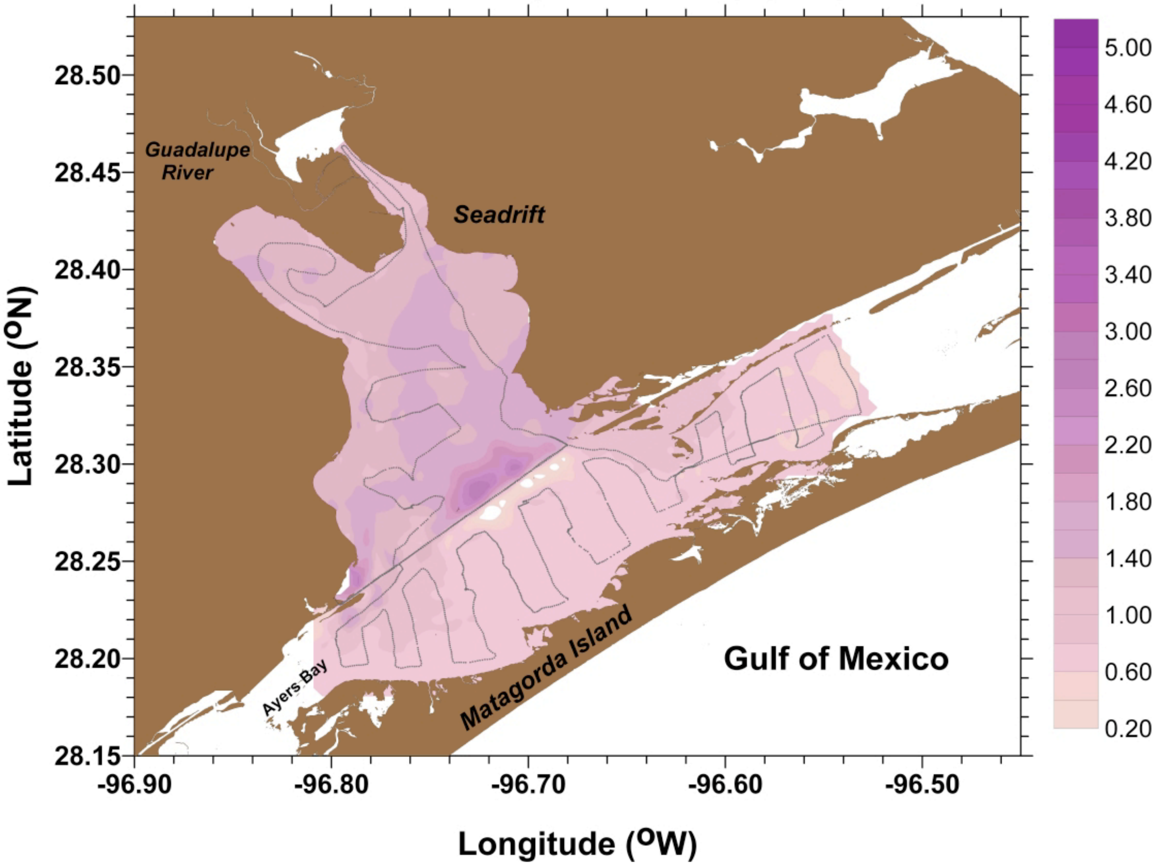

San Antonio Bay, December 05
Dissolved Organic Matter (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
5.00
4.60
4.20
3.80
3.40
3.00
2.60
2.20
1.80
1.40
1.00
0.60
0.20


San Antonio Bay, January 06
Dissolved Organic Matter (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
5.00
4.60
4.20
3.80
3.40
3.00
2.60
2.20
1.80
1.40
1.00
0.60
0.20


San Antonio Bay, February 06
Dissolved Organic Matter (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
5.00
4.60
4.20
3.80
3.40
3.00
2.60
2.20
1.80
1.40
1.00
0.60
0.20

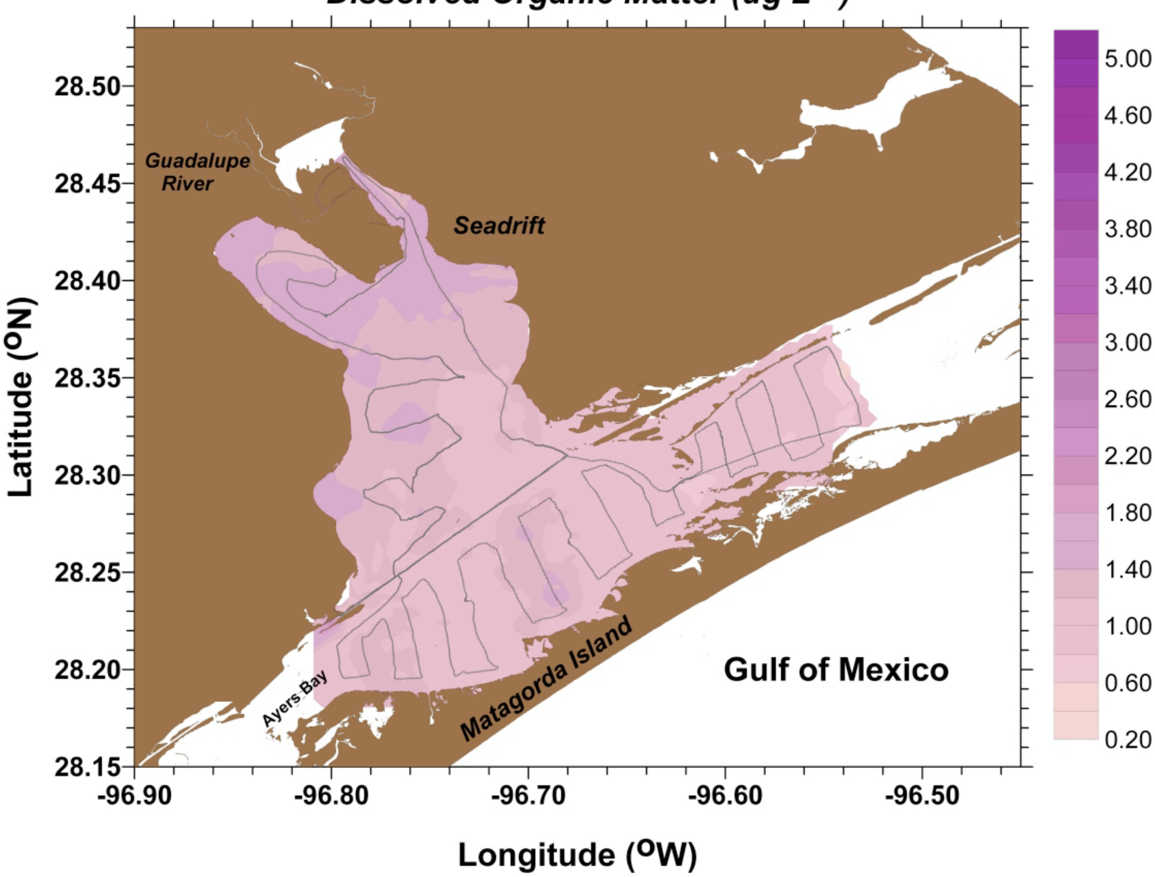
San Antonio Bay, April 06

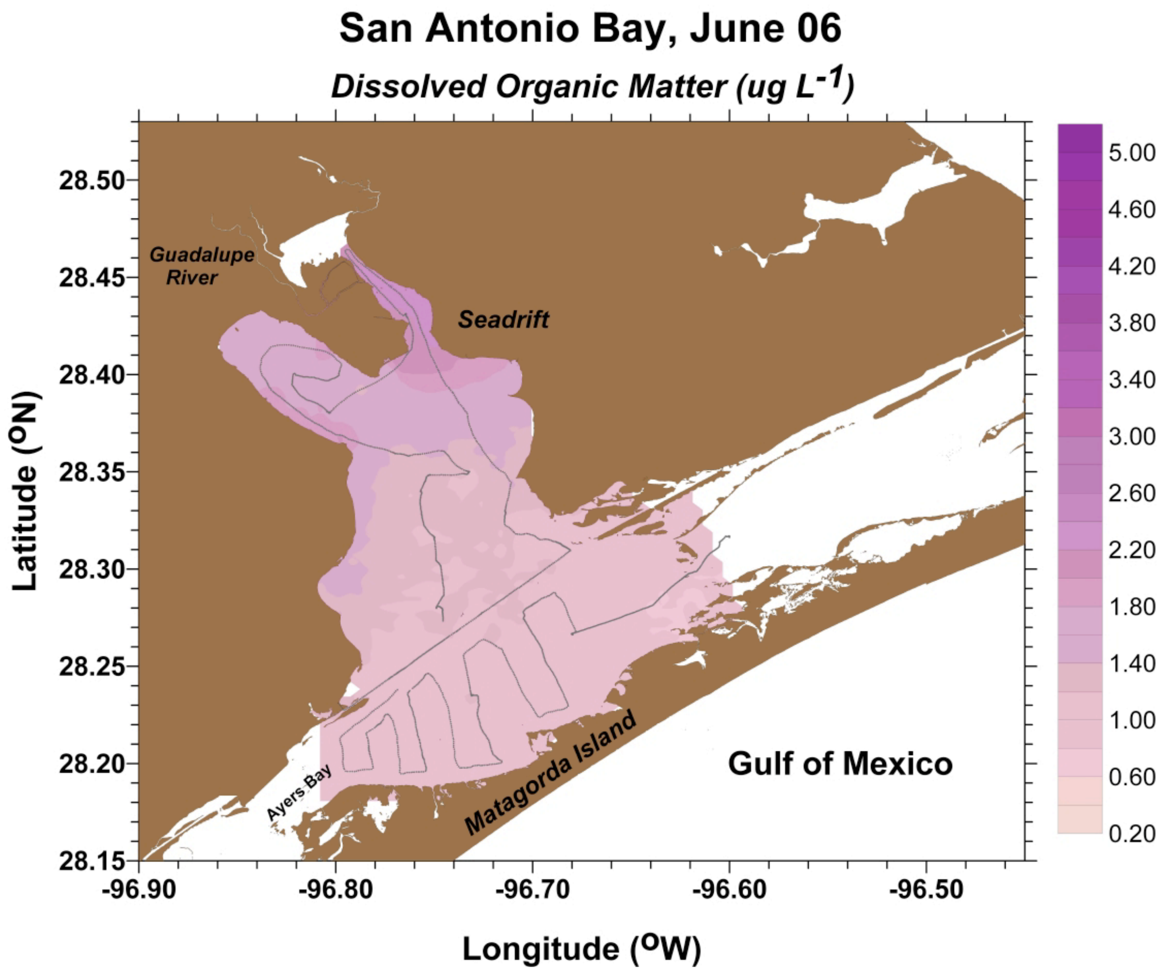
Dissolved Organic Matter (ug L^{-1})

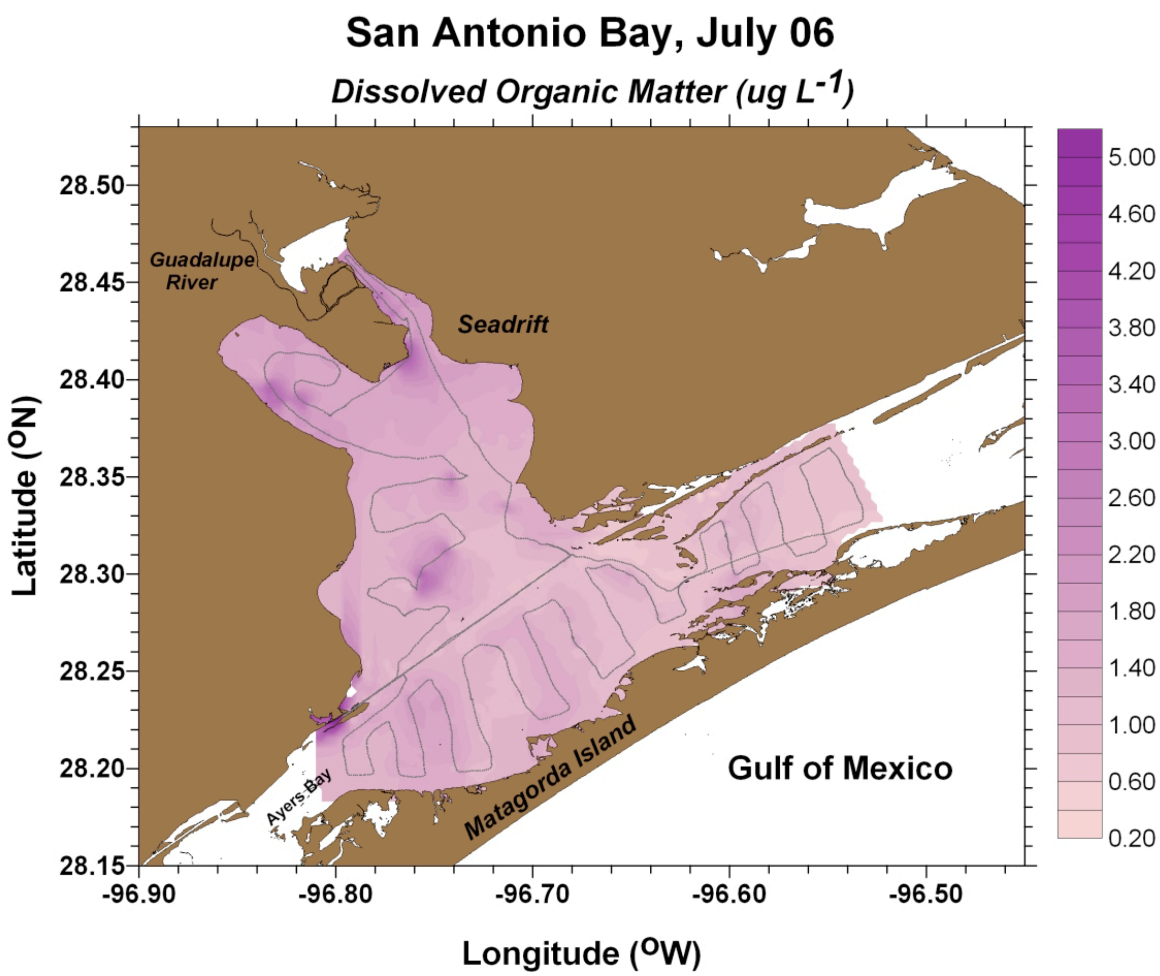


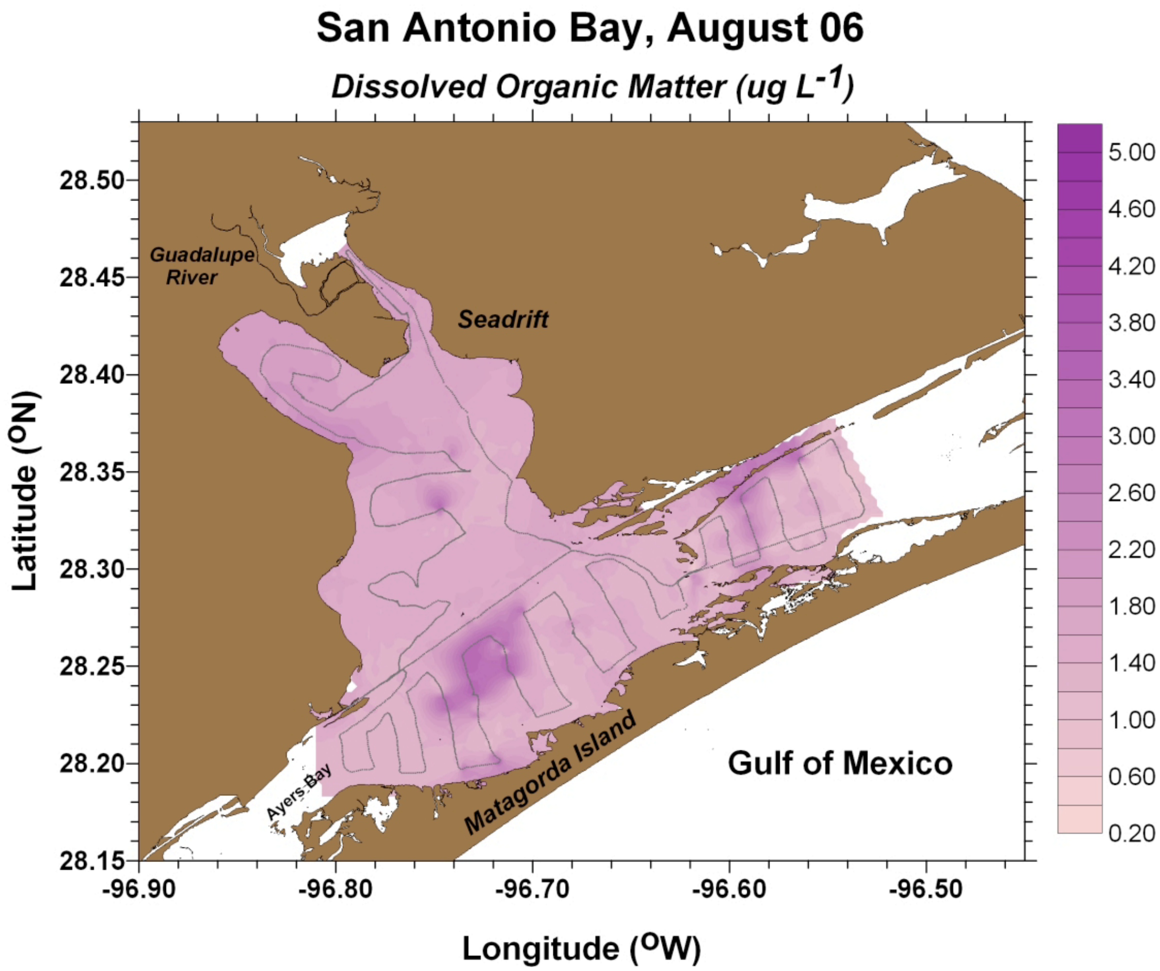
San Antonio Bay, May 06

Dissolved Organic Matter (ug L^{-1})

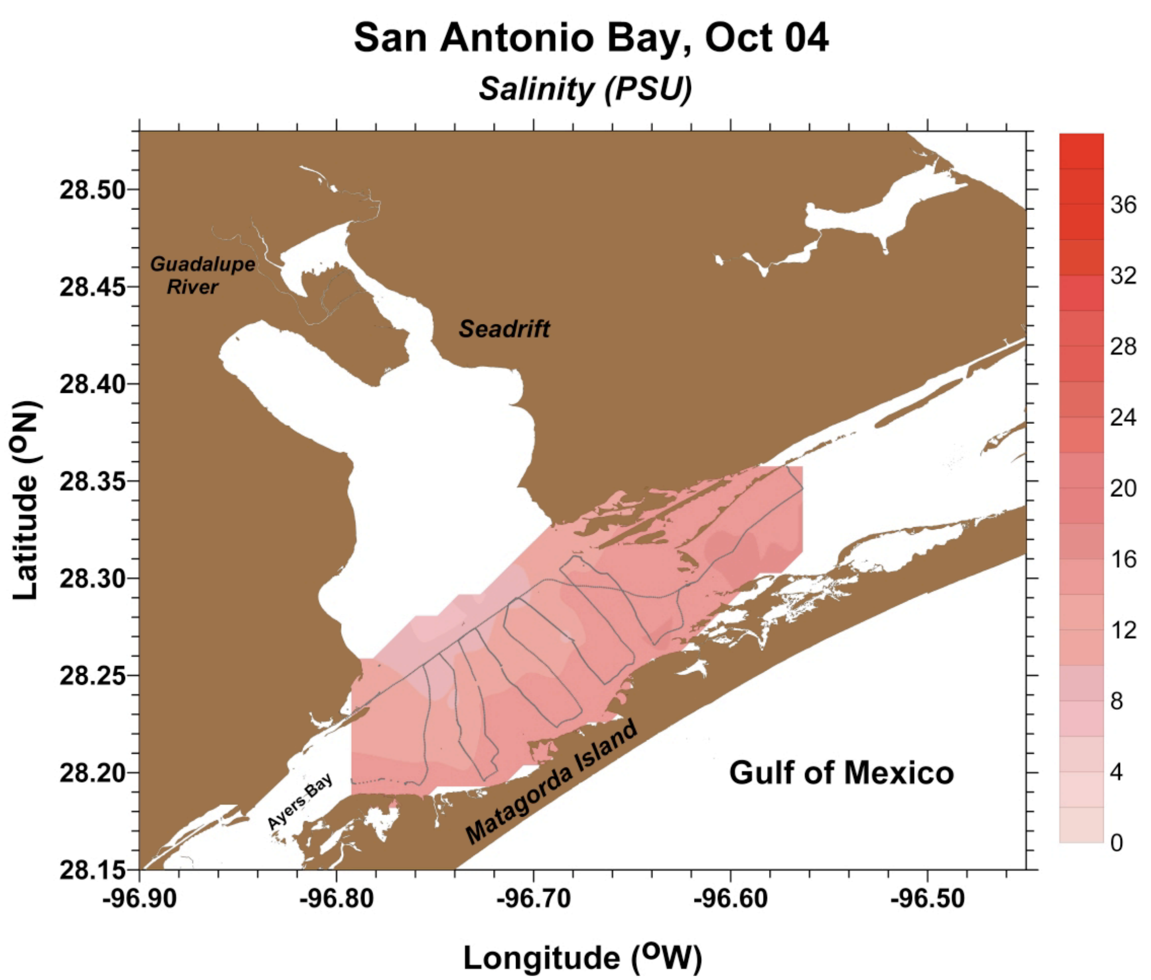



San Antonio Bay, June 06
Dissolved Organic Matter (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
5.00
4.60
4.20
3.80
3.40
3.00
2.60
2.20
1.80
1.40
1.00
0.60
0.20


San Antonio Bay, July 06
Dissolved Organic Matter (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
5.00
4.60
4.20
3.80
3.40
3.00
2.60
2.20
1.80
1.40
1.00
0.60
0.20



San Antonio Bay, August 06
Dissolved Organic Matter (ug L-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
5.00
4.60
4.20
3.80
3.40
3.00
2.60
2.20
1.80
1.40
1.00
0.60
0.20



San Antonio Bay, Oct 04
Salinity (PSU)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
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-96.80
-96.70
-96.60
-96.50
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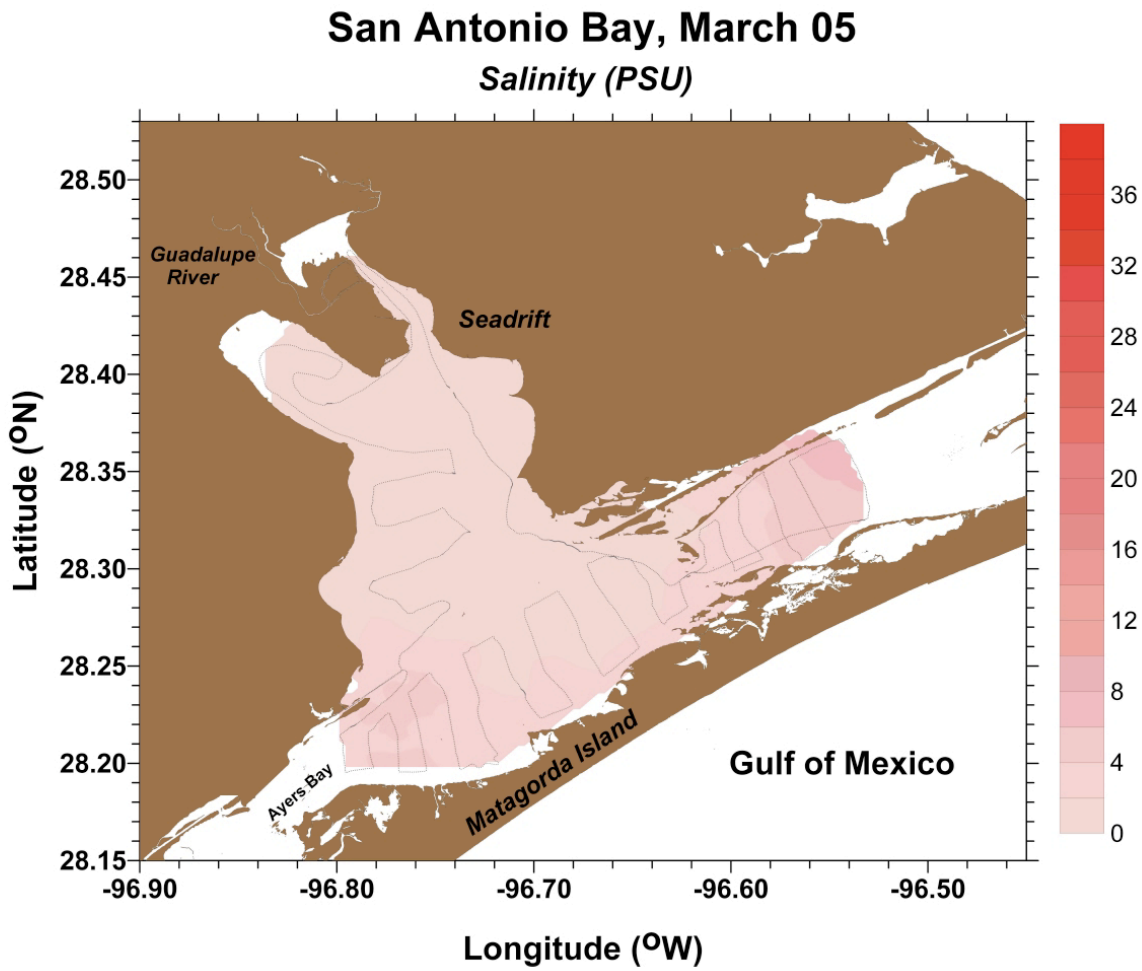
28
24
20
16
12
8
4
0


San Antonio Bay, March 05
Salinity (PSU)
Latitude (°N)
Longitude (°W)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
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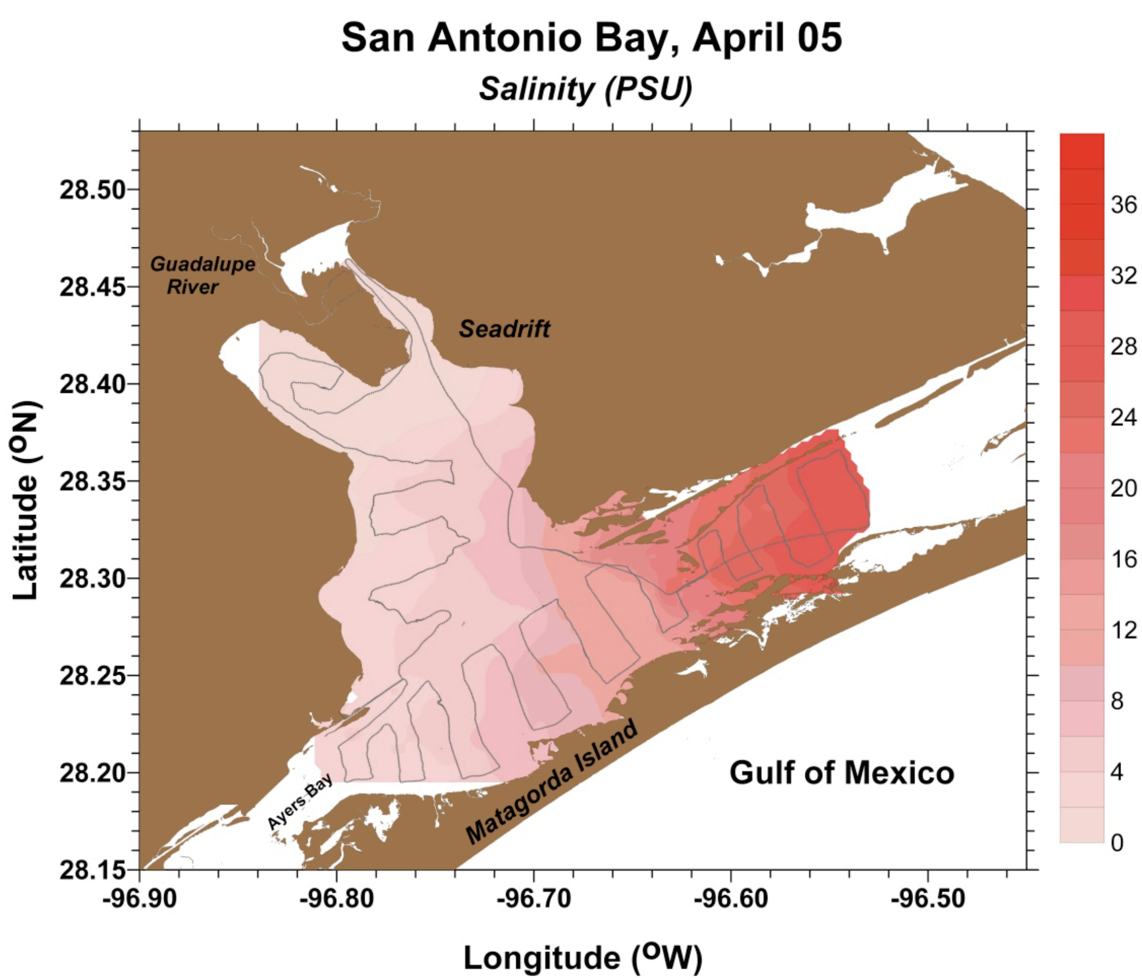
16
12
8
4
0


San Antonio Bay, April 05
Salinity (PSU)
Latitude (°N)
Longitude (°W)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
36
32
28
24
20
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12
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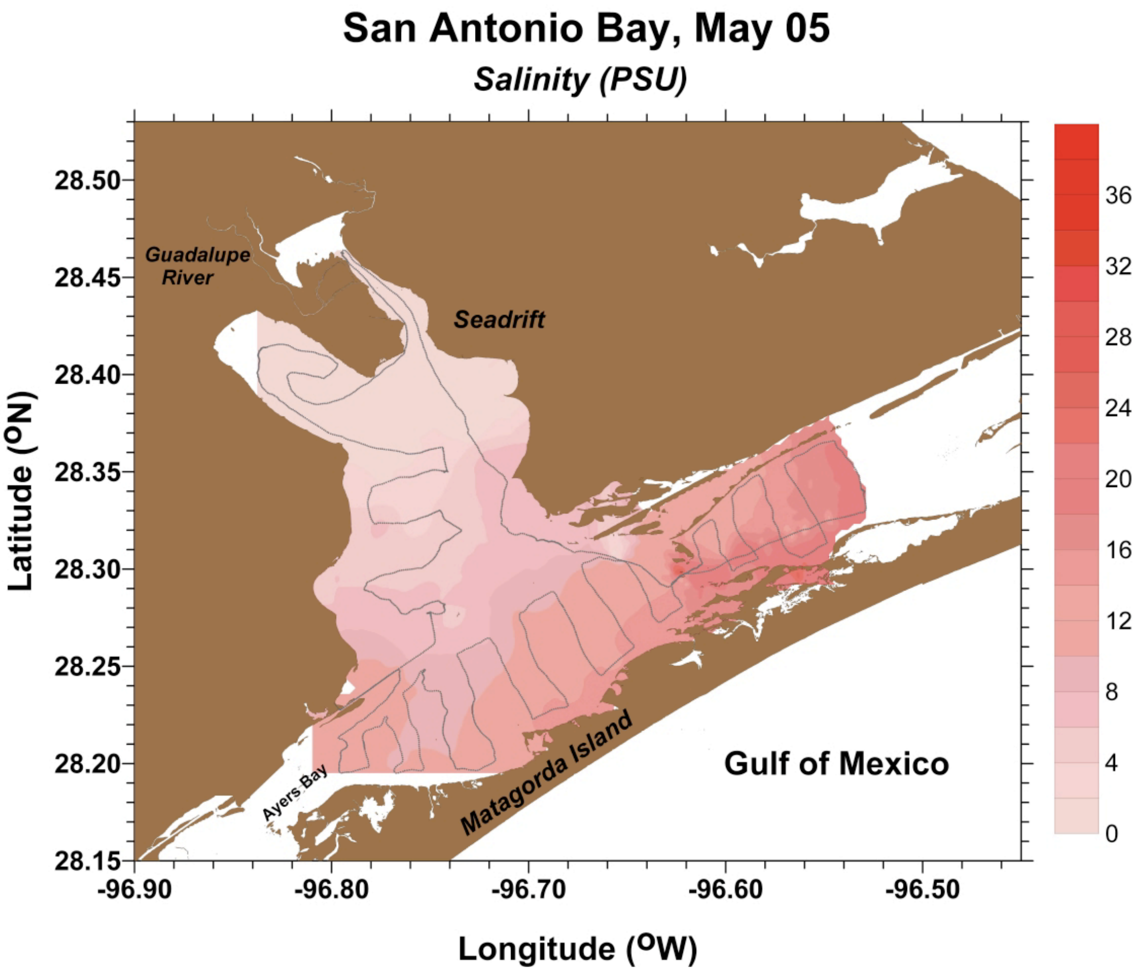
4
0


San Antonio Bay, May 05
Salinity (PSU)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
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-96.60
-96.50
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28
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16
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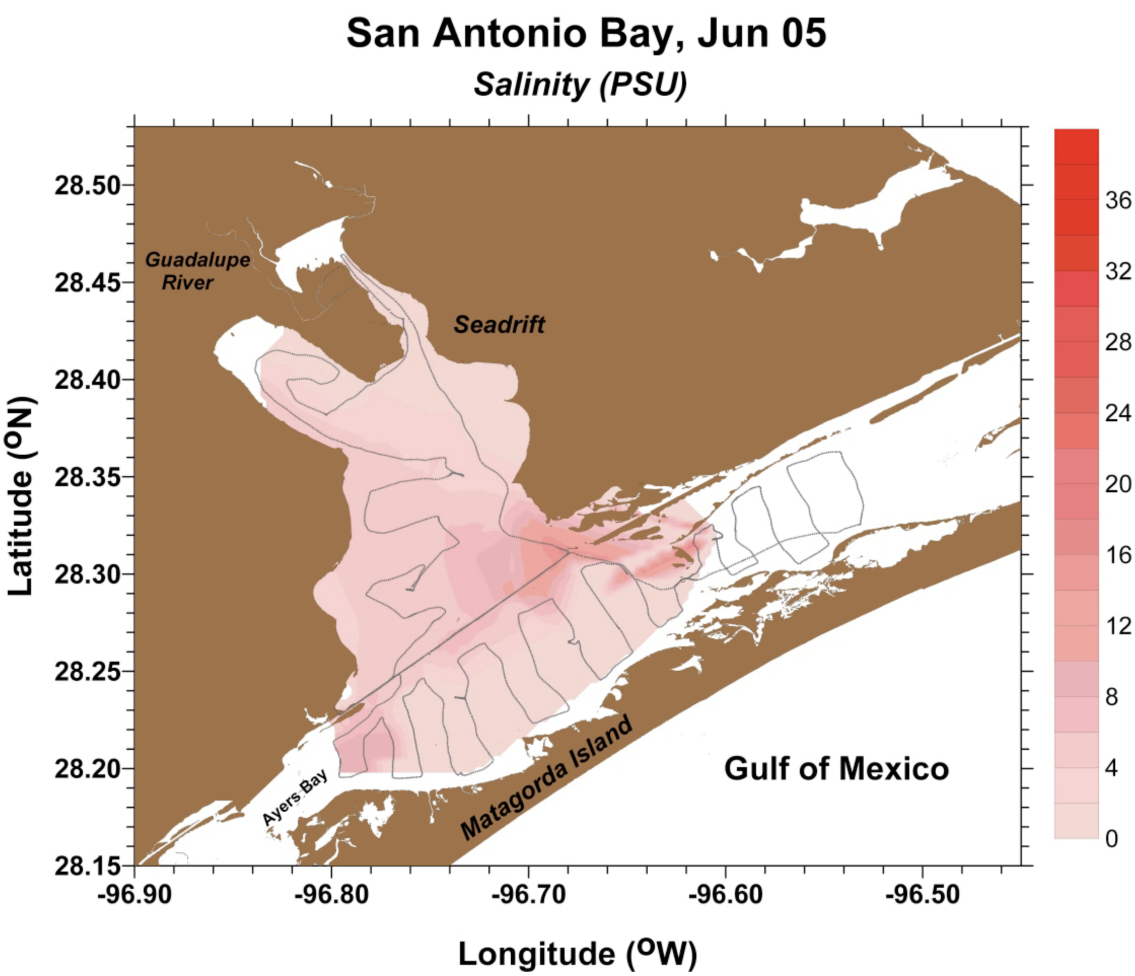
0


San Antonio Bay, Jun 05
Salinity (PSU)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
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-96.60
-96.50
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16
12
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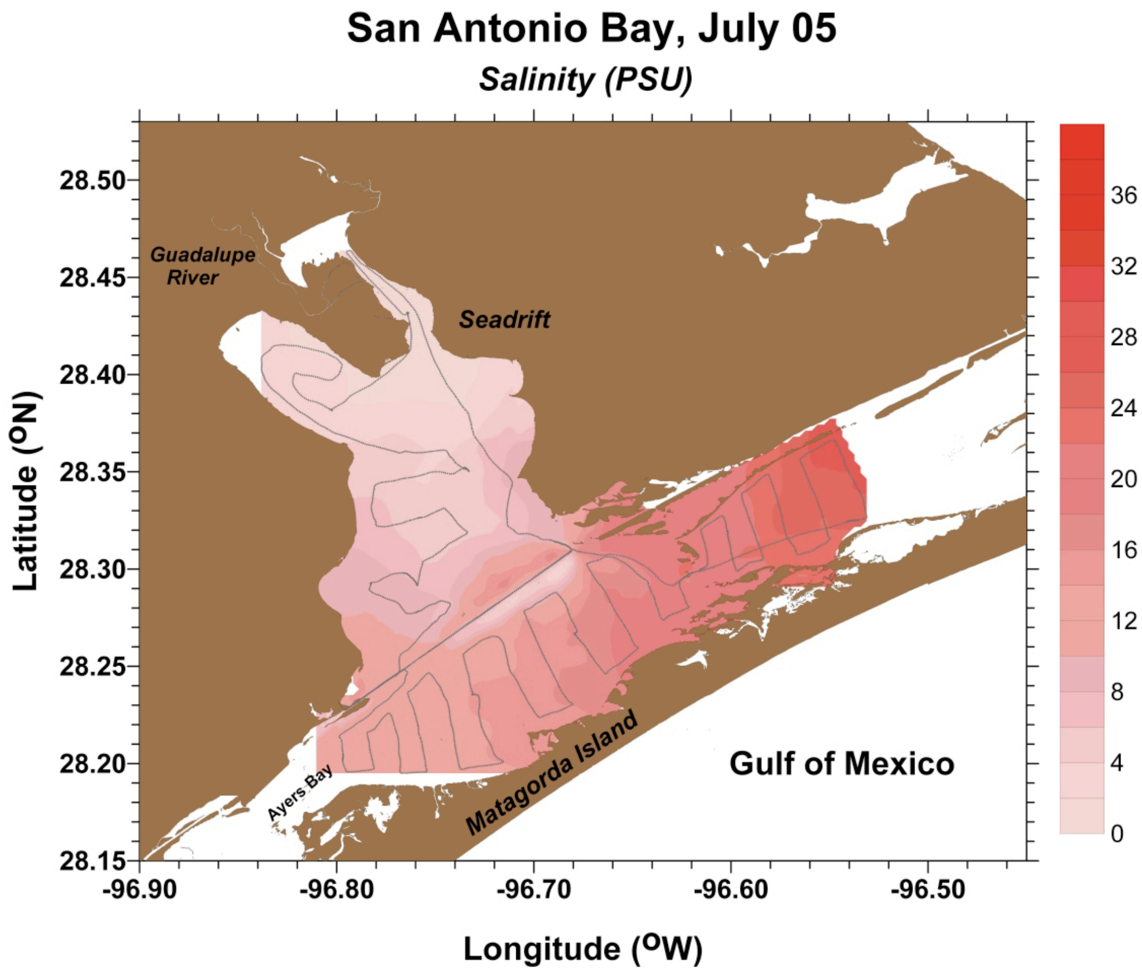
4
0


San Antonio Bay, July 05
Salinity (PSU)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ºN)
Longitude (ºW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
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-96.50
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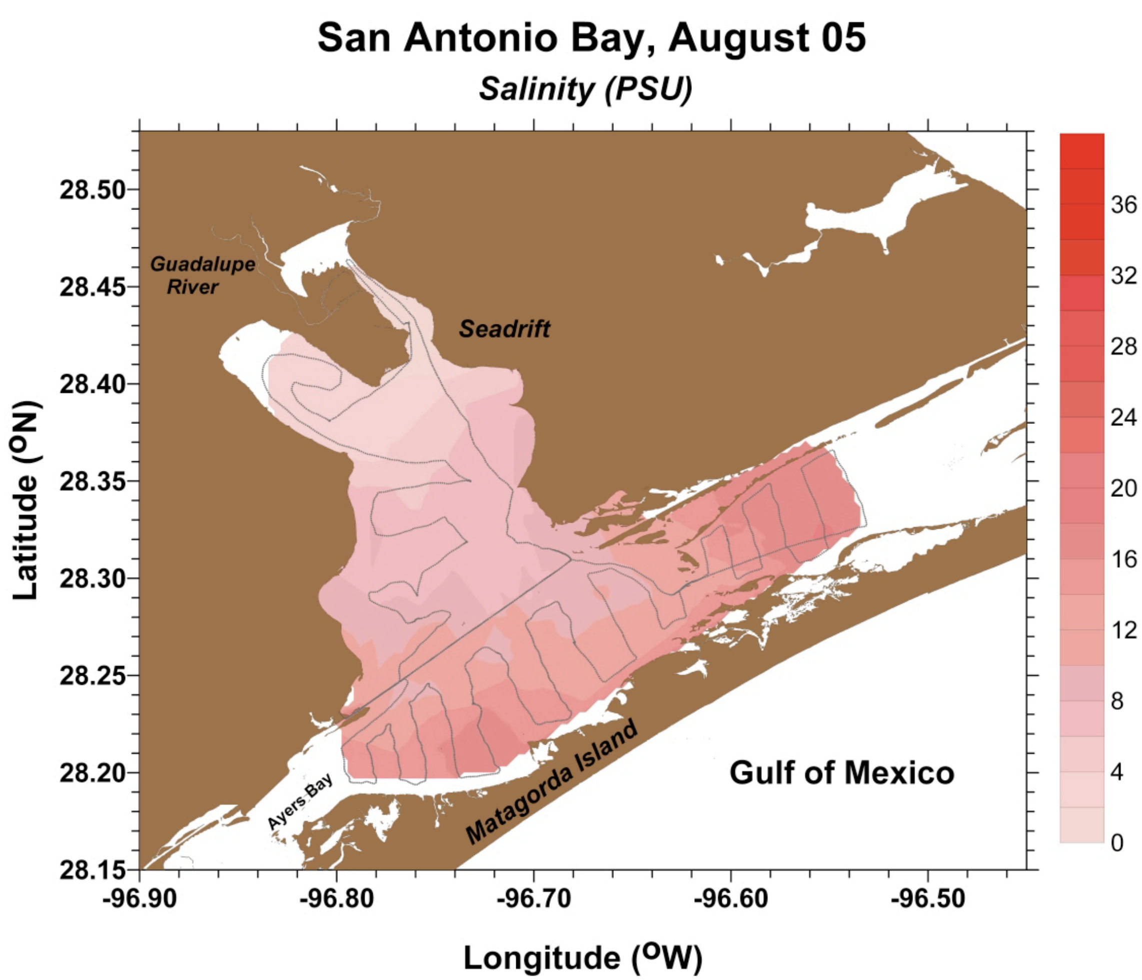
San Antonio Bay, August 05
Salinity (PSU)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ºN)
Longitude (ºW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
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-96.70
-96.60
-96.50
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24
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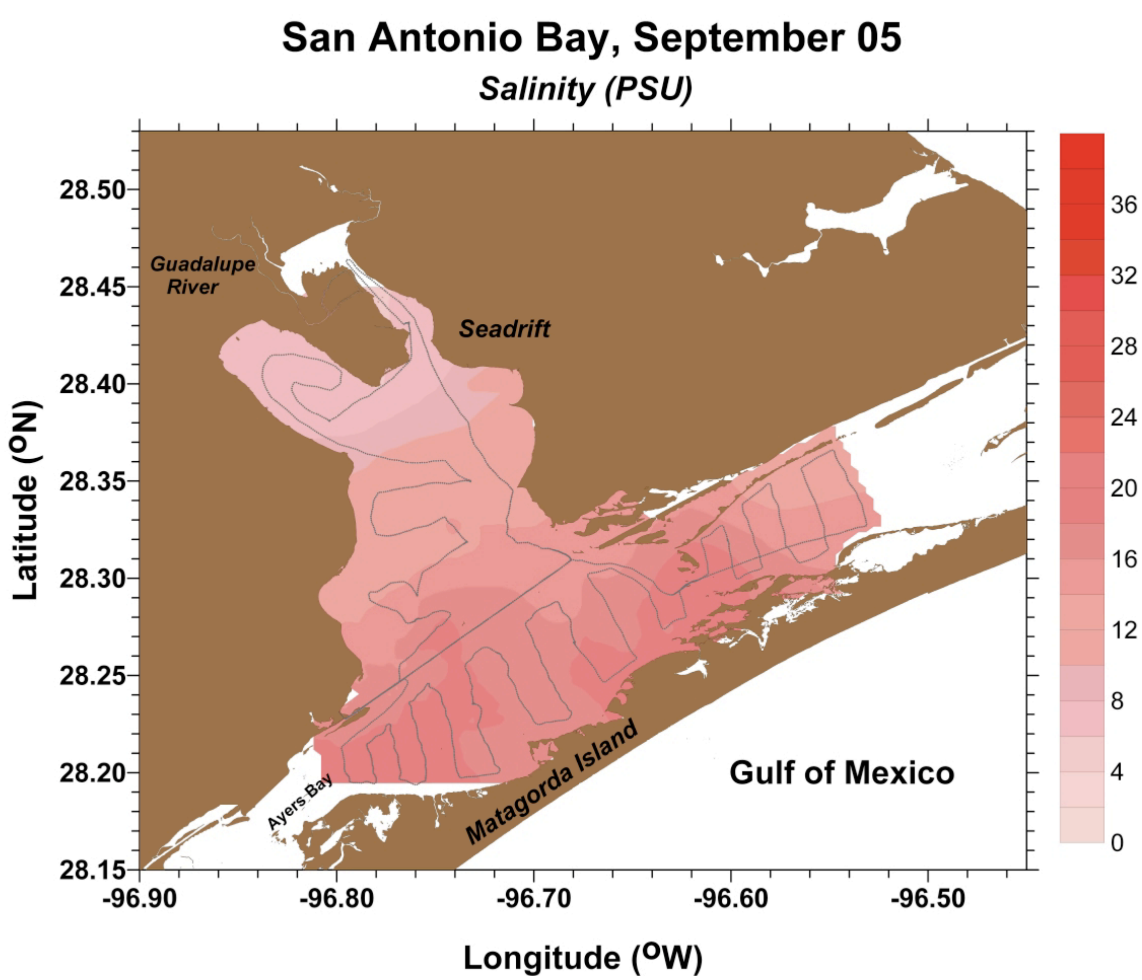
San Antonio Bay, September 05
Salinity (PSU)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
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-96.70
-96.60
-96.50
36
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28
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16
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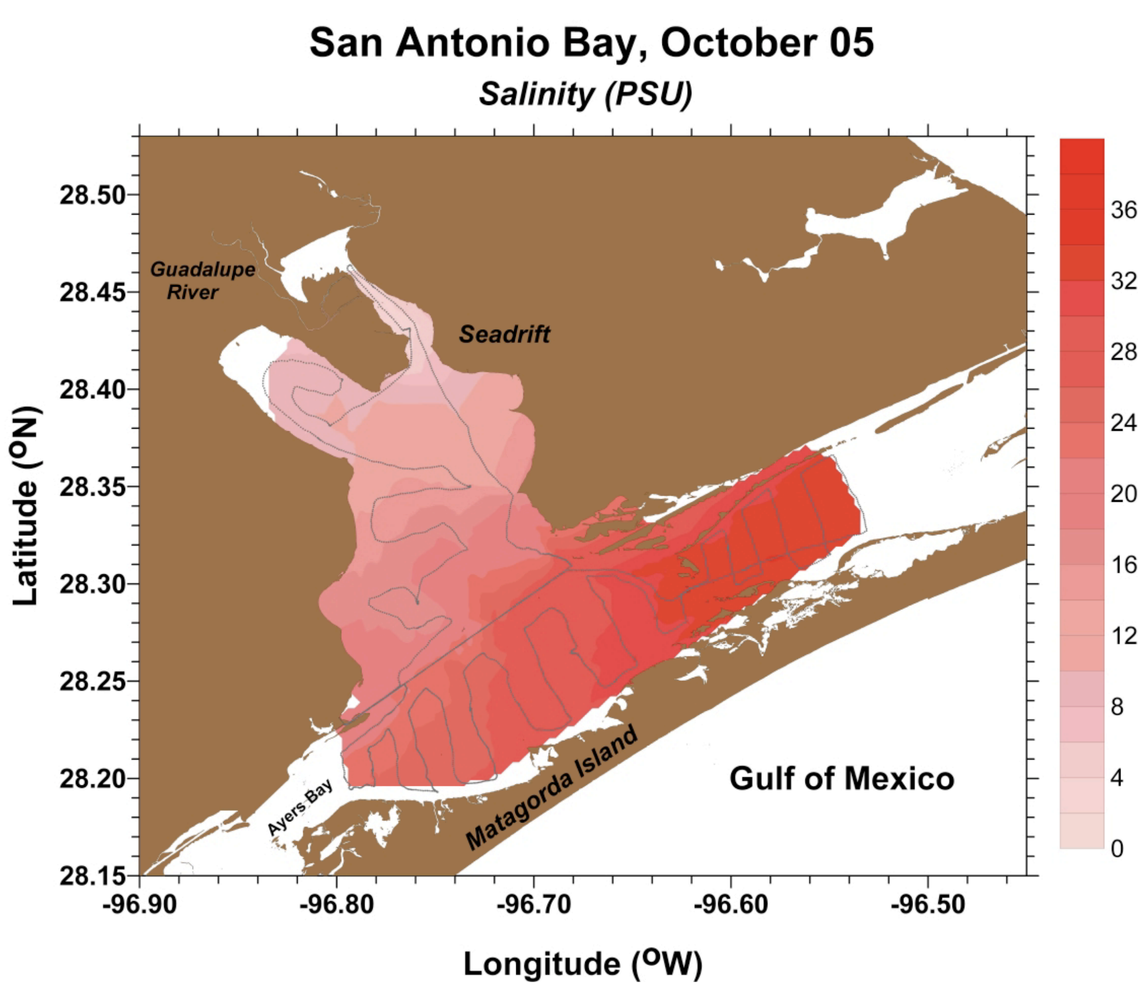
4
0


San Antonio Bay, October 05
Salinity (PSU)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
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-96.70
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-96.50
36
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28
24
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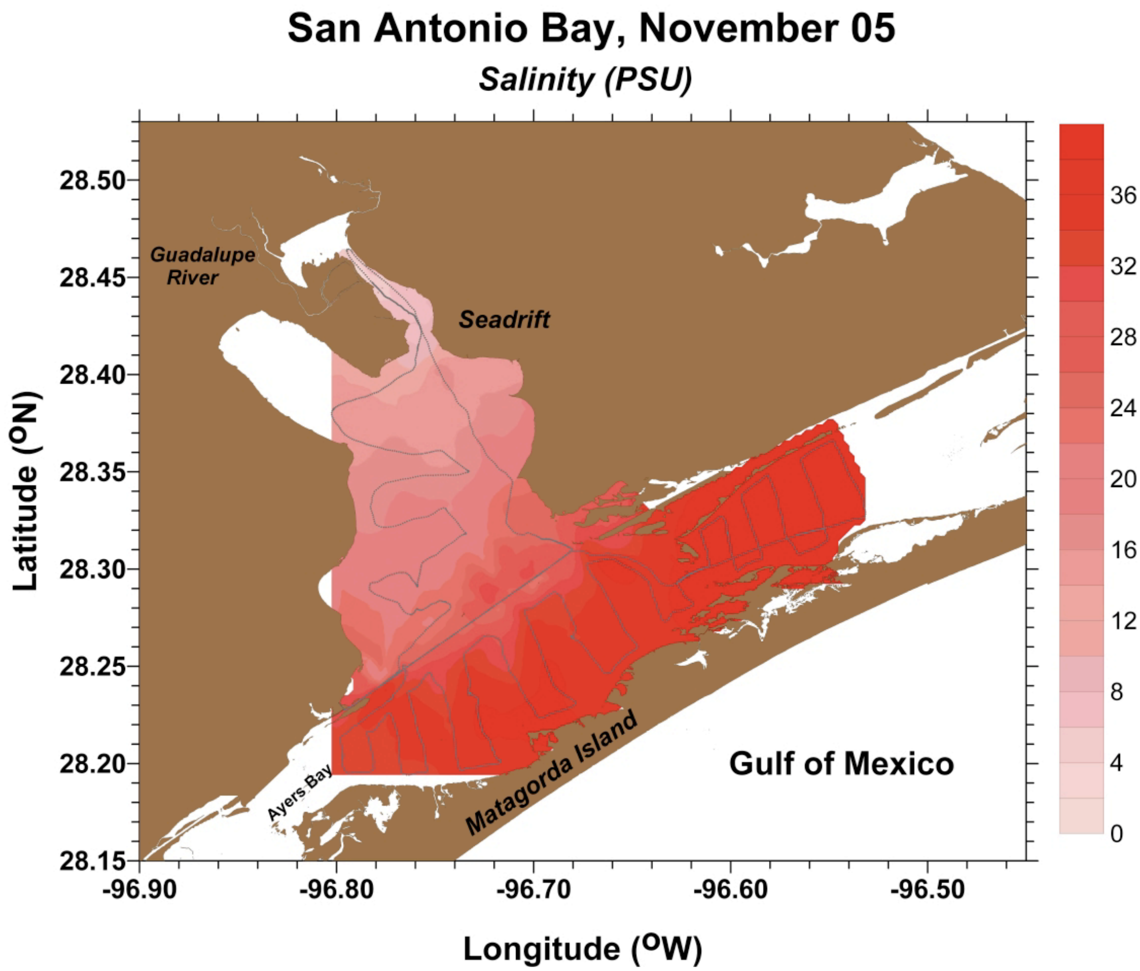
San Antonio Bay, November 05
Salinity (PSU)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
36
32
28
24
20
16
12
8
4
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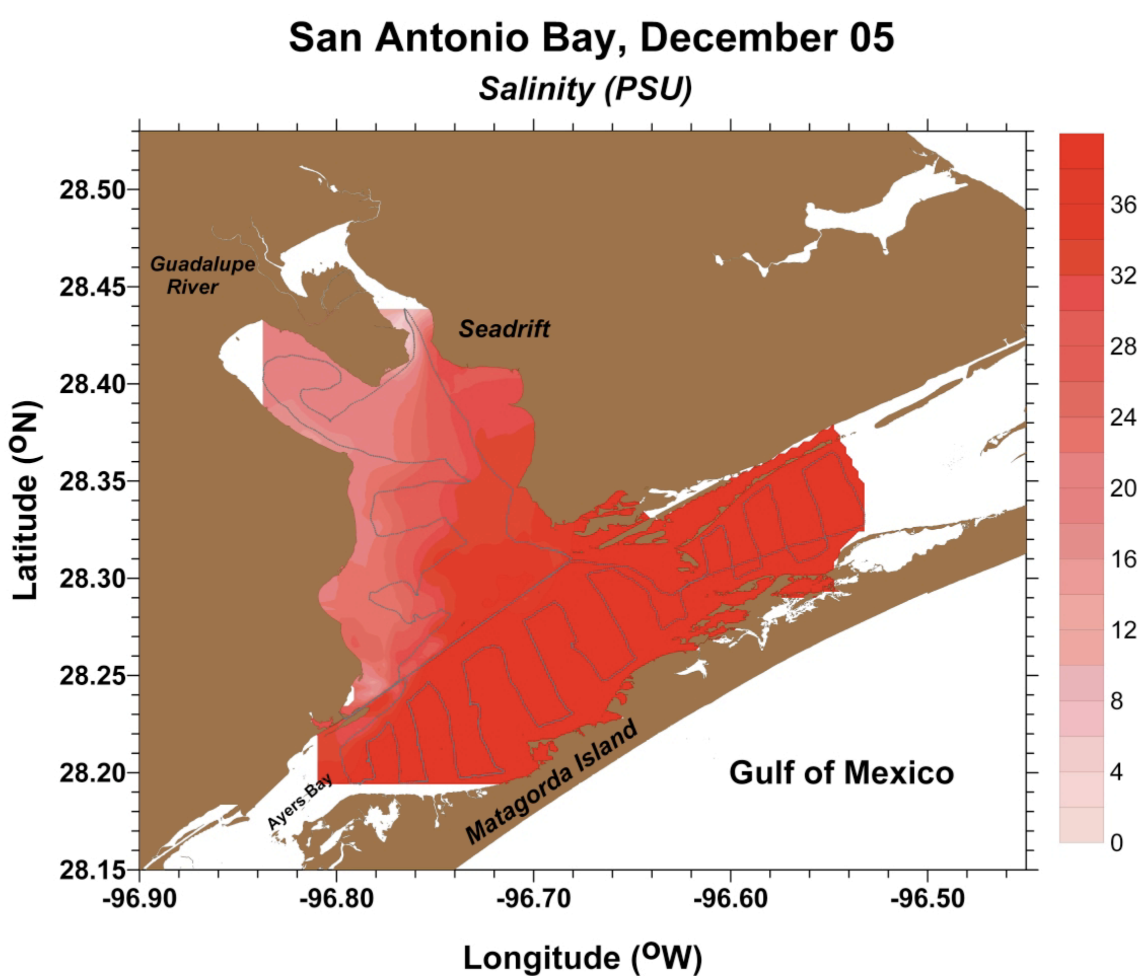
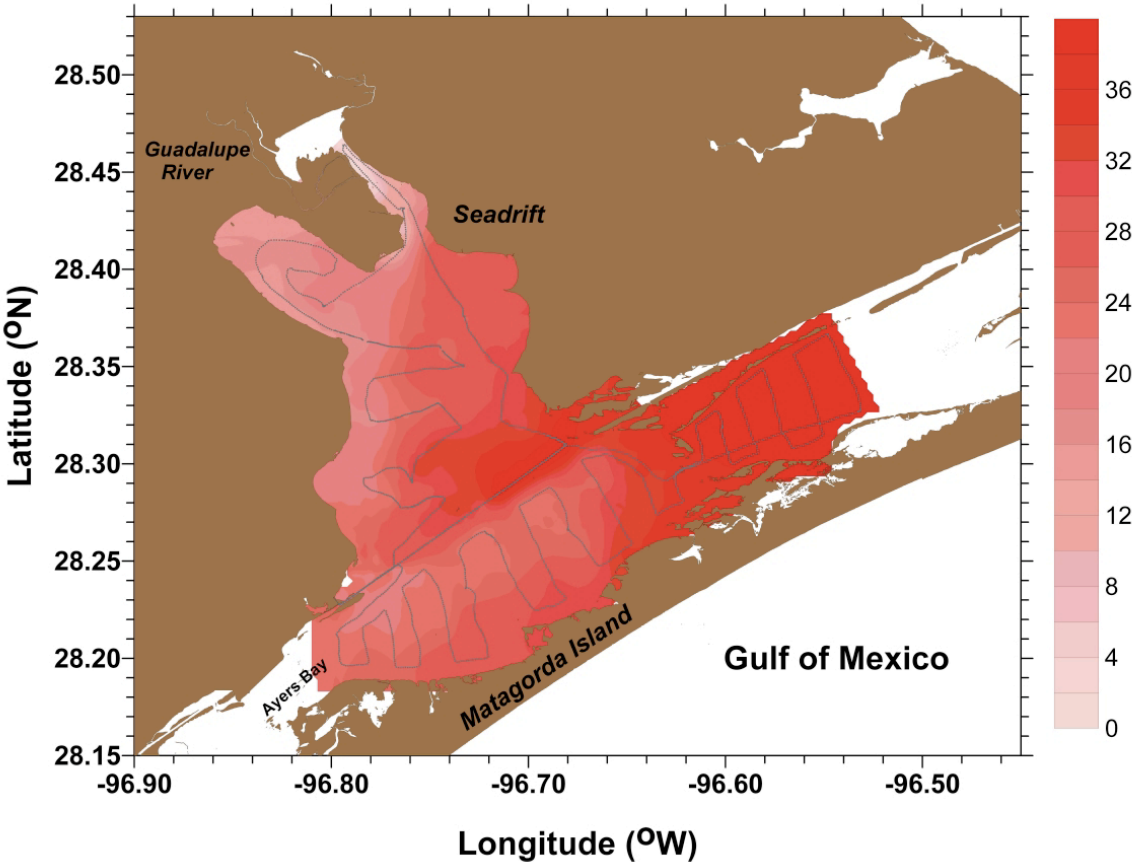

San Antonio Bay, December 05
Salinity (PSU)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
36
32
28
24
20
16
12
8
4
0

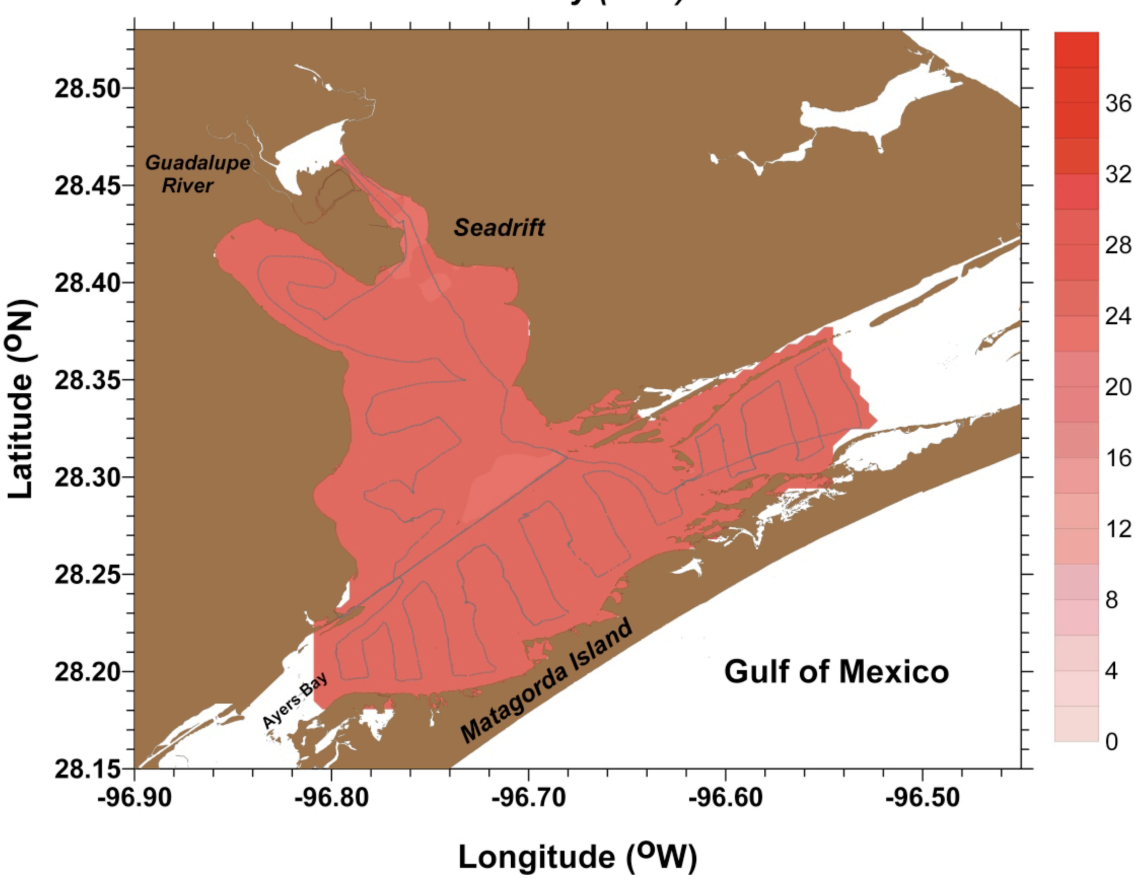
San Antonio Bay, February 06

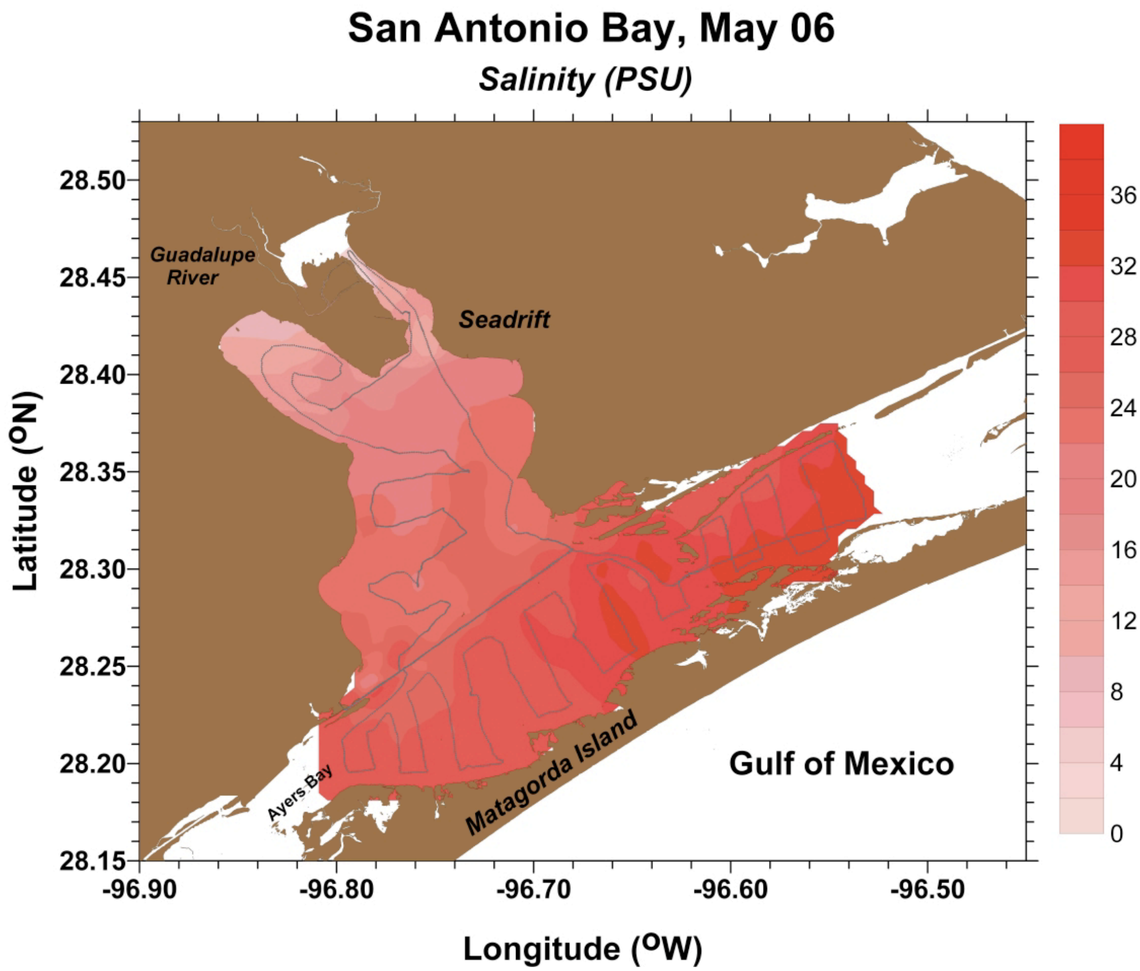
Salinity (PSU)



San Antonio Bay, April 06

Salinity (PSU)




San Antonio Bay, May 06
Salinity (PSU)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)
28.15
28.20
28.25
28.30
28.35
28.40
28.45
28.50
-96.90
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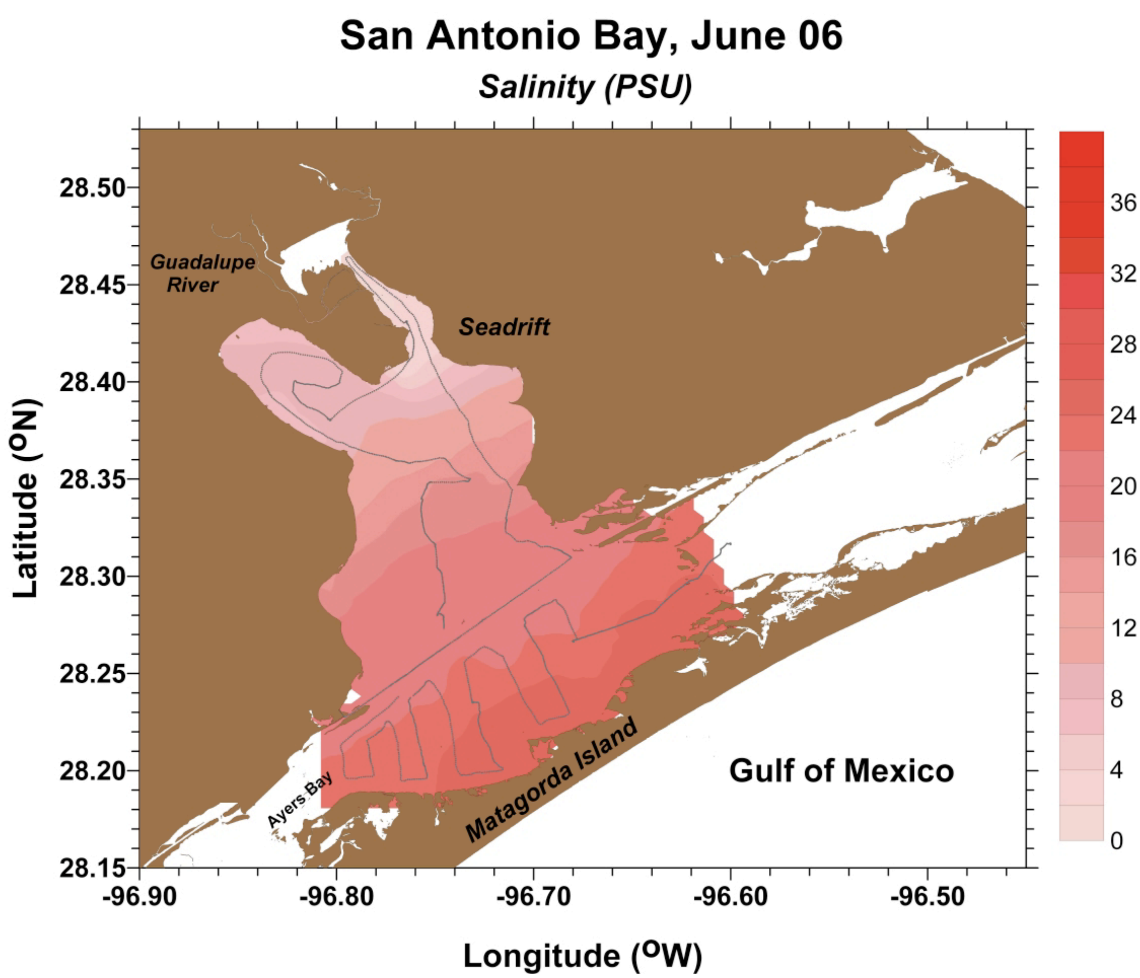
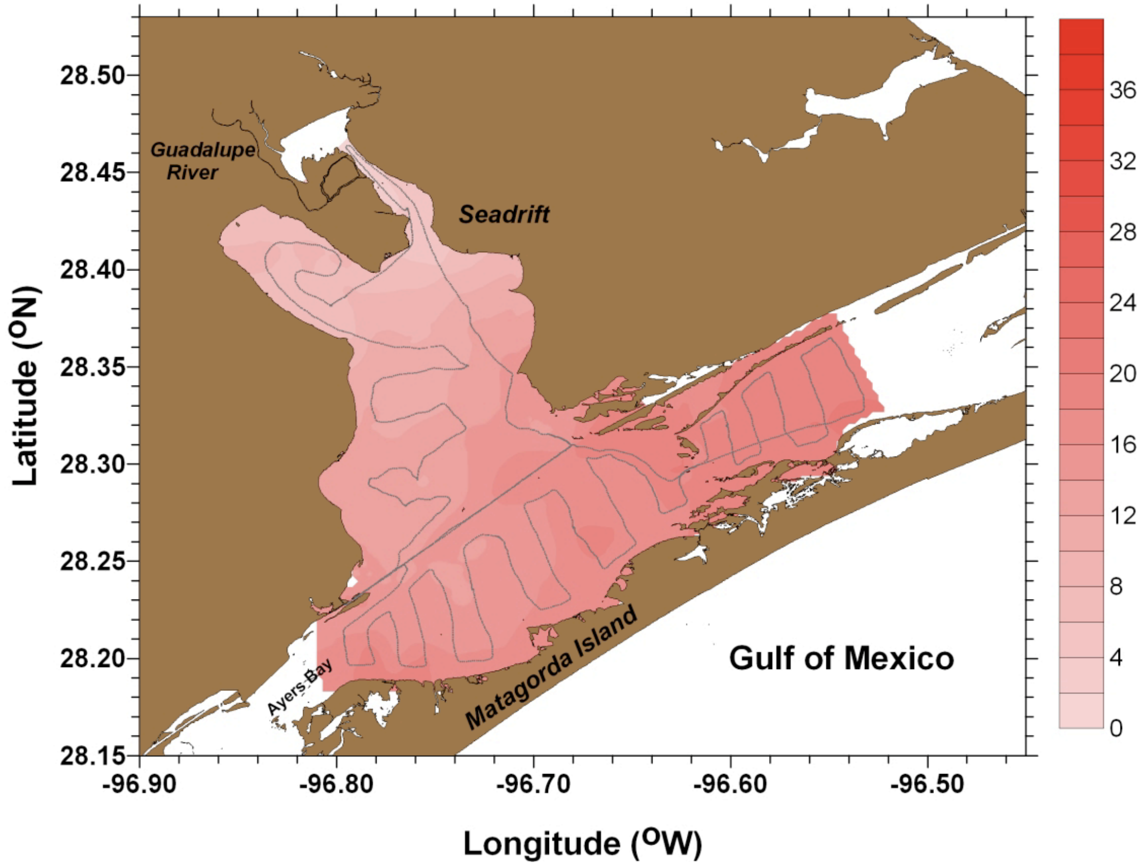
20
24
28
32
36


San Antonio Bay, June 06
Salinity (PSU)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)
28.15
28.20
28.25
28.30
28.35
28.40
28.45
28.50
-96.90
-96.80
-96.70
-96.60
-96.50
0
4
8
12
16
20
24
28
32
36

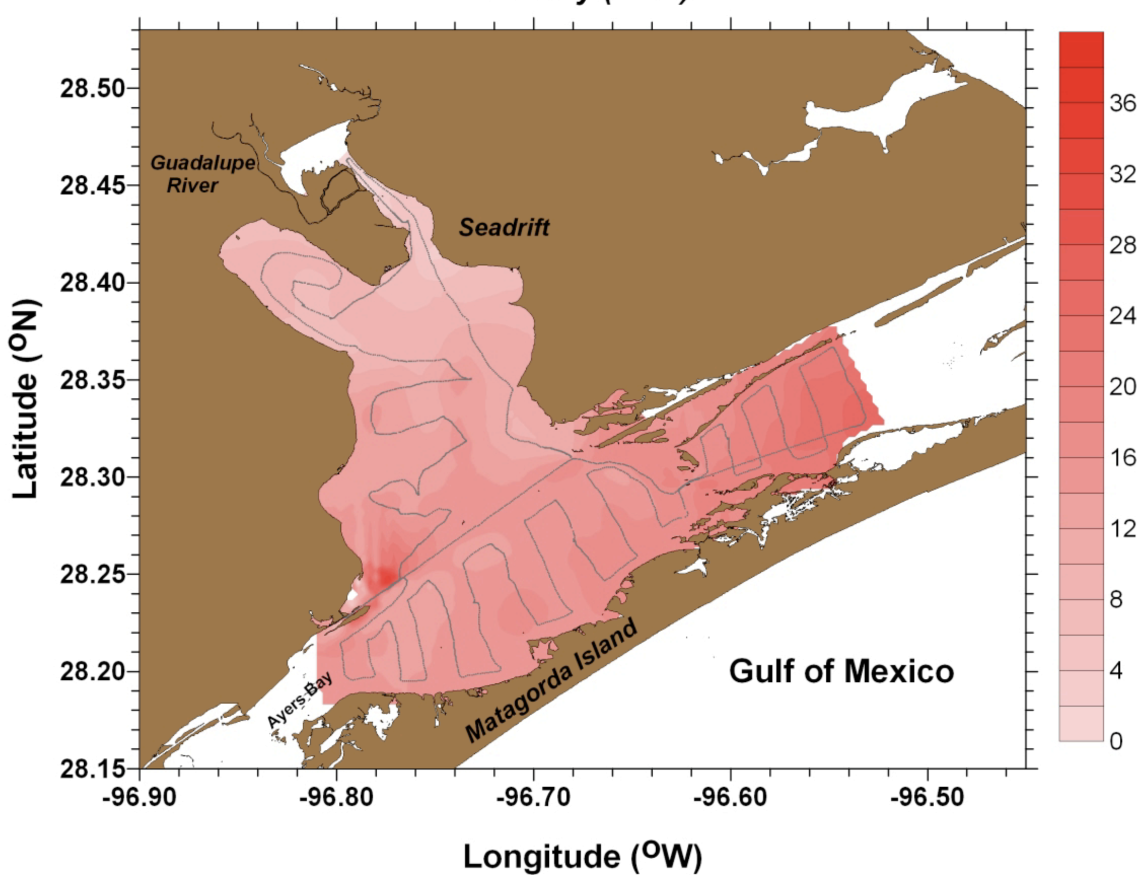
San Antonio Bay, July 06

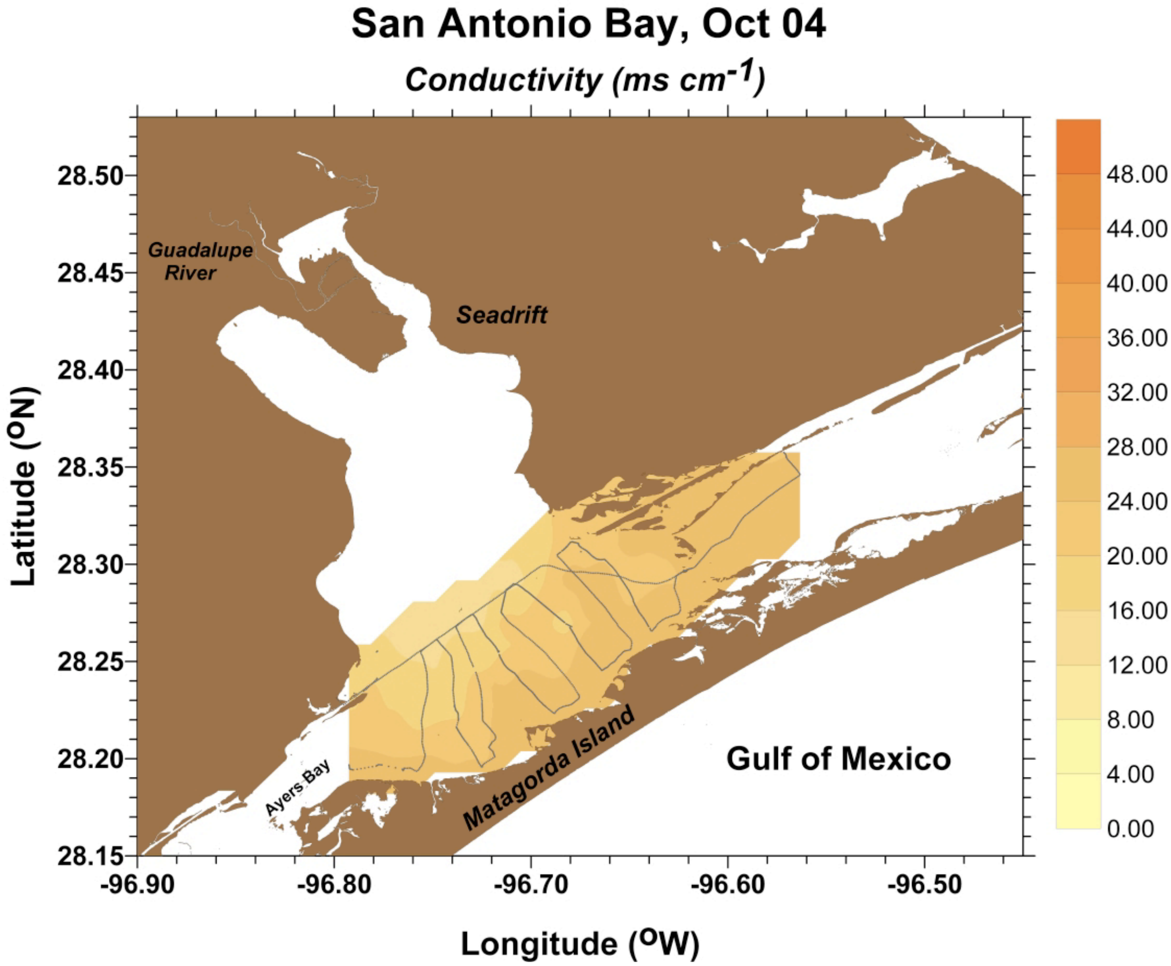
Salinity (PSU)

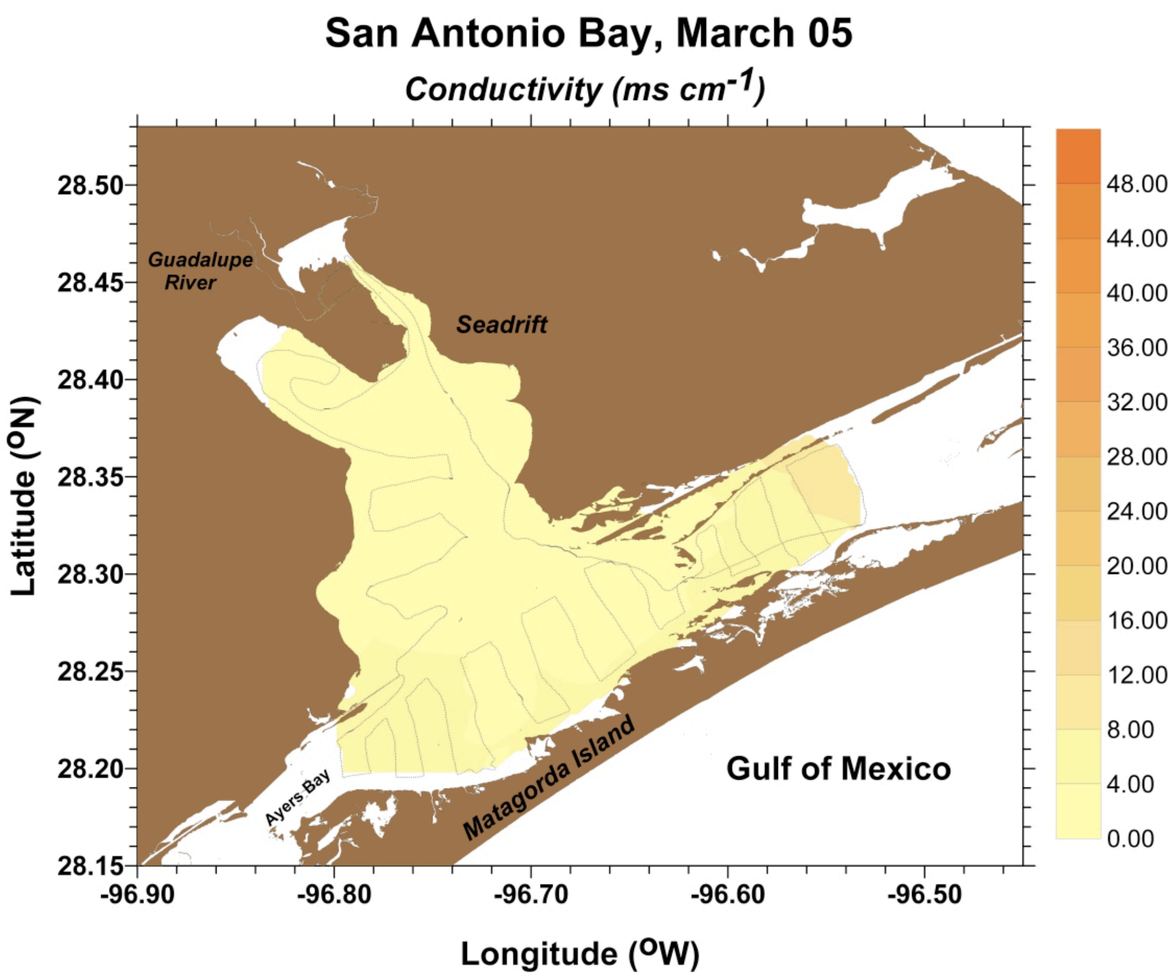


San Antonio Bay, August 06

Salinity (PSU)

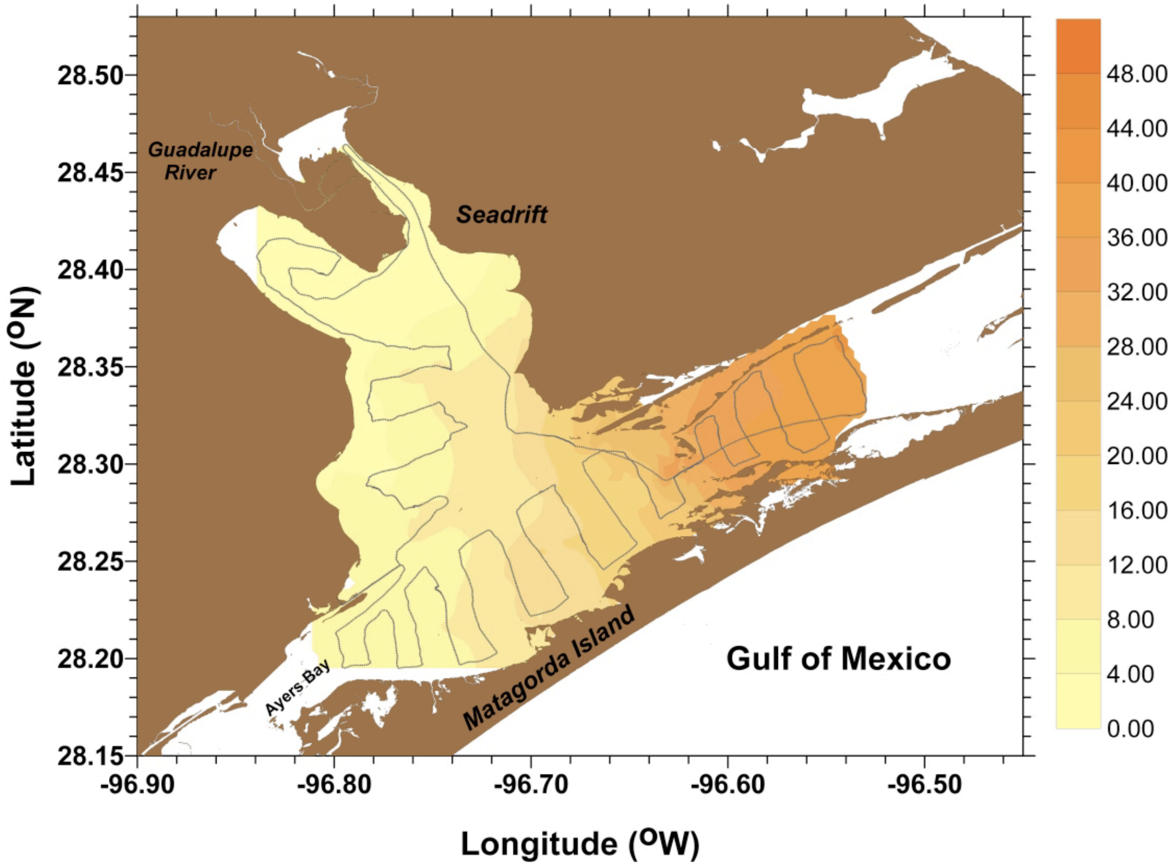



San Antonio Bay, Oct 04
Conductivity (ms cm-1)
Latitude (ON)
Longitude (OW)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
48.00
44.00
40.00
36.00
32.00
28.00
24.00
20.00
16.00
12.00
8.00
4.00
0.00


San Antonio Bay, March 05
Conductivity (ms cm-1)
Latitude (ON)
Longitude (OW)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
48.00
44.00
40.00
36.00
32.00
28.00
24.00
20.00
16.00
12.00
8.00
4.00
0.00

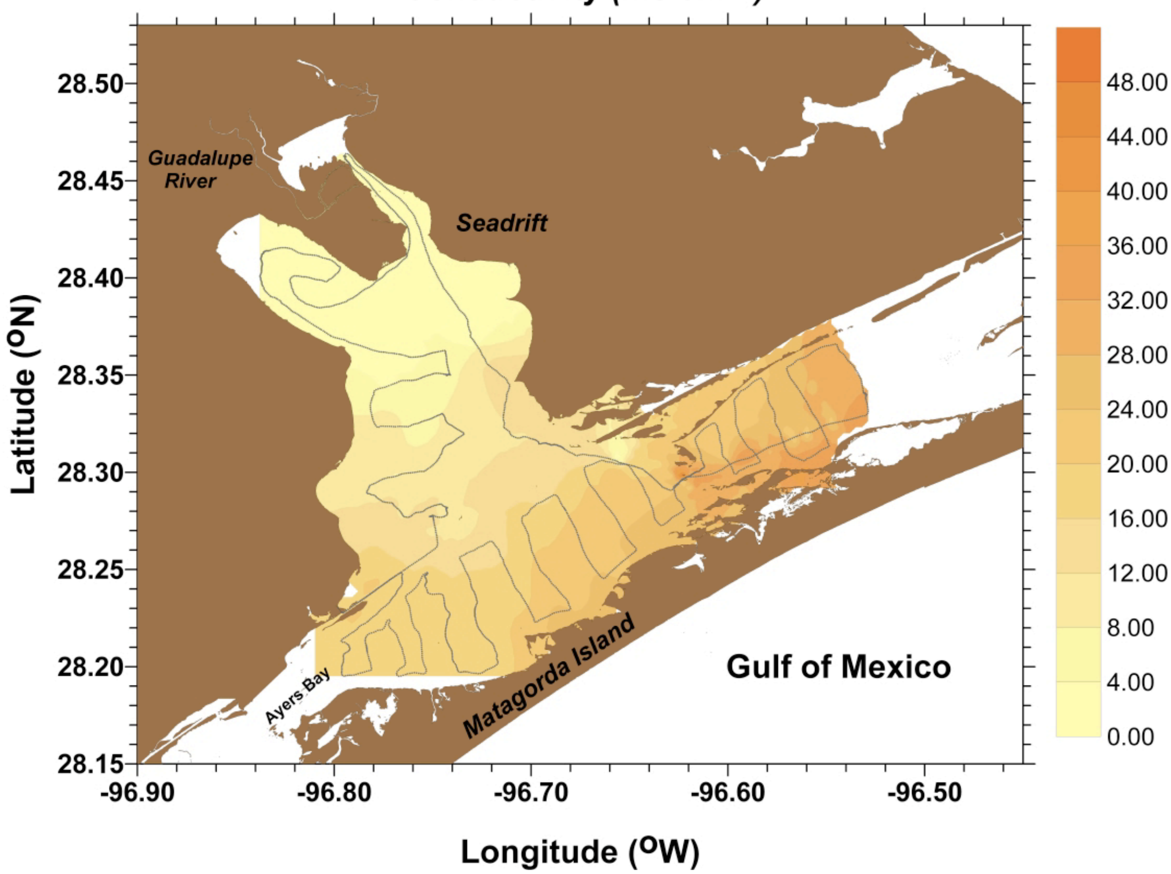
San Antonio Bay, April 05

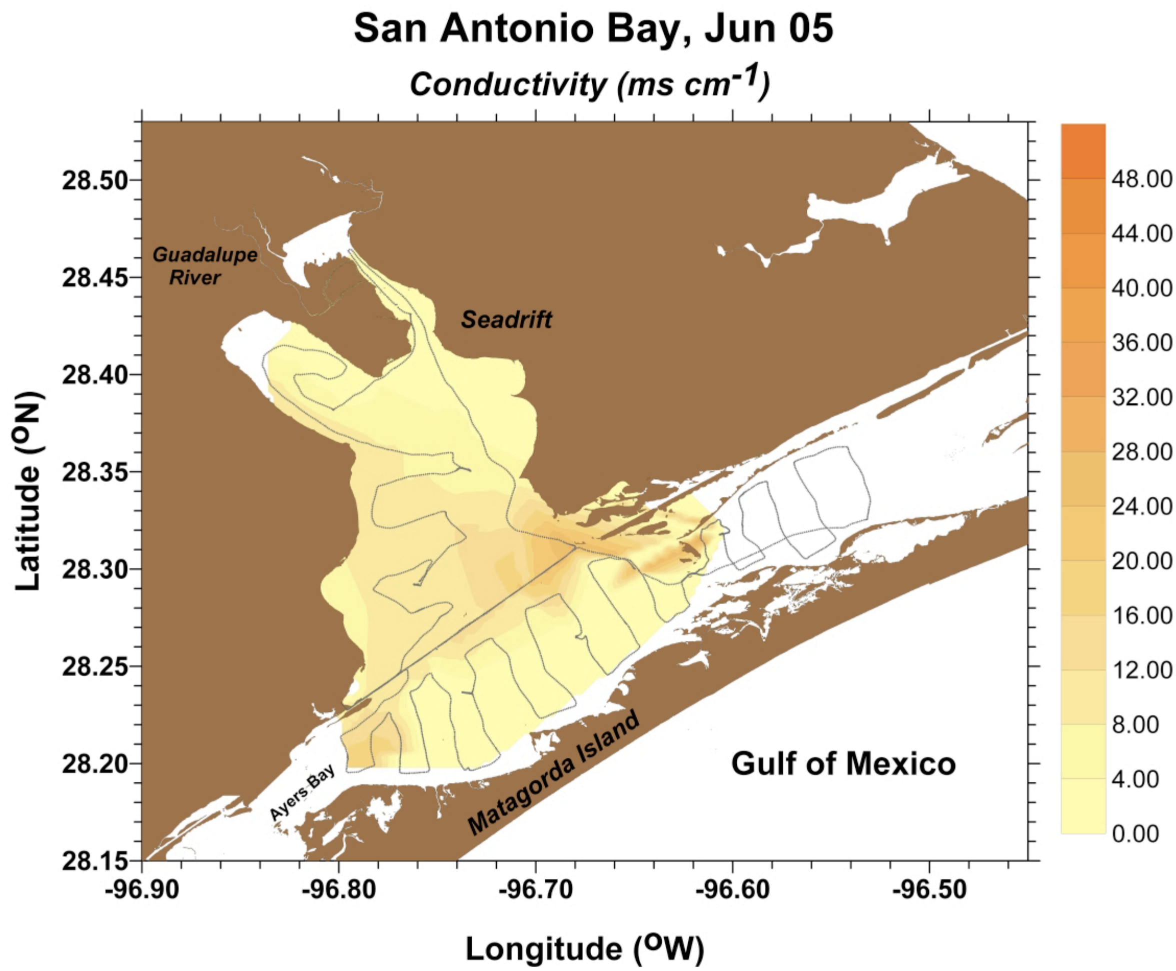
Conductivity (ms cm^{-1})

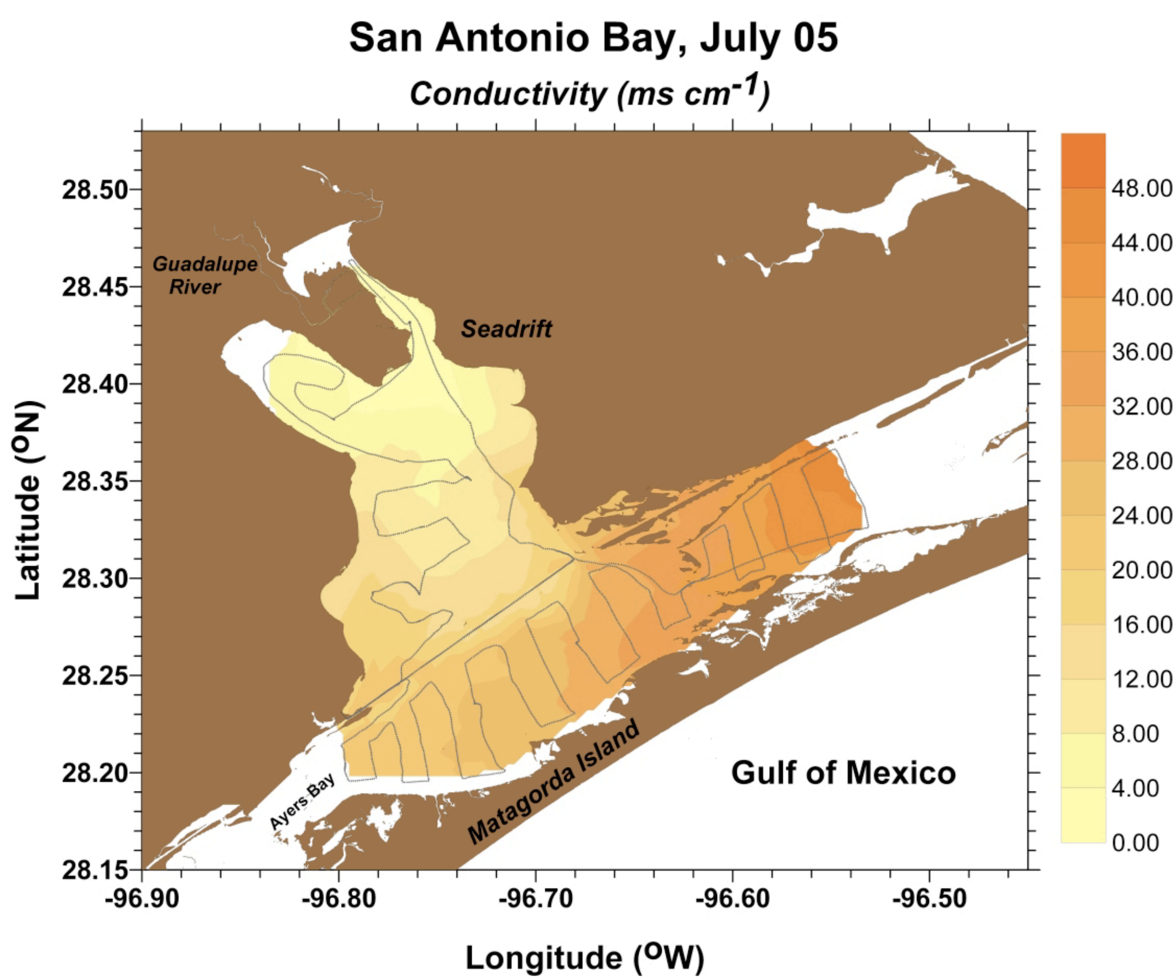


San Antonio Bay, May 05

Conductivity (ms cm^{-1})




San Antonio Bay, Jun 05
Conductivity (ms cm-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
48.00
44.00
40.00
36.00
32.00
28.00
24.00
20.00
16.00
12.00
8.00
4.00
0.00


San Antonio Bay, July 05
Conductivity (ms cm-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
48.00
44.00
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36.00
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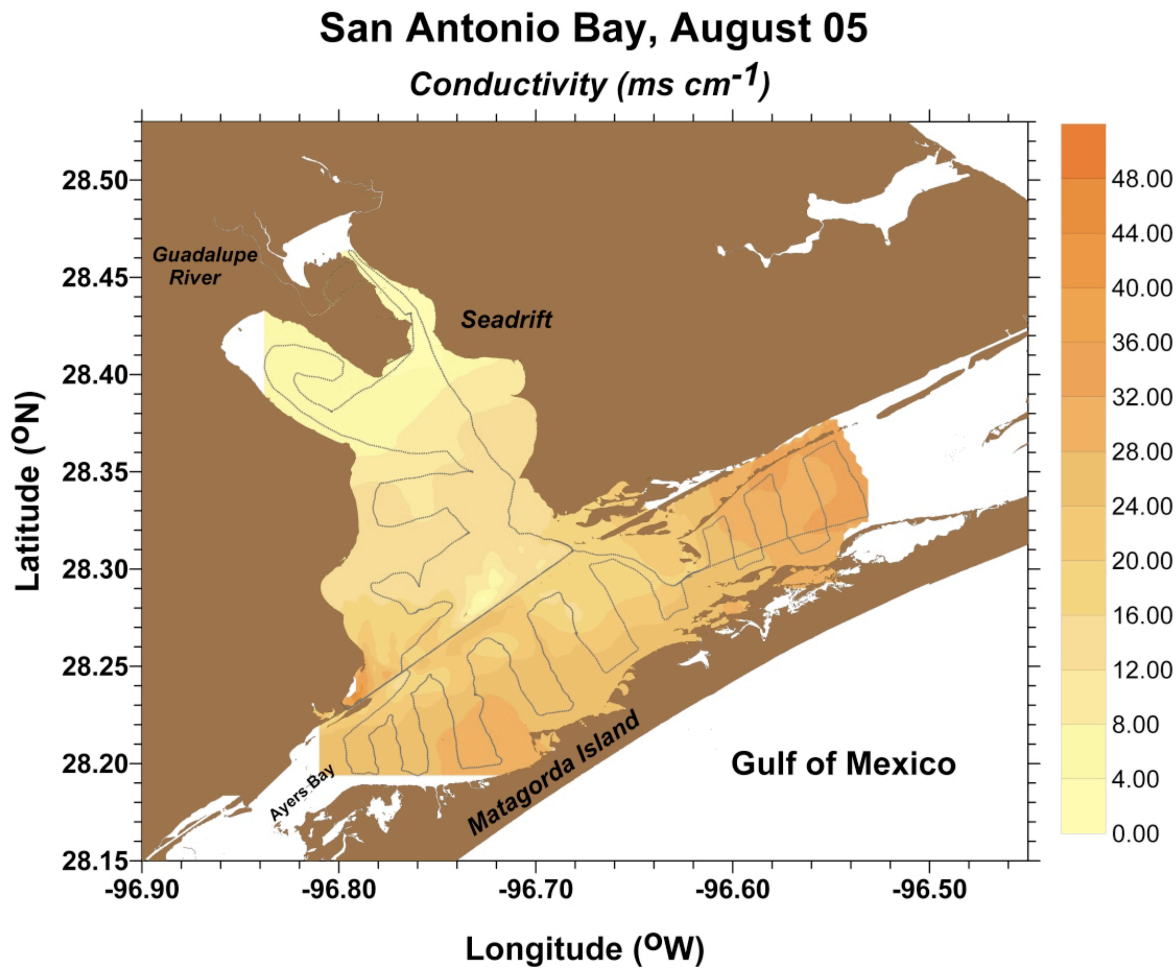
24.00
20.00
16.00
12.00
8.00
4.00
0.00


San Antonio Bay, August 05
Conductivity (ms cm-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
48.00
44.00
40.00
36.00
32.00
28.00
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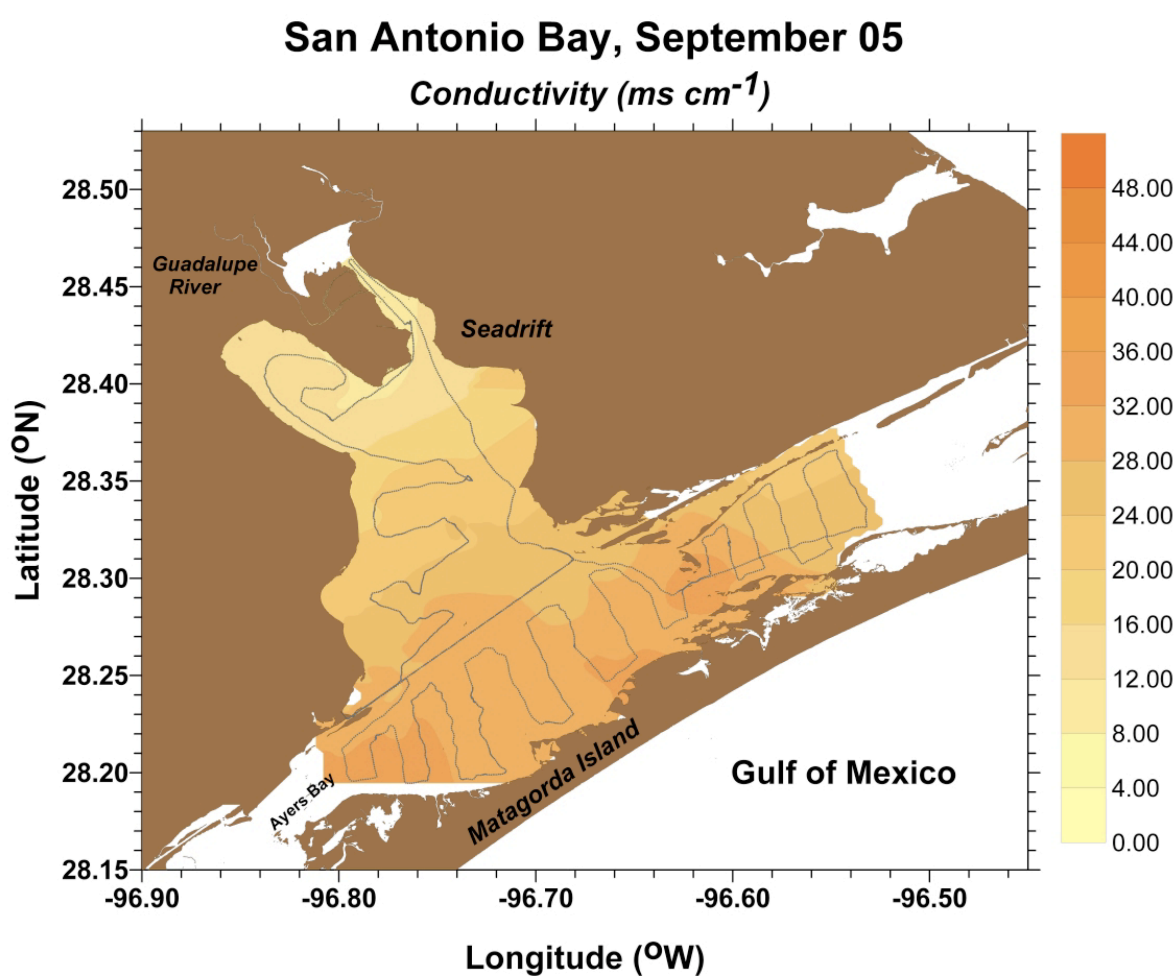
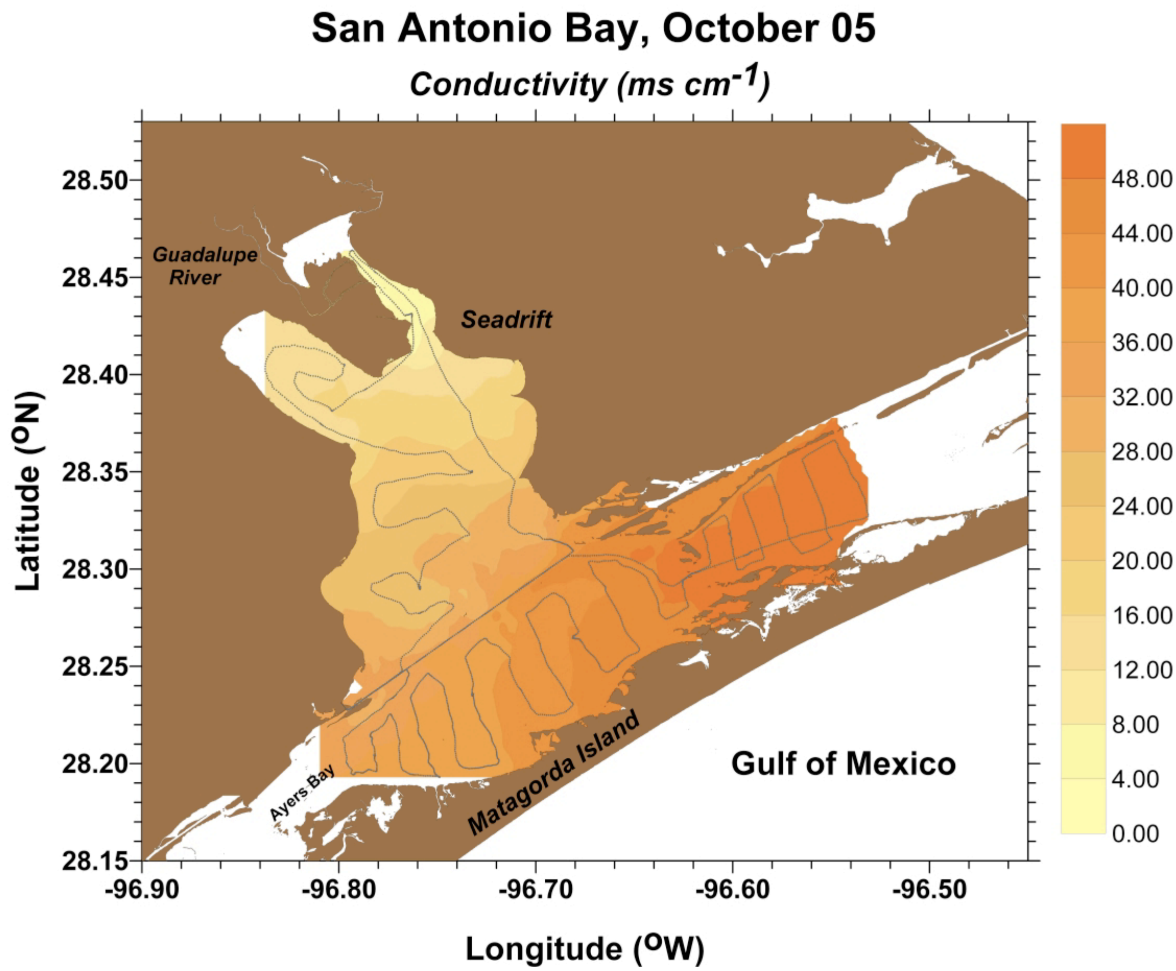
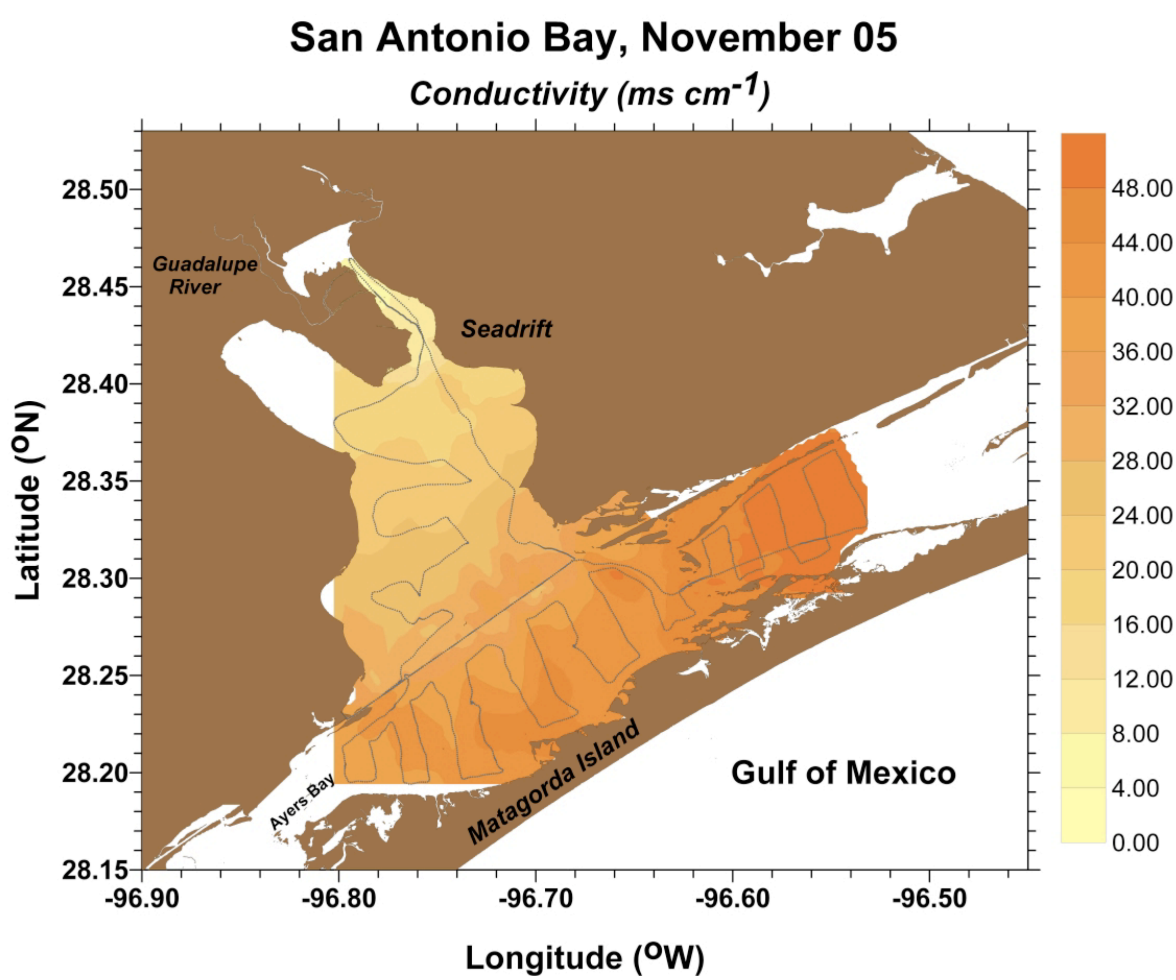
8.00
4.00
0.00

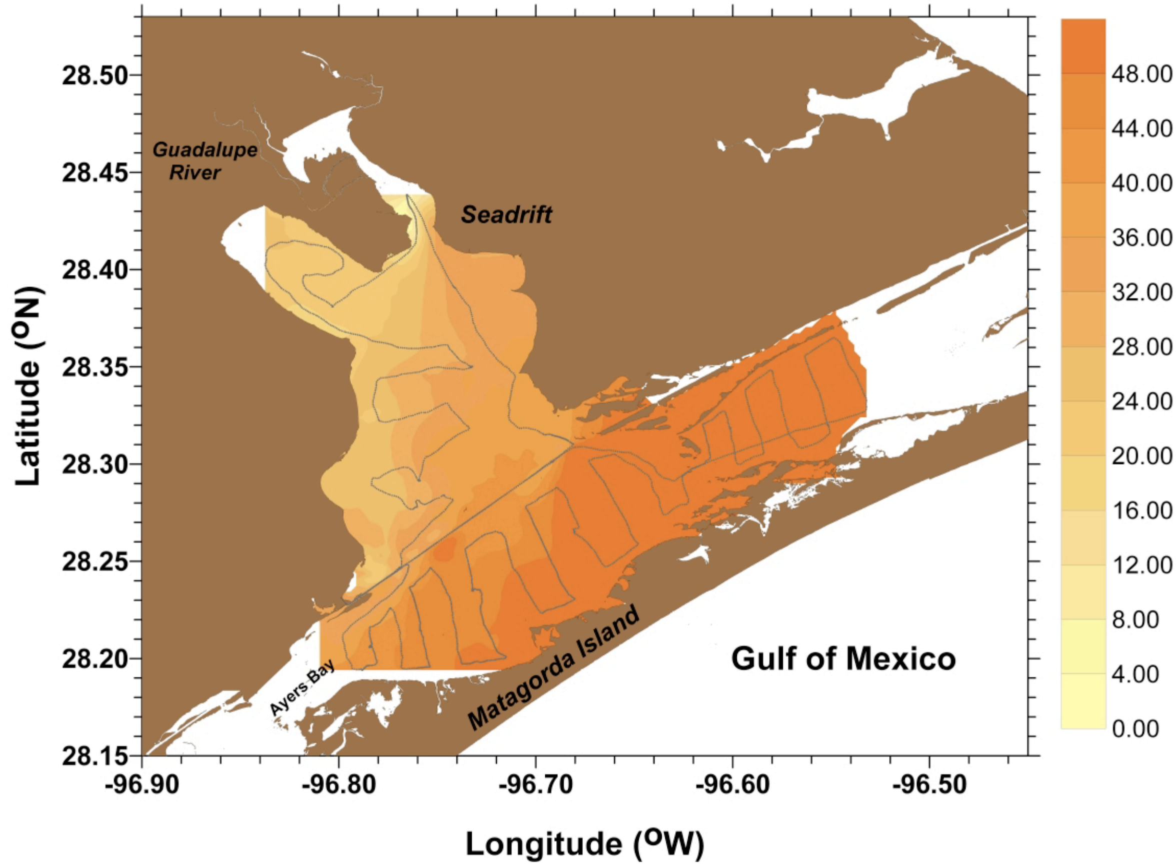

San Antonio Bay, September 05
Conductivity (ms cm-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
48.00
44.00
40.00
36.00
32.00
28.00
24.00
20.00
16.00
12.00
8.00
4.00
0.00


San Antonio Bay, October 05
Conductivity (ms cm-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
48.00
44.00
40.00
36.00
32.00
28.00
24.00
20.00
16.00
12.00
8.00
4.00
0.00


San Antonio Bay, November 05
Conductivity (ms cm-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
48.00
44.00
40.00
36.00
32.00
28.00
24.00
20.00
16.00
12.00
8.00
4.00
0.00

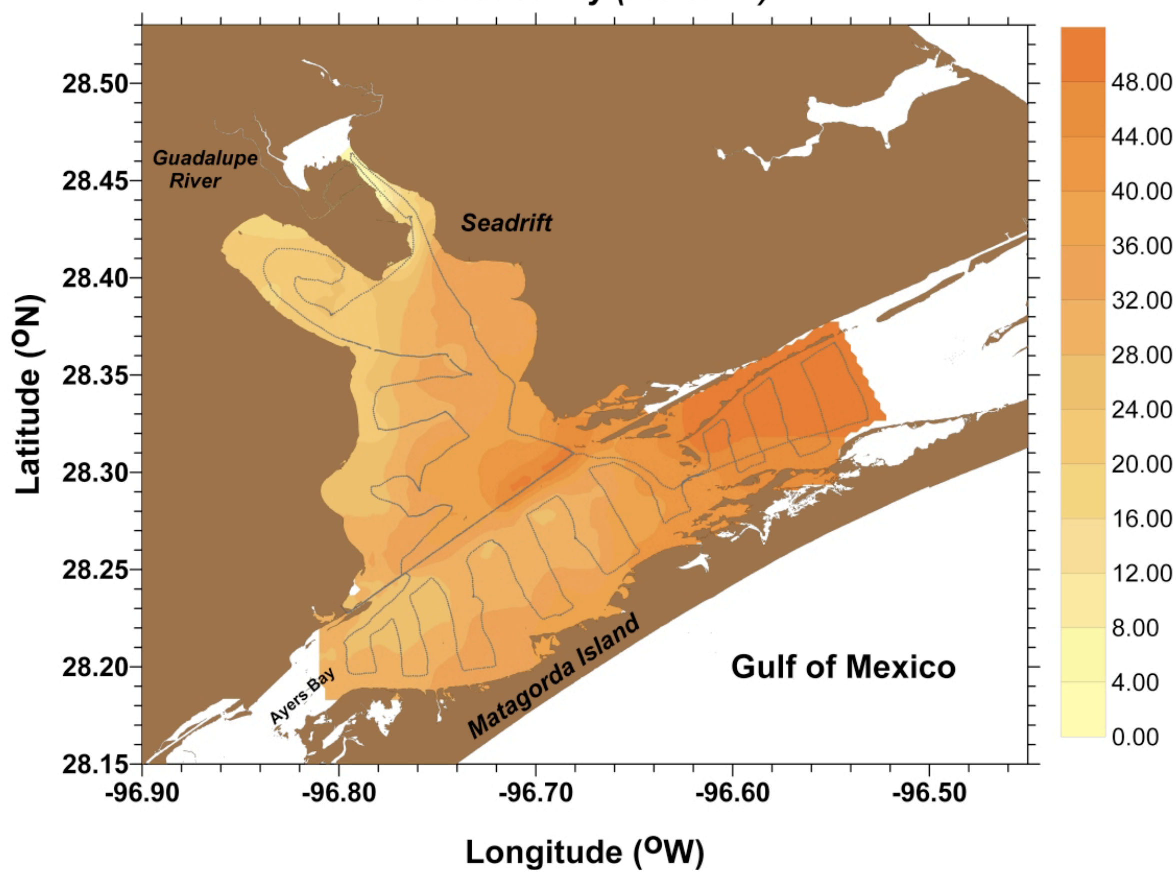
San Antonio Bay, December 05

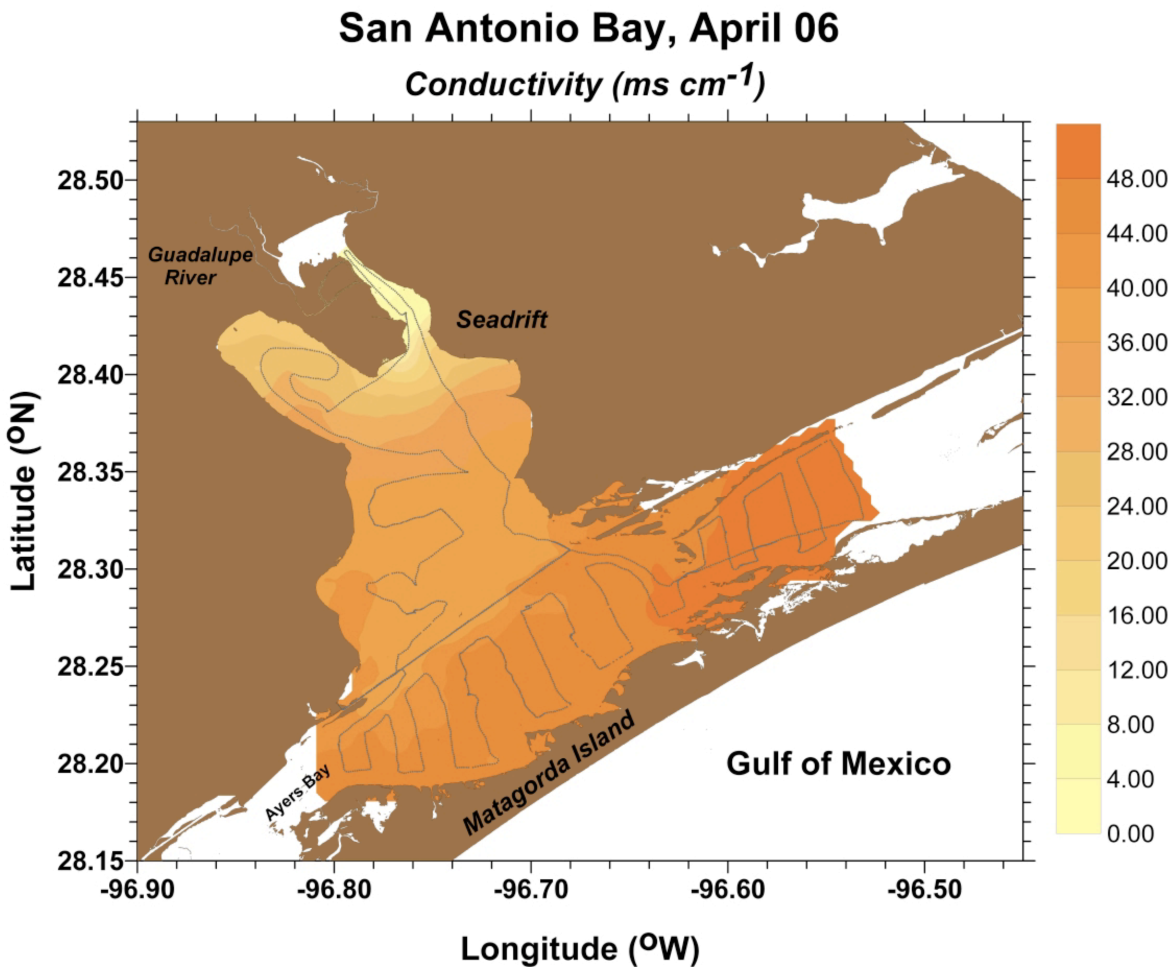
Conductivity (ms cm^{-1})

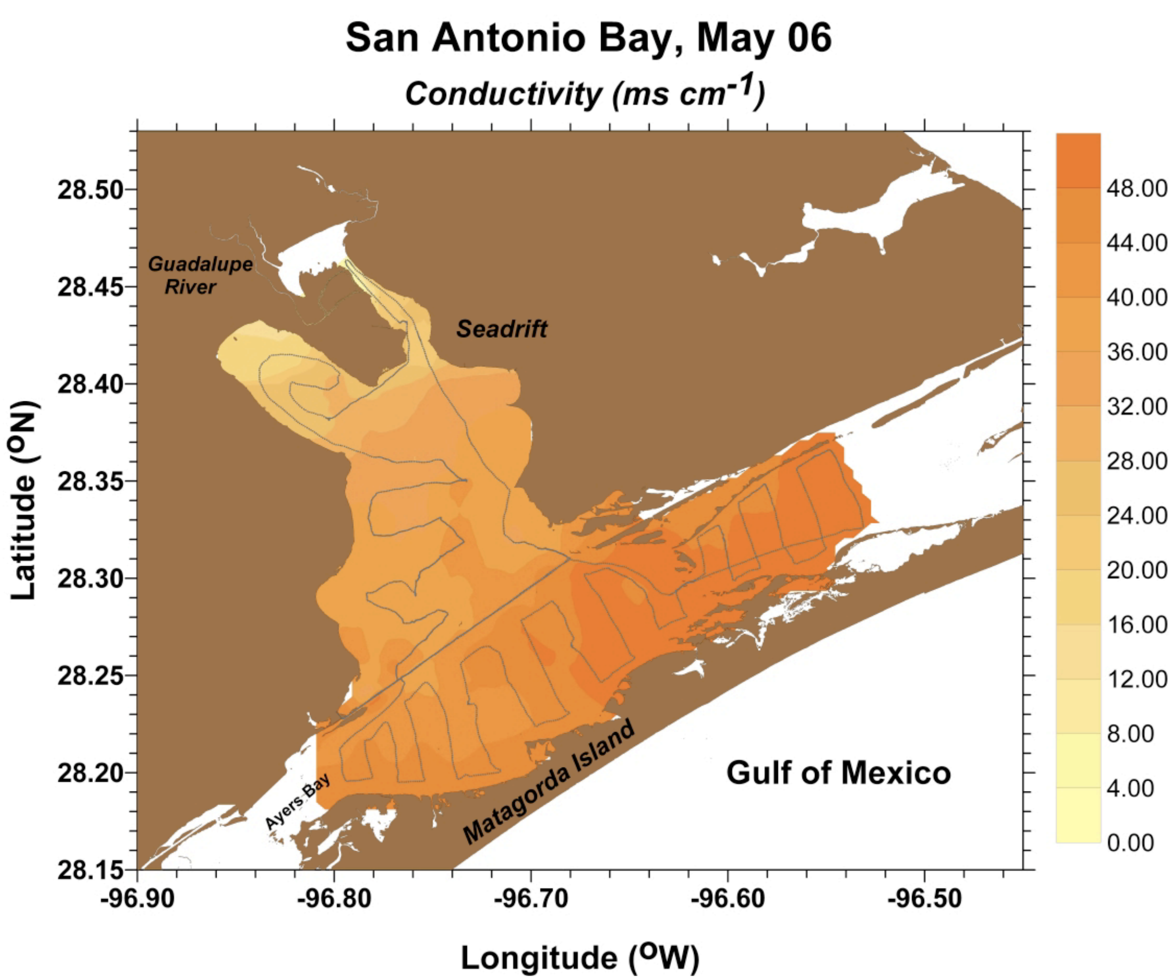


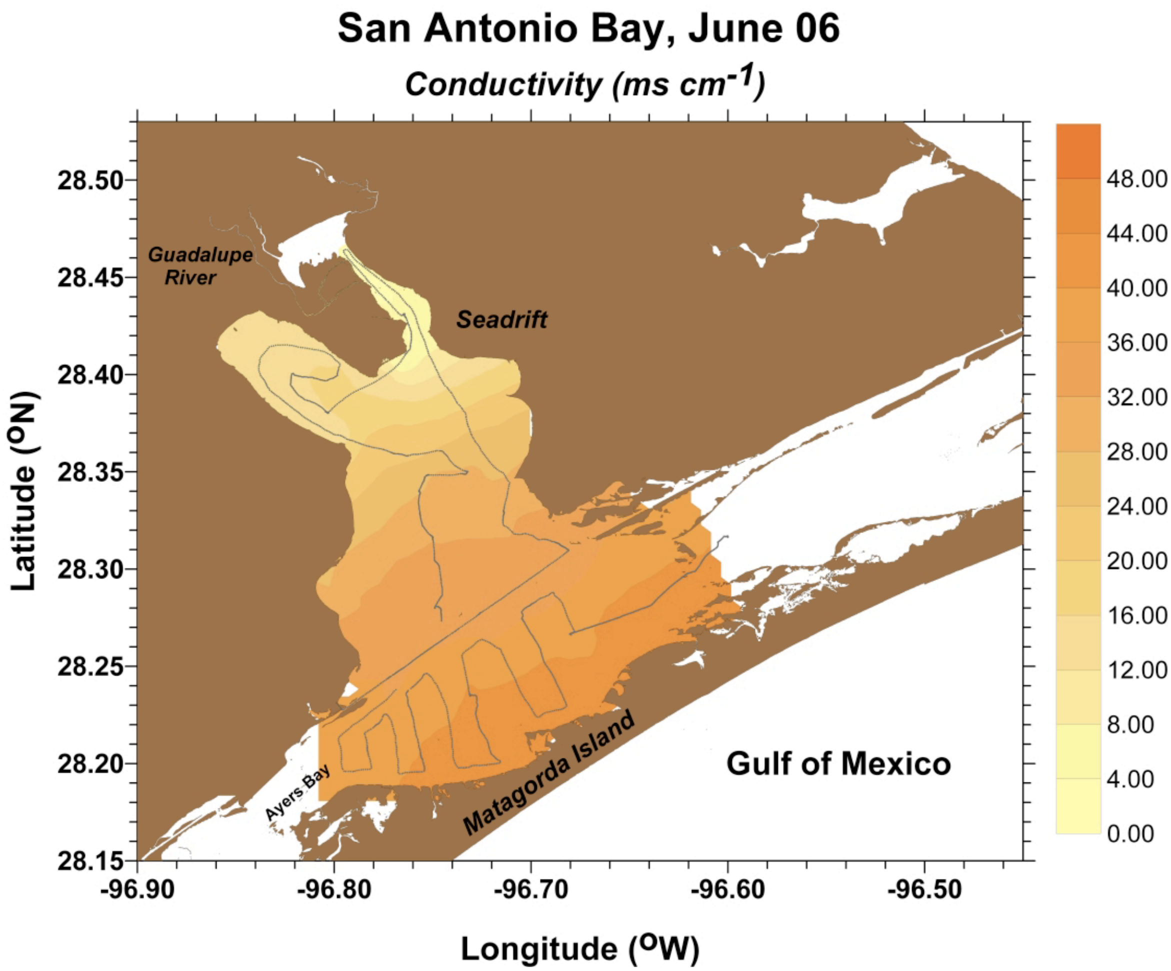
San Antonio Bay, February 06

Conductivity (ms cm^{-1})




San Antonio Bay, April 06
Conductivity (ms cm-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
48.00
44.00
40.00
36.00
32.00
28.00
24.00
20.00
16.00
12.00
8.00
4.00
0.00


San Antonio Bay, May 06
Conductivity (ms cm-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
48.00
44.00
40.00
36.00
32.00
28.00
24.00
20.00
16.00
12.00
8.00
4.00
0.00


San Antonio Bay, June 06
Conductivity (ms cm-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
48.00
44.00
40.00
36.00
32.00
28.00
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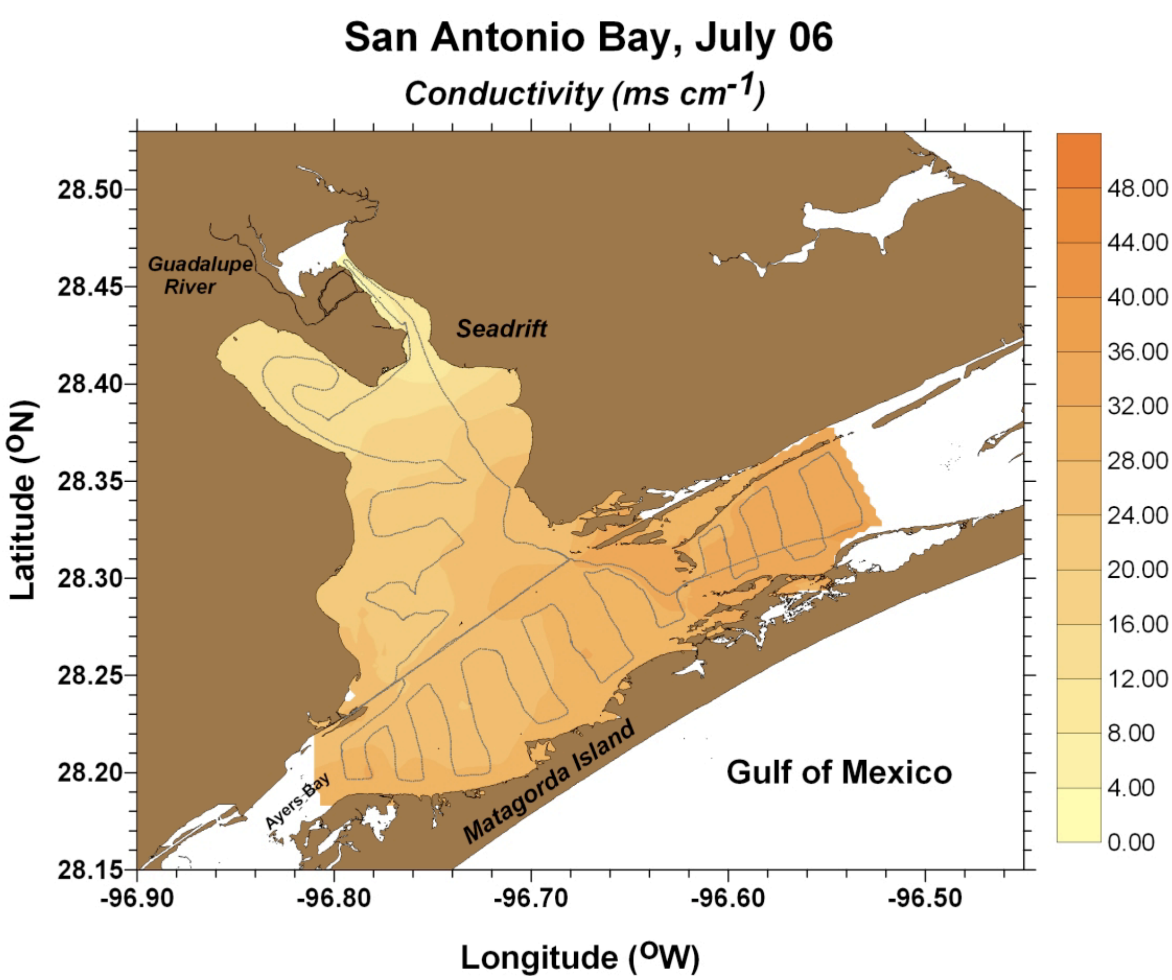
8.00
4.00
0.00


San Antonio Bay, July 06
Conductivity (ms cm-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
48.00
44.00
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36.00
32.00
28.00
24.00
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16.00
12.00
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4.00
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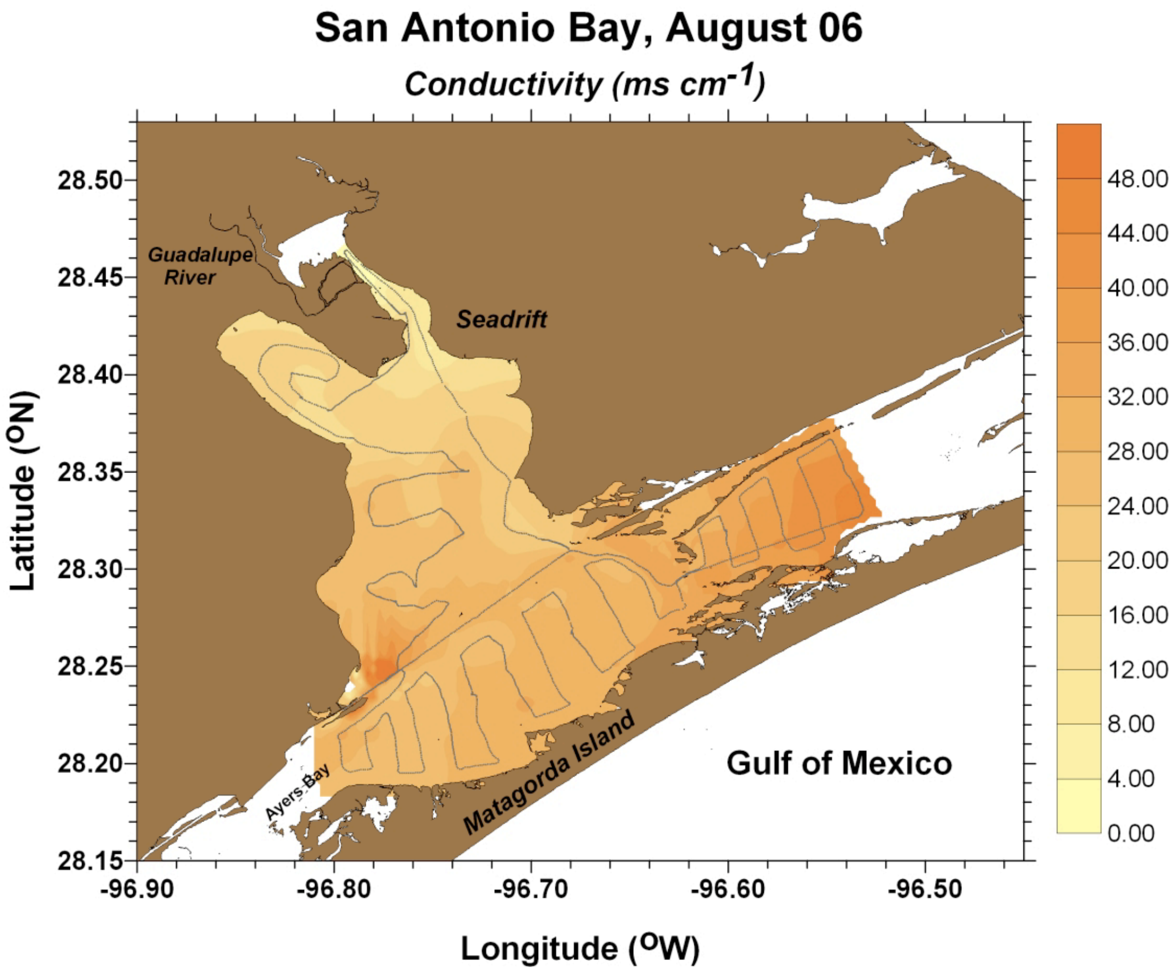
San Antonio Bay, August 06
Conductivity (ms cm-1)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
48.00
44.00
40.00
36.00
32.00
28.00
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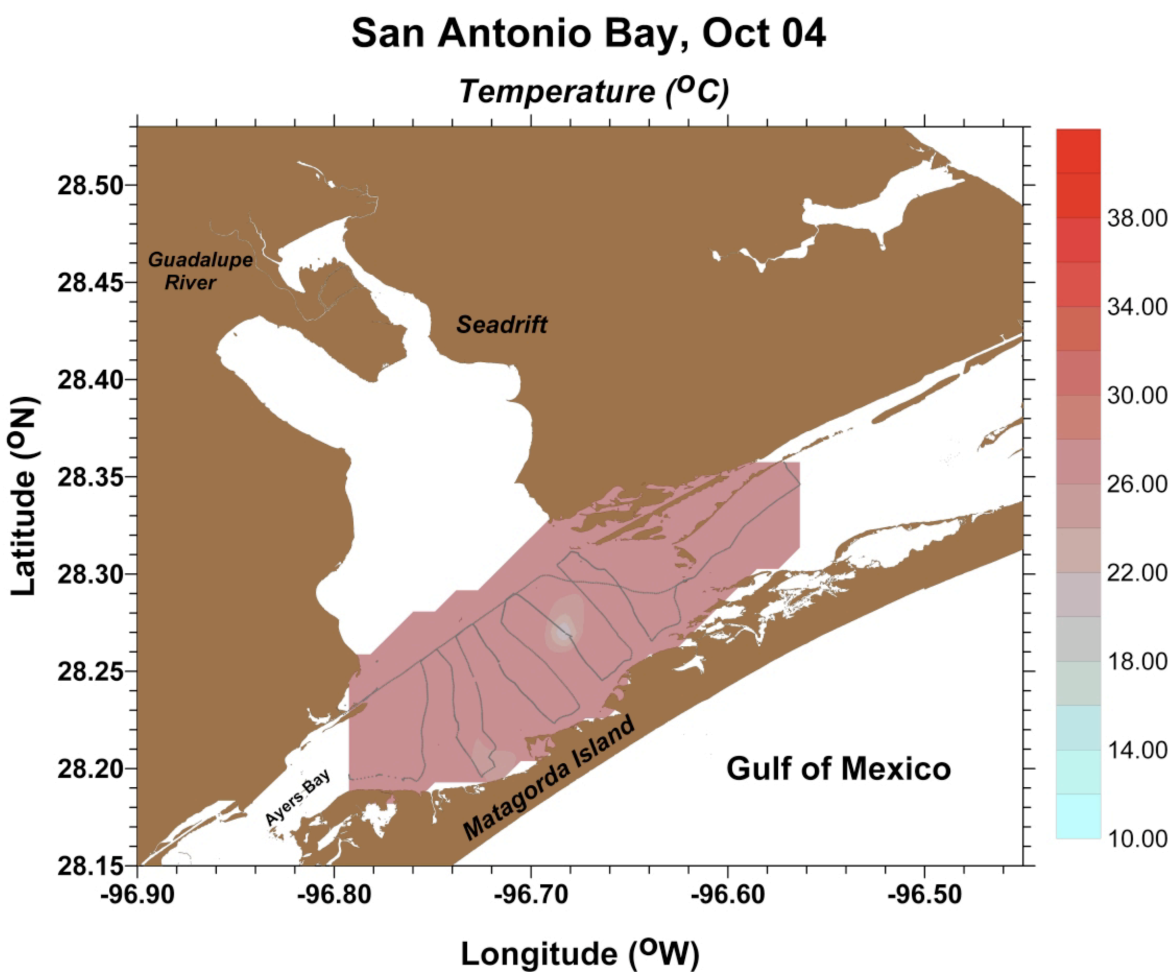
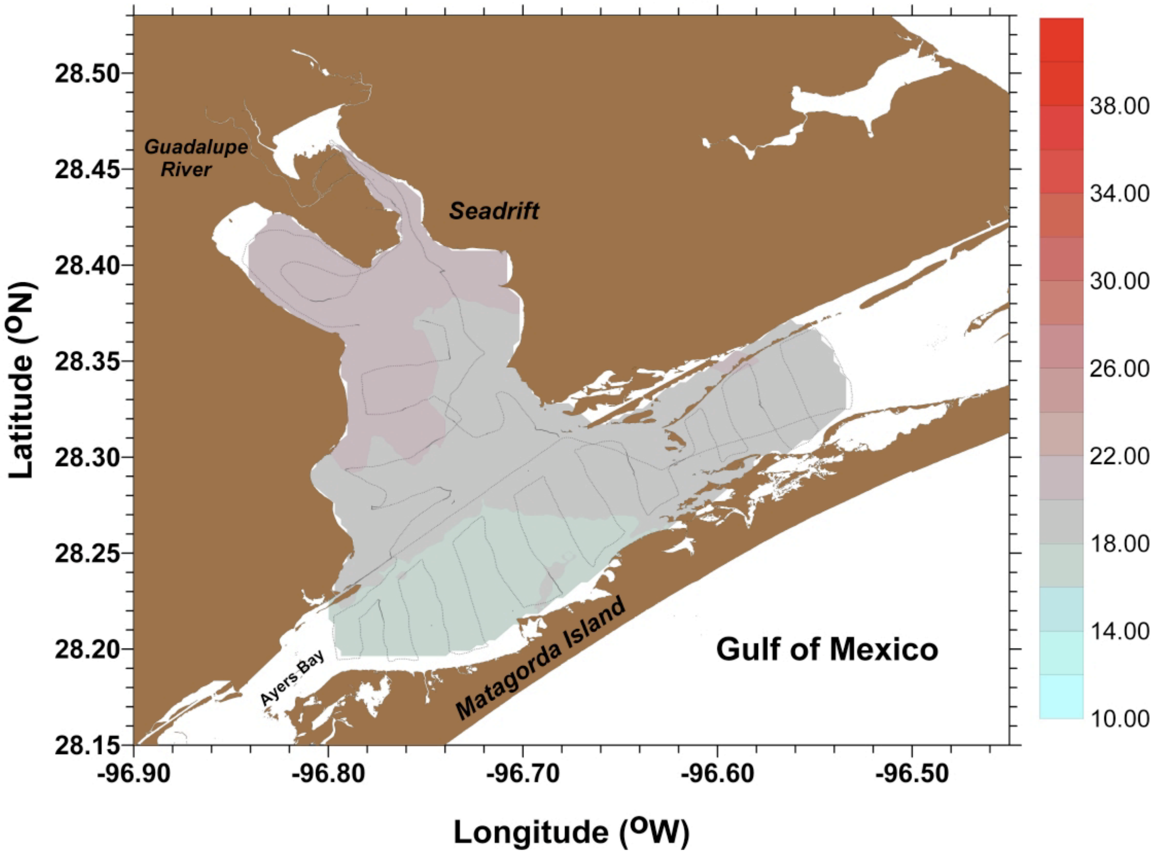
8.00
4.00
0.00


San Antonio Bay, Oct 04
Temperature (OC)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
38.00
34.00
30.00
26.00
22.00
18.00
14.00
10.00

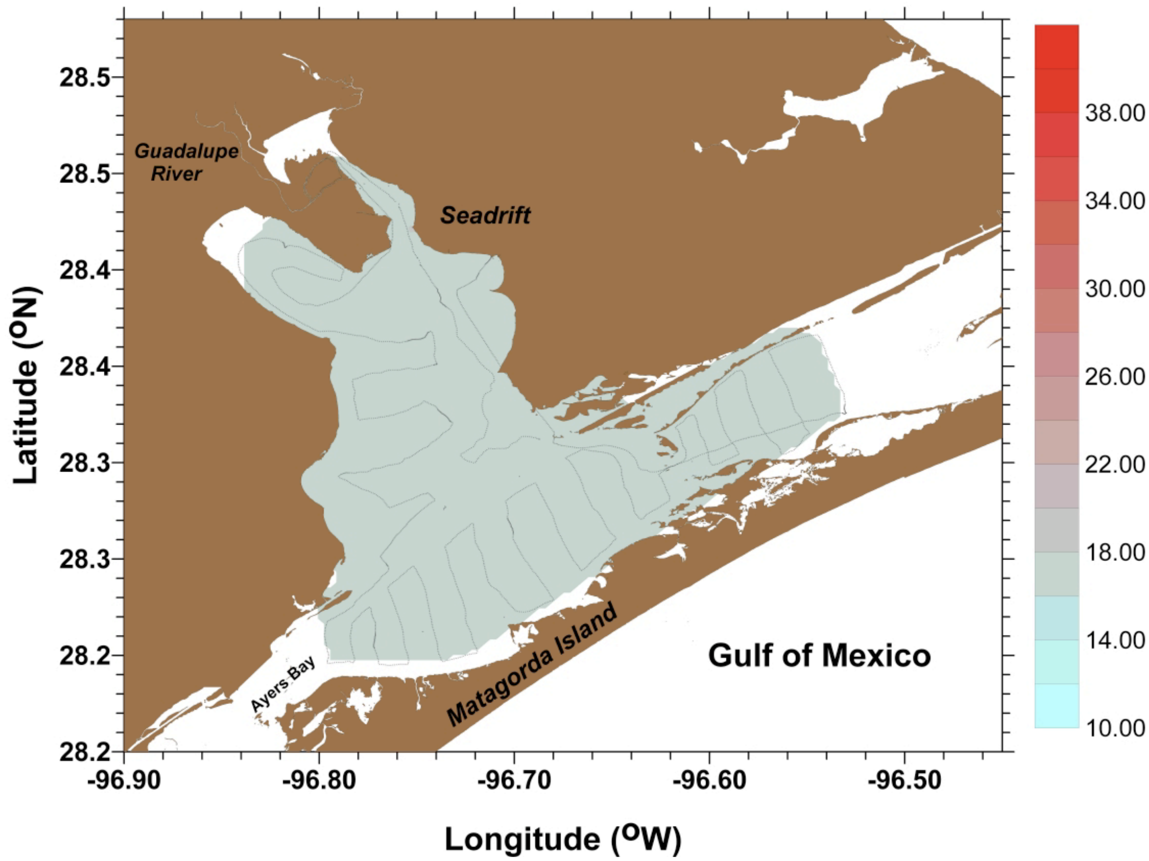
San Antonio Bay, January 05

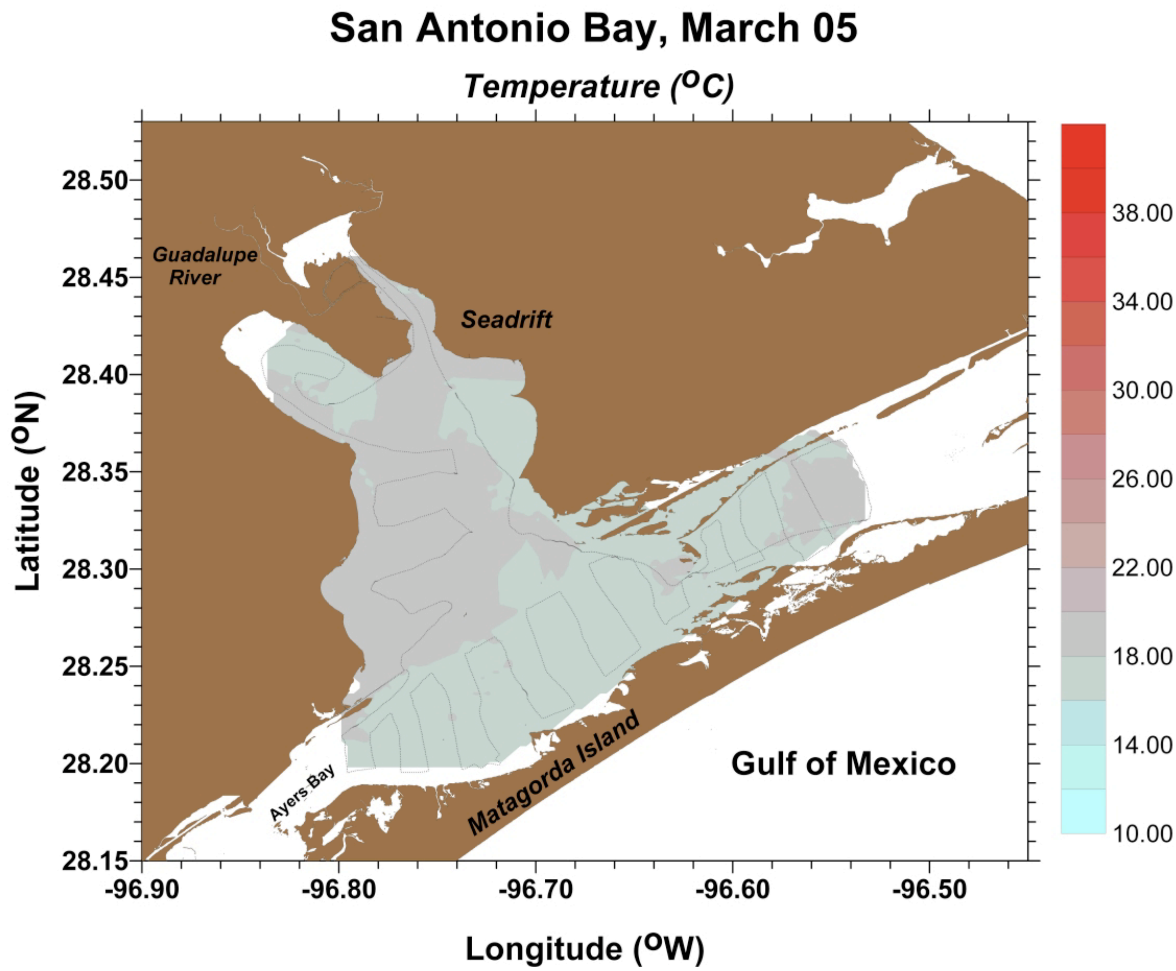
Temperature (^oC)



San Antonio Bay, February 05

Temperature (^oC)




San Antonio Bay, March 05
Temperature (°C)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
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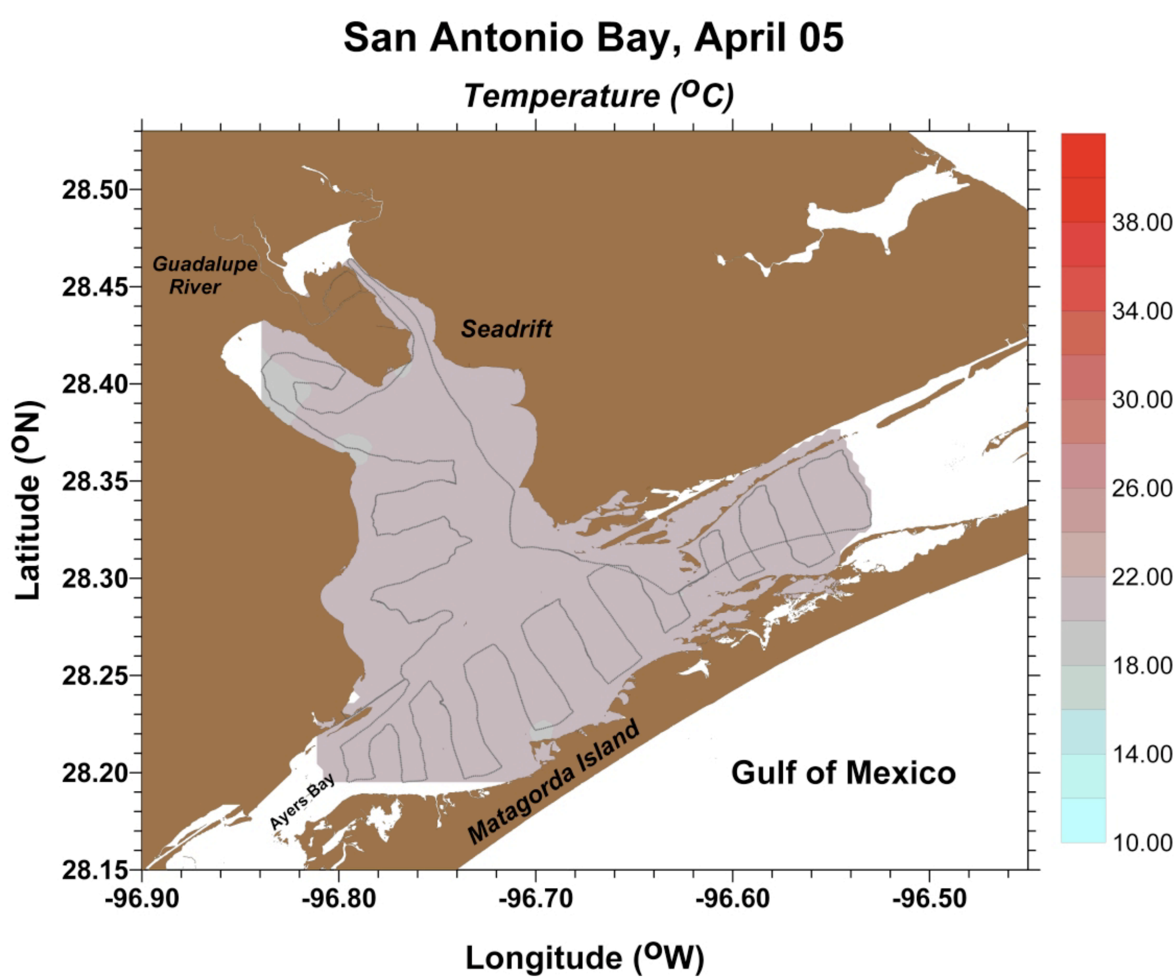
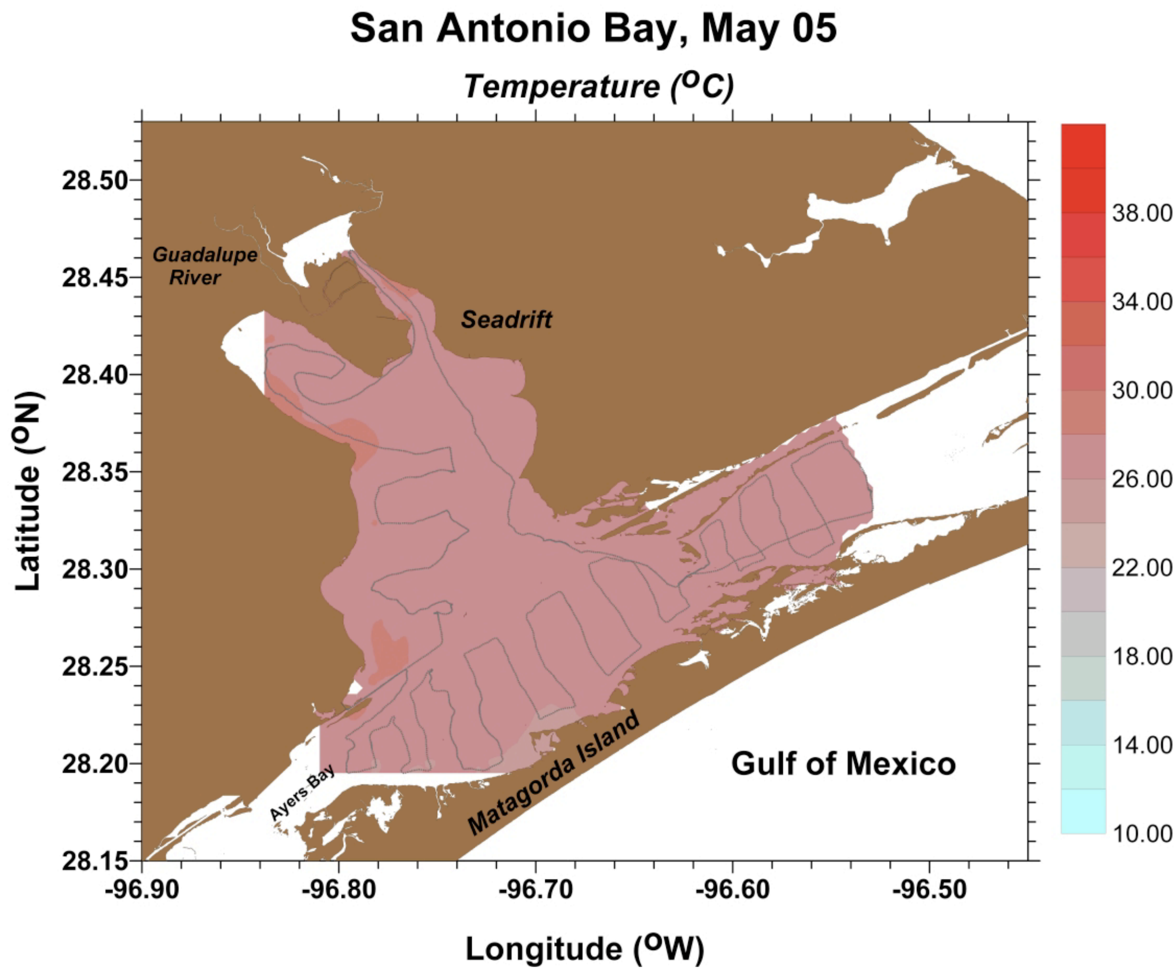
-96.50
38.00
34.00
30.00
26.00
22.00
18.00
14.00
10.00


San Antonio Bay, April 05
Temperature (°C)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
38.00
34.00
30.00
26.00
22.00
18.00
14.00
10.00


San Antonio Bay, May 05
Temperature (OC)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
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-96.50
38.00
34.00
30.00
26.00
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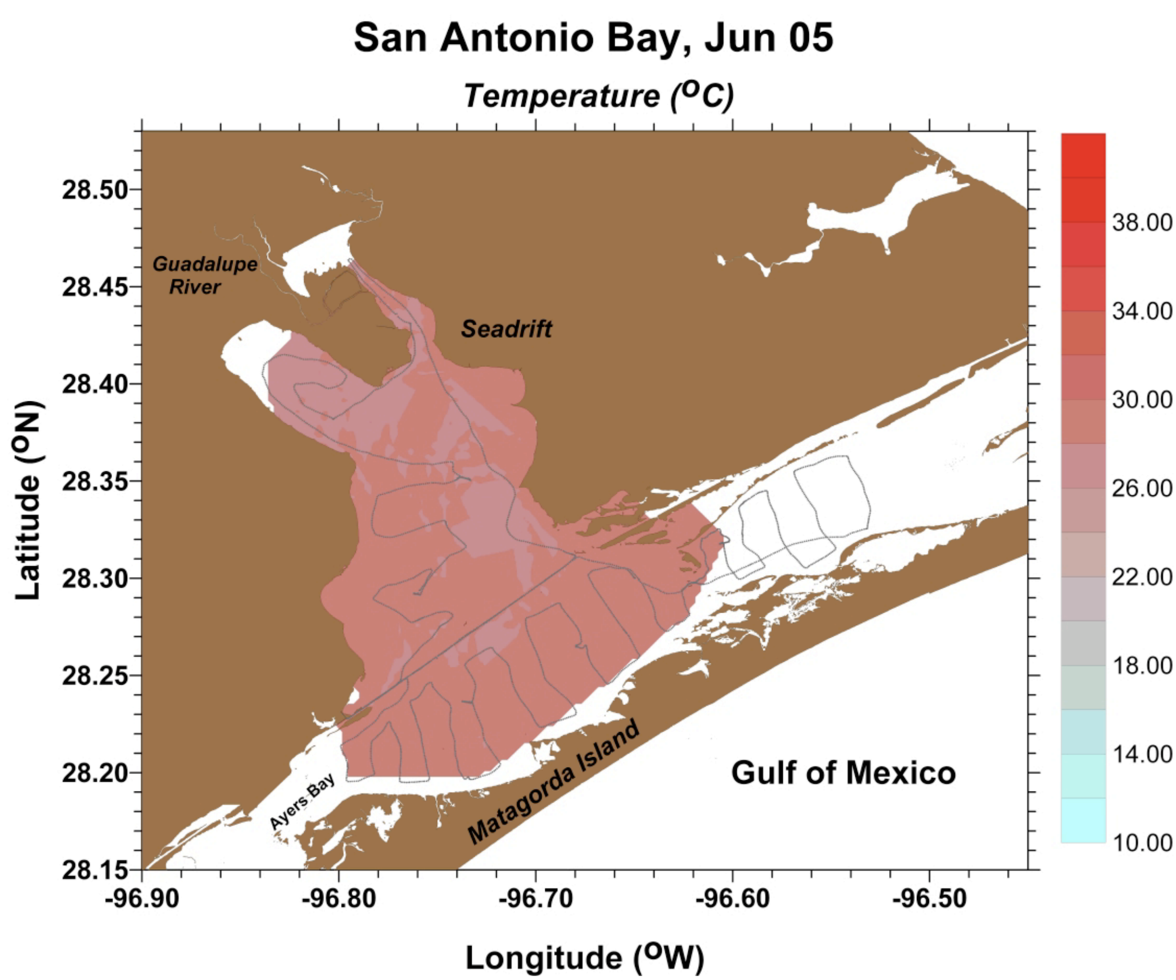
18.00
14.00
10.00


San Antonio Bay, Jun 05
Temperature (OC)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
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26.00
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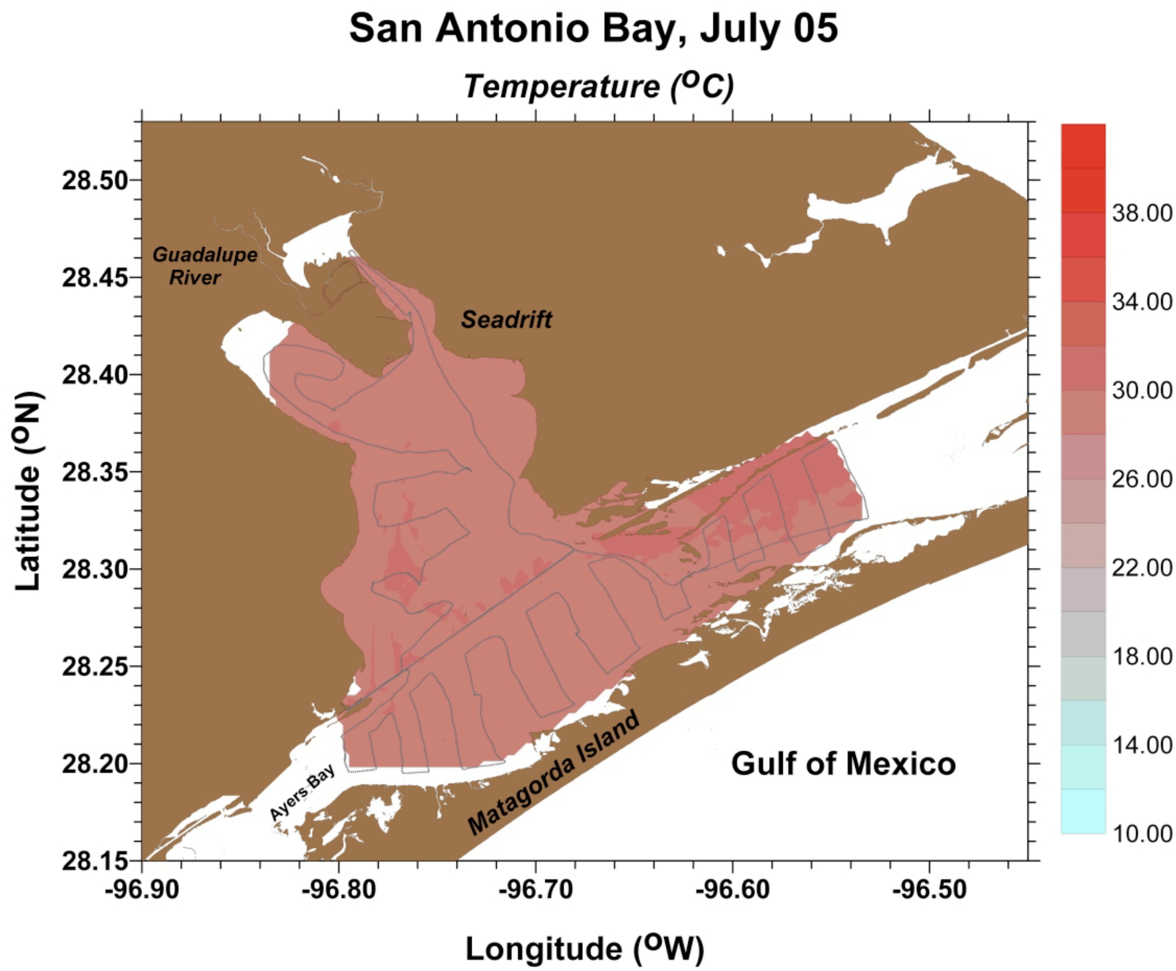
14.00
10.00


San Antonio Bay, July 05
Temperature (°C)
Latitude (°N)
Longitude (°W)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
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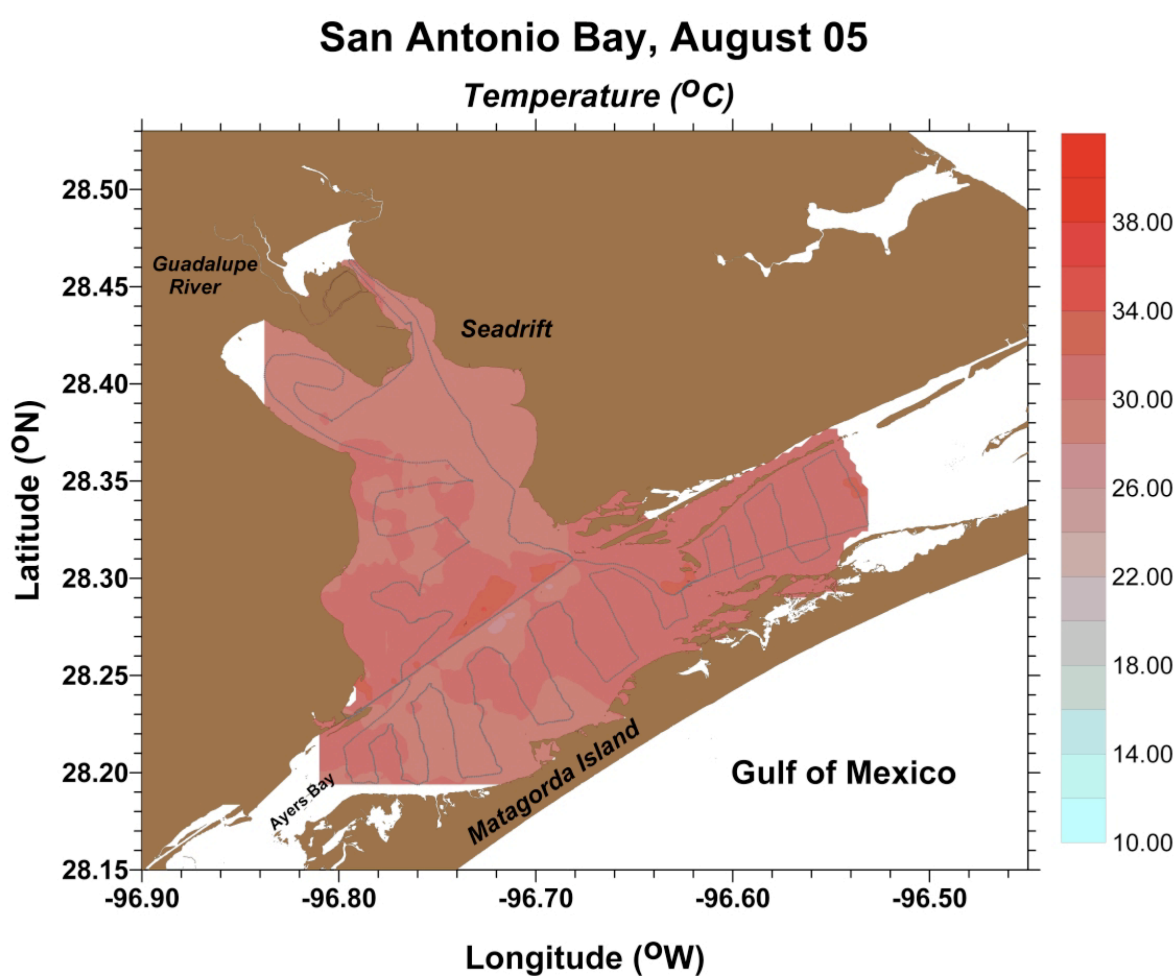
26.00
22.00
18.00
14.00
10.00


San Antonio Bay, August 05
Temperature (°C)
Latitude (°N)
Longitude (°W)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
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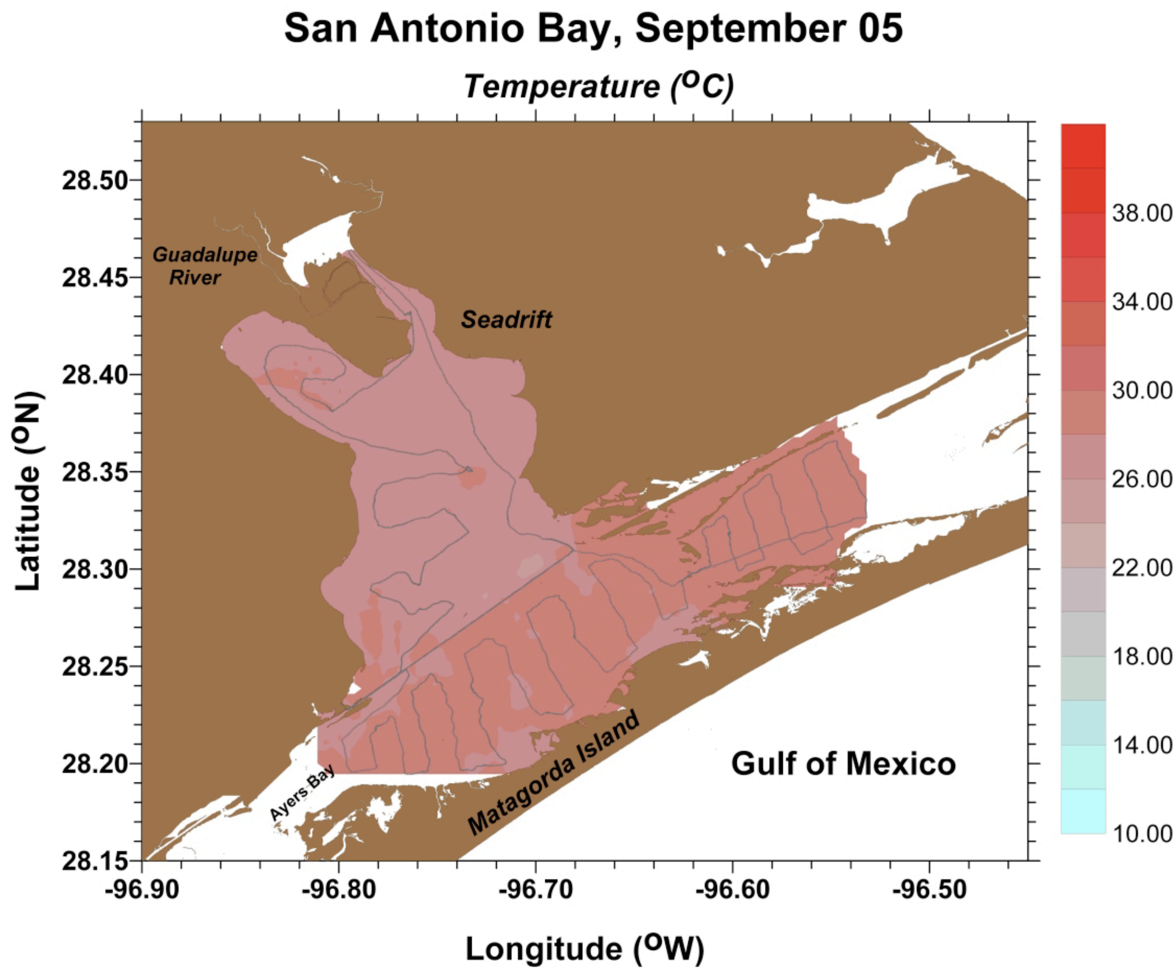
-96.50
38.00
34.00
30.00
26.00
22.00
18.00
14.00
10.00


San Antonio Bay, September 05
Temperature (°C)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
38.00
34.00
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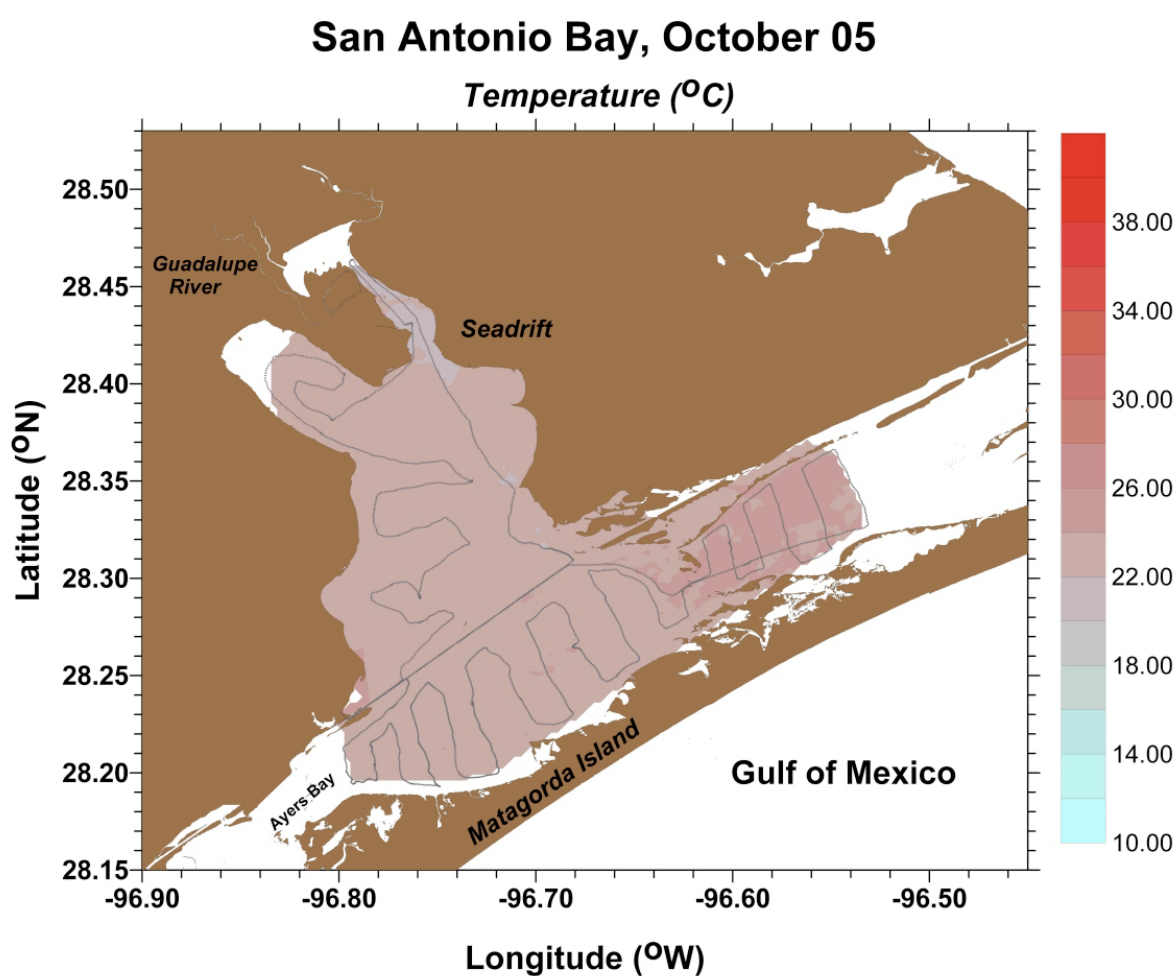
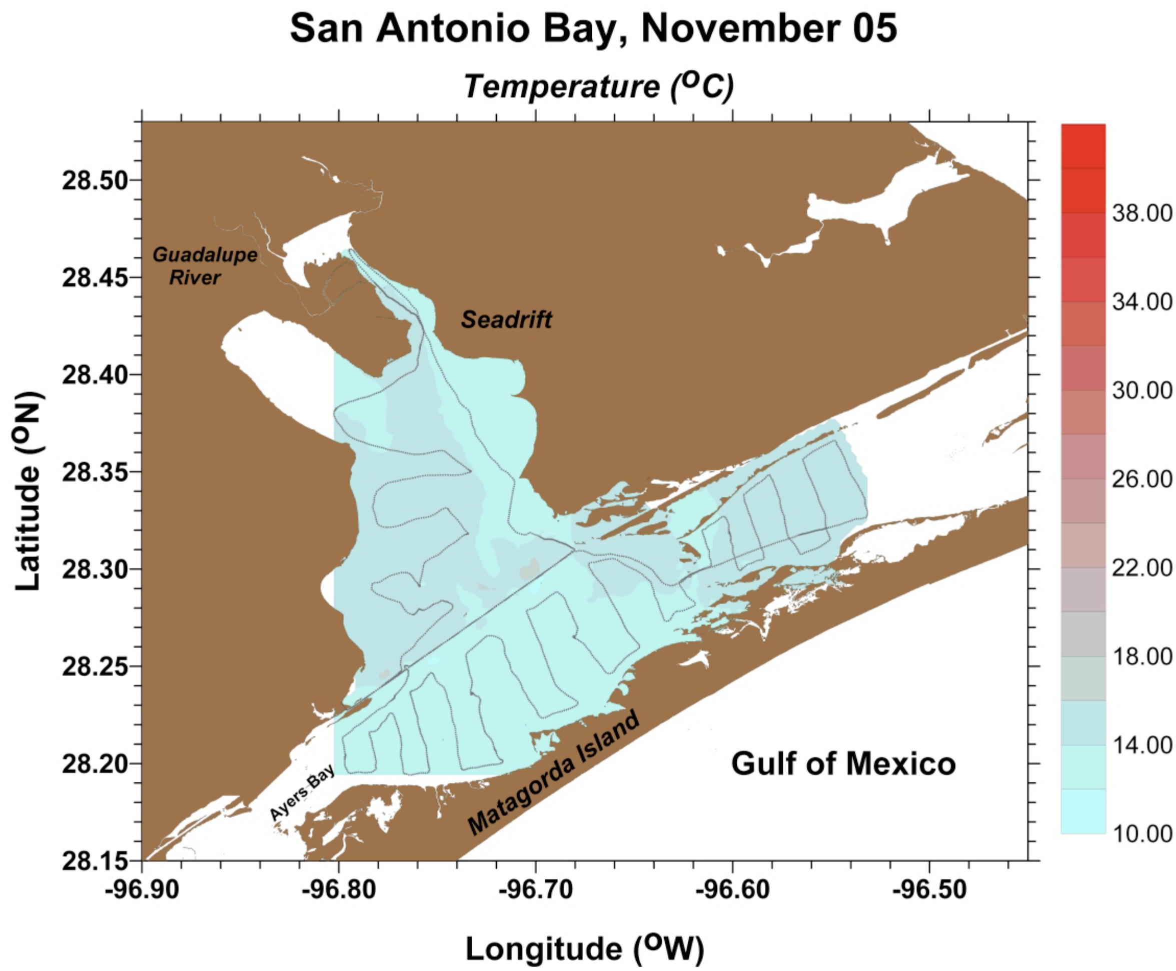
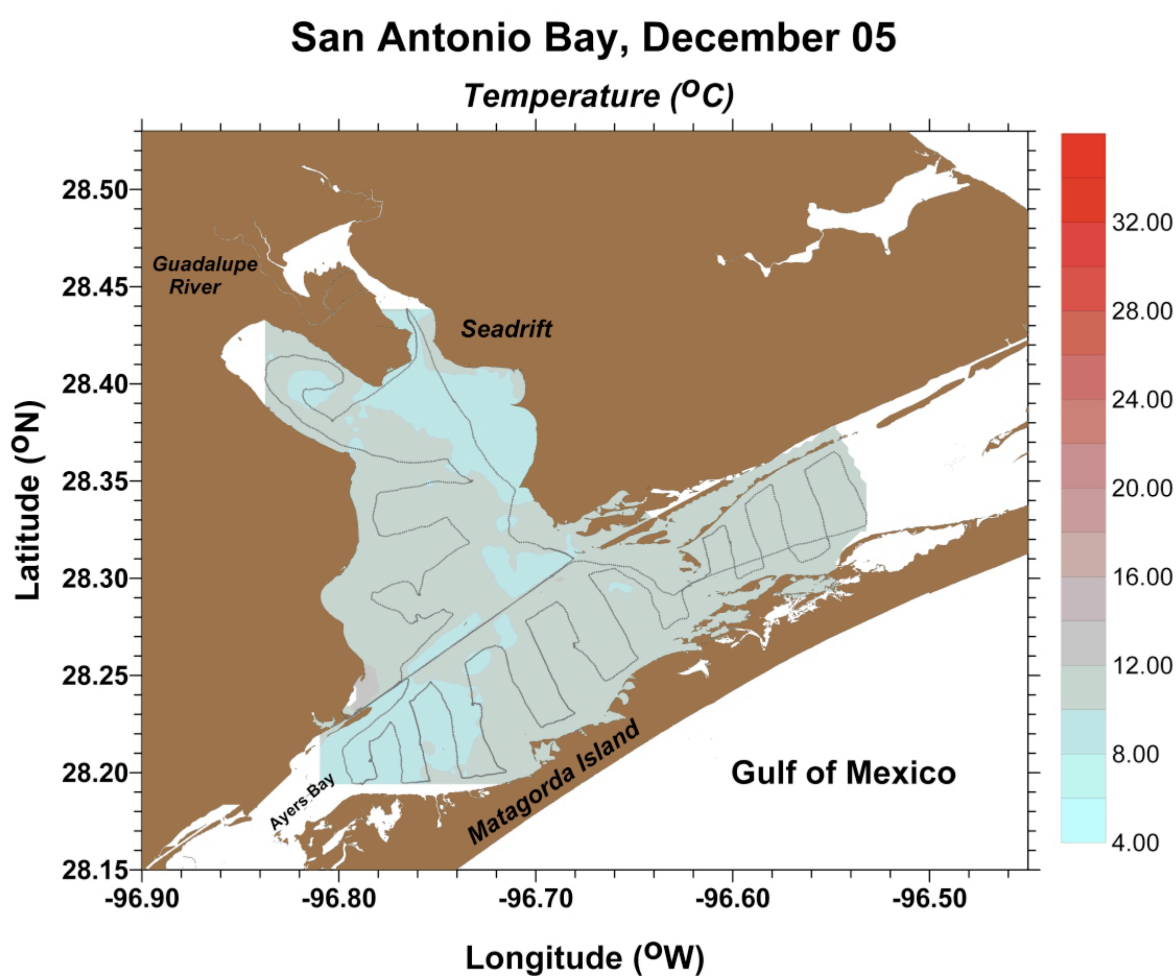
26.00
22.00
18.00
14.00
10.00

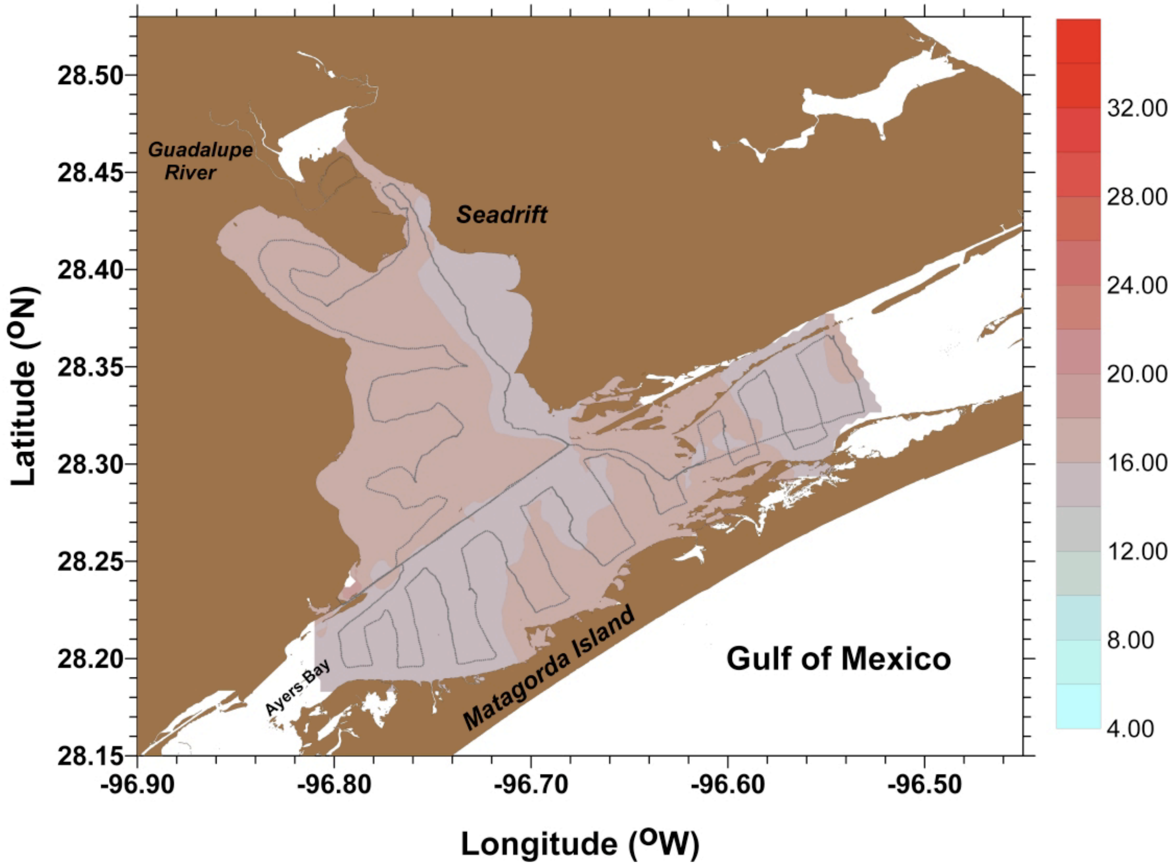

San Antonio Bay, October 05
Temperature (°C)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
38.00
34.00
30.00
26.00
22.00
18.00
14.00
10.00


San Antonio Bay, November 05
Temperature (°C)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
38.00
34.00
30.00
26.00
22.00
18.00
14.00
10.00


San Antonio Bay, December 05
Temperature (°C)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
32.00
28.00
24.00
20.00
16.00
12.00
8.00
4.00

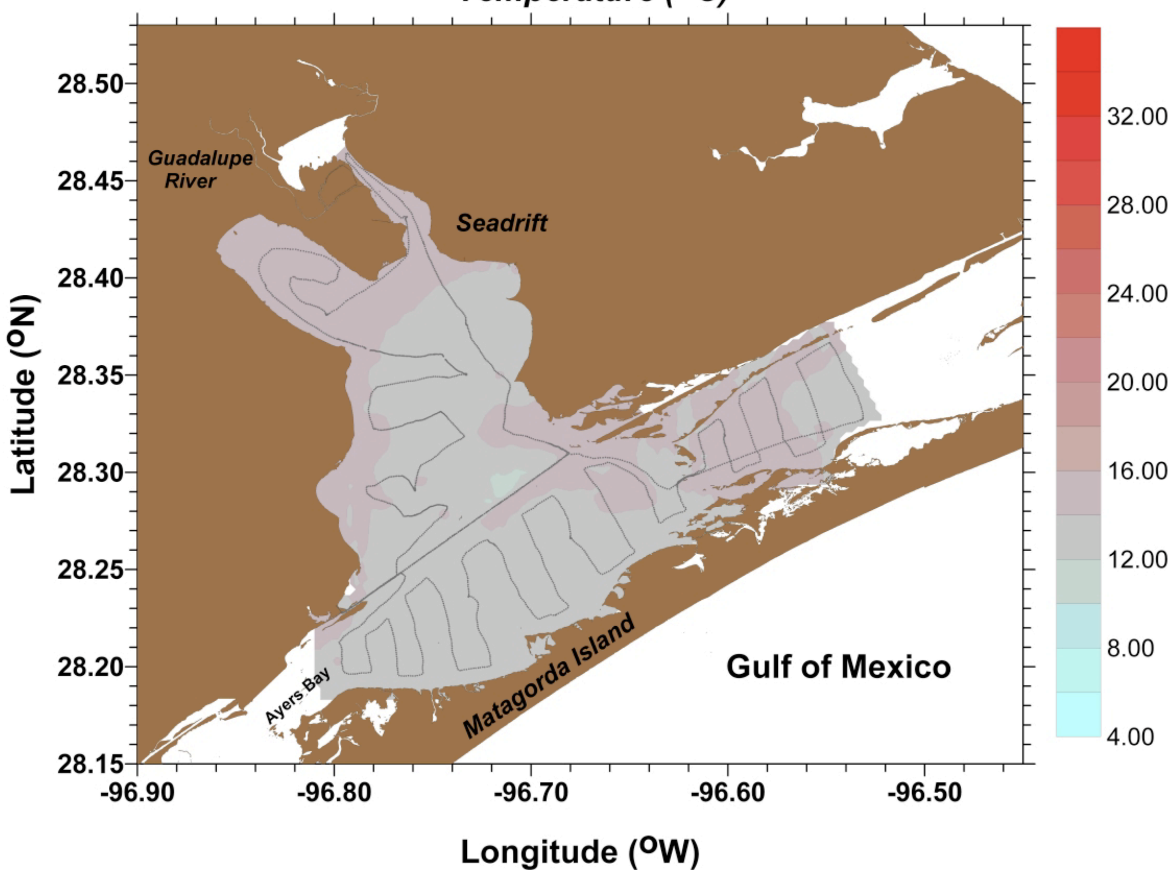
San Antonio Bay, January 06

Temperature (°C)



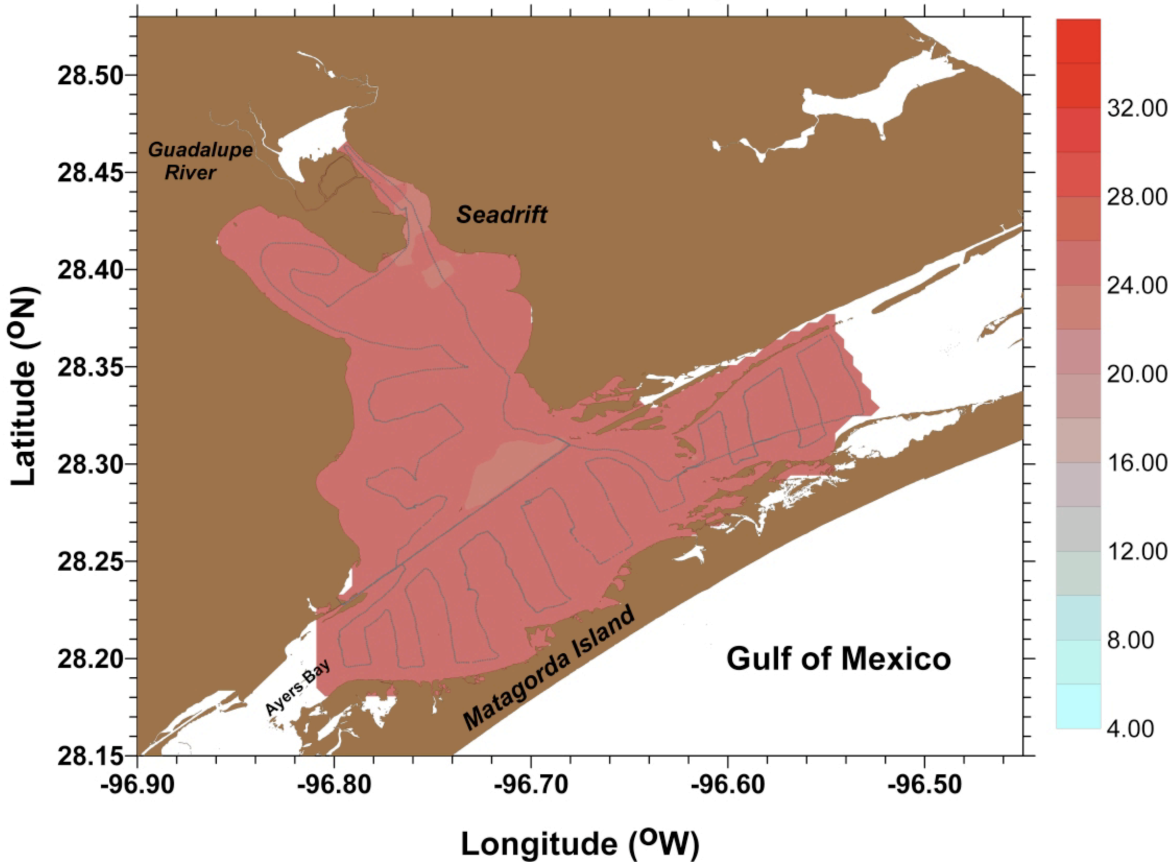
San Antonio Bay, February 06

Temperature (°C)



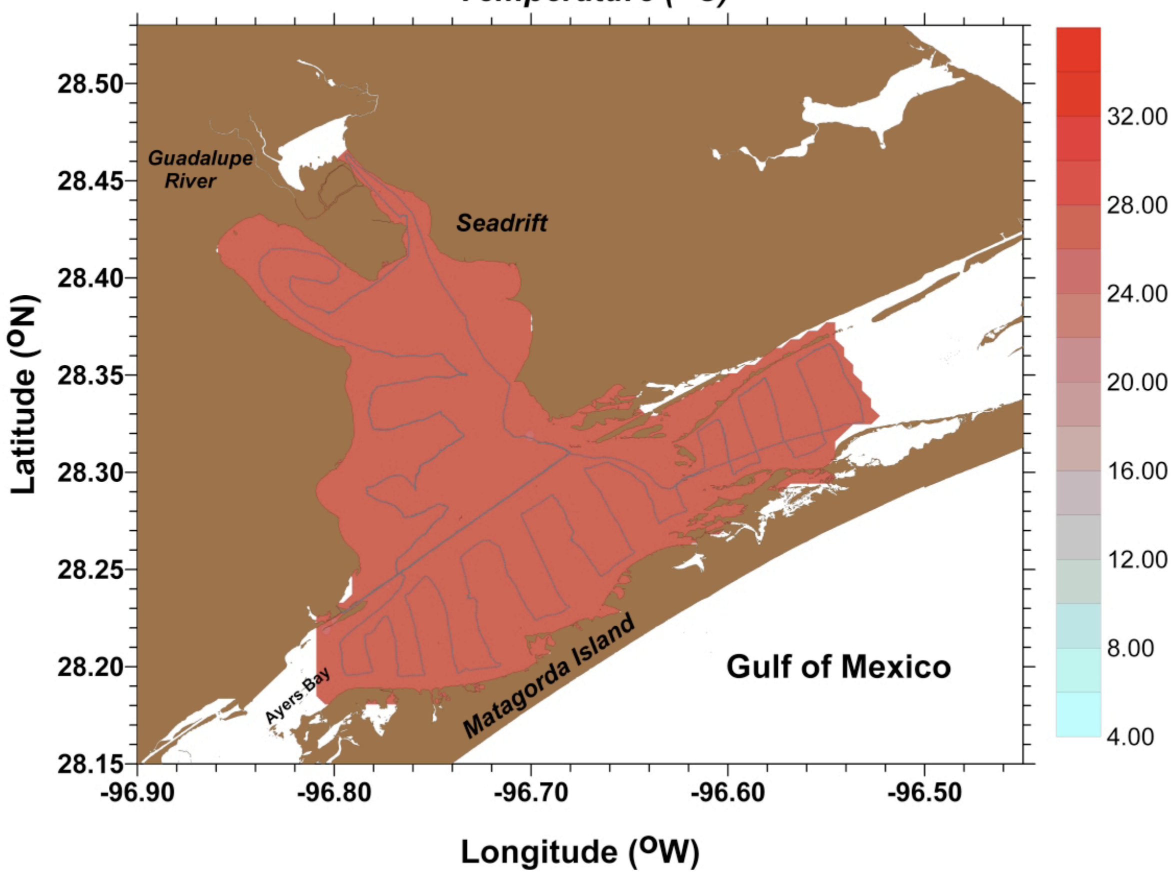
San Antonio Bay, Apr 06

Temperature (^{O}C)



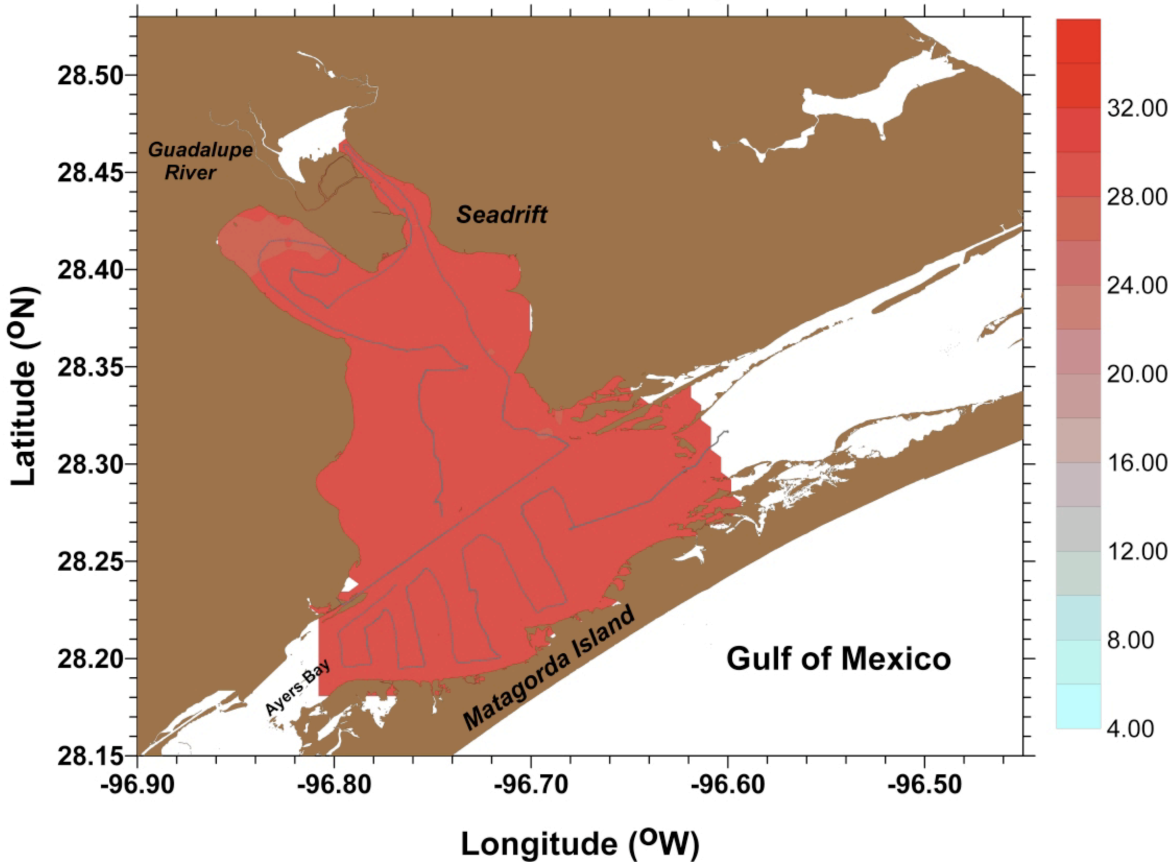
San Antonio Bay, May 06

Temperature (^{O}C)



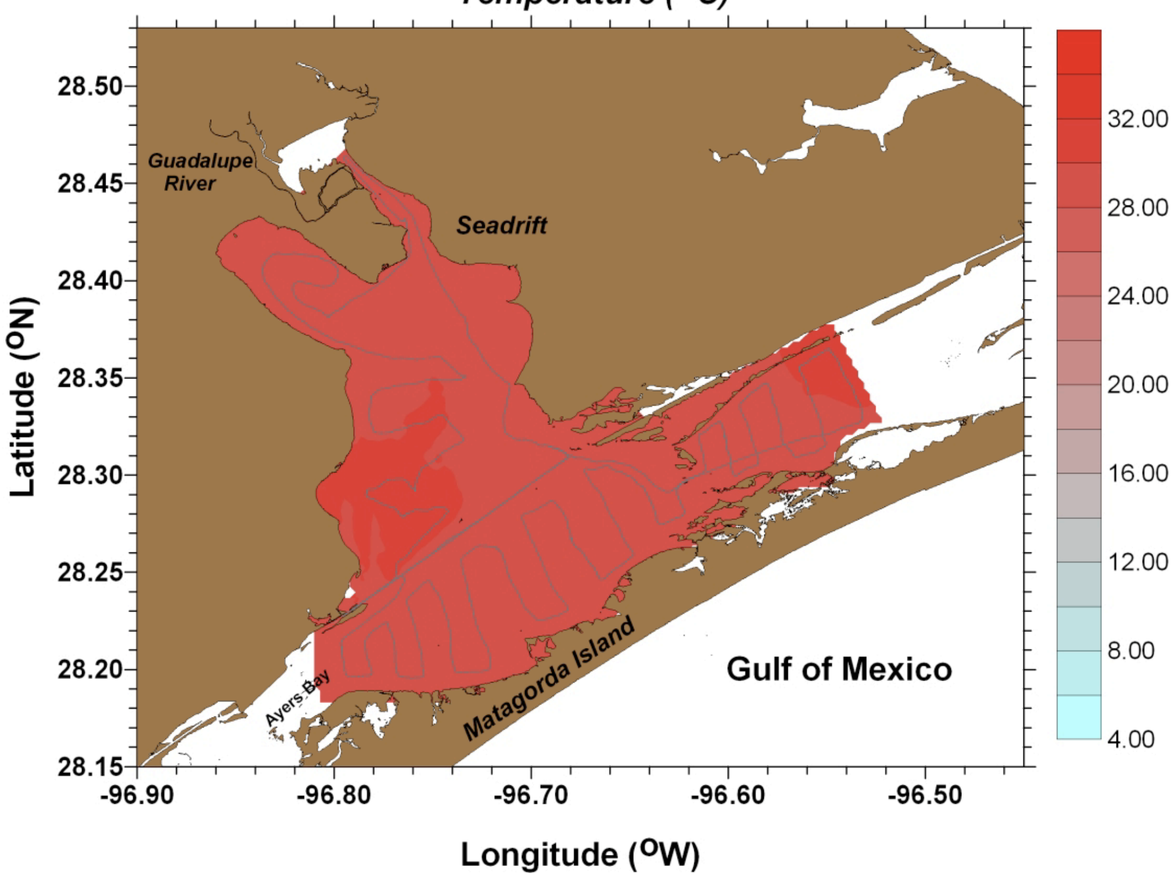
San Antonio Bay, June 06

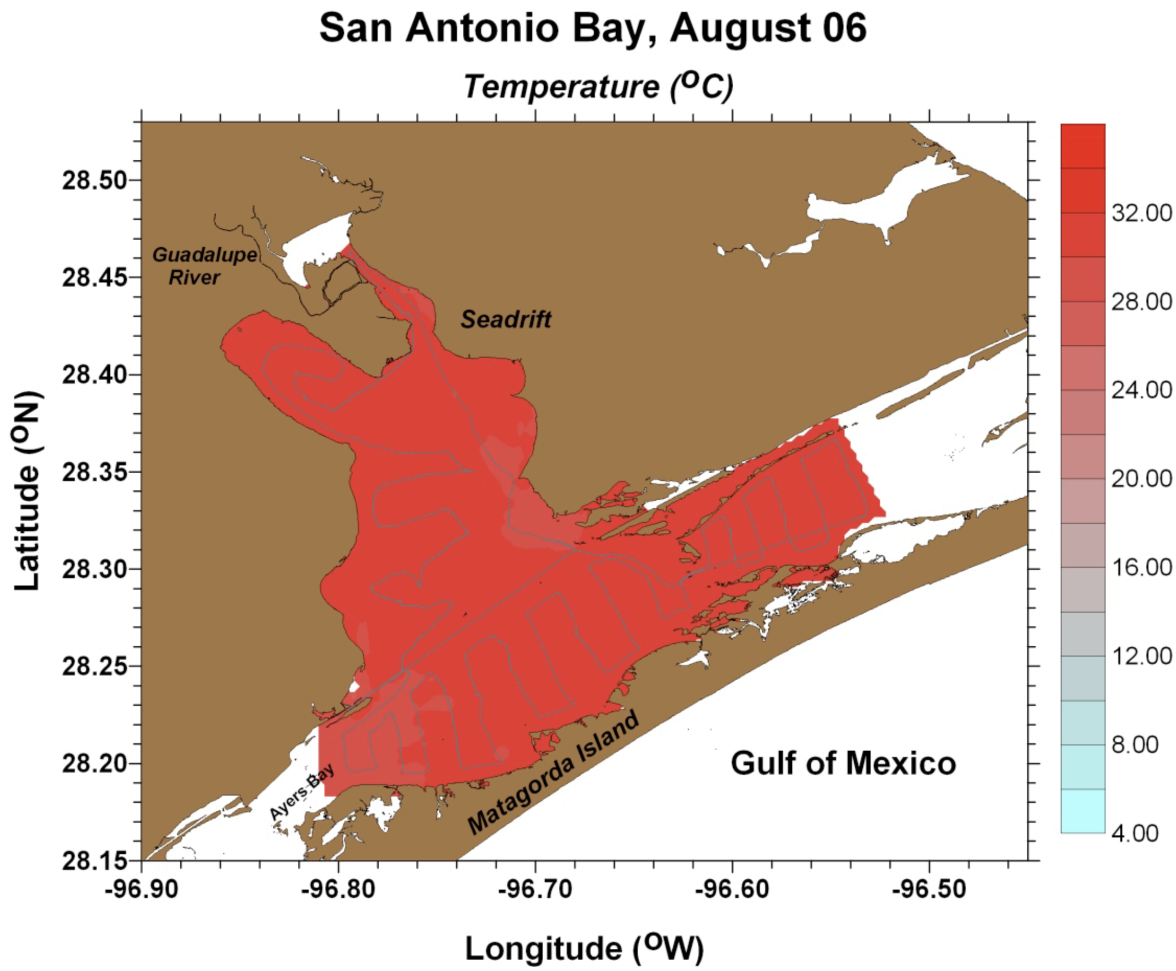
Temperature (^{O}C)

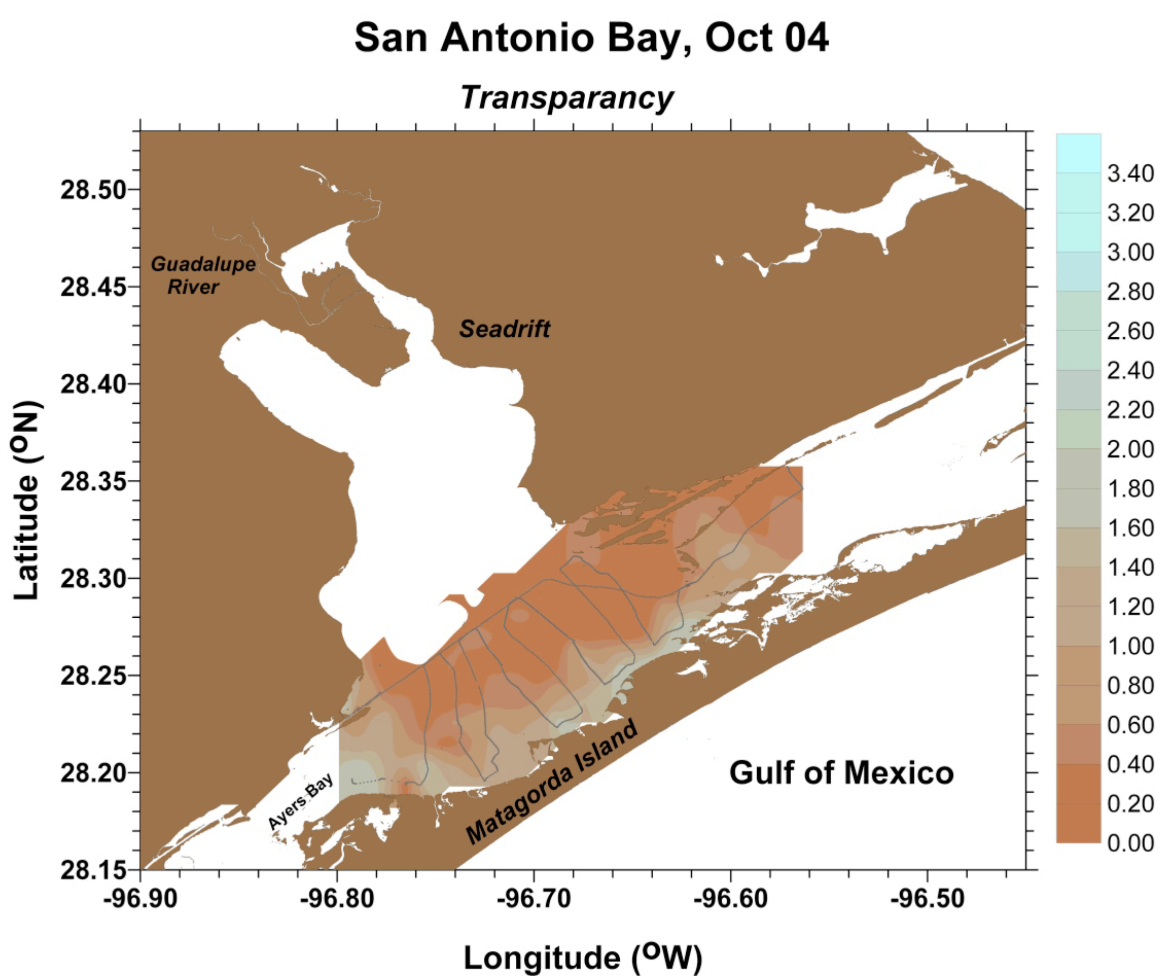


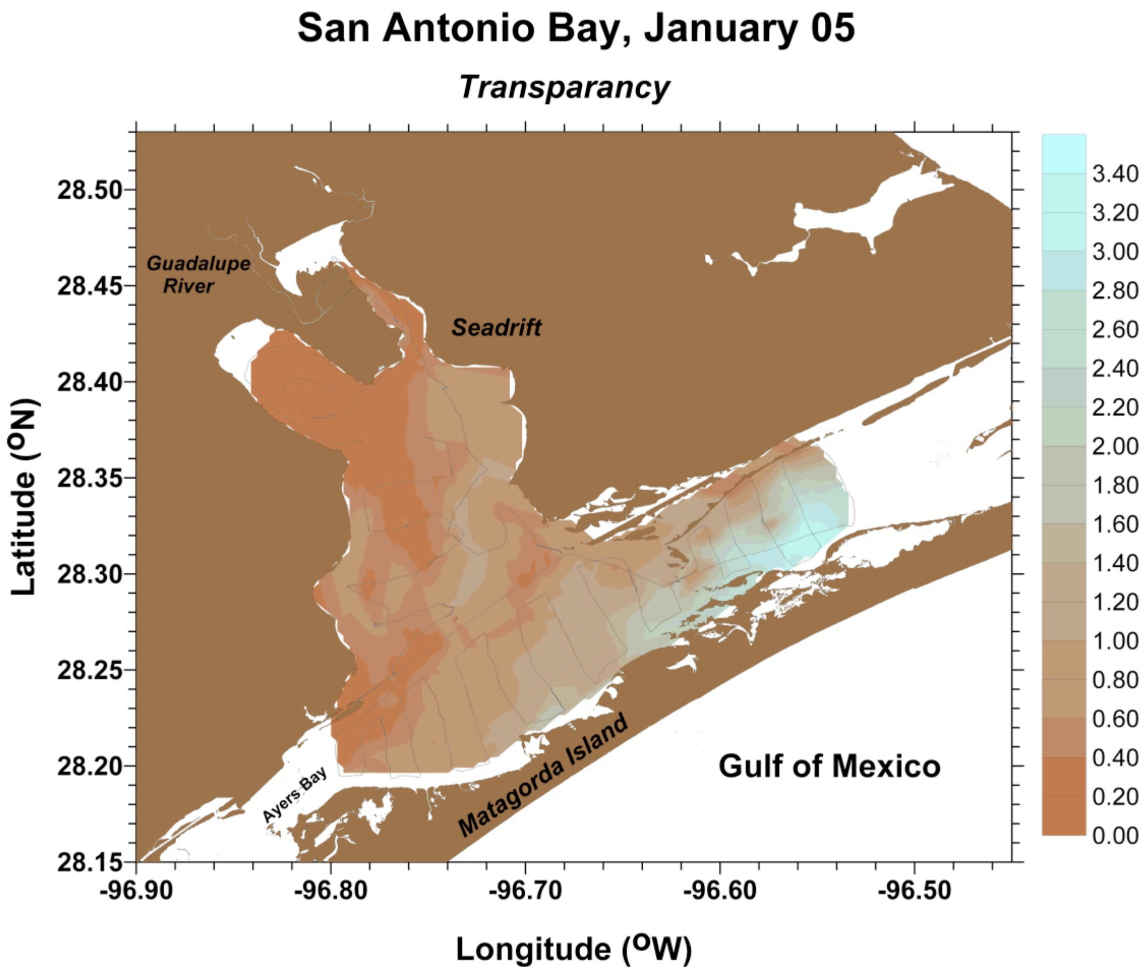
San Antonio Bay, July 06

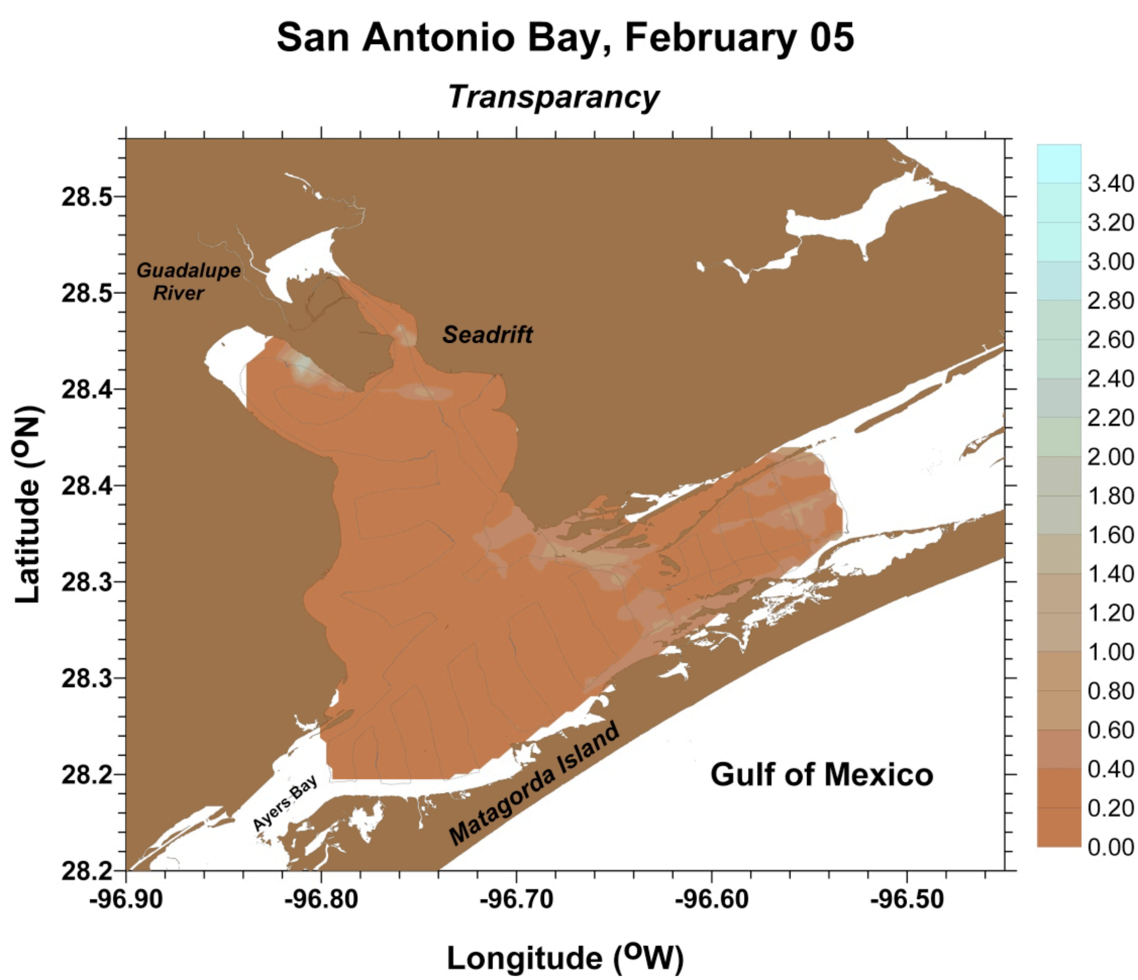
Temperature (^{O}C)




San Antonio Bay, August 06
Temperature (ºC)
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ºN)
Longitude (ºW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
32.00
28.00
24.00
20.00
16.00
12.00
8.00
4.00

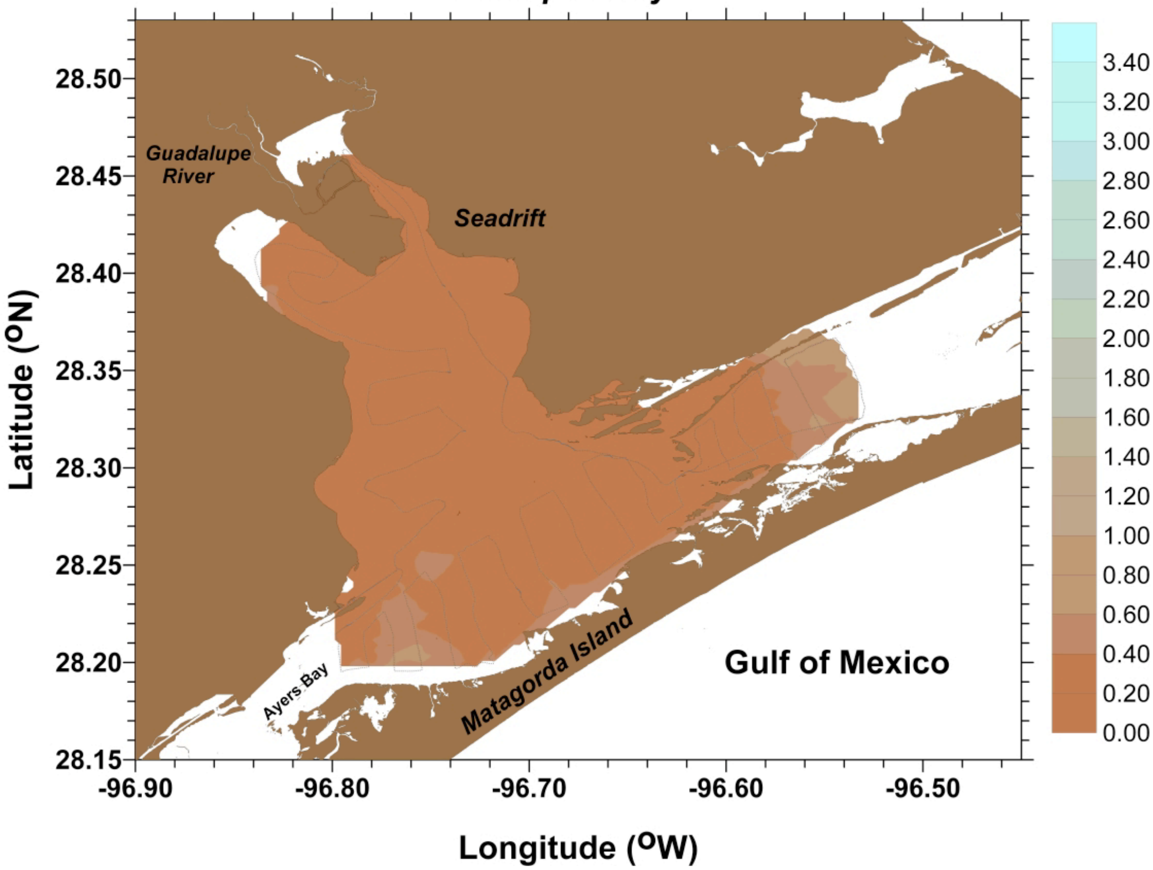

San Antonio Bay, Oct 04
Transparancy
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ºN)
Longitude (ºW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3.40
3.20
3.00
2.80
2.60
2.40
2.20
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00


San Antonio Bay, January 05
Transparancy
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ºN)
Longitude (ºW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3.40
3.20
3.00
2.80
2.60
2.40
2.20
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00


San Antonio Bay, February 05
Transparancy
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ºN)
Longitude (ºW)
28.5
28.5
28.4
28.4
28.3
28.3
28.2
28.2
-96.90
-96.80
-96.70
-96.60
-96.50
3.40
3.20
3.00
2.80
2.60
2.40
2.20
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00

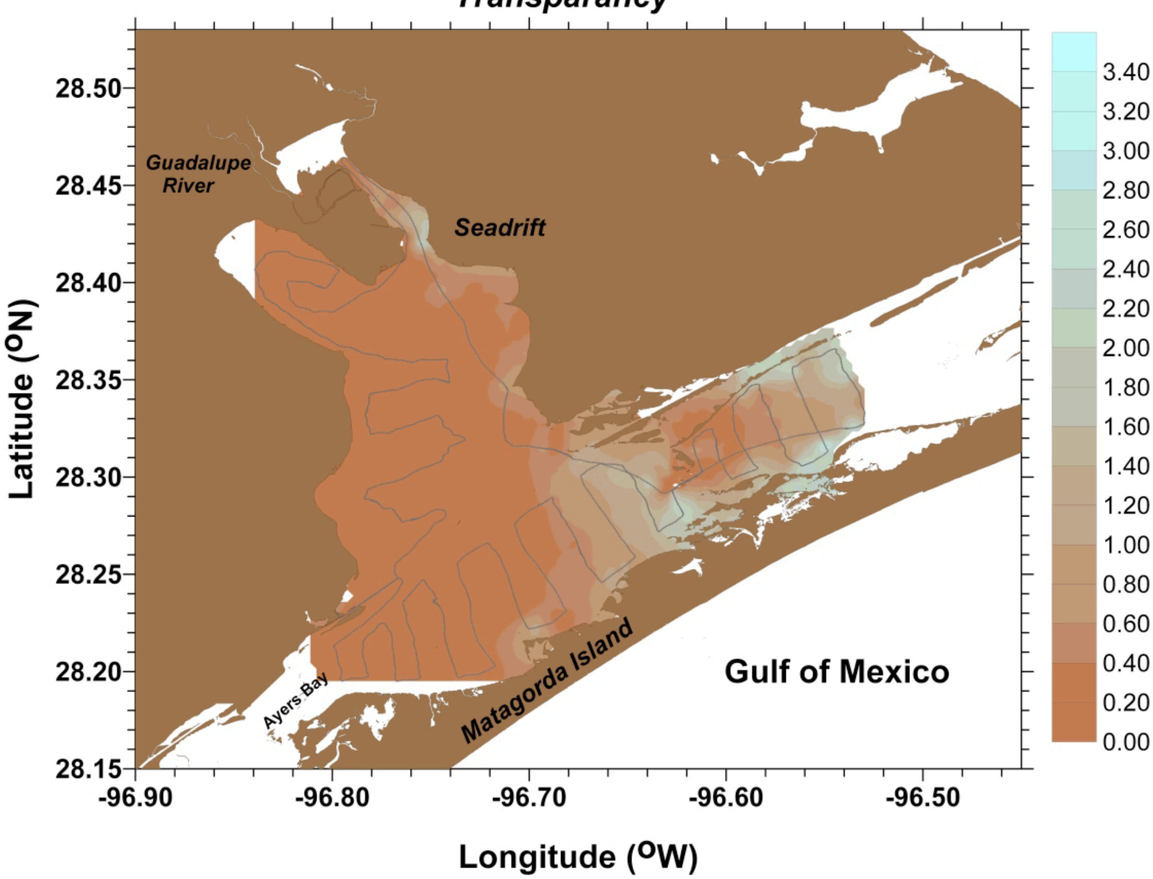
San Antonio Bay, March 05

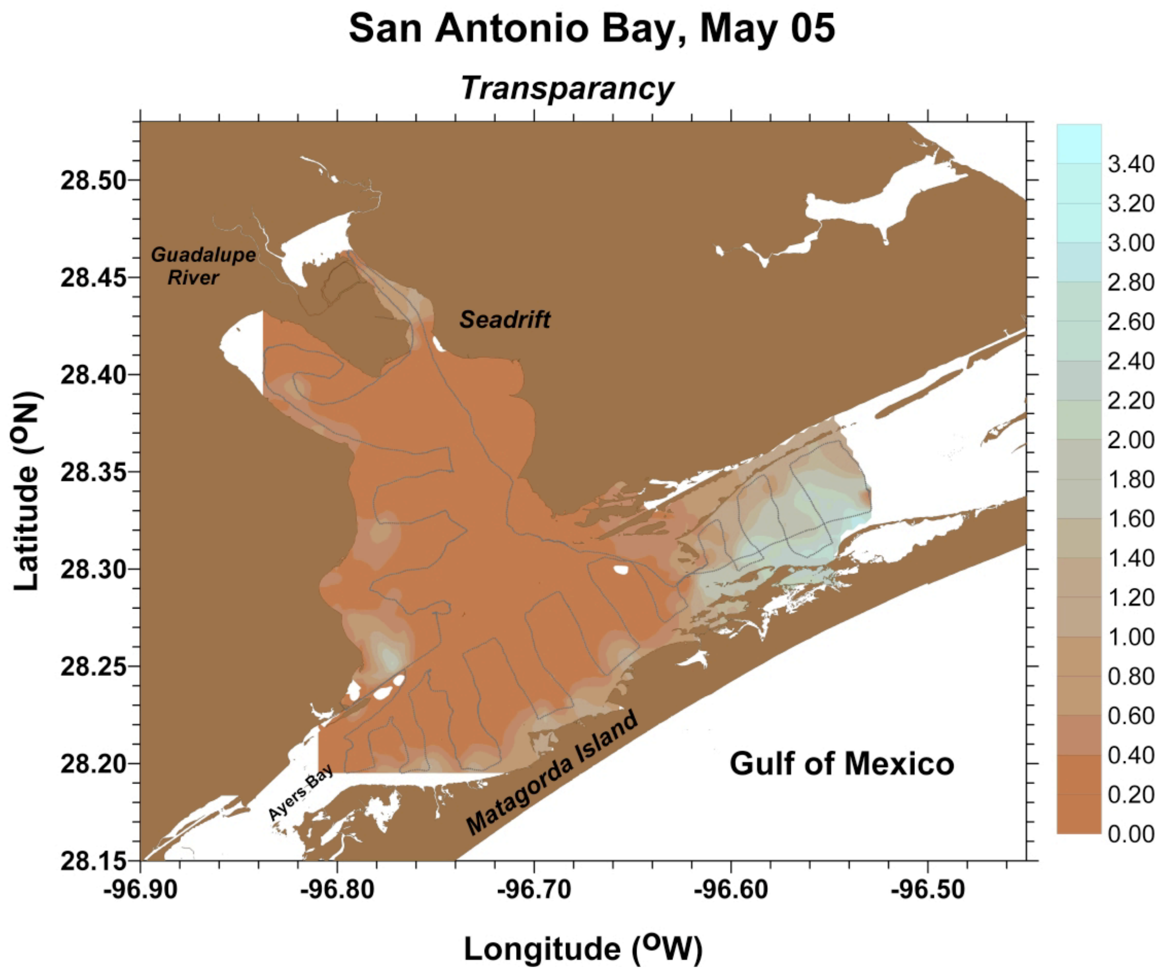
Transparancy

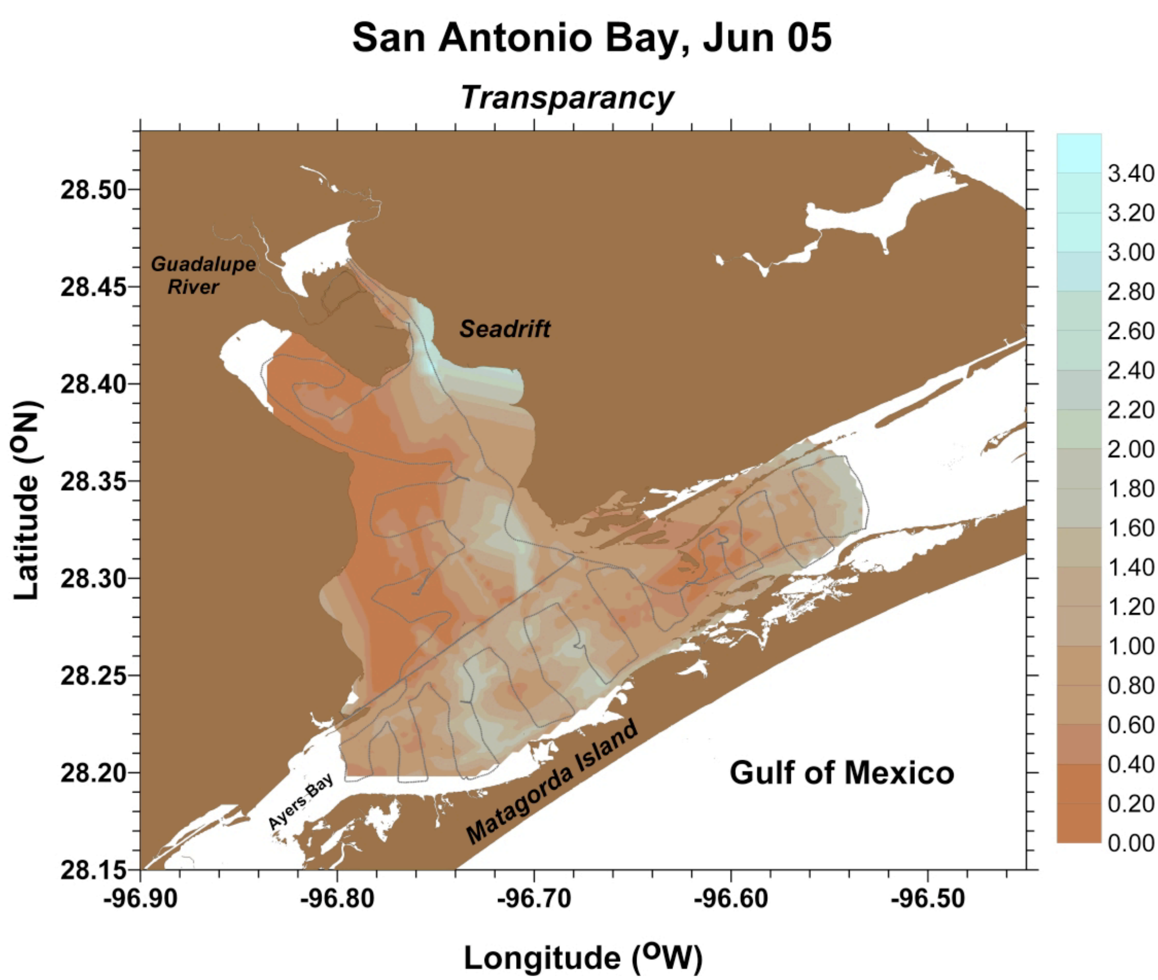


San Antonio Bay, April 05

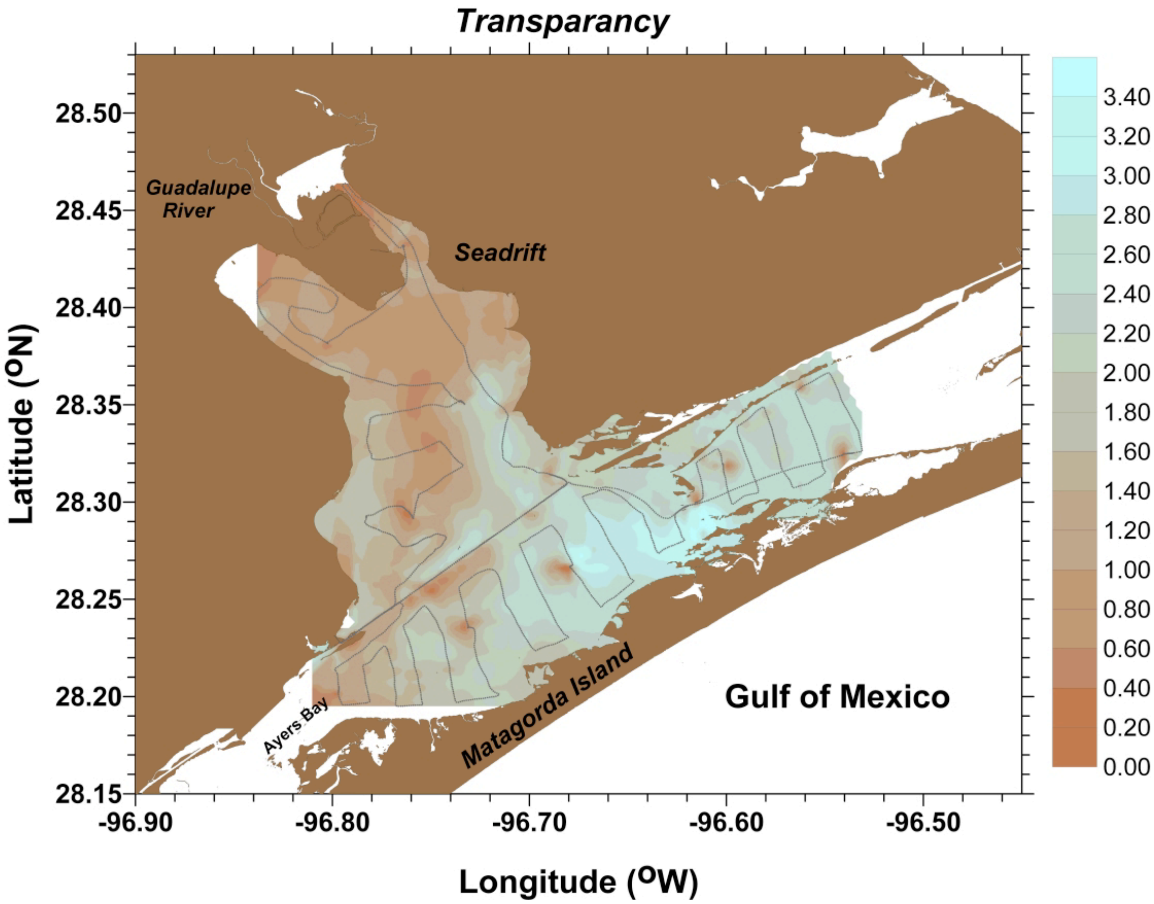
Transparancy



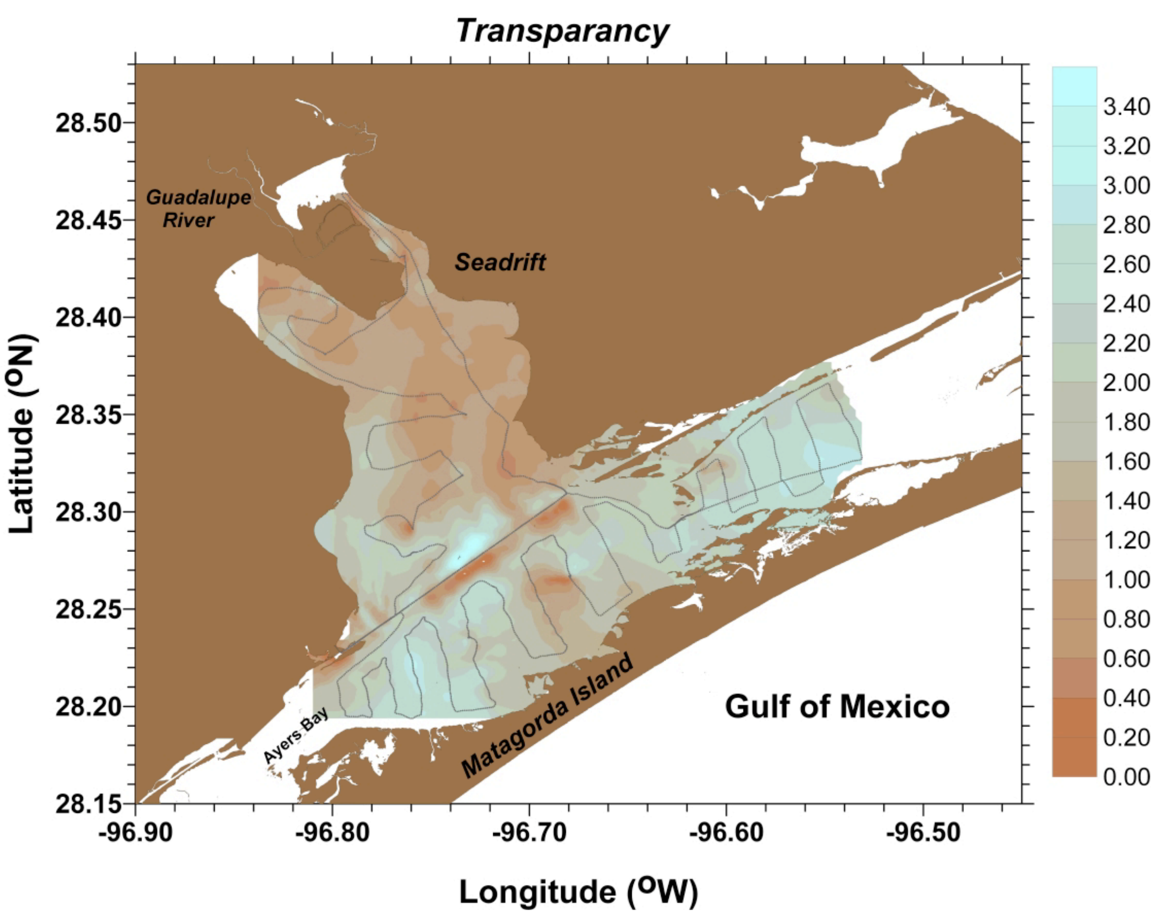

San Antonio Bay, May 05
Transparancy
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3.40
3.20
3.00
2.80
2.60
2.40
2.20
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00

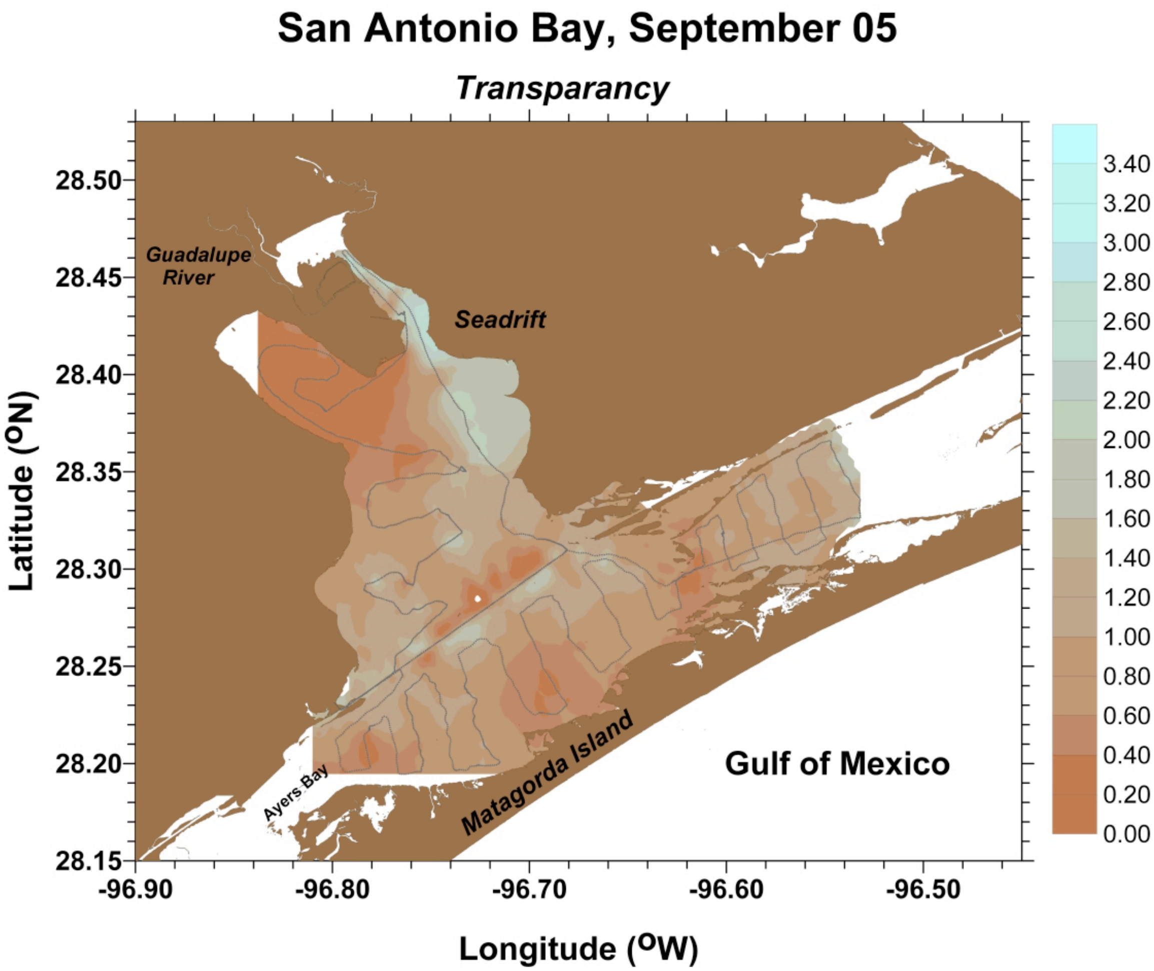

San Antonio Bay, Jun 05
Transparancy
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3.40
3.20
3.00
2.80
2.60
2.40
2.20
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00

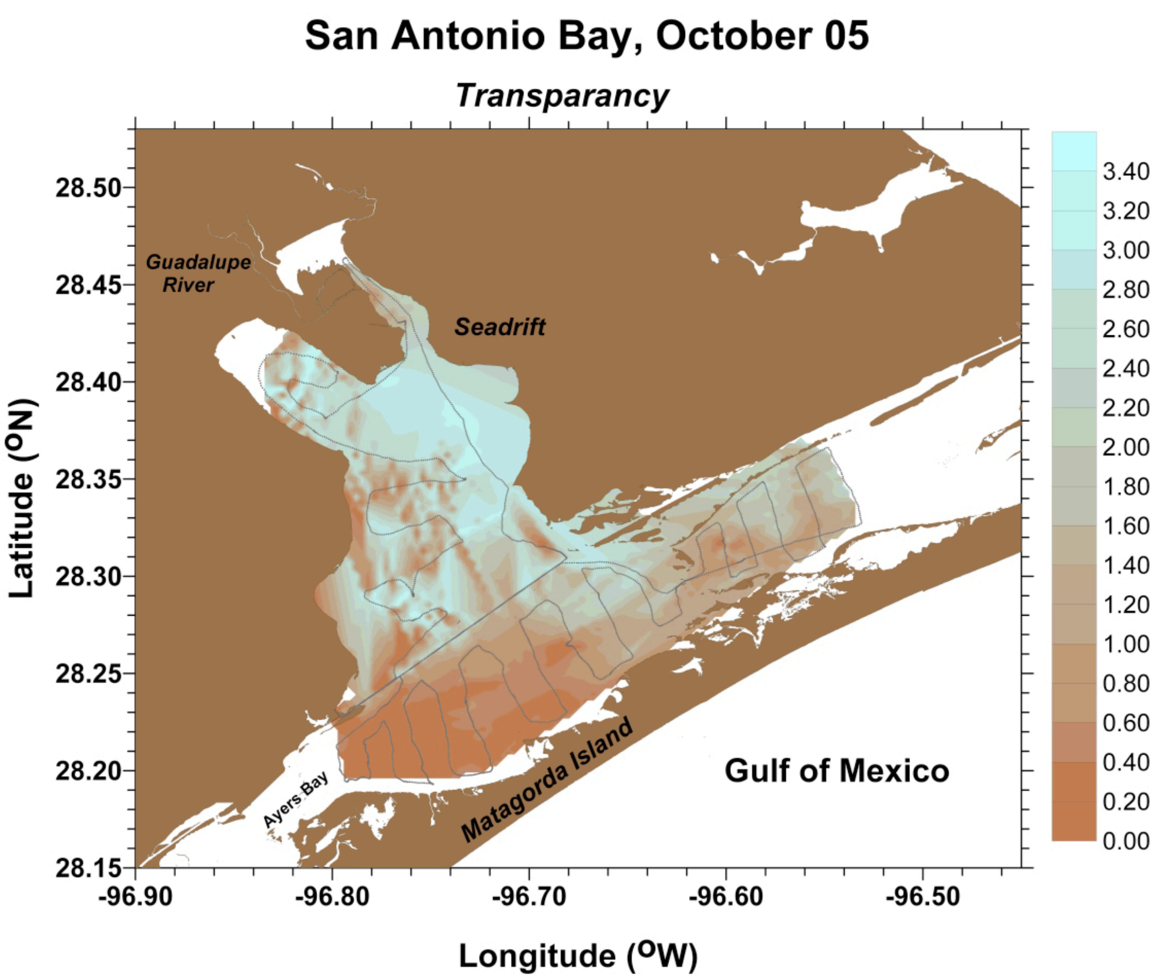
San Antonio Bay, July 05



San Antonio Bay, August 05

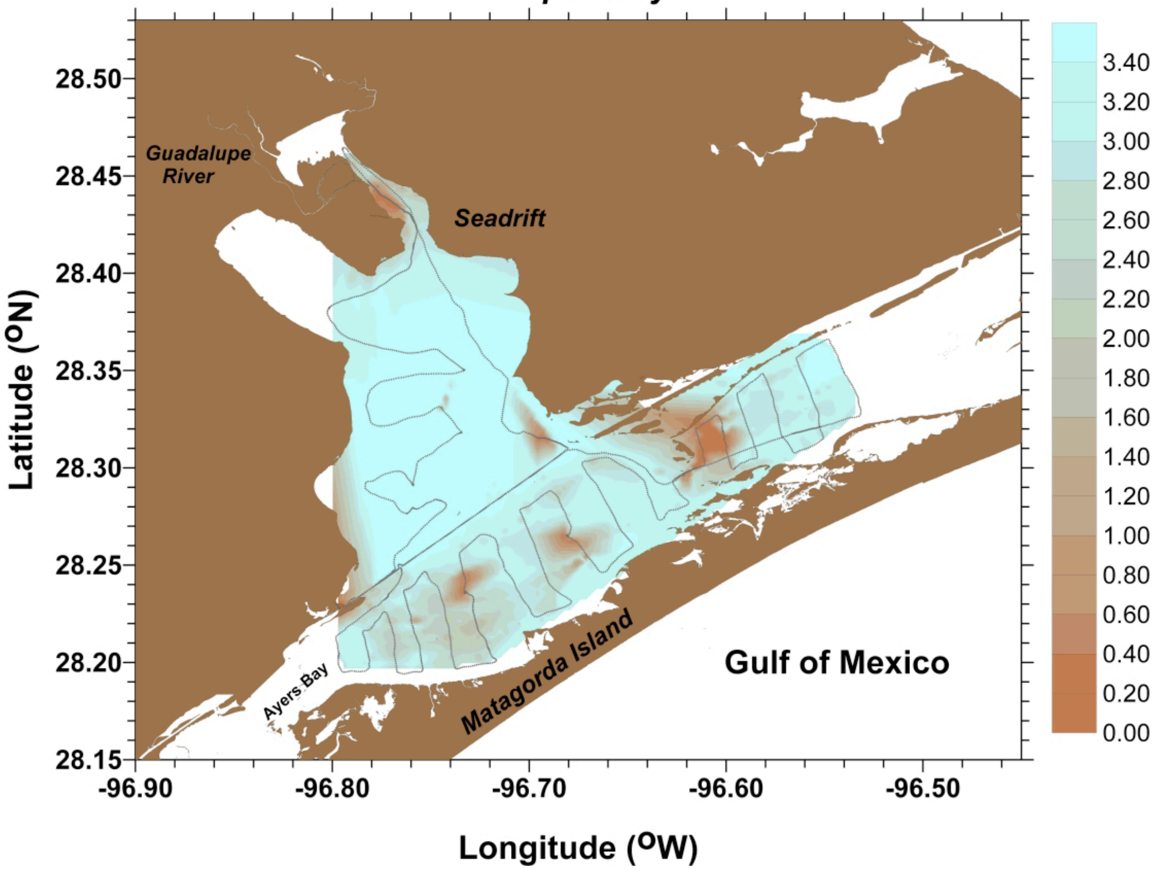



San Antonio Bay, September 05
Transparancy
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3.40
3.20
3.00
2.80
2.60
2.40
2.20
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00


San Antonio Bay, October 05
Transparancy
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3.40
3.20
3.00
2.80
2.60
2.40
2.20
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00

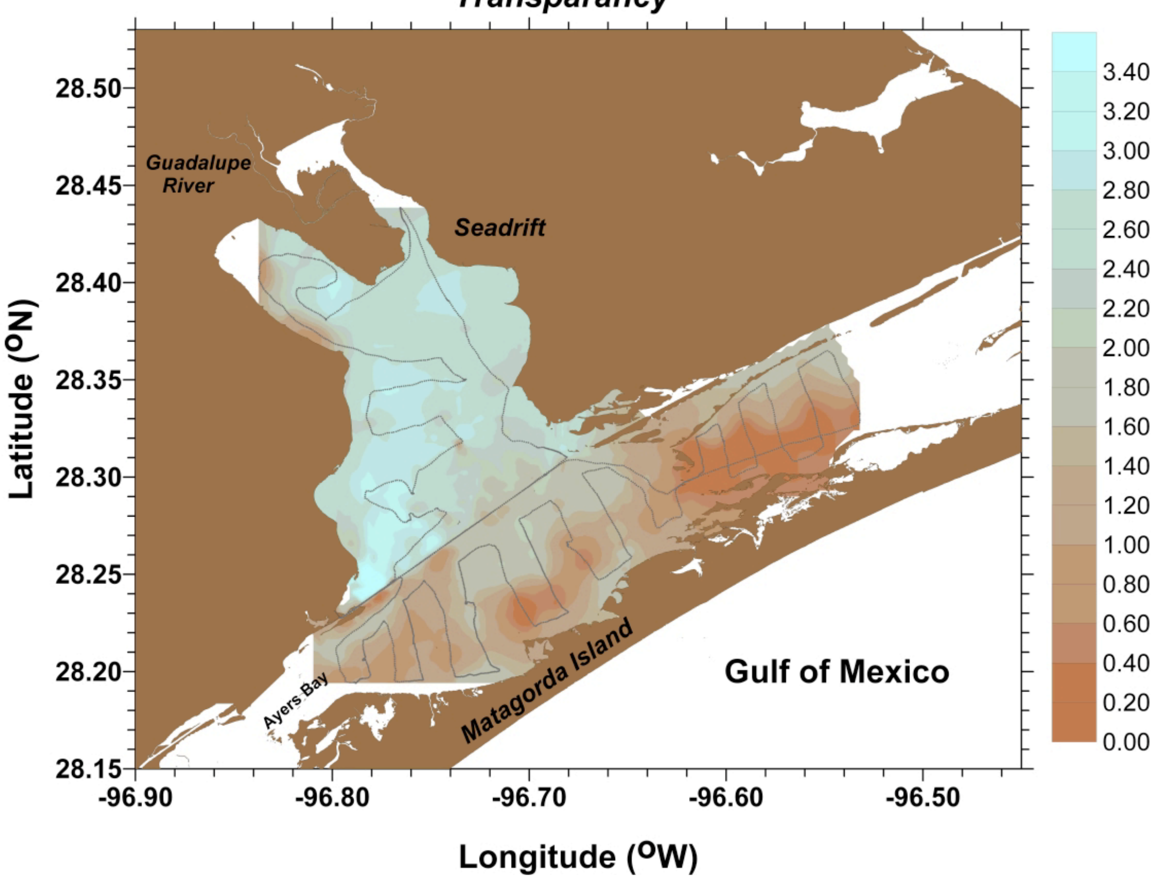
San Antonio Bay, November 05

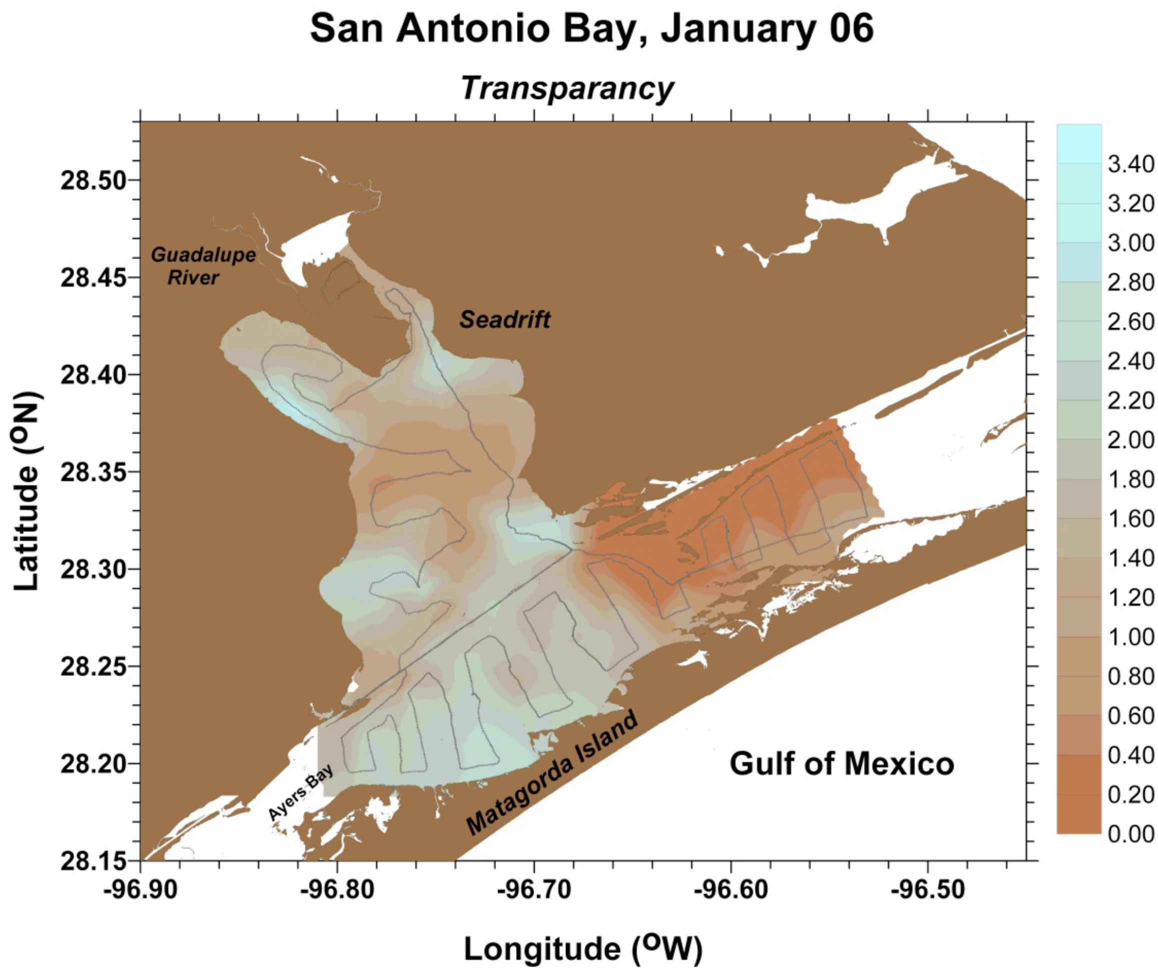
Transparancy



San Antonio Bay, December 05

Transparancy




San Antonio Bay, January 06
Transparancy
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3.40
3.20
3.00
2.80
2.60
2.40
2.20
2.00
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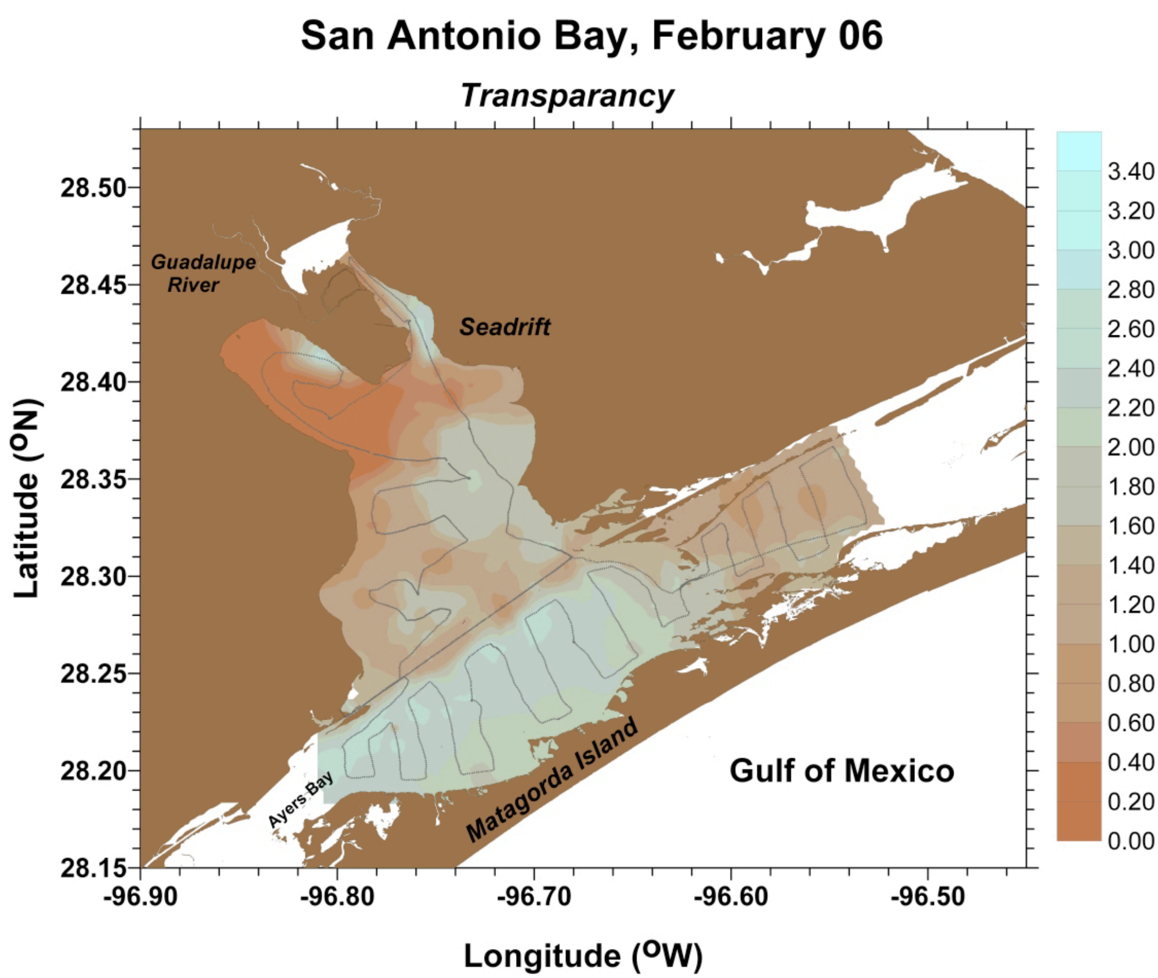
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00


San Antonio Bay, February 06
Transparancy
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3.40
3.20
3.00
2.80
2.60
2.40
2.20
2.00
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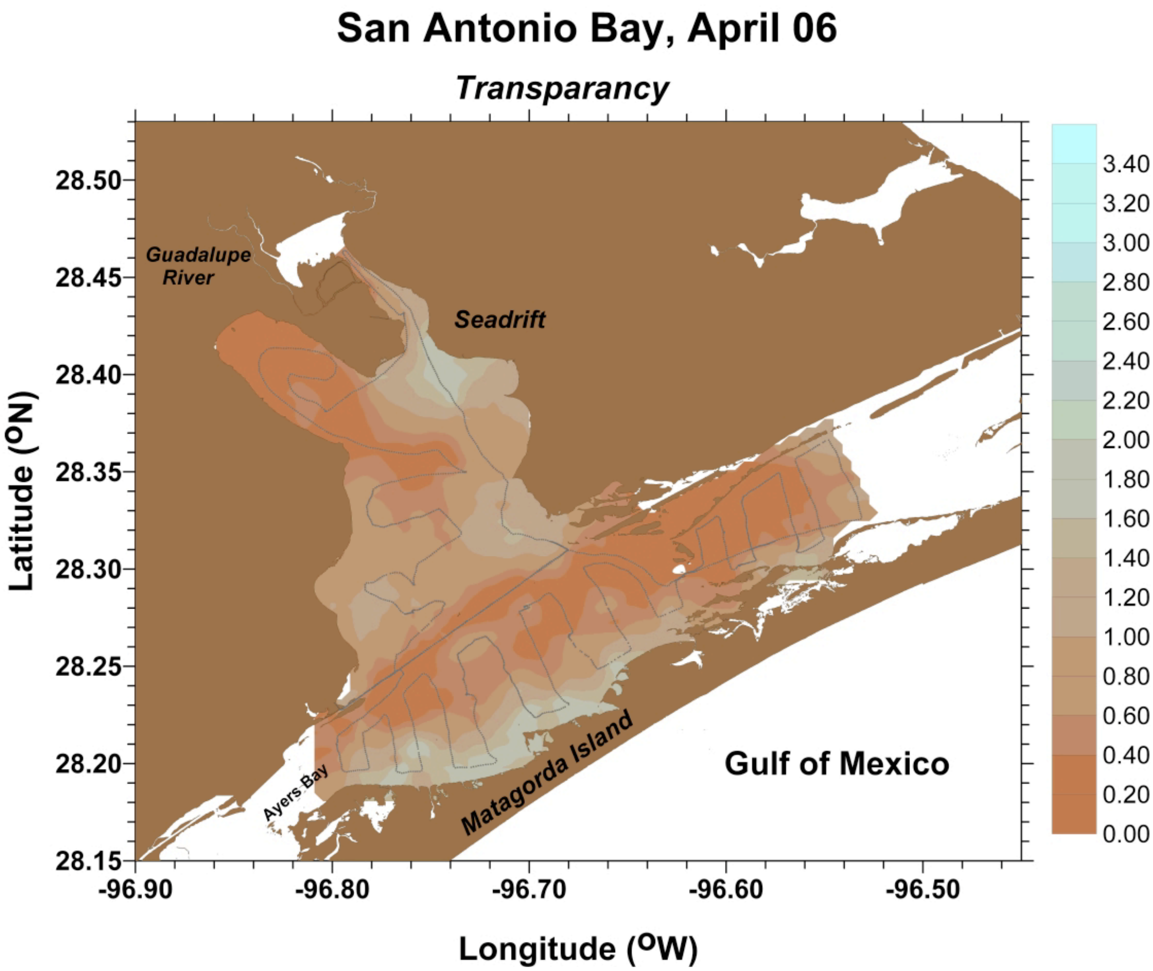
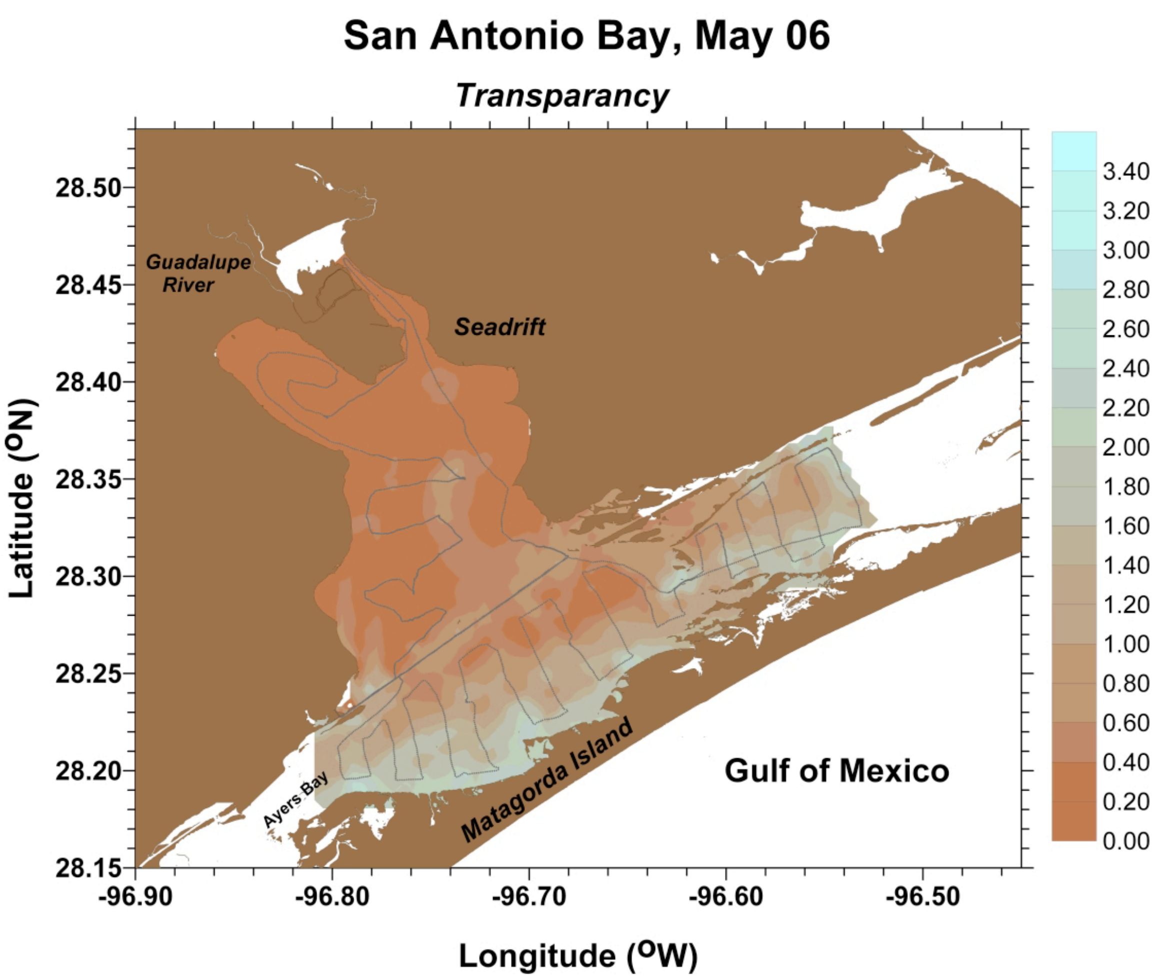
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00


San Antonio Bay, April 06
Transparancy
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3.40
3.20
3.00
2.80
2.60
2.40
2.20
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00


San Antonio Bay, May 06
Transparancy
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (ON)
Longitude (OW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3.40
3.20
3.00
2.80
2.60
2.40
2.20
2.00
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1.60
1.40
1.20
1.00
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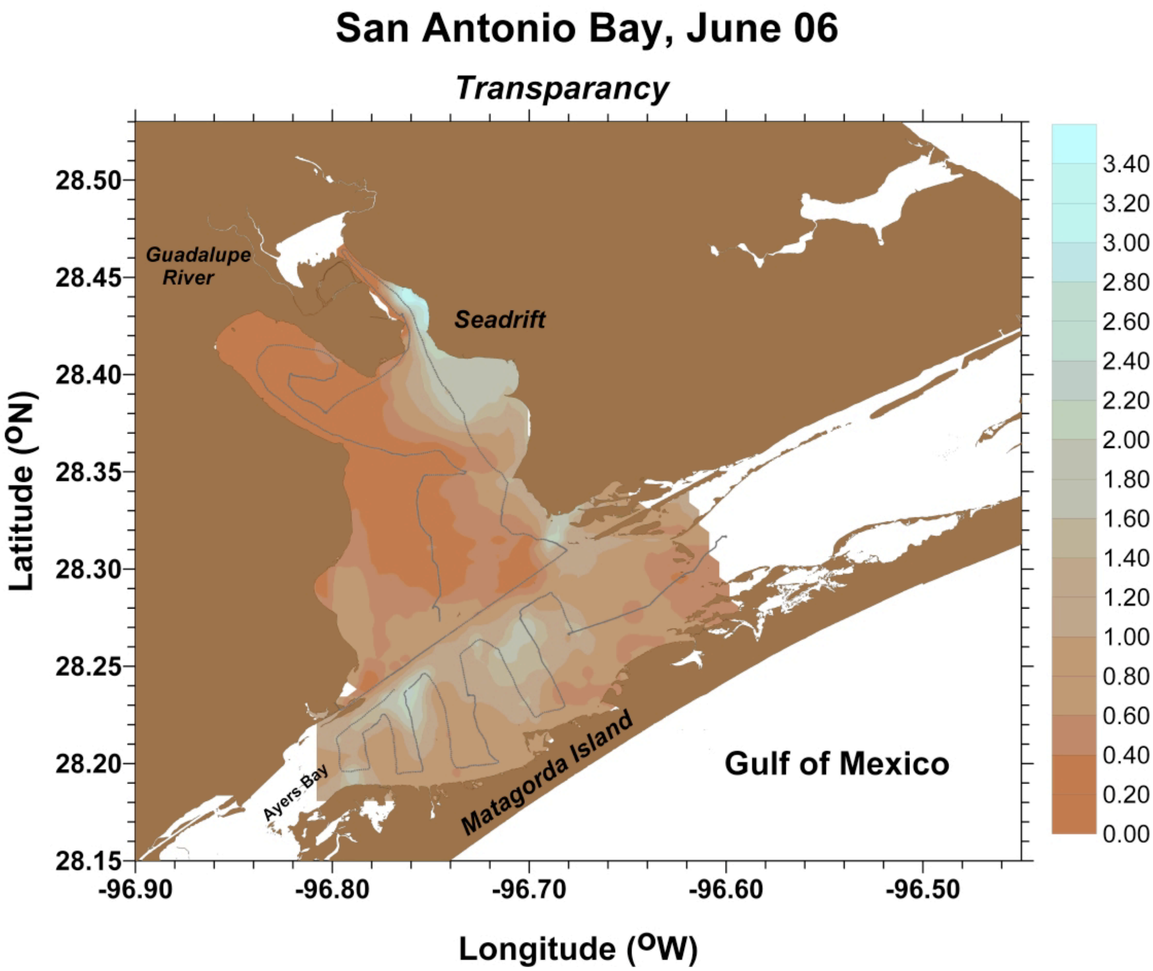
0.00


San Antonio Bay, June 06
Transparancy
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3.40
3.20
3.00
2.80
2.60
2.40
2.20
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1.60
1.40
1.20
1.00
0.80
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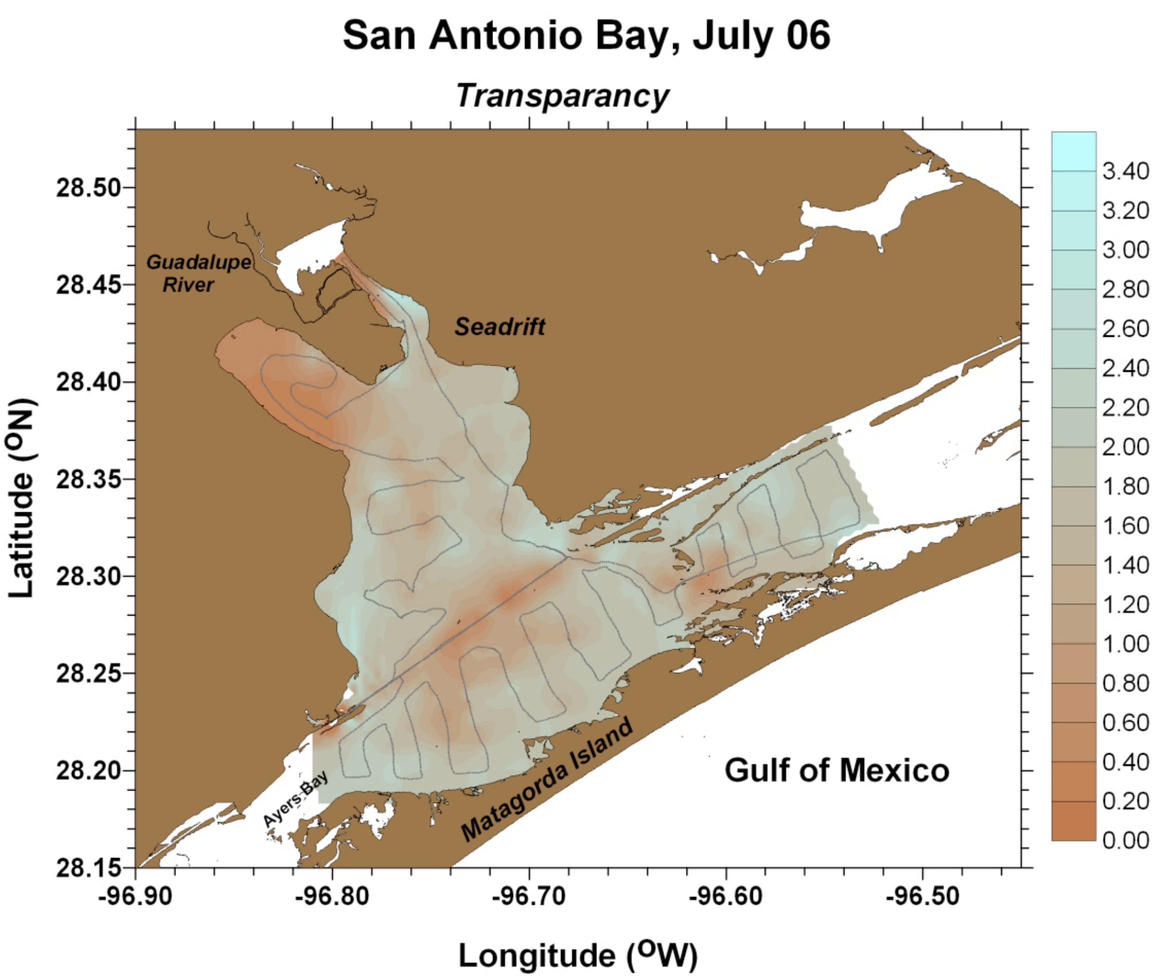
0.00


San Antonio Bay, July 06
Transparancy
Guadalupe River
Seadrift
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
-96.90
-96.80
-96.70
-96.60
-96.50
3.40
3.20
3.00
2.80
2.60
2.40
2.20
2.00
1.80
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1.20
1.00
0.80
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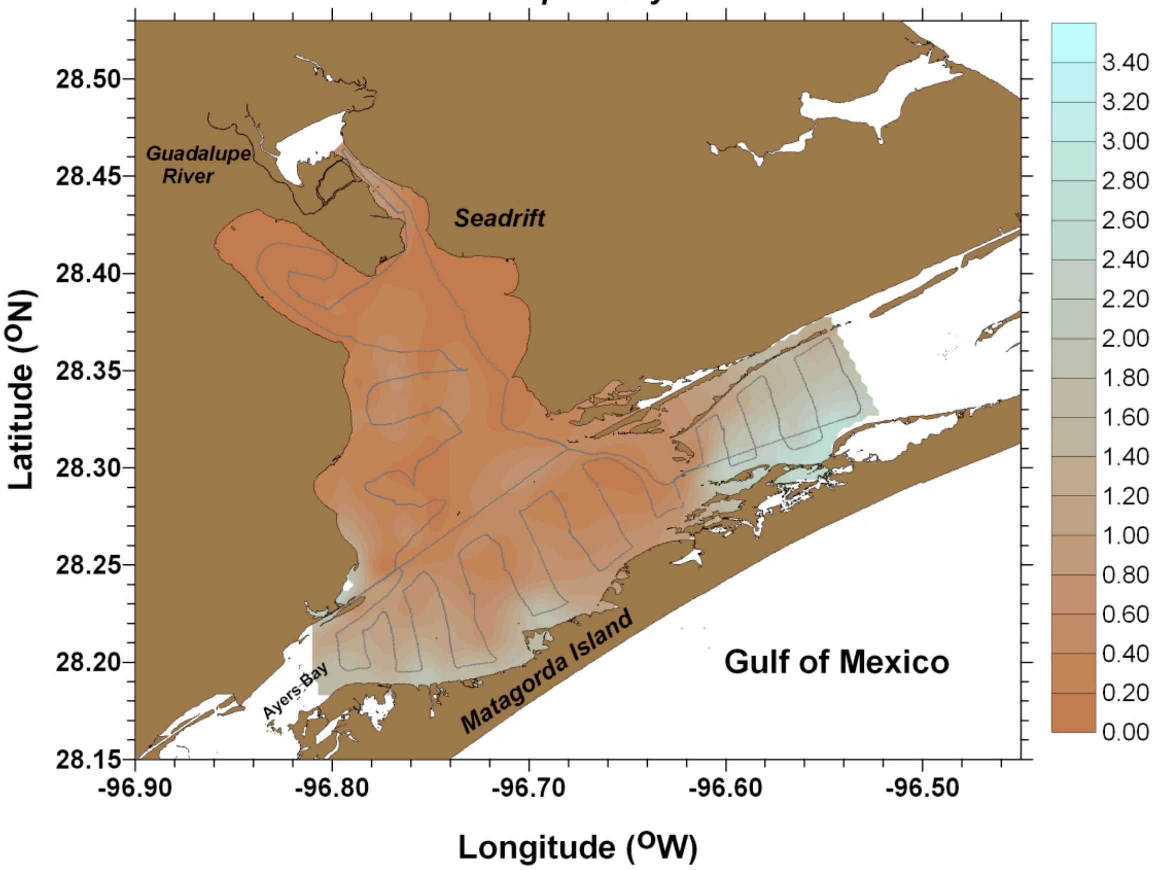
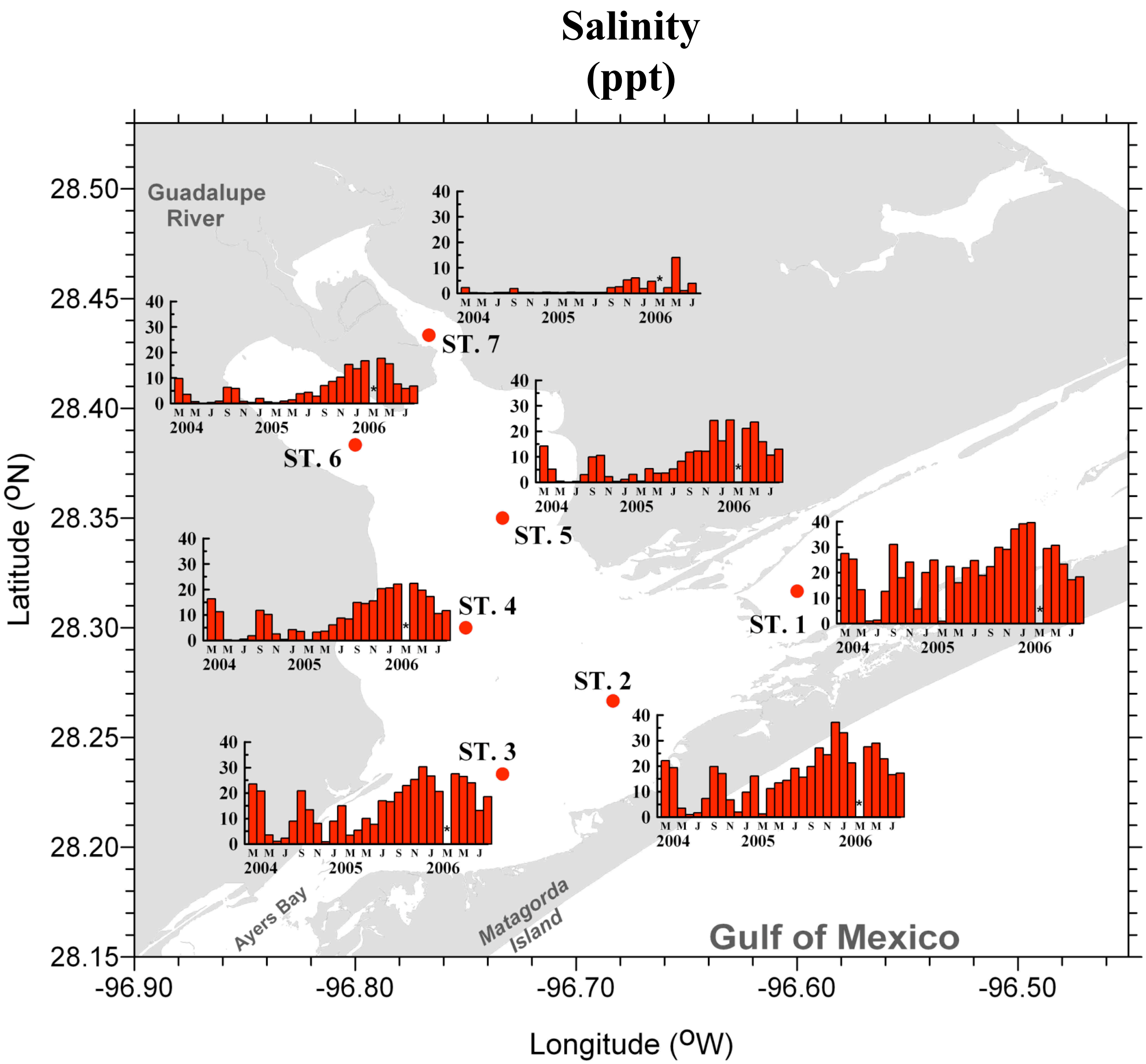
0.20
0.00

San Antonio Bay, August 06

Transparancy



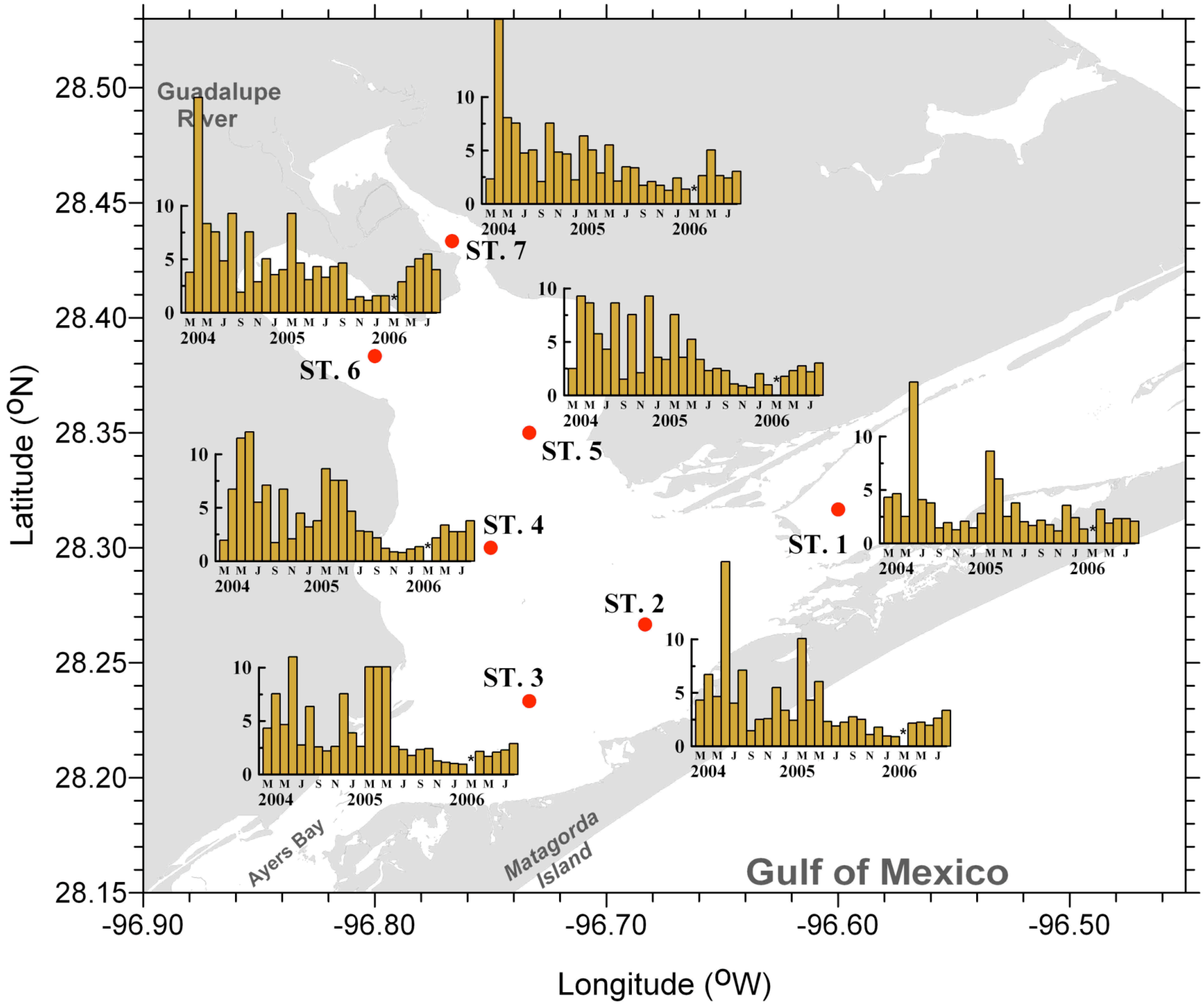
Fixed Station Data across all samplings

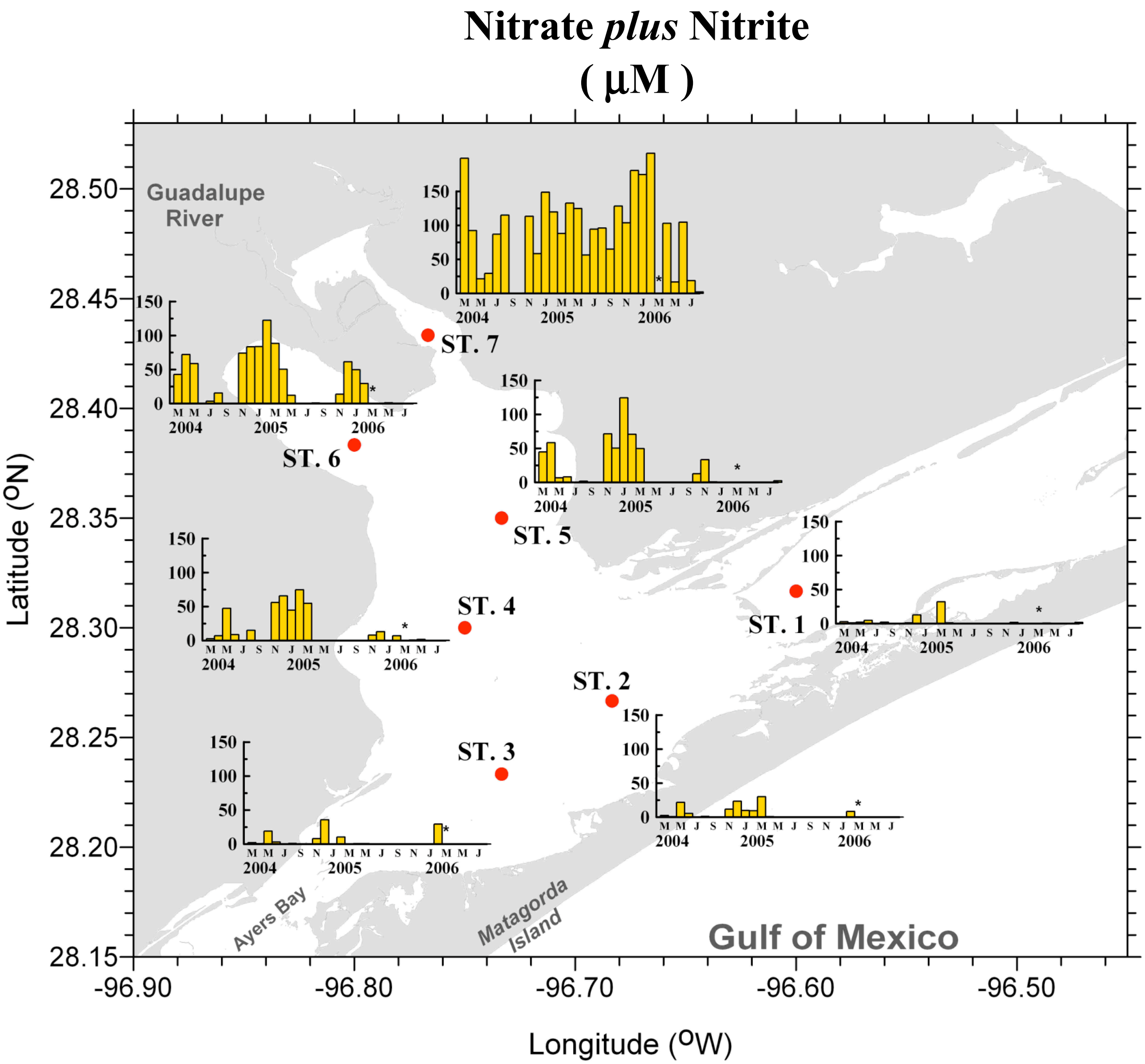


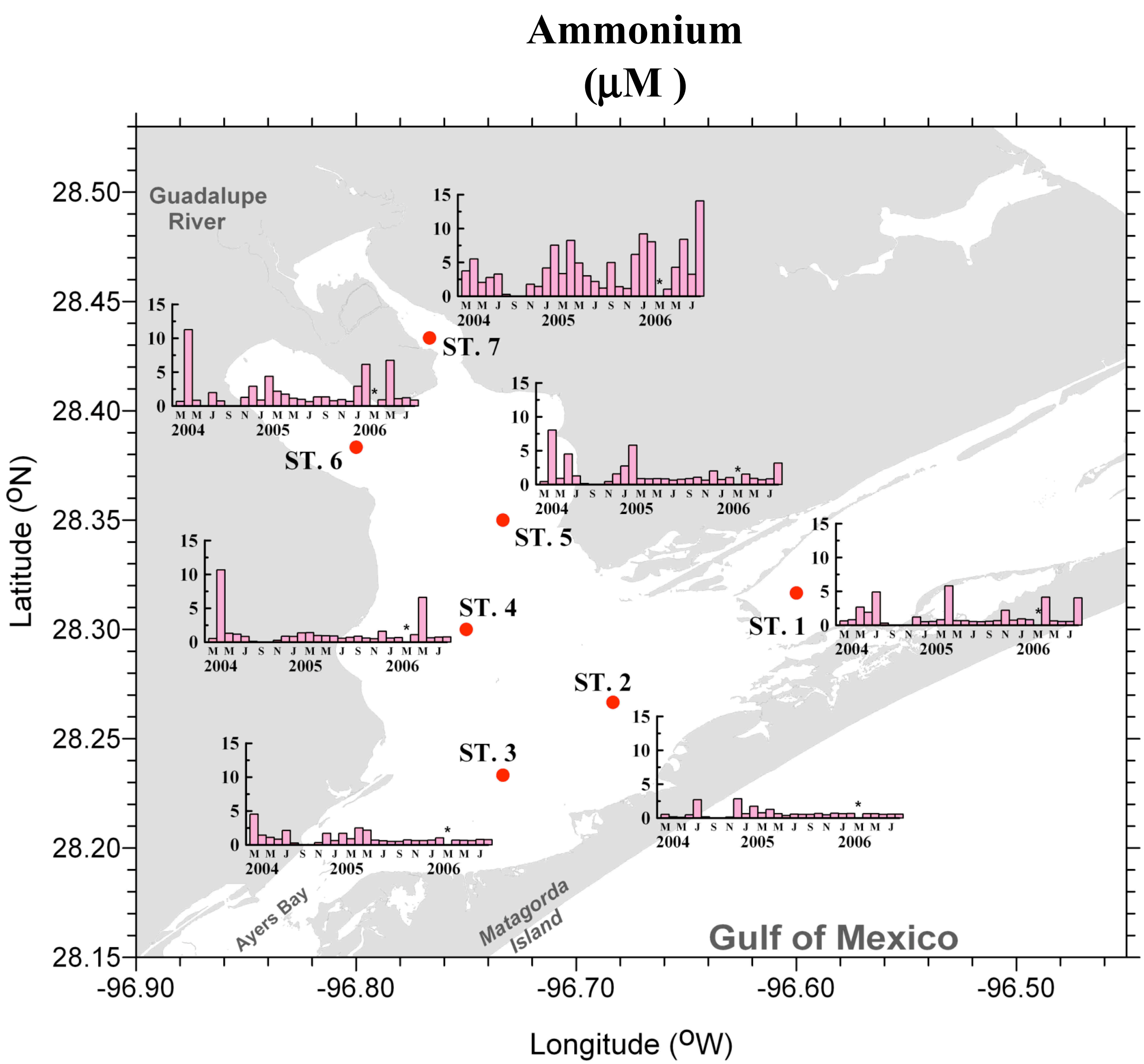
Salinity
(ppt)
Guadalupe River
ST. 1
ST. 2
ST. 3
ST. 4
ST. 5
ST. 6
ST. 7
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)

Light Attenuation

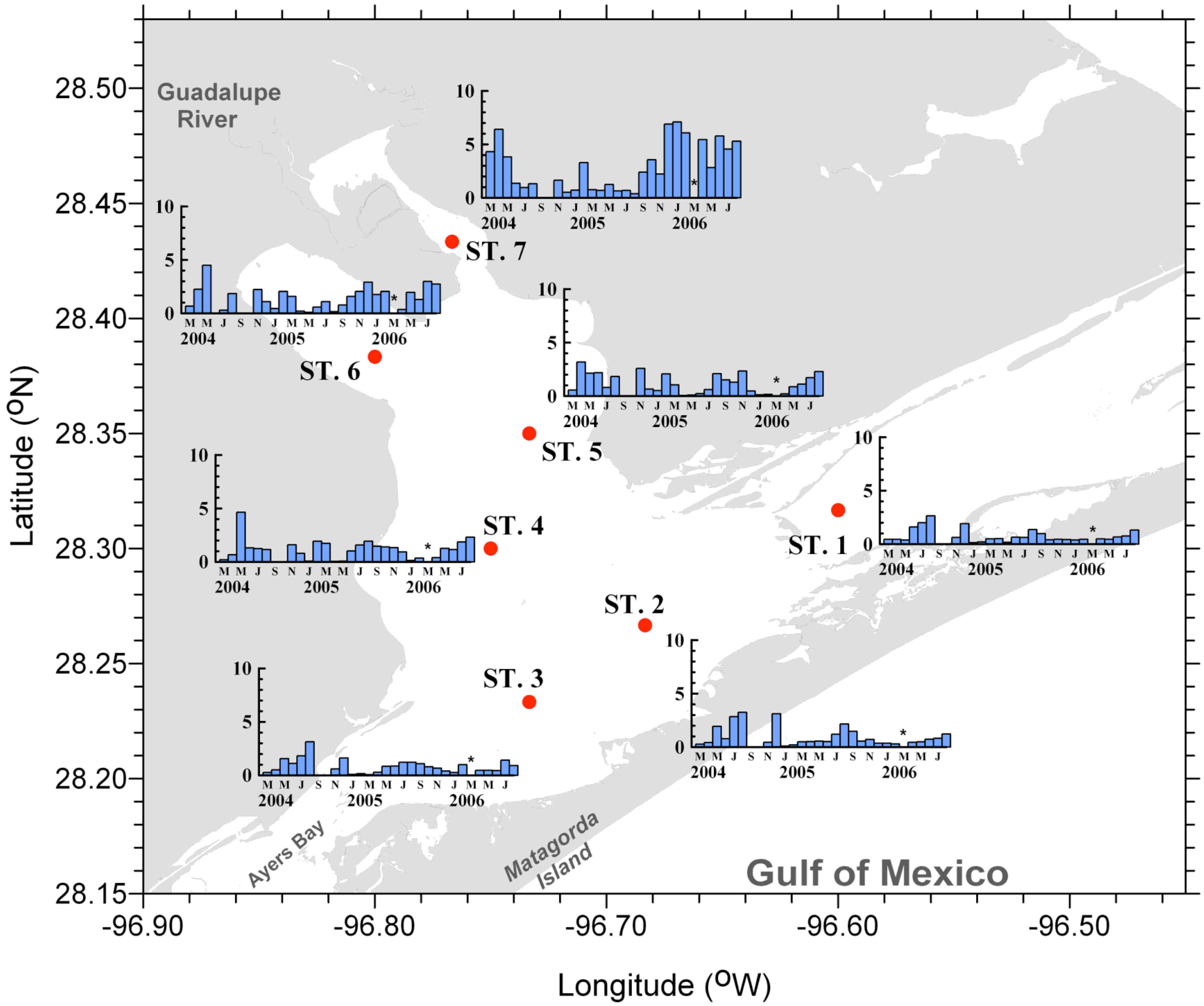
(m^{-1})

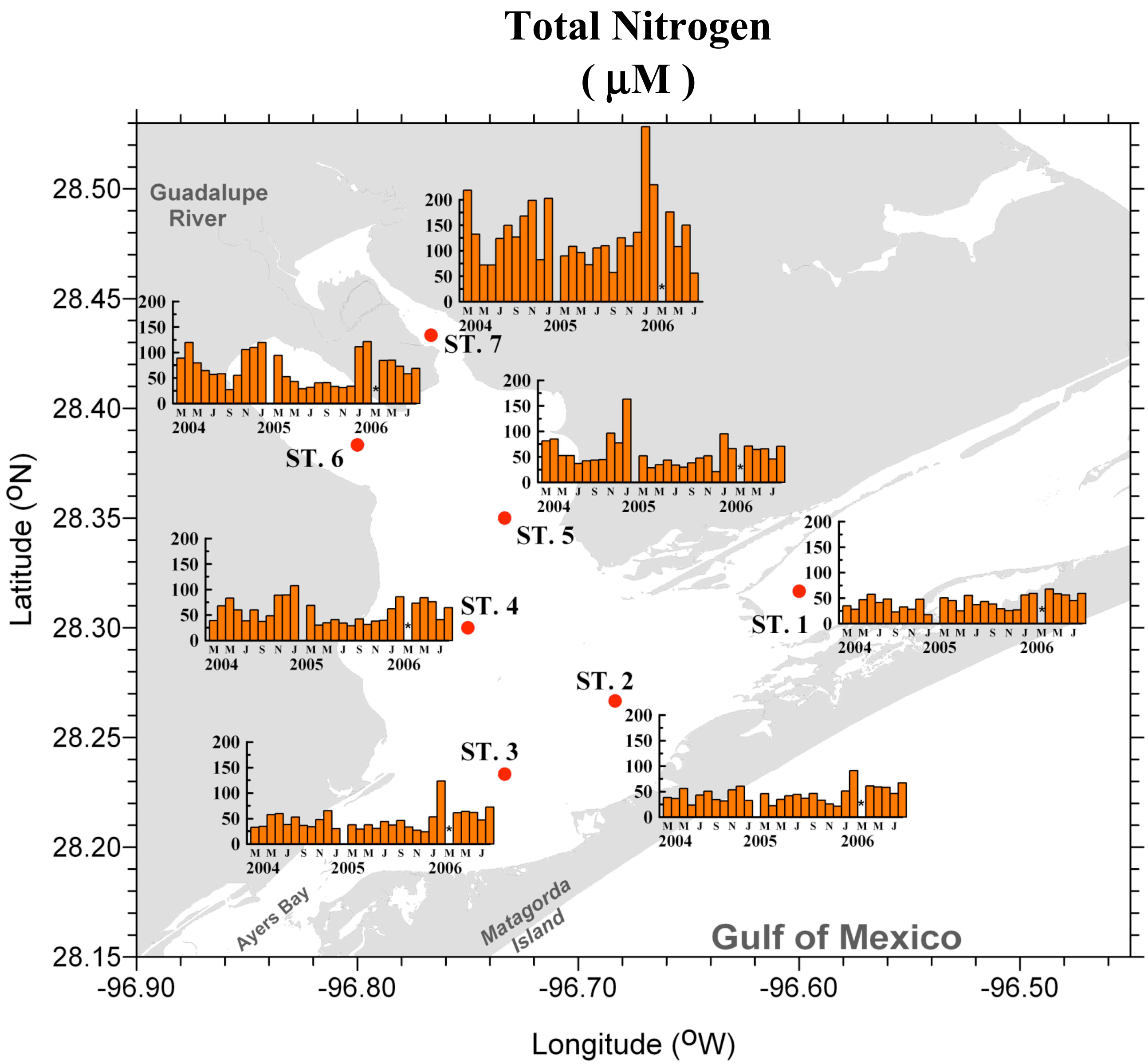



Nitrate plus Nitrite
(µM)
Guadalupe River
ST. 7
ST. 6
ST. 5
ST. 4
ST. 3
ST. 2
ST. 1
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)
2004
2005
2006


Ammonium
(µM)
Guadalupe River
ST. 7
ST. 6
ST. 5
ST. 4
ST. 3
ST. 2
ST. 1
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
-96.90
-96.80
-96.70
-96.60
-96.50
28.50
28.45
28.40
28.35
28.30
28.25
28.20
28.15
2004
2005
2006

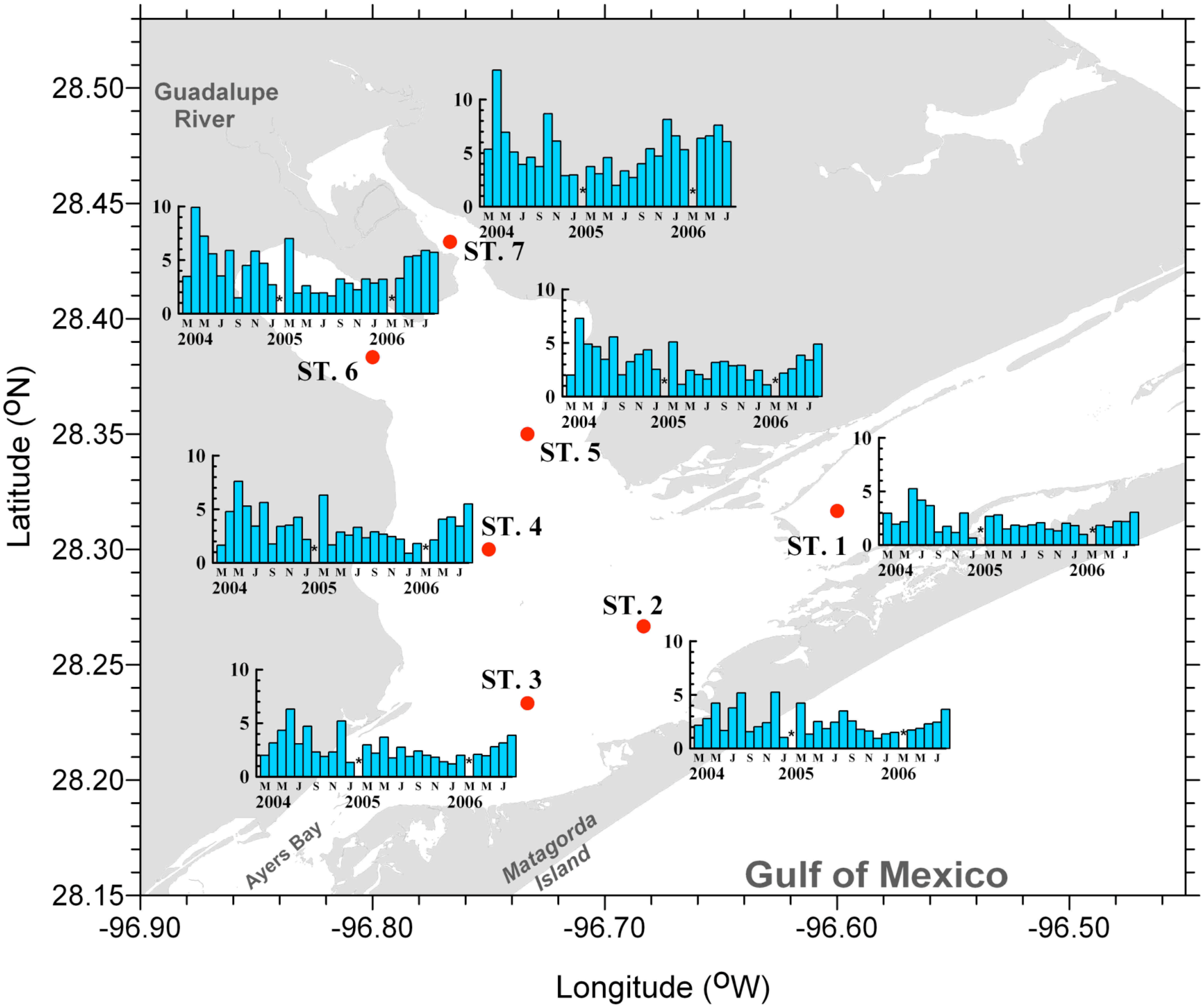
Orthophosphate
(μM)

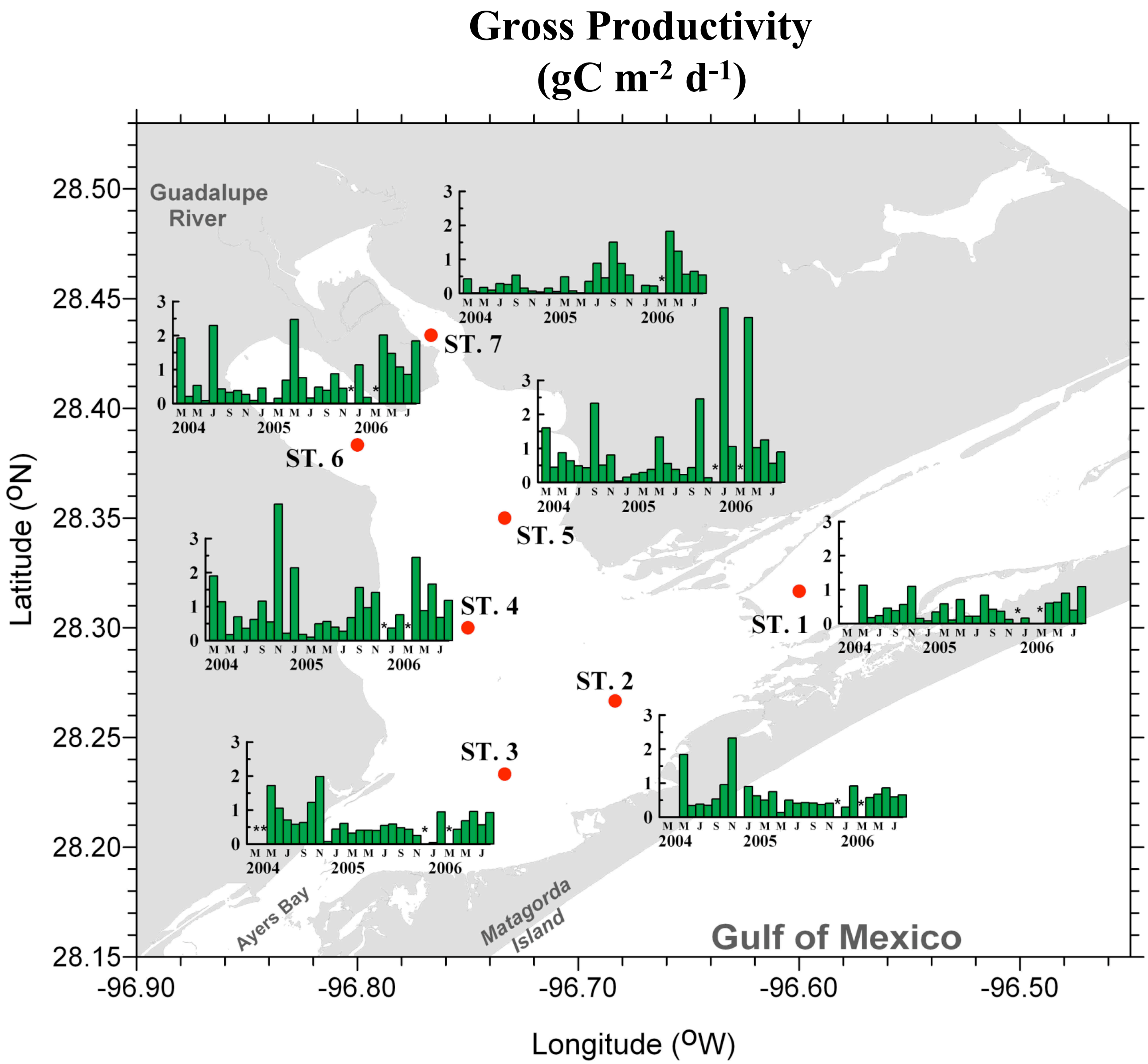




Total Nitrogen
(μM)
Guadalupe River
ST. 1
ST. 2
ST. 3
ST. 4
ST. 5
ST. 6
ST. 7
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (°N)
Longitude (°W)
28.15
28.20
28.25
28.30
28.35
28.40
28.45
28.50
-96.90
-96.80
-96.70
-96.60
-96.50
2004
2005
2006

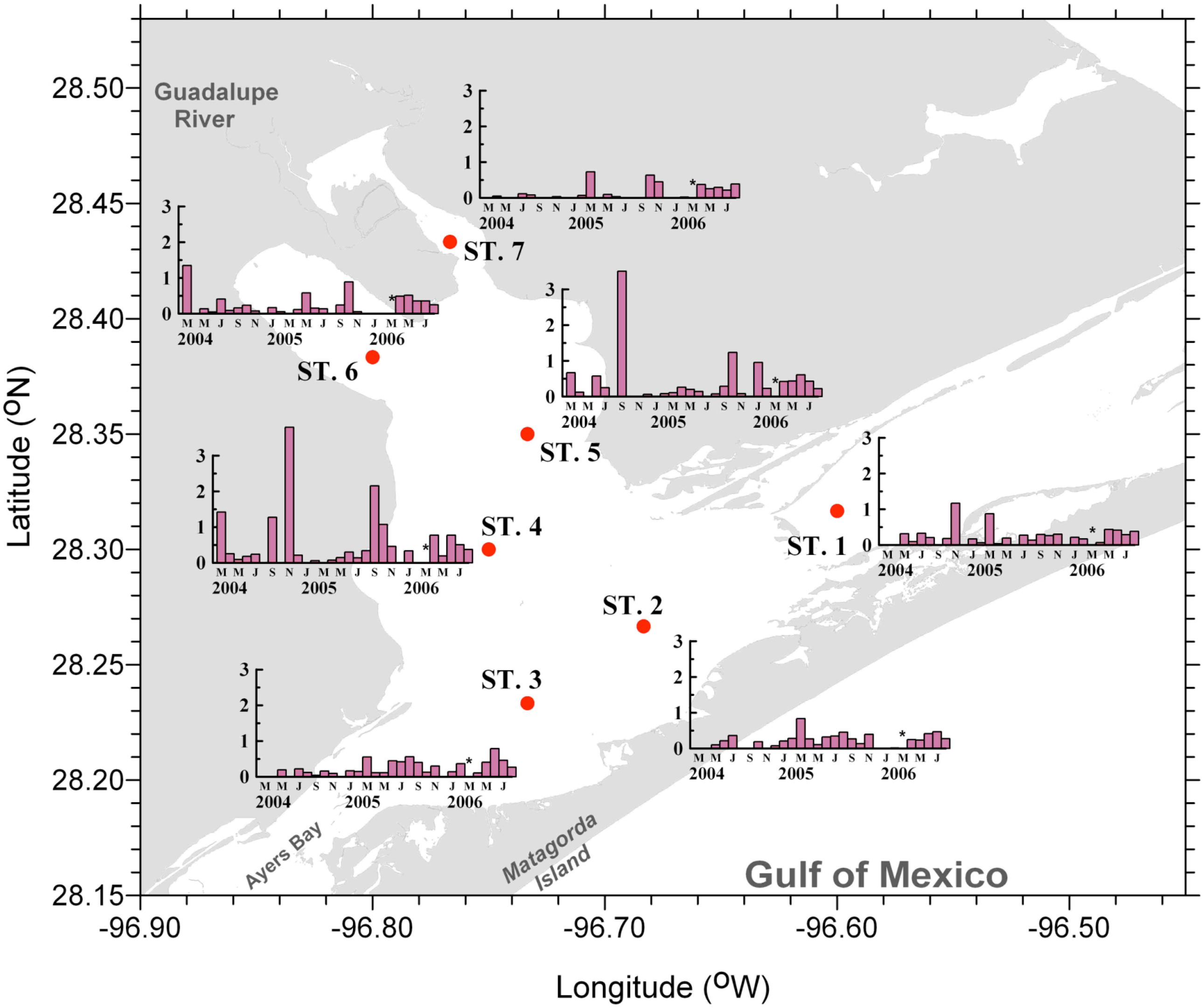
Total Phosphorus
(μM)

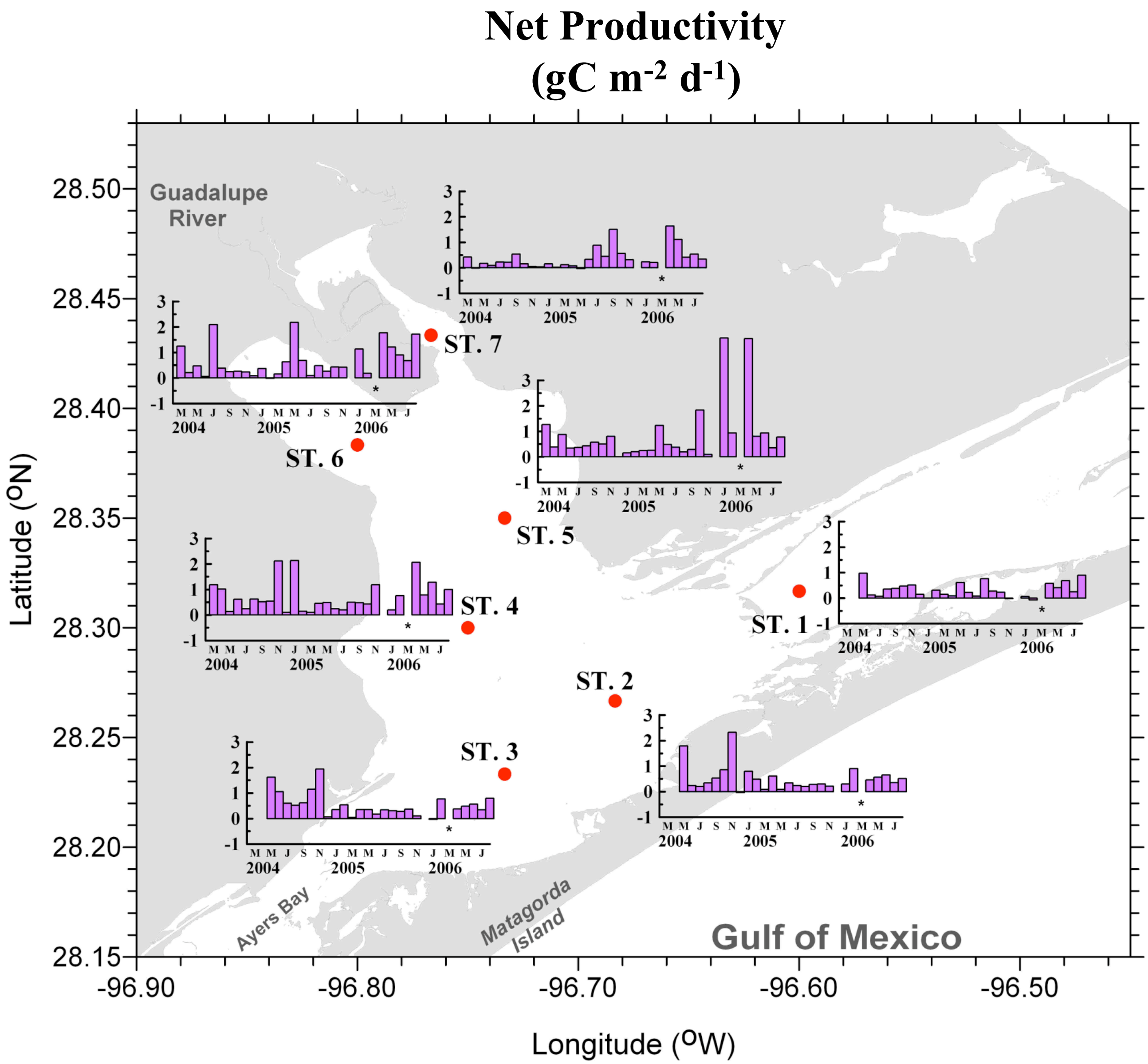




Gross Productivity
(gC m-2 d-1)
Guadalupe River
ST. 7
ST. 6
ST. 5
ST. 4
ST. 1
ST. 2
ST. 3
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)
2004
2005
2006

Respiration
($gC\ m^{-2}\ d^{-1}$)




Net Productivity
(gC m-2 d-1)
Guadalupe River
ST. 1
ST. 2
ST. 3
ST. 4
ST. 5
ST. 6
ST. 7
Ayers Bay
Matagorda Island
Gulf of Mexico
Latitude (oN)
Longitude (oW)

Contour Plots of Fixed Station Nutrients

San Antonio Bay

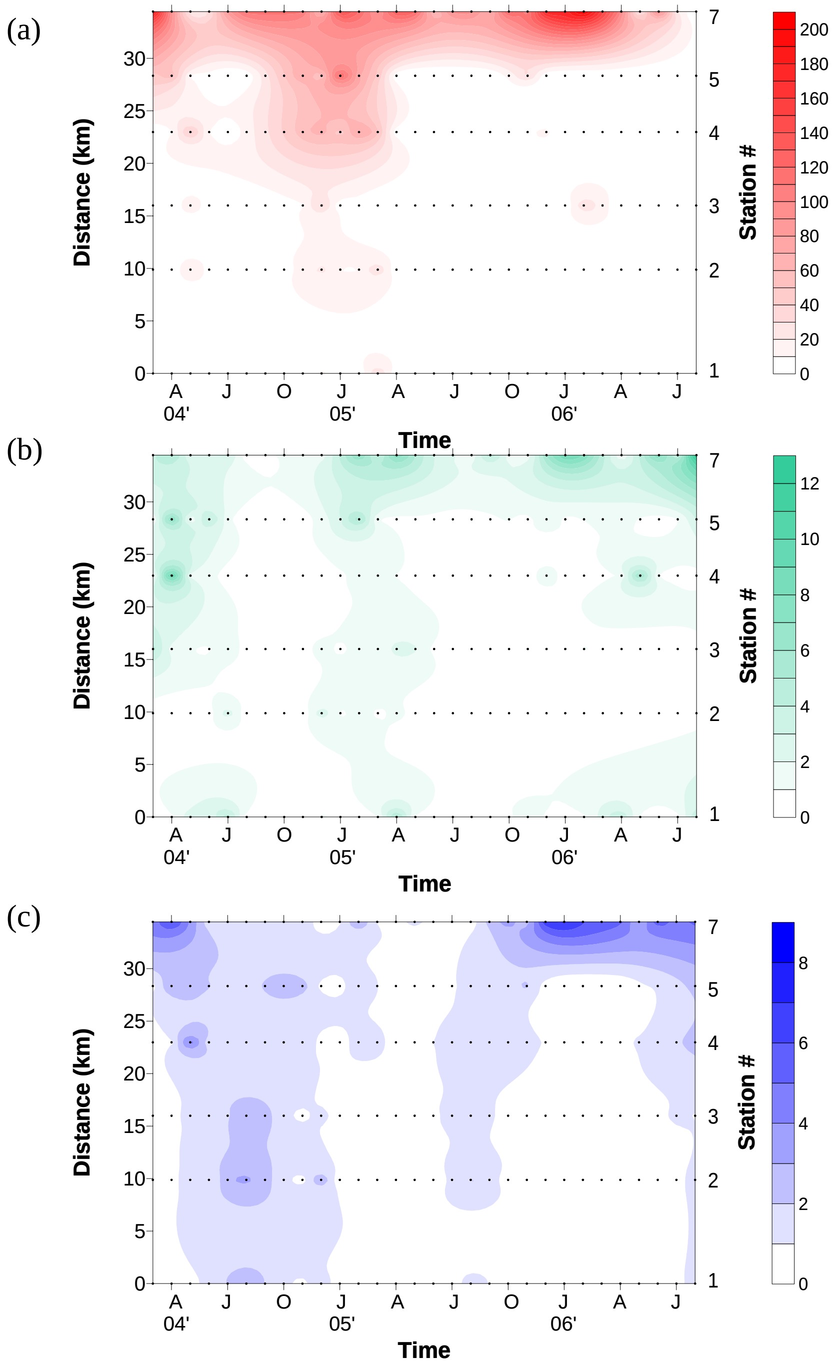


Figure 1 Inorganic nutrient spatial and temporal contour from March, 2004 to Aug, 2006. (a) Nitrate plus nitrite (μM); (b) Ammonium (μM); (c) Orthophosphate (μM).

(a)

(b)

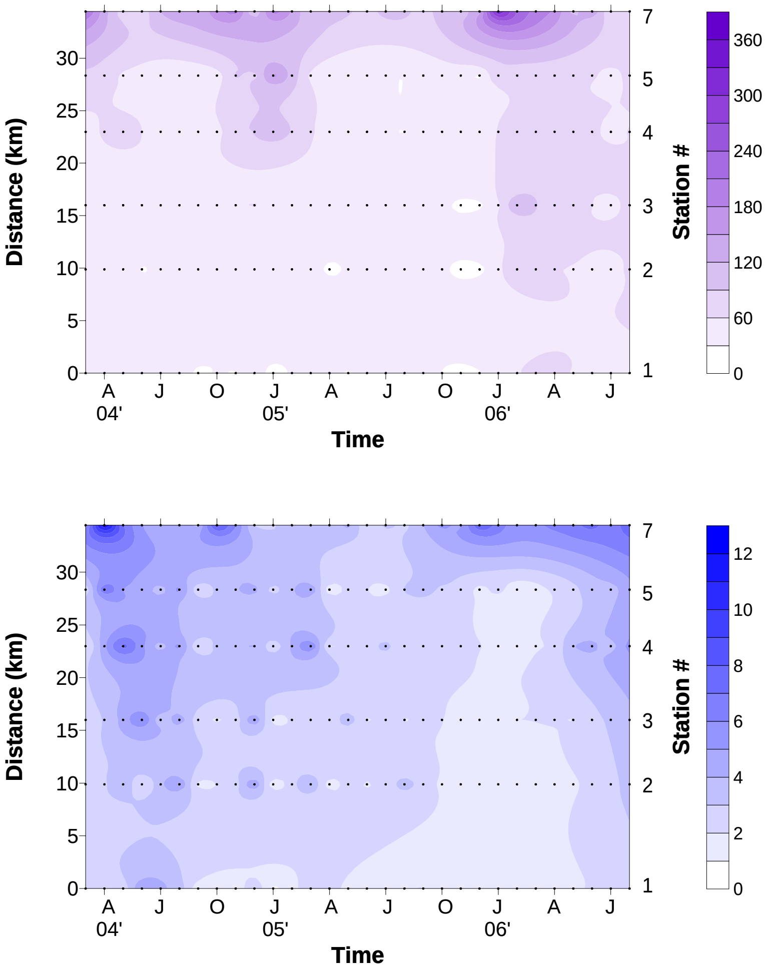


Figure 2 Total Nitrogen (TN) and phosphorous (TP) spatial and temporal contour from March, 2004 to Aug, 2006. (a) TN (μM); (b) TP (μM).

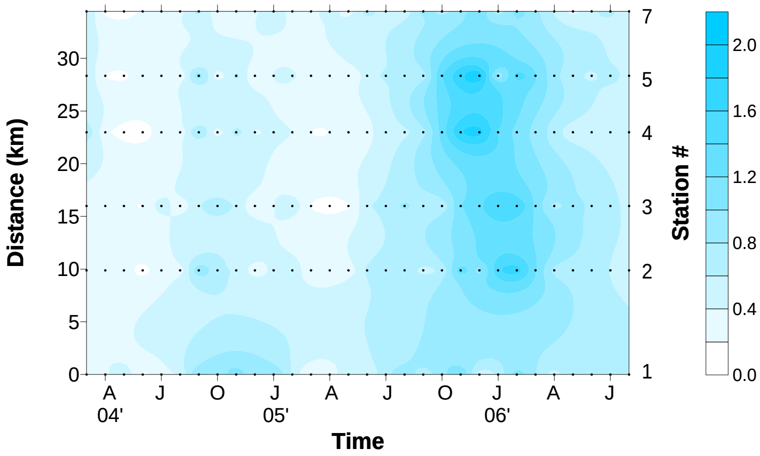


Figure 3 Secchi depth (m) spatial and temporal contour from March, 2004 to Aug, 2006.

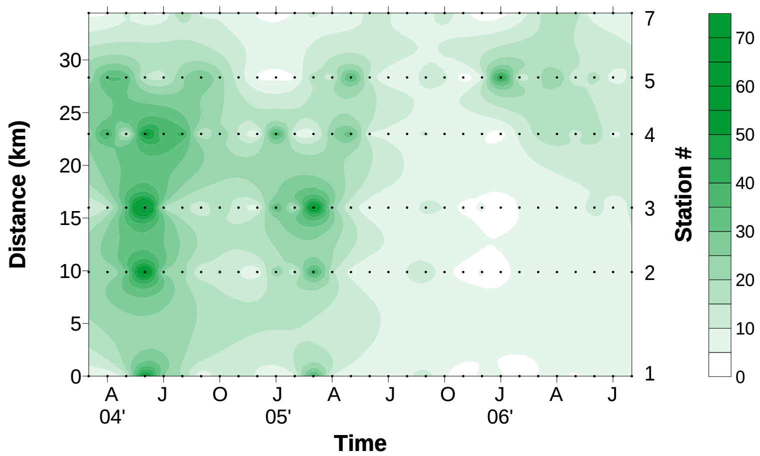


Figure 4 Chlorophyll *a* concentration (μg L^{-1}) spatial and temporal contour from March, 2004 to Aug, 2006.

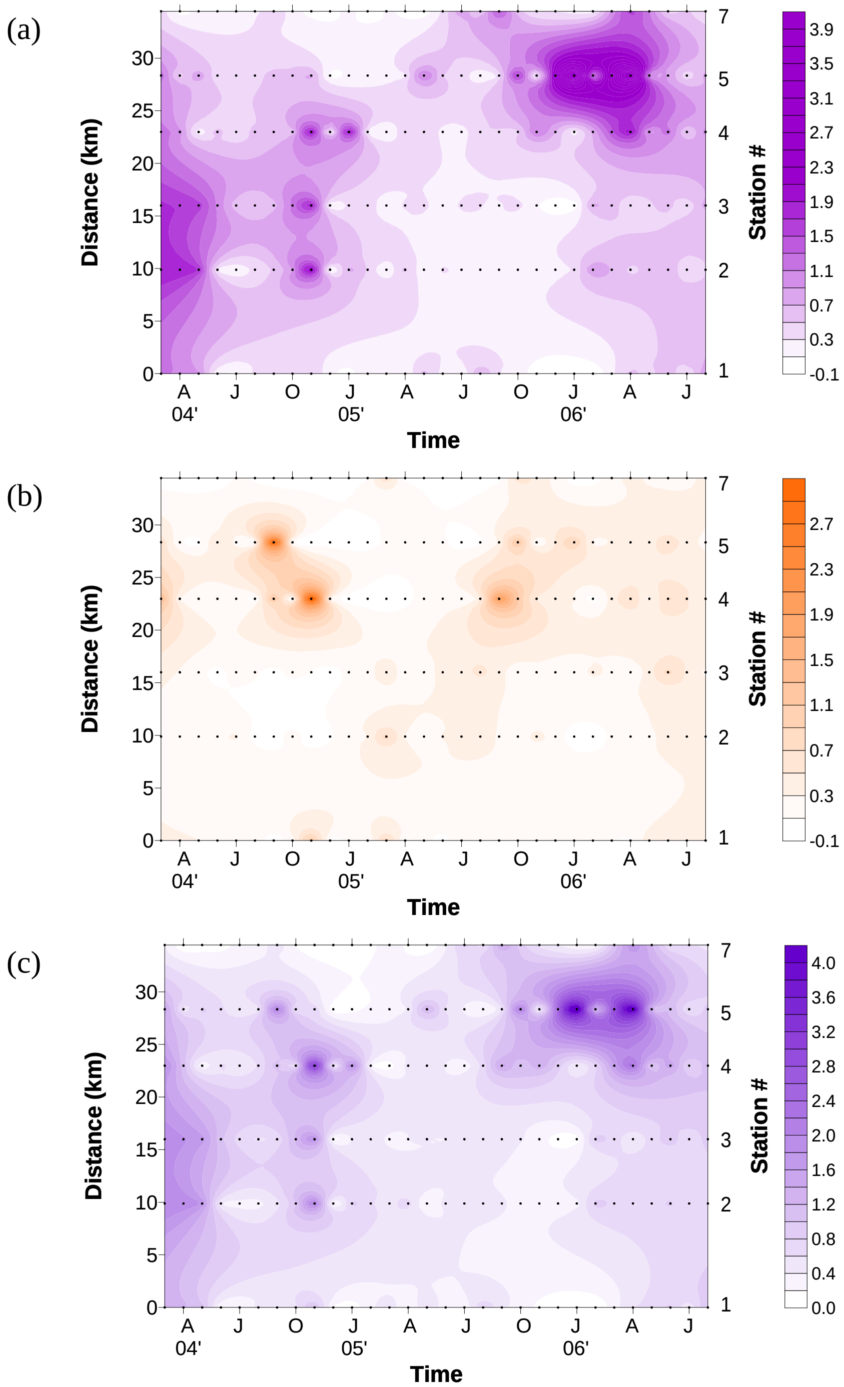


Figure 5 Producutivity (gC m^{-2} d^{-1}) contour from March, 2004 to Aug, 2006. (a) Net productivity; (b) Respiration; (c) Gross Productivity.

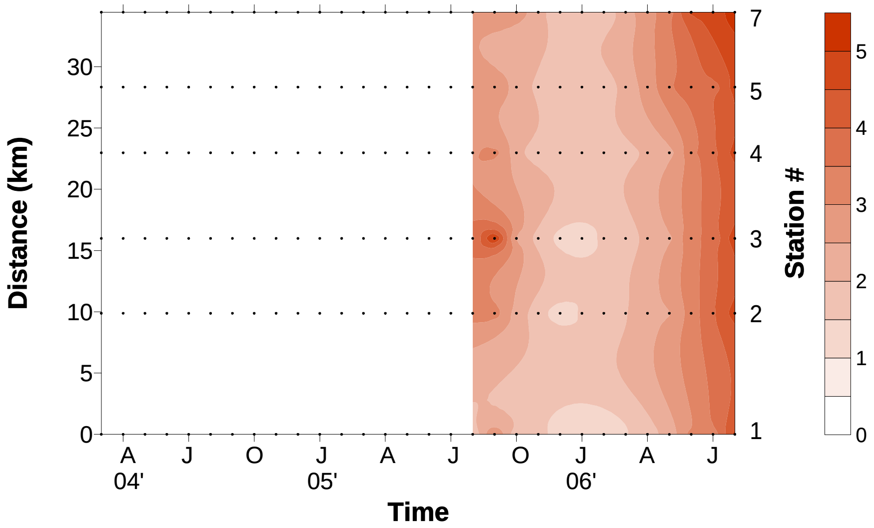


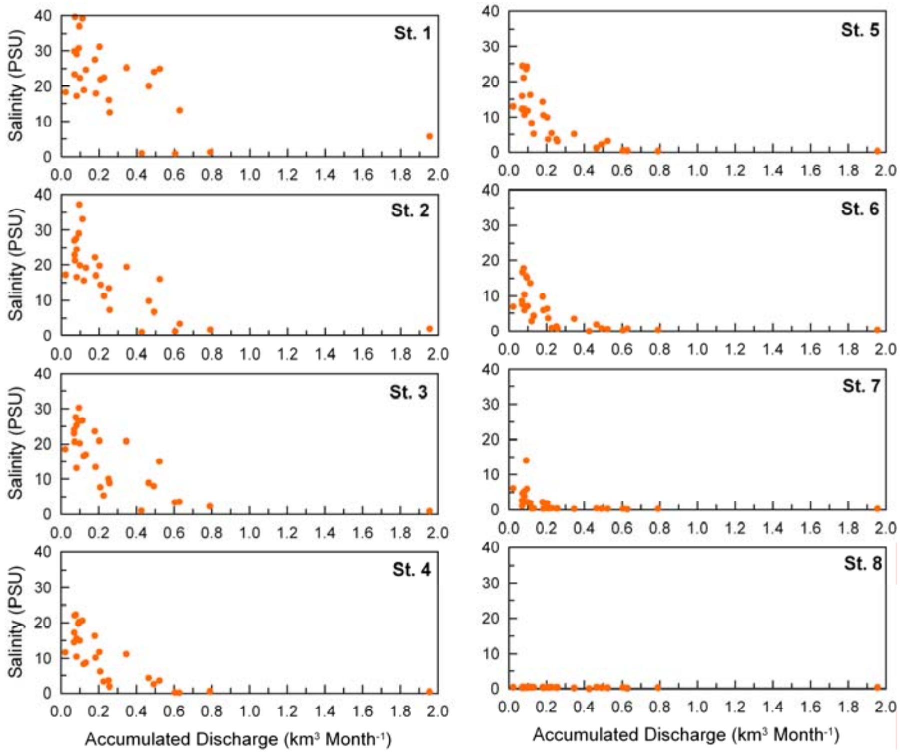
Figure 6 Dissolved organic carbon (mgC L^{-1}) spatial and temporal contour.

Relationships between flow and fixed station data

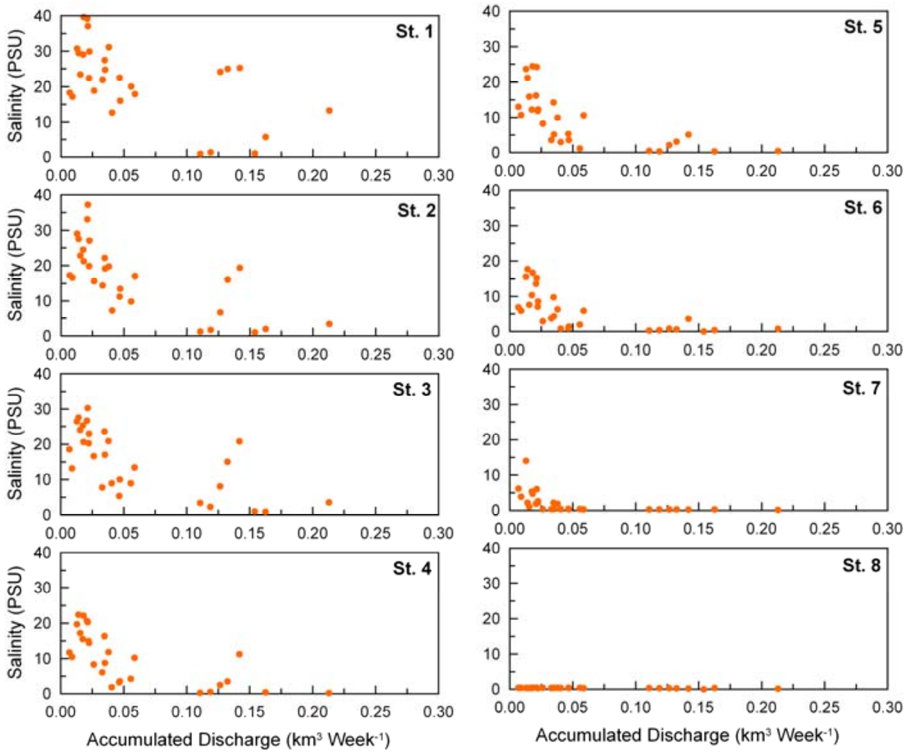
San Antonio Bay

Salinity v.s. Discharge

(A)



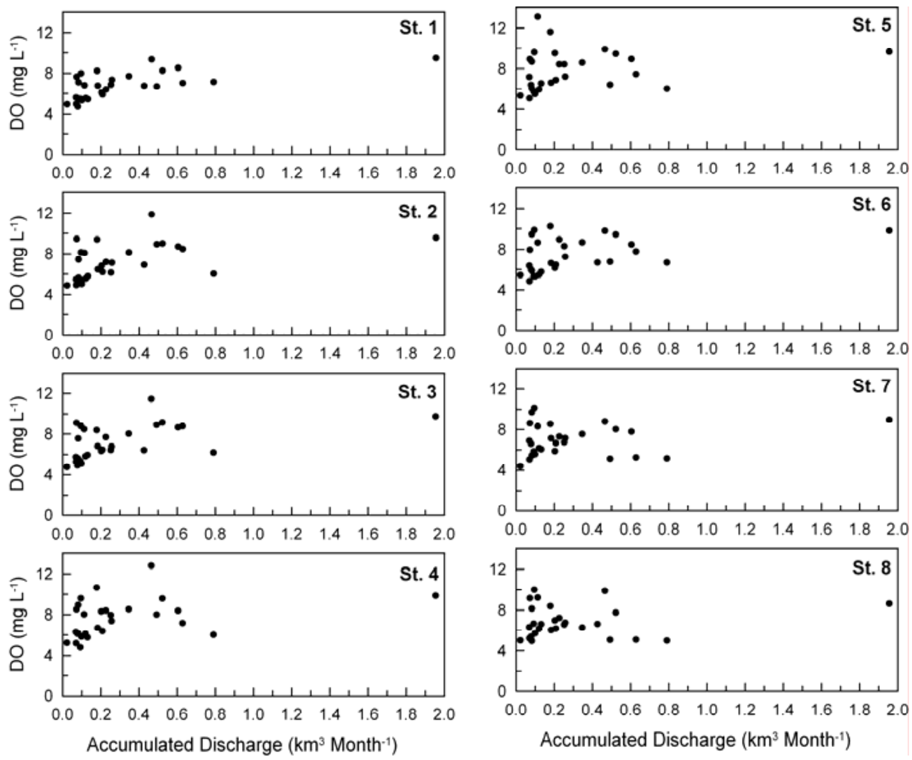
(B)



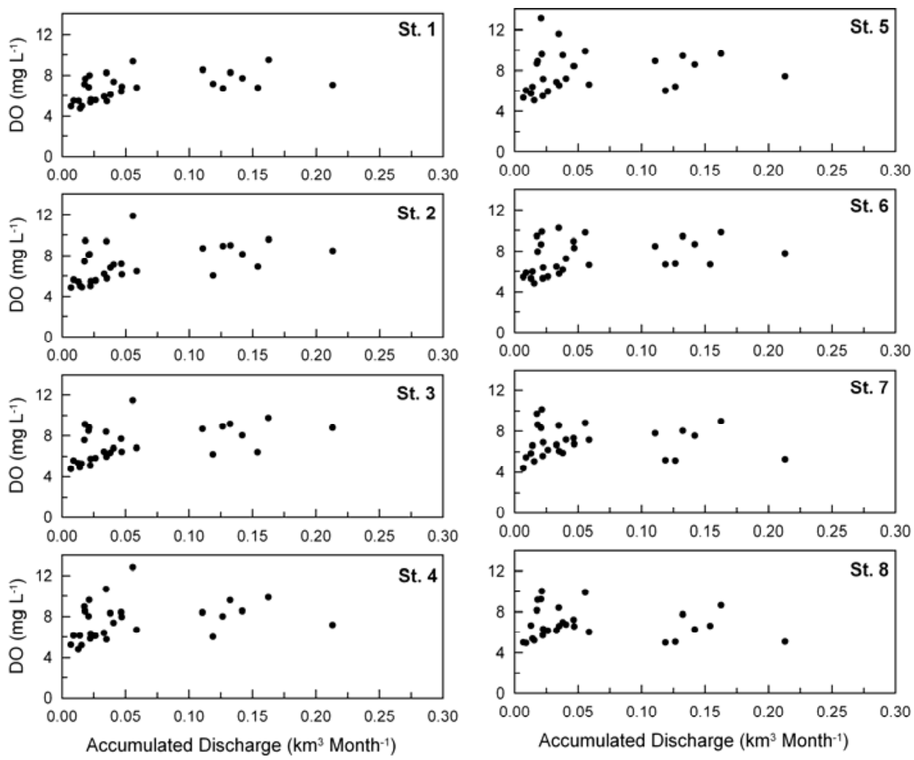
San Antonio Bay

Surface Dissolved Oxygen v.s. Discharge

(A)



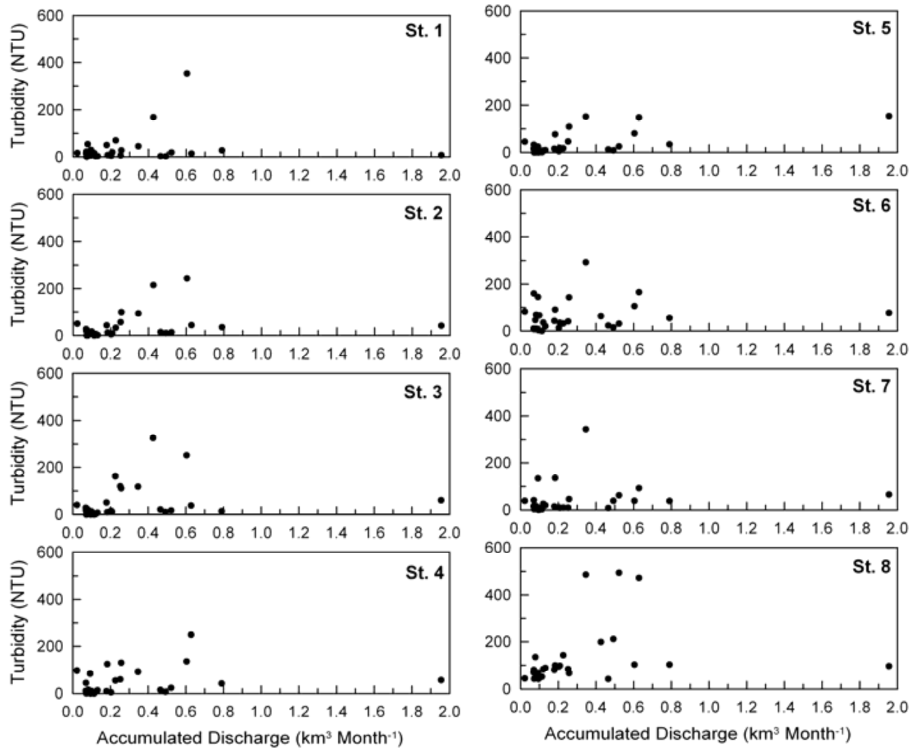
B)



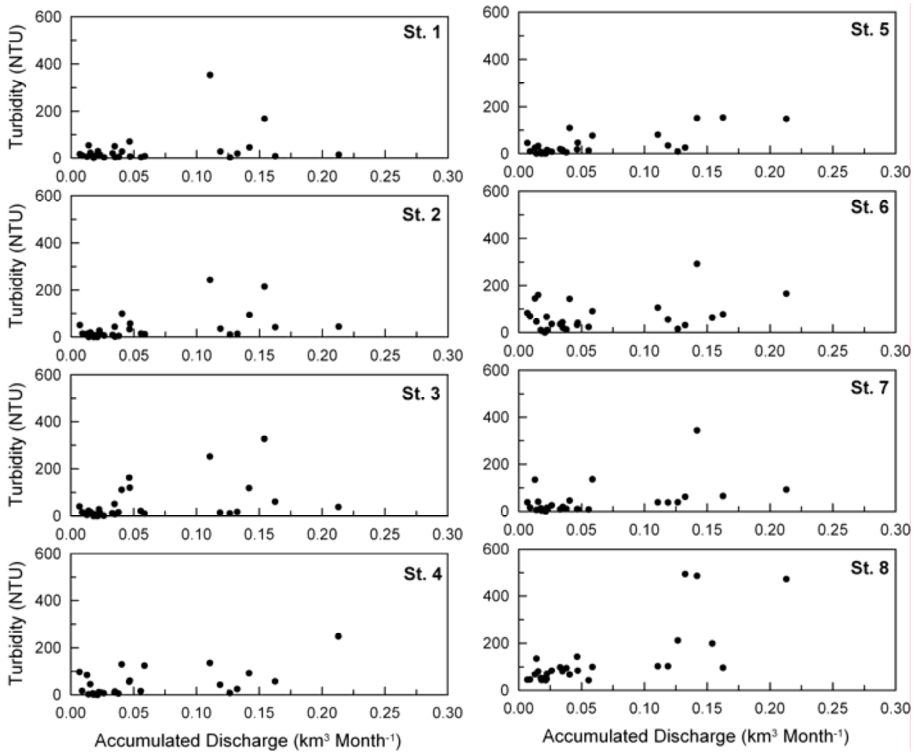
San Antonio Bay

Turbidity v.s. Discharge

(A)



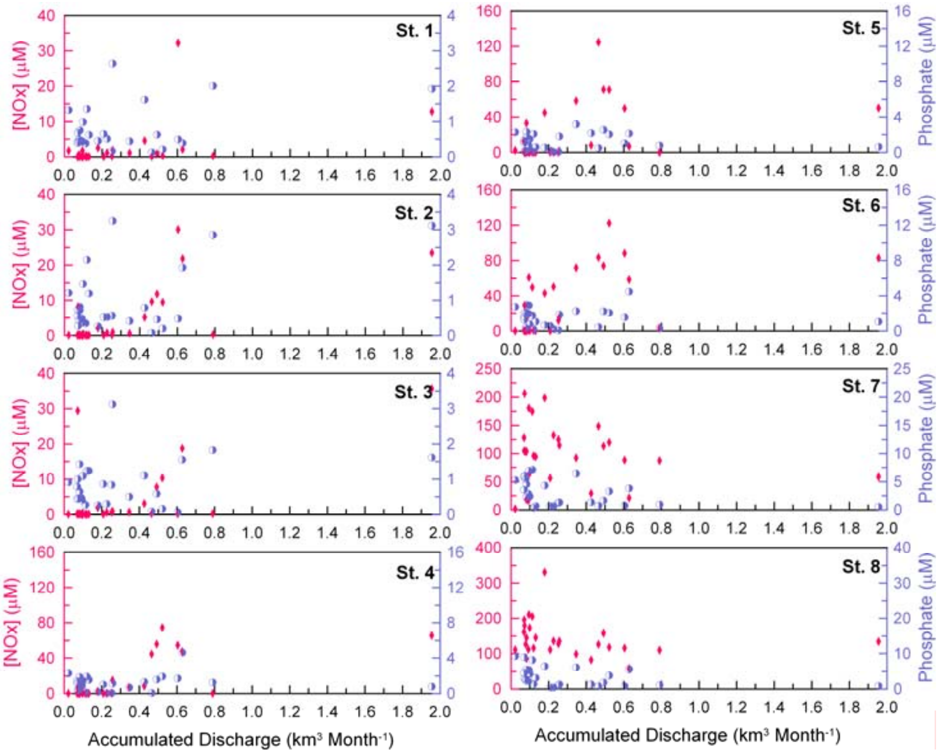
(B)



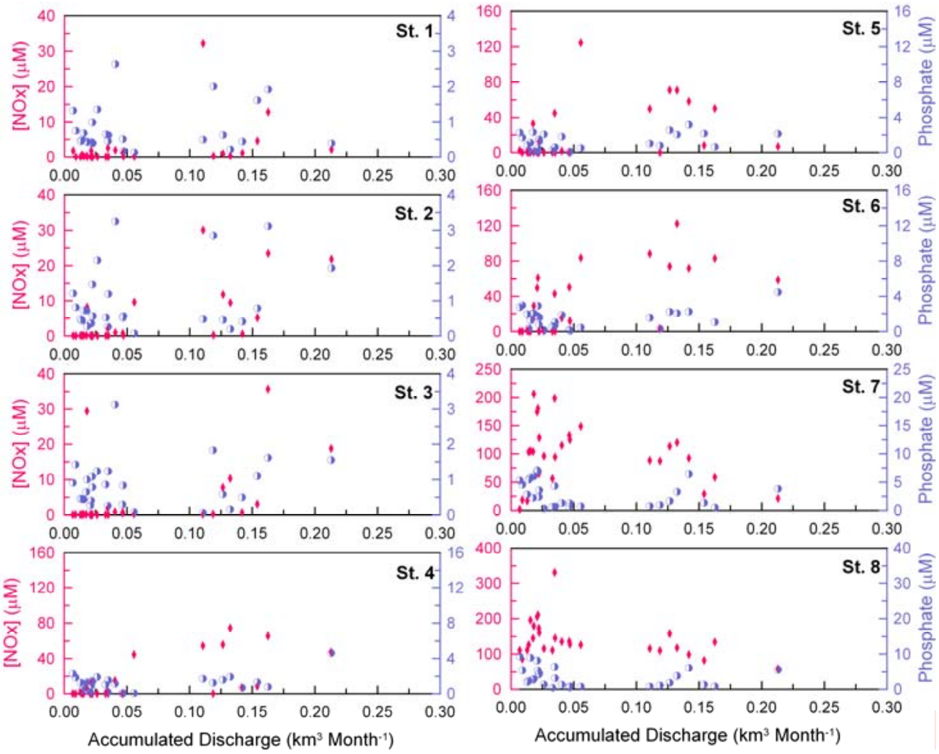
San Antonio Bay

NOx / Phosphate v.s. Discharge

(A)



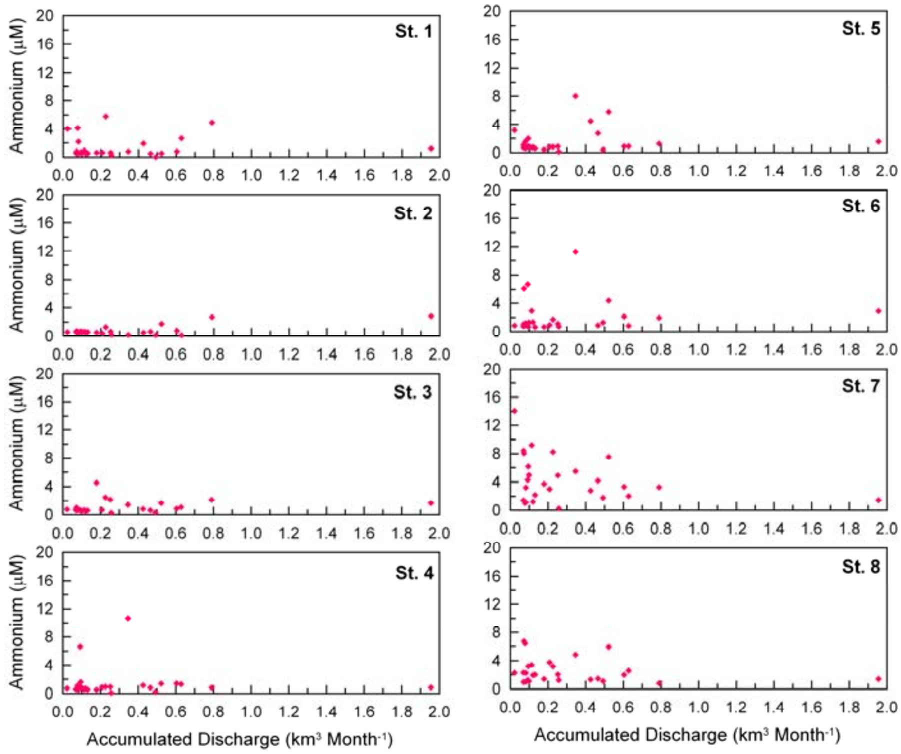
(B)



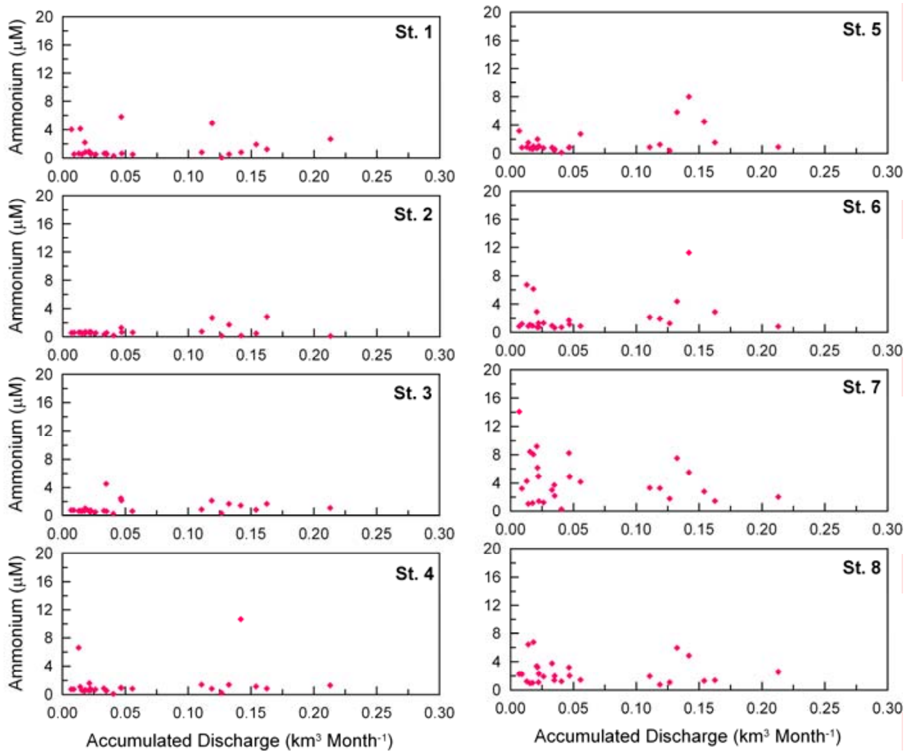
San Antonio Bay

Ammonium v.s. Discharge

(A)



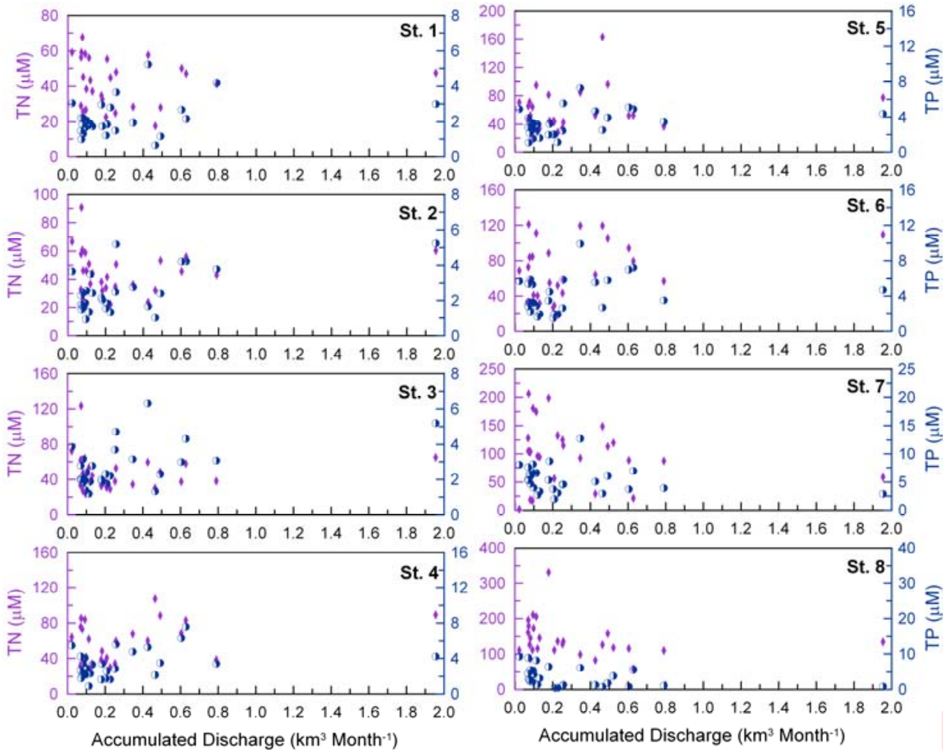
(B)



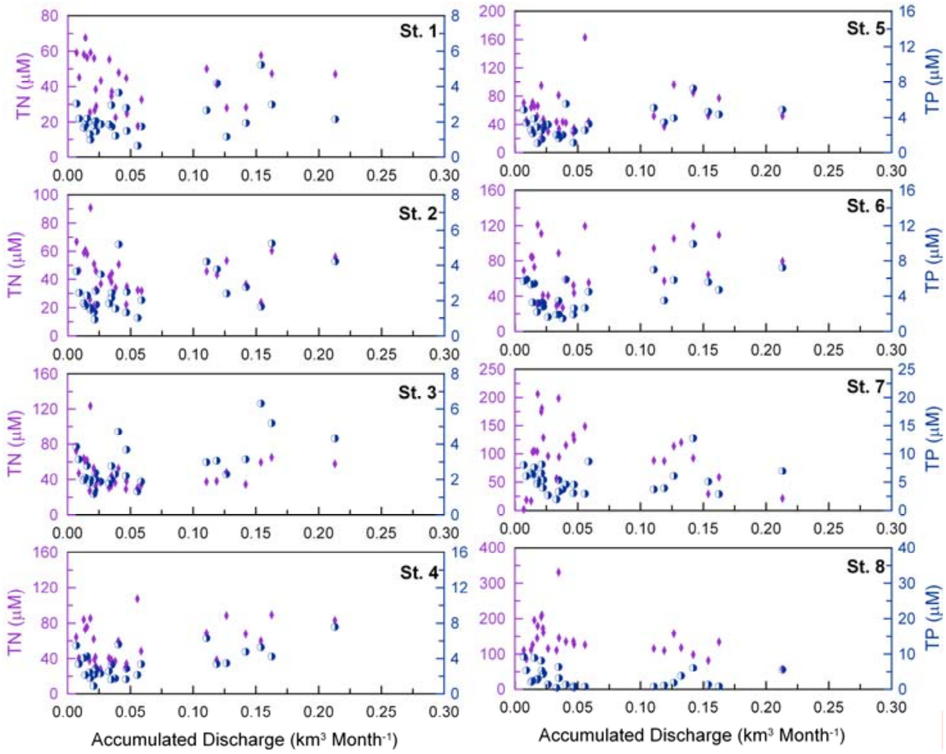
San Antonio Bay

Total Nitrogen/Phosphorus v.s. Discharge

(A)



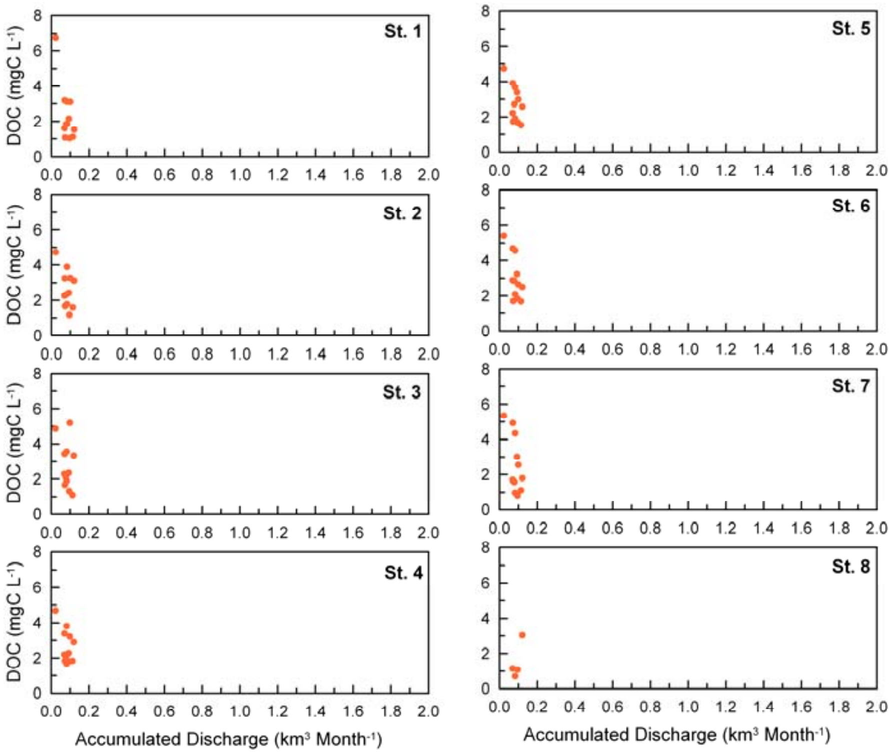
(B)



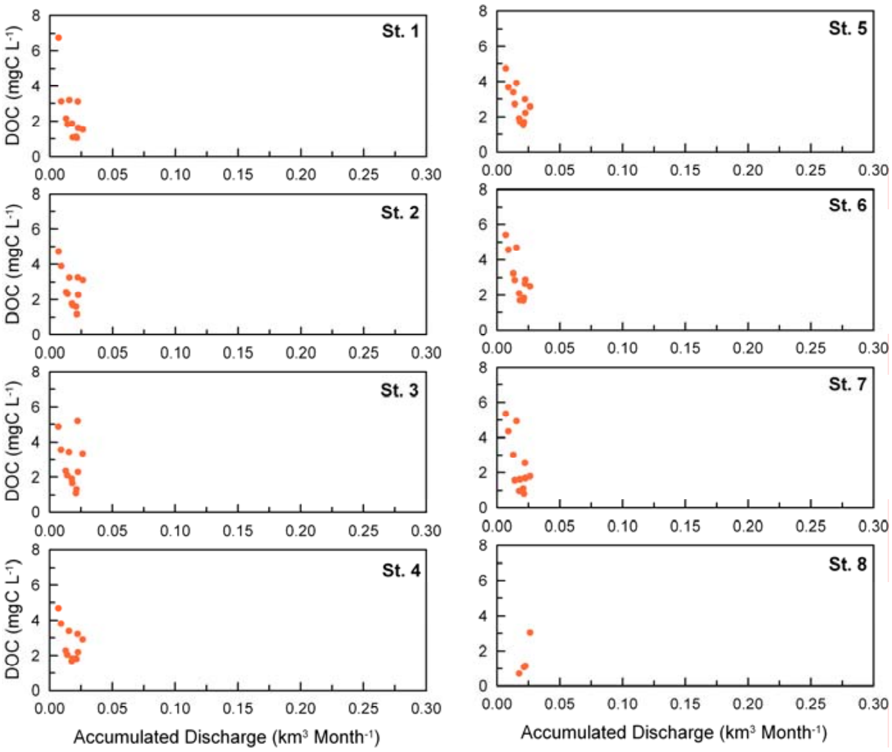
San Antonio Bay

DOC v.s. Discharge

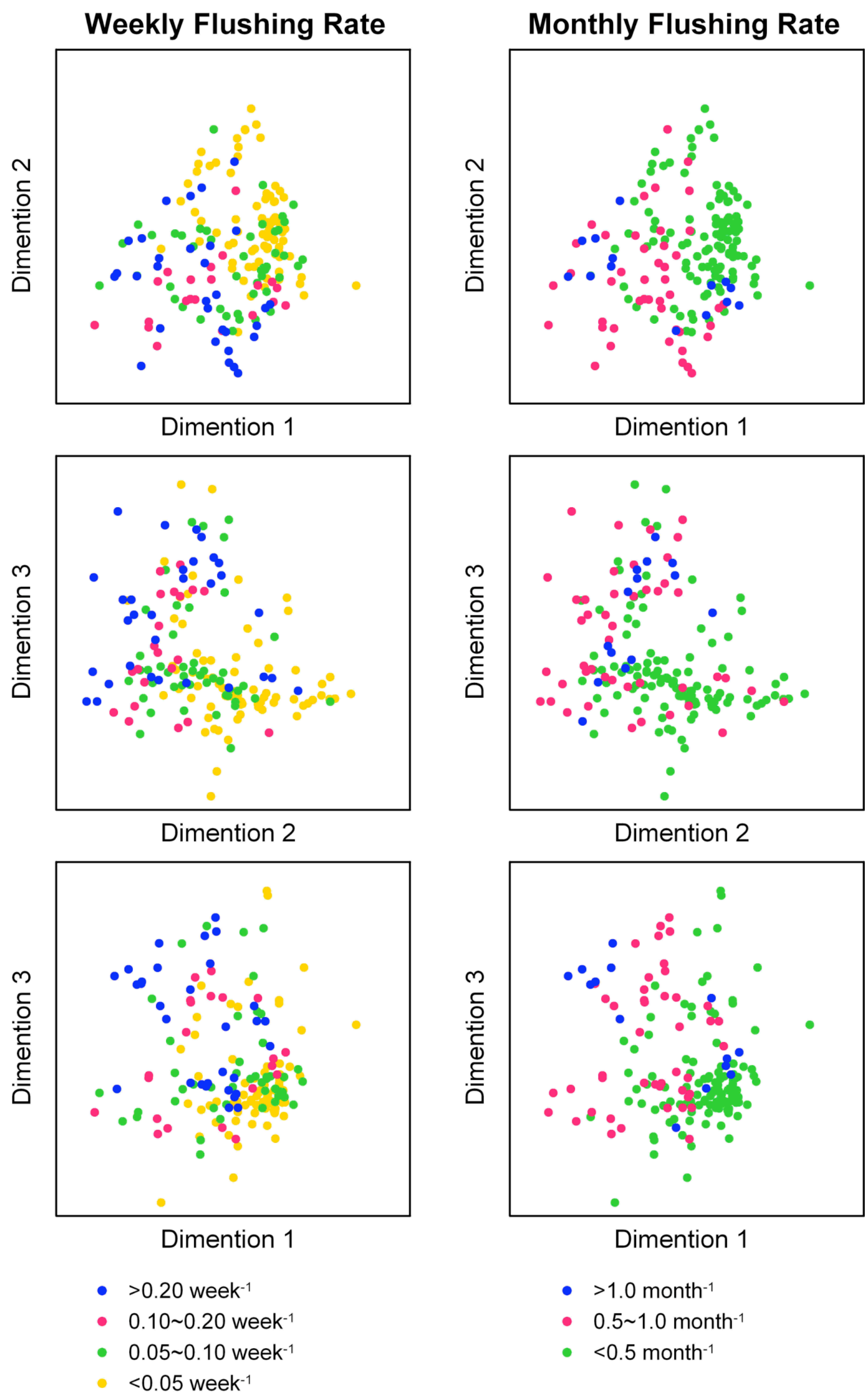
(A)



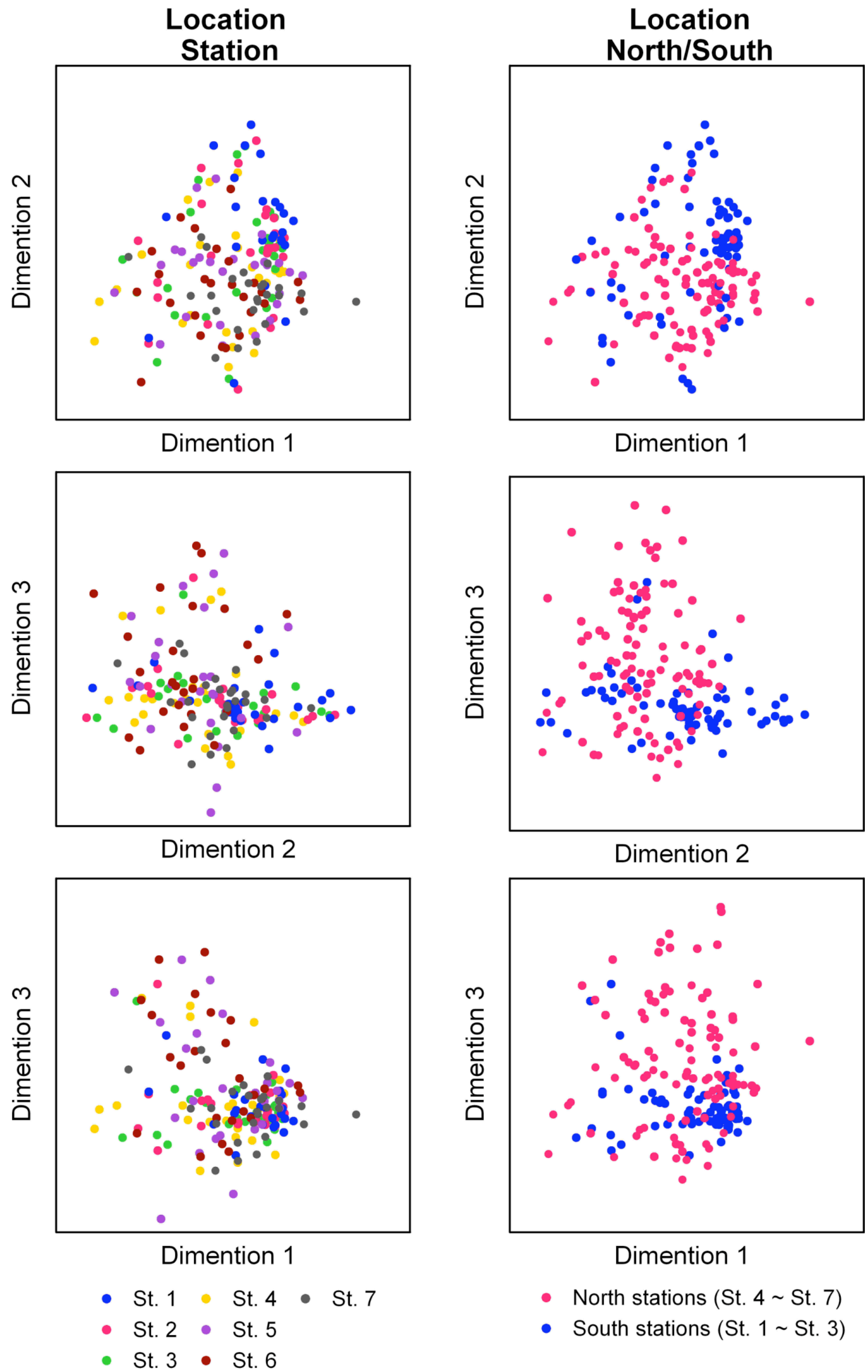
(B)



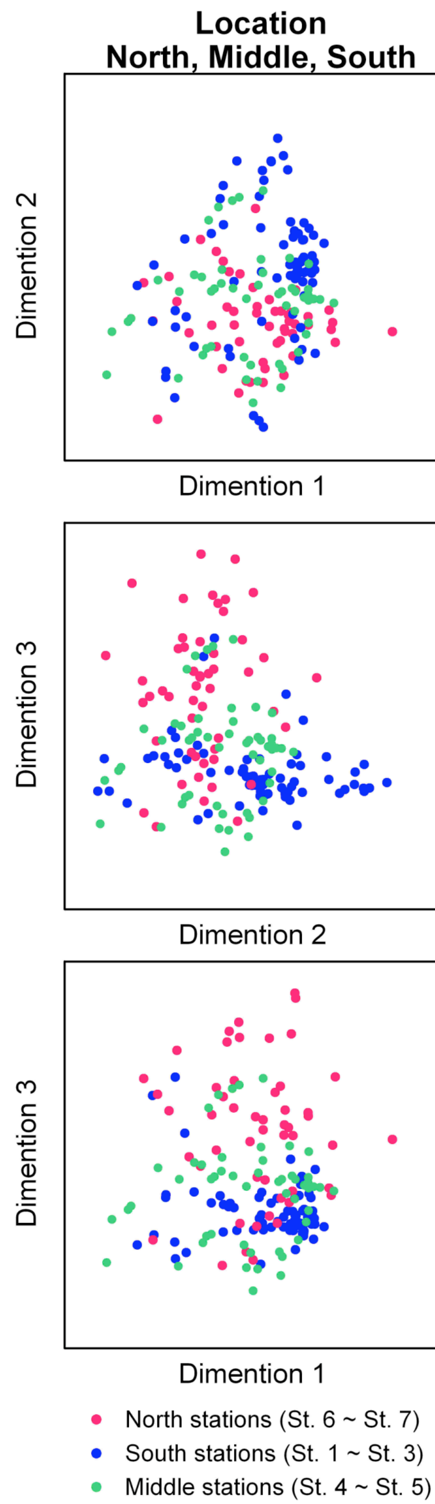
NMS output showing the clustering of sites based on flushing, location, and pulse character



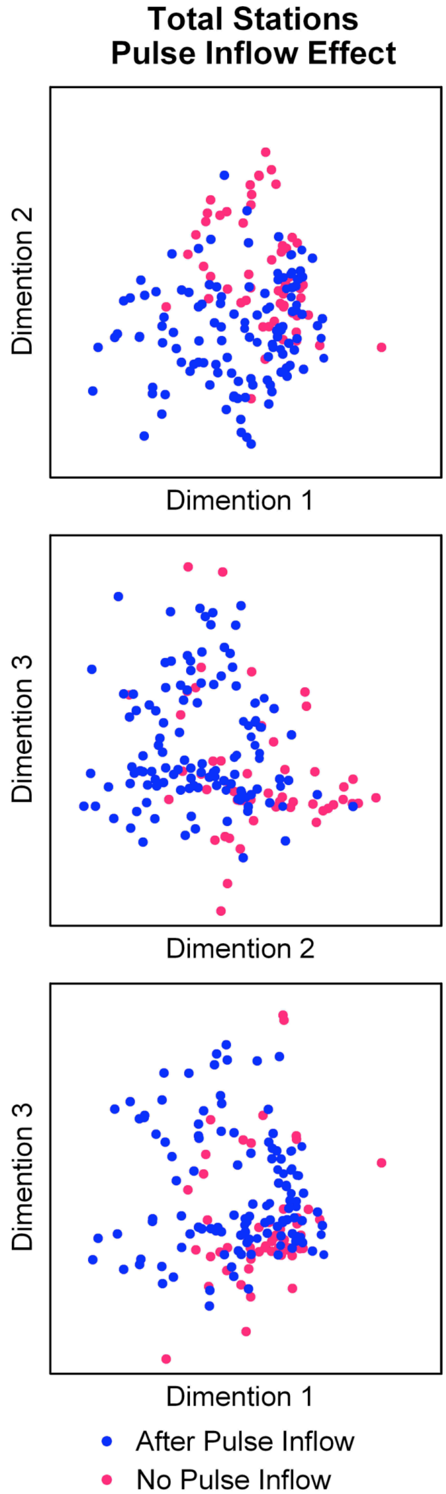
- NMS analysis, 3-D, stress: 12.210.
- Not clearly separation by 4 different flushing rate.
- (Note: dots of <0.05 week^{-1} and <0.5 month^{-1} also indicate dry year, Aug 05 ~ Aug 06.)



- No distinguish separation can be classified by each station, or just by north/south locations.

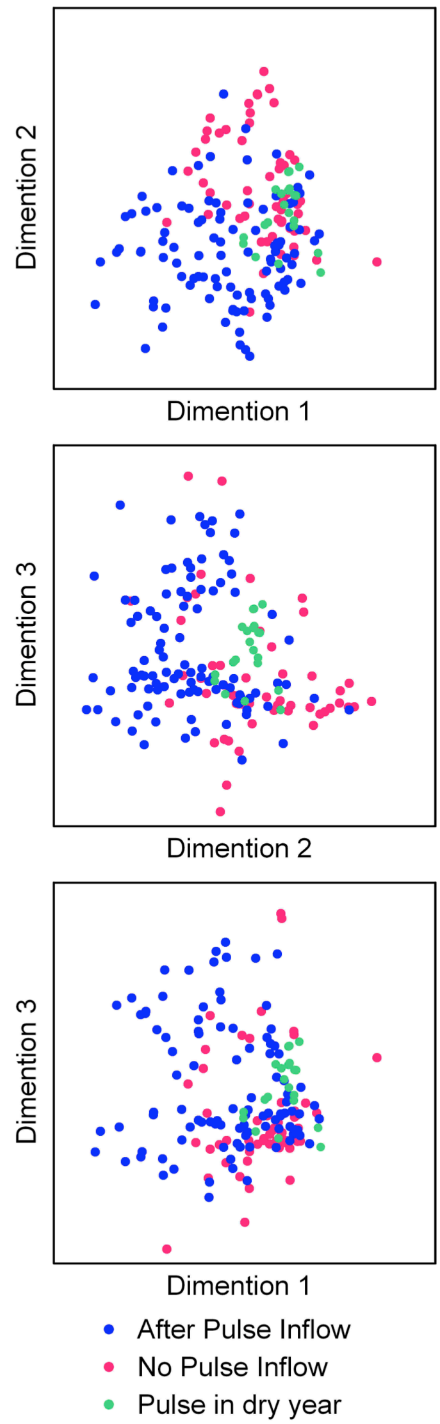


- Classifying stations by three locations, data show that clear separation of north (St. 6~7) and south (St. 1~3) locations, and the middle locations are in between.

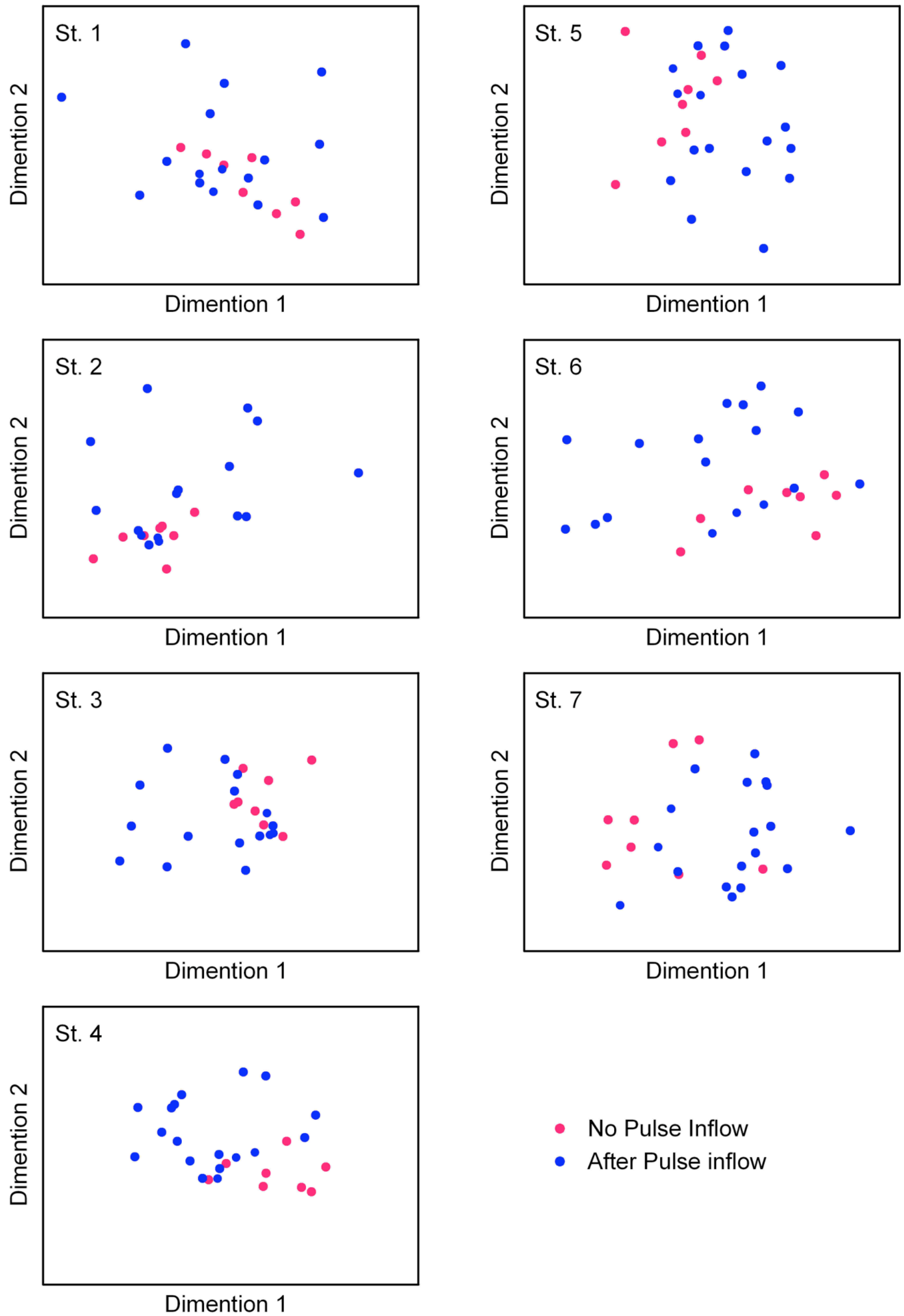


• Defined separation of NMS results by pulse and non pulse inflow event shows that the type of inflow could affect the water quality parameters.

Total Stations
Pulse Inflow Effect



Flushing Rate
(Pulse / Non pulse)



•All results of these 6 stations can not be divided by different level of flushing rate.

• Pulse inflow could affect whole area of San Antonio Bay based on the clear separation, despite Station 1.

Determining Effects of Brush Clearing on Deep Drainage Using Soil Chloride; a Feasibility Study for South Texas Rangelands

Basic Information

Title:	Determining Effects of Brush Clearing on Deep Drainage Using Soil Chloride; a Feasibility Study for South Texas Rangelands
Project Number:	2006TX222B
Start Date:	3/1/2006
End Date:	2/28/2007
Funding Source:	104B
Congressional District:	28
Research Category:	Climate and Hydrologic Processes
Focus Category:	Groundwater, Ecology, Invasive Species
Descriptors:	None
Principal Investigators:	David Barre, Georgianne Moore

Publication

Effects of Brush Clearing on Deep Drainage Using Soil Chloride; Identifying Potential Recharge and the Important Driving Variables

David Barre – USGS Research Grant Final Report, February 2007

Project Goals

The purpose of this study is to provide decision makers with qualitative data on potential recharge in managed rangelands in Texas. This study will facilitate insight into the fundamental elements and processes operating at a plot scale that might affect the potential for recharge at the local scale and ultimately help land owners better manage their land in order to replenish regional groundwater.

Introduction

The effects of groundwater recharge by removal of mesquite-dominated vegetation are currently under investigation in southwest Texas. Water recharge is important in the region since groundwater aquifer levels have lowered around 30 m in the last 85 years. Competitive xeric woody-shrub-dominated plant communities are also known to utilize the episodic rainfall events efficiently before water can penetrate below the rooting zone. Evapotranspiration is thought to be the dominant factor limiting groundwater recharge in semi-arid regions, such as La Salle County, where high rainfall events are rare and sporadic. There are two ways in which evapotranspiration is potentially reduced to a level that invokes groundwater recharge: reduced vegetation cover via land management, and reduced vegetation water use during winter dormancy. This study focuses on land management, particularly clearing of woody shrubs, as a potential mechanism to increase groundwater recharge. Around 70% of the annual rainfall of 555 mm (Soil Survey of La Salle County 1994) falls during the growing season (May-Oct). Warm, humid weather can, in some years, persist until late November, effectively reducing the dormant season to around four months. Winter precipitation has the capability of providing potential recharge, given favorable soil properties for water movement. The rooting depth of vegetation helps dictate the extent to which water can be removed from the soil profile through transpiration and is helpful in determining potential recharge or deep drainage below the root zone. In this study we use the Chloride Mass Balance approach (CMB) based on chloride concentration in the soil, chloride atmospheric inputs and precipitation, to compare deep drainage among areas managed for woody vegetation.

The water budget and soil properties

Deep drainage, or the percolation of water through the soil profile and beyond the root zone, can be expressed on an annual basis simply as:

$$D_D = P – (A_{ET} + \Delta S)$$

where D_D is the deep drainage, P is the water inputs by precipitation, A_{ET} is the combined loss of water through evapotranspiration, and ΔS is the change in root zone water storage. The units of the equation are expressed in depth per time (usually mm/yr).

Soil texture, bulk density and existence of impenetrable soil layers affect the movement of water through the soil profile. Other studies that model recharge rates (Scott et. al. 2000) use soil texture, bulk density and antecedent soil moisture at varying depths to estimate soil infiltration, percolation and subsequent recharge rates below the rooting zone. For potential recharge to increase there needs to be favorable soil properties to facilitate water movement down through the profile, beyond the maximum rooting depth. Coarser textured, low bulk density soils, with fragmented or no impermeable layers, are expected to provide faster water movement and greater recharge rates.

With the aid of volumetric soil moisture probes, and with a better understanding of the soil properties, actual soil moisture flux through the soil profile can be monitored following precipitation events throughout the year.

Vegetation effects on groundwater recharge

Recharge has been documented to have occurred where native vegetation of forest/ shrubland have been converted to grassland or pasture, or where forests or grassland have been cleared for agricultural practices, such as irrigation or dryland cropping. Subsequent shallow rooting depths, decreased canopy interception, potential decrease in evapotranspiration and periods of fallow, all allow for water infiltration and percolation to occur. Conversely, for vegetation to effectively move water upward and out of the soil as transpiration, plants must possess morphological and physiological adaptations which would allow for extended survival in the water-limited environment typical of semiarid and arid regions.

The buffering capacity of the vegetation to maintain soil water at depth is documented and likely to occur -- especially in semiarid regions, where rainfall is periodic and seasonal. But this affect is more likely during winter dormancy than in the active growing season. Rather, large precipitation events during the growing season tend to promote positive vegetation response, excess biomass production, increased root densities and deeper rooting depths. When rainfall occurs in-sync with high evapotranspiration, as it does in many semi-arid regions such as in southwest Texas, possible soil water gains from rainfall are countered by losses due to high temperature and subsequent evaporation. The problem is compounded by the fact that in a lot of these areas, vegetation responds actively to summer rain and associated increases in biomass utilize any excess water. Seyfried et. al. (2005) explains that it is possible for multi-year trends in annual precipitation to overwhelm the buffering capacity of the soil-plant system; however, excess rain during periods of winter dormancy are the most likely contributor, e.g. over a decade of wetter than average winters.

Much of the research on how woody vegetation removal affects water resources has focused on potential increases in surface water flow rather than deep drainage. Wilcox (2002) reviewed the literature and recognized the lack of evidence supporting the fact that removal of woody vegetation to favor grassland would increase water yield. Wilcox also identified the importance of knowing the influence that soil depth, soil morphology, and the depth to bedrock may have on increasing or decreasing water yield in streams. These same ideas help recognize that groundwater recharge may also be possible, under similar conditions, and indeed in some instances, while streamflow remains unchanged. Deep, sandy soils have the greatest potential for groundwater recharge following removal of woody vegetation.

Land use change is also a significant factor when trying to understand the historical dynamics of subsurface water flow. Pasture development, agriculture, irrigation and forestry all impact on how the water coming into the system will be utilized by the vegetation. Tolmie et. al. (2004) has suggested that with a change in land-use from native woodland to crop or pasture, water will be lost below the rooting zone and into the groundwater recharge zone. In temperate systems, when converting woodland to crops, enough water can be moved below the root zone in a matter of a few decades to flush carbonates, nitrates and chloride from the system. Flushing of chloride results in a shift of maximum concentration downwards as water escapes the root zone of the more shallow-rooting crop species compared to the more deeply-rooted woody species that occupied the soils previously.

In this study we track soil chloride concentration profiles in order to test the hypothesis that clearing shrub vegetation in a semi-arid Texas rangeland will increase deep drainage below the root zone. By comparing soil chloride among treatment plots that were cleared at different times in the past, a chronosequence can be established to see whether deep drainage has occurred in the period of time the shrubs take to regain dominance in the community.

Chloride: Historical Evidence of Recharge

Chloride is useful as an indicator to document recharge of water into saturated aquifers and beyond the root zone through deep drainage (Allison and Hughes 1978; Scanlon 1992; Phillips 1994, Allison and Hughes 1983; Reedy et. al. 2000; Scanlon 2000, Scanlon et. al. 2005). Chloride in precipitation, as well as dry deposition, is transported into the root zone with infiltrating water. Soil chloride concentrations increase within the root zone as a result of evapotranspiration because chloride is non-volatile and is not removed by evaporation or plant transpiration (Reedy et. al. 2000). White and Broadley (2001) indicate that chloride is largely moved through the soil by water flow due to its relative inability to form complexes and little adsorptive properties with soil. The distribution of chloride in the soil profile therefore represents the balance attained through downward percolation in solution and the concentration due to root uptake of water.

Low chloride concentrations in the soil indicate high water fluxes that flush chloride through the unsaturated zone, indicating either humid climate or unseasonably wet conditions in semi-arid settings. High chloride concentrations indicate low or upward moving water that allows chloride to build up in high concentrations. When mapping chloride concentrations with depth, a pattern can usually be seen where maximum chloride concentration represents the long-term maximum extent that water has reached. Below this depth, if water has been consistently removed from the profile, chloride concentrations drop as water has not been able to transport chloride lower. This “bulge” in chloride concentration, observed in chloride concentration profiles, signifies the removal of water at that soil layer due to evaporation or, more importantly, plant uptake and transpiration.

To quantify the rate of water movement, using soil chloride, a variety of techniques can be adopted, however the Chloride Mass Balance method (CMB) is a useful technique for semi-arid regions where recharge rates are expected to be below a few millimeters per year (Gee et. al. 2005). Others (Reedy et. al. 2000; Scanlon et. al. 2005; Scanlon 2000; Scanlon 1991; Scanlon 1994) have used the CMB approach to identify maximum extent of wetting fronts and recharge rates in semi-arid and arid areas to varying degrees of precision. The CMB method balances chloride inputs (through atmospheric deposition, both dry and in precipitation) with the chloride output (downward percolation through the soil). Confidence in recharge rate estimates require accurate estimates of atmospheric chloride input, precipitation and soil pore water chloride content . Chloride Mass Balance can be expressed as:

$$PC_P = D_DC_S \qquad (1)$$

where P is the precipitation (mm/yr), C_P is the chloride concentration by atmospheric deposition (mg/L), D_D is the rate of deep drainage (mm/yr), and C_S is the cumulative chloride concentration in the soil pore water to a depth of interest (mg/L). Rearranging for D_D gives:

$$D_D = PC_P / C_S \qquad (2)$$

Water flux can be estimated from the degree of chloride enrichment in pore water as a result of evapotranspiration relative to the chloride concentration in precipitation (Scanlon 2000). Estimates of recharge are possible if dry and wet deposition from the atmosphere is assumed to be the only source of chloride input to subsurface layers. An estimate of deep drainage can be calculated by dividing the cumulative amount of chloride down to a depth of interest by the chloride input (equation 2). Chloride concentrations in the soil profile are inversely proportional to recharge rates.

In this study we used CMB to see if clearing of shrub vegetation changes deep drainage from mesquite-dominated rangelands in South Texas over time periods of 15 years or less. We expect to see a decrease in cumulative chloride with depth in plots that have been cleared of shrub vegetation compared to control plots. For plots that have been cleared longer, cumulative chloride concentrations should be less. The position of the bulge, or zone of greatest removal of water through evapotranspiration should be lower in the profile for plots that have been cleared than control plots. To test our hypothesis we will compare soil moisture and chloride profiles among a chronosequence of vegetation successional stages of woody dominance: recently cleared (<1 year), after 5 years of recovery from clearing, after 15 years of recovery from clearing, and mature sites that have never been cleared of large mesquite trees. In each stage of the chronosequence we relate differences in vegetative cover to differences in deep drainage that cannot otherwise be explained by soil properties. This project is a part of a larger study which aims to better understand deep drainage from a wider range of vegetation management scenarios with the primary goal of identifying which elements of this particular landscape might contribute to recharge and under what conditions deep drainage may occur.

Methods

The study area is located at the 400 acre Northcut Ranch, a private ranch approximately three miles east of Cotulla, Texas in La Salle County. Three treatment plots and a control have been established at three replicate sites on the ranch to represent a chronosequence, in which time is substituted for space, for a total of twelve experimental plots. The control plots are considered a native, undisturbed stand of rangeland brush dominated by mature honey mesquite (*Prosopis glandulosa*) and C4 grasses. The other three treatments were plowed of vegetation, using a horizontal blade that cuts the shrubs 30 cm below ground level, at different times in the past (2005, 2001 and 1991) and subsequently allowed to recover. This root plowing process is a common management practice in this region to remove woody vegetation and increase grass production. Thus, the treatment plots represent vegetative regrowth 1, 5, and 15 years since root plowing.

Precipitation records were obtained from the United States Department of Agriculture (Soil Survey of La Salle County 1994). The yearly average is 555 mm and the data consists of monthly averages for the period 1951-1984.

Over a period of one week in April 2006 and two weeks in July 2006, two soil cores were taken from each of three plots within each of the three sites for a total of 18 cores. The recently plowed plots in each site were not sampled since we expect that insufficient time has elapsed for water movement to have differed from the control plots to have affected chloride concentrations. A Giddings soil auger, mounted on either the back of a tractor or trailer, was used to excavate 50-mm diameter cores from depths up to 4.2 meters. The exact depth of each soil core was limited by the machinery's physical dimensions and power, and depended highly on the depth to rock or any other impenetrable layer encountered, such as gravel or highly-compacted silt.

Each soil core was sampled in 10-cm increments; however, not every increment of the core was sampled. Since we expected most of the chloride variability to occur in the first two meters, we spaced the increments further apart with depth, either 20 or 30 cm, as follows: 10, 20, 40, 60, 80, 100, 120, 140, 160, 180, 210, 240, 270 cm, etc. The number of samples per core ranged anywhere from nine to eighteen, depending on the total depth. If possible, the bottom 10 cm increment was sampled even if it fell outside the sampling protocol depths. Field observations were also made of soil morphology, including depth to calcium carbonate, color, mottles and soil structure, in order to aid soil classification once laboratory data had been obtained.

Soil profile samples were used to characterize a variety of soil descriptive parameters including volumetric soil moisture, bulk density, gravel fraction, particle size, fine roots, pH, electrical conductivity and chloride. Samples were oven dried at 105 C to a constant weight. Soil moisture was calculated on a percent by volume basis according to bulk density. Dry soil was then passed through a 2 mm sieve to remove gravel, carbonate nodules and large roots. The gravel fraction was determined as a percentage of the initial mass of dried soil. Homogenized and sieved soil samples were further sub-sampled, whereby 60 g was used for particle size analysis using the hygrometer method, the equivalent weight of soil in 50 cm^3 was allocated to measure fine roots, and 50 g of soil was taken for an aqueous extract. The sub-samples for particle size analysis and the aqueous extract were ground on a roller grinder (custom made by Kansas State University) for four hours prior to their further analysis.

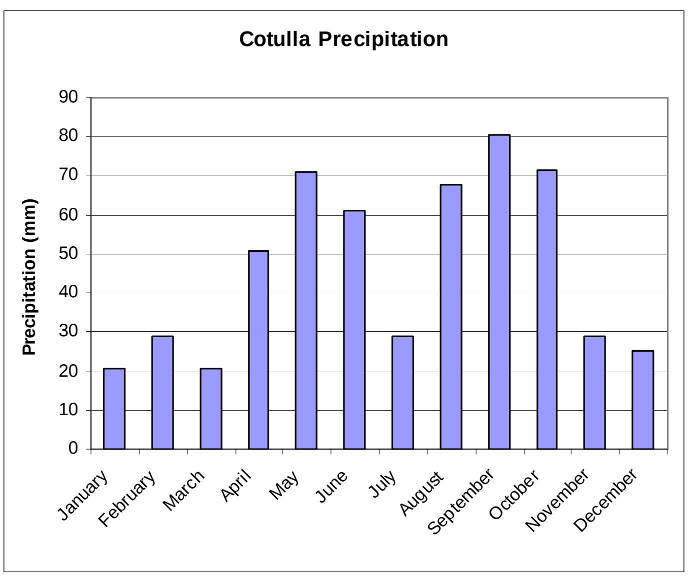
The particle size and fine root procedures of the study are in the process of being measured, results of which are yet to be determined. The results obtained from these analyses will to provide supporting evidence of the role that soil properties and maximum rooting depth play in affecting drainage rates.

The ground samples allocated for aqueous extracts were then shaken in flasks for 4 hours with 100 ml of distilled water. In mixtures where the soil swelled, absorbing much of the water, an additional 100ml of distilled water was added and noted. The 1:2 soil water slurry (similar to that used by Dyck et. al. 2003 and described by Dellavalle 1992) was then left to settle for approximately 30 minutes and pH and electrical conductivity measurements recorded using a hand-held YSI and Hanna instrument, respectively. The soil slurry was then filtered through a Bachar Funnel with a #2 Whatman filter using a vacuum flask. The water extract was then bottled and later analyzed for chloride using the ion chromatography method described by Pfaff 1993 and employed by the New Mexico Bureau of Geology and Mineral Resources.

Chloride deposition data was obtained for a seven year period (1999-2005), from the National Atmospheric Deposition Program, and collated to provide average chloride depositions for the two closest known observation points to Cotulla, La Salle County, Texas. Cotulla lies between Beeville, which is nearer to the coast, and Sonora, which lies further inland. Cotulla is located approximately 80 miles from Beeville and 160 miles from Sonora. A distance-weighted interpolation of monthly chloride deposition values was made from those values obtained for each of the two observation stations at Beeville and Sonora. The monthly values for Sonora are around one quarter of those values at Beeville, which is nearer to the coast. The interpolated rate of monthly chloride deposition in rainfall for Cotulla was 0.7 mg L^{-1} $month^{-1}$ (8.4 mg L^{-1} yr^{-1}).

Two methods were adopted to describe the above-ground vegetation pattern, represented in each of the twelve study plots: line transects and quadrats. Observations were made in July and so represent the relative growth distribution at that time of year. Shrub percent cover by species was classified along three 15-meter line transects placed in random directions, each from a randomly located point near the center of each plot. Vegetation intersecting the entire transect length in each plot was described to a 5-cm resolution and expressed as a percentage of the total linear distance. Along each line transect, five 0.25 m^2 quadrats were placed randomly to further classify ground cover of vegetation, bare ground, rock, and leaf litter, expressed as a percent of the soil surface area. The middle of the first quadrat along the line transect was randomly selected within the first 3 meters of the transect. The side of the line was also determined randomly. Each successive quadrat was then placed every 3 meters down the transect, alternating sides.

Figure 1. Average monthly precipitation for Cotulla, TX
(Soil Survey of La Salle County 1994)



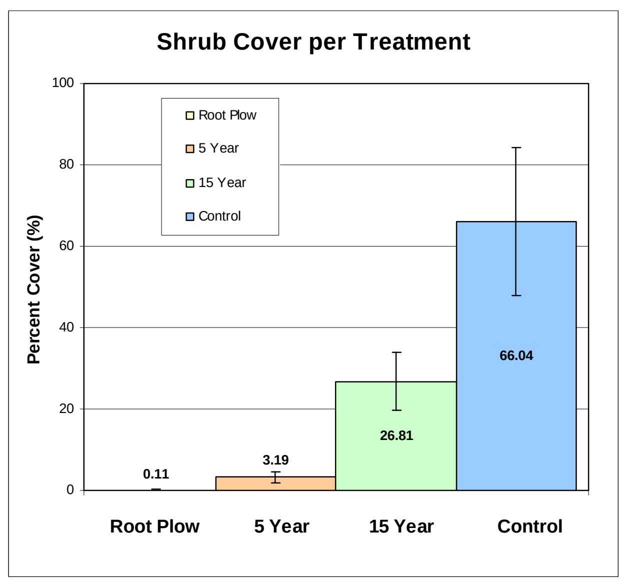


Figure 2. Percent shrub cover and standard error between treatments for the three sites combined**.**

Results and Discussion

A summation of precipitation is presented in Figure 1 and shows the average monthly precipitation for Cotulla. Total annual precipitation in La Salle County, as reported by the United States Department of Agriculture is 555 mm^{-1} $year^{-1}$. Around 70% of the annual precipitation falls in the summer months (May-October) and 30% falls during winter (November-April).

Soil Results

Preliminary investigations of soil properties show fairly uniform morphology within sites, however soil characteristics between Site 3 and the other two (Sites 1 and 2) seem markedly different (data not shown). Landscape position and differing parent material are thought to be responsible for Site 3 to have visibly sandier textures throughout. Further particle size analysis in the laboratory is hoped to support this explanation.

Vegetation

Average shrub cover for all sites between treatments is shown in Figure 2. The approximate ratio of shrub cover between treatments at each site are similar, however Site 1 supports considerably more cover than both Site 2 and 3, despite Site 1 and 2 being in a similar landscape position (data not shown). Inadequate sample size could be the reason why Site 2 is lower in shrub cover than Site 1. The five year plots have very little shrub re-growth, but by fifteen years after clearing, shrubs are again dominant and canopy cover has increased to around 27% (7.1 SE), with shrubs further increasing to around 66% (18.1 SE), observed in the control plot. There is an apparent threshold between five and fifteen years after clearing where shrubs replace grasses as the dominant vegetation type.

The herbaceous level ground cover observations reflect the change in grass to shrub dominance between five and fifteen years since clearing. Figure 3 (a-d) shows herbaceous cover estimates, which were largely influenced by the conditions at the time they were collected (July 2006). Prior to most summer rain, C4 gasses are still quite dormant; therefore, an under-estimation of grass cover is predicted compared to later in the growing season (e.g. September) when grasses are at their maximum extent. Once woody vegetation had been cleared there is a rapid increase in grass and forb cover (3a) and within five years grasses dominate the herbaceous layer, with 28.6% (6.6 SE) cover (3b). Percent bare ground reduces quite quickly after the first growing season. Five years after clearing, mesquite shrubs have yet to mature, with a canopy cover of only about 3.19% (Figure 2). After earlier periods of grass dominance, the shading/competitive effect of the shrub canopy and subsequent reduction in grass cover led to bare ground increases by fifteen years (3c) to the levels observed in the control plots (3d). However, variation in bare ground cover is substantially greater in the control plots, explained by the relatively bare soil in large inter-canopy spaces. Litter in the control plot is high because of the extensive shrub canopy cover of around 66%.

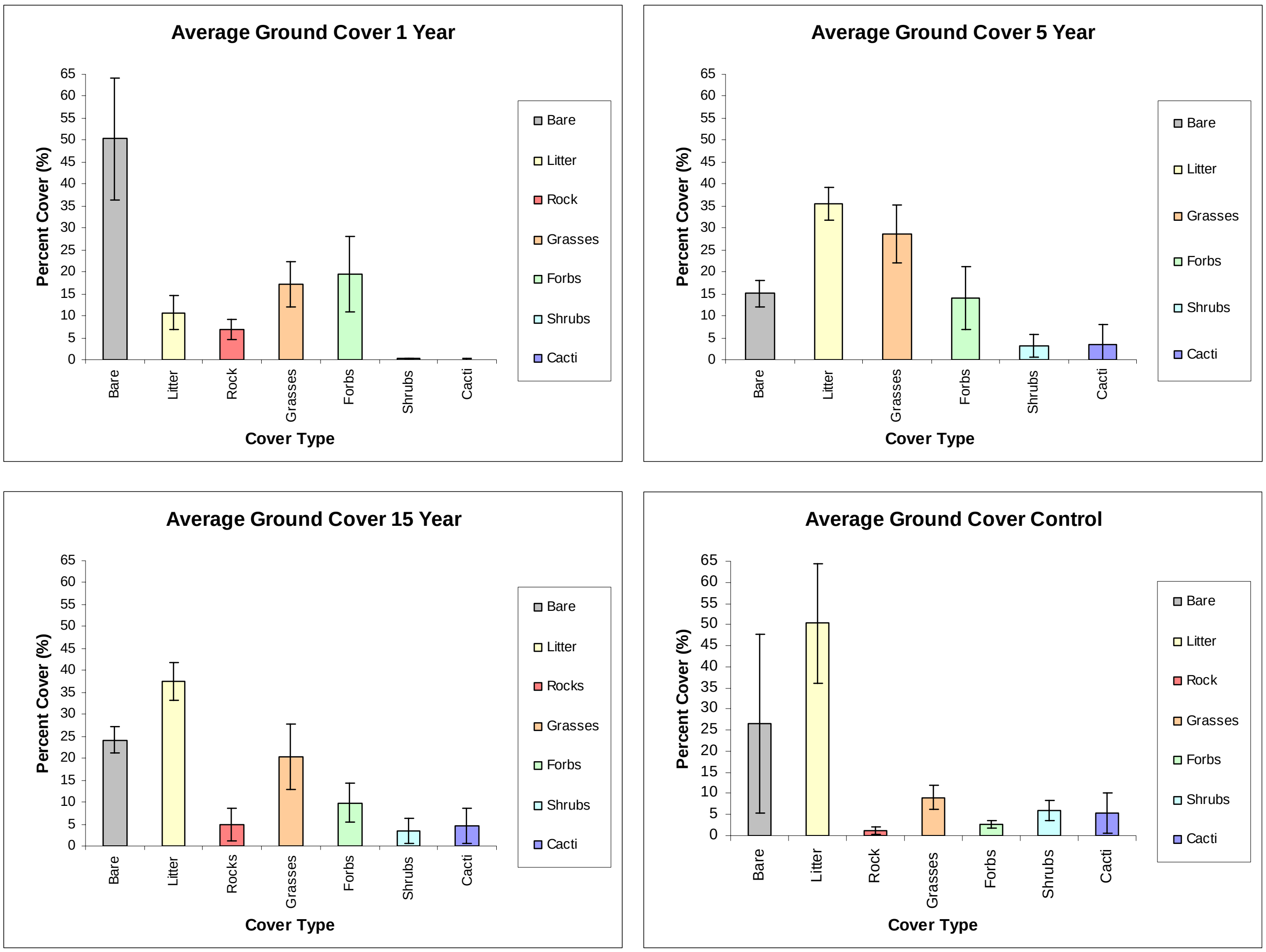


Figure 3. Percent ground cover for all four treatments; 1 year since root plowing (a), 5 years since plowing (b), 15 years since plowing (c) and the control plot (d).

Chloride

Soil chloride concentrations, for those of the 18 profiles where analyses have been completed, are plotted with depth in Figure 4 (a-c). Results from the control plot(s) are consistent with the theory of an accumulation of chloride within the root zone for a significant period of time under a native, untreated stand of vegetation. Depth of the peak of maximum chloride concentration in the control plots are around 170, 240 and 260 cm for Sites 2, 3 and 1 respectively. This explains the build up of chloride over a long period of time in an un-cleared state. In those plots which had been cleared fifteen years ago, no chloride bulge is evident for four out of five of the plots. Chloride builds up where water has been removed through ET, and this is more evident for the control plots than the treatments. In the three treatment plots that were cleared 5 years ago, a chloride bulge is evident, however these chloride concentrations are lower in the profile, indicating that perhaps the chloride has been flushed to lower depths through increased deep drainage in these sites.

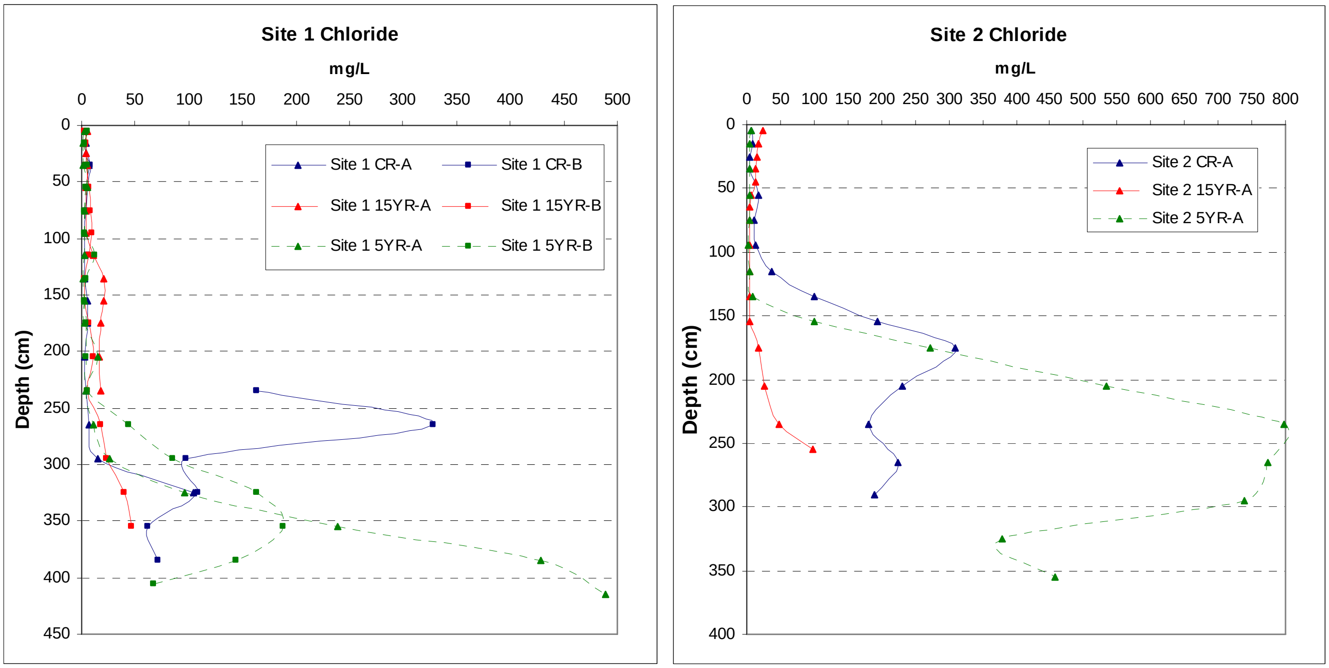


Figure 4. Chloride concentrations with depth for Site 1 (Figure a), Site 2 (Figure b) and Site 3 (Figure c). Treatments are 5 years since plowing (5YR), 15 years since plowing (15YR) and the control plots (CR). Different profiles within treatments are designated A (triangle symbols) and B (square symbols).

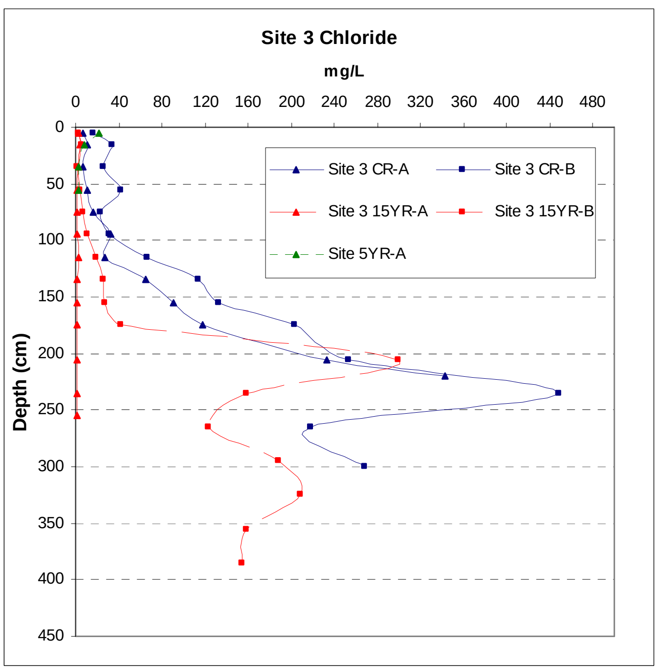
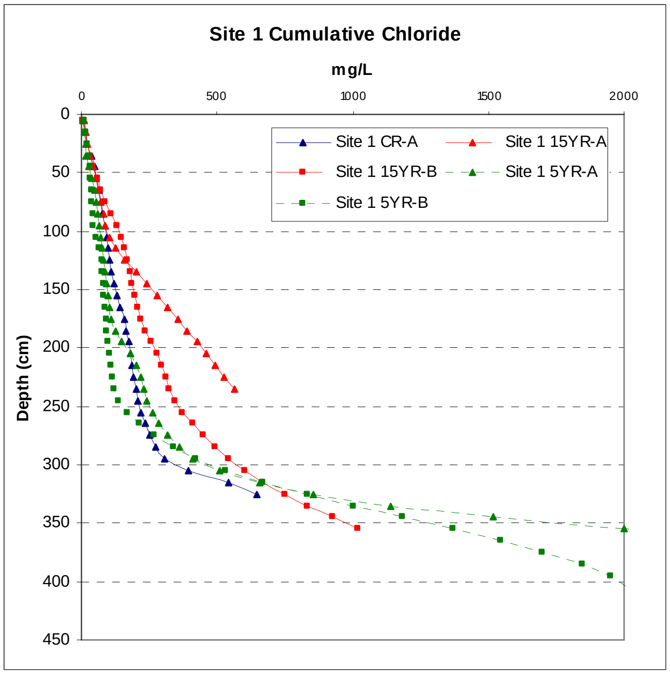


Figure 5 (a-c) represents the cumulative chloride in mg/L with depth and shows that substantially more total chloride is evident in the soil under the control plots compared to the plots that were treated fifteen years ago and allowed natural re-growth to occur. The steeper curves in Figure 5 indicate an absence of chloride with depth and represent flushing of chloride with increased deep drainage. Site 3 (Figure 5c) shows good evidence of reduced chloride due to the distinct difference in cumulative chloride curves between the control plot and the treatments. During the last fifteen years the chloride had flushed to lower parts of the soil profile and, in some cases (Site 2 15YR-A and Site 3 5YR-A), beyond the maximum depth sampled in this study. We attribute this chloride movement to the removal of vegetation, allowing water to penetrate through the shallower rooting zone of that of the grasses that colonized the area post-clearing.

These data suggest that root plowing, in most plots, allowed more water to penetrate to deeper depths over the 15 years since clearing and resulted in greater potential groundwater recharge.



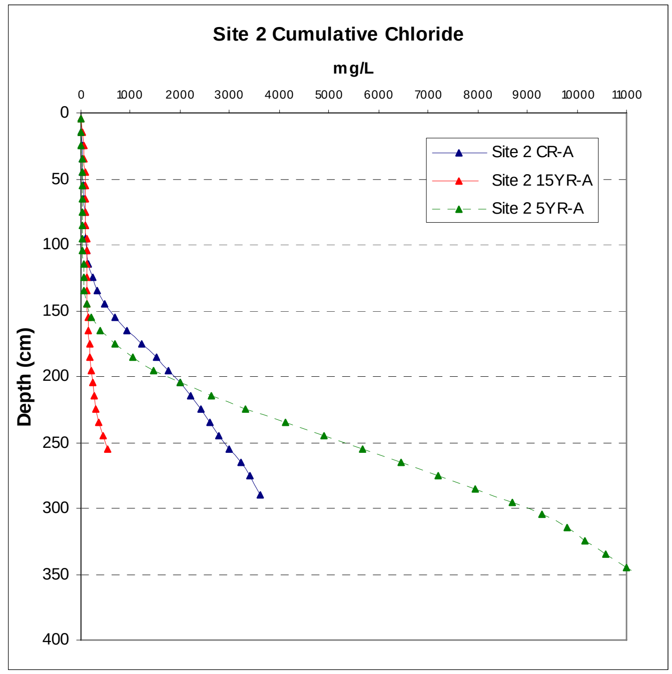
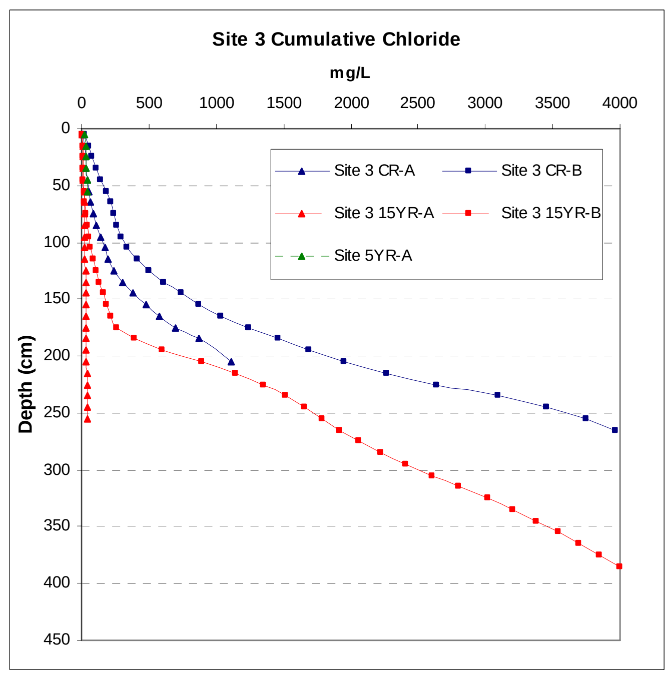


Figure 5. Cumulative chloride concentrations with depth for Site 1 (Figure a), Site 2 (Figure b) and Site 3 (Figure c).



Estimates of deep drainage have been calculated using Equation 2 and the results have been compiled for those profiles analyzed in Table 1. Depths are given that indicate where deep drainage is less than 1 mm per year. Some profiles show a greater than sign if the deep drainage result was estimated to be deeper than the maximum sampling depth. Deep drainage rates were also compared across profiles at a reference depth of 205 cm (Table 1). The results were consistent with our hypothesis, with control plots have less deep drainage rates than those plots that had been cleared of vegetation. Profiles that were inconsistent with expected results are assumed to have either chloride inputs from other sources (high chloride values) or coarse textures to facilitate water movement (low chloride values).

Conclusions

For each landscape the driving variables on potential recharge will be dependent on an interaction between soils, vegetation and climate. The transport of water through the landscape will be ultimately driven by multiple processes all interacting between and within different scales of focus. The relative magnitude or importance of these driving variables will be fundamental in determining the possibility for potential recharge in the landscape in question. To apply this theory to the research in this paper, and using the model by Huxman et. al. (2005), a setting can be hypothesized where recharge could potentially occur given certain scenarios. Further, a model can be designed in order to incorporate every variable that might facilitate water movement through the landscape and their relative effect on potential recharge. Conditions to favor recharge would be close proximity to riparian areas, ET and precipitation out of phase (i.e. winter-dominated rainfall), shallow soils, fractured bedrock, sandy or gravelly texture and a vegetation cover that minimizes water use. This model could be applied on a site by site basis.

Site	**Plot**	**Profile**	**D_D < 1.0 mm^{-1} yr^{-1} (cm)**	**D_D past 205 cm (mm^{-1} yr^{-1})**
1	C	4	>325 cm	25.78 mm^{-1} yr^{-1}
1	15	2	>235 cm	10.16 mm^{-1} yr^{-1}
1	15	9	>355 cm	16.67 mm^{-1} yr^{-1}
1	5	5	385 cm	26.08 mm^{-1} yr^{-1}
1	5	6	>405 cm	45.27 mm^{-1} yr^{-1}
2	C	3	215 cm	1.16 mm^{-1} yr^{-1}
2	15	1	>255 cm	9.91 mm^{-1} yr^{-1}
2	5	13	215 cm	1.15 mm^{-1} yr^{-1}
3	C	16	>205 cm	1.34 mm^{-1} yr^{-1}
3	C	17	185 cm	0.63 mm^{-1} yr^{-1}
3	15	18	>255 cm	47.90 mm^{-1} yr^{-1}
3	15	19	295 cm	2.56 mm^{-1} yr^{-1}

Table 1. Estimated deep drainage rates for treatment plots, expressed as the depth at which D_D rates are less than 1.0 mm per year and D_D rates past a reference depth of 205 cm for all profiles.

It is evident from the information discussed above that potential recharge might be possible to determine if the driving variables and their relative importance are identified, monitored and tested using a hypothesis similar to the objectives of this paper. Each driving variable can have a positive, negative or neutral effect on potential recharge depending on whether the movement of water is facilitated or not. With climate and landscape position variables held constant in this study, the predominant driving variables identified and tested were vegetation and soil texture. Clearing of woody vegetation increased deep drainage, as seen by reduced chloride concentrations with soil depth in treatment plots. Results of deep drainage rates were affected by texture (results not yet available) and in some profiles provided unexpected drainage rates. For example, the control plot at Site 1 (profile 4) had a deep drainage rate comparable to the five year plots and a rate greater than the fifteen year treatment plots. This would indicate that soil texture is facilitating water movement in this profile and also shows the inherent heterogeneity of soil properties at the plot scale.

Larger-scale processes, like climate (including rainfall and ET), will be more important at determining the possibility for recharge, because without precipitation no water will enter the system. More importantly, cool season rain will have a positive affect on potential recharge. Whether the site is in a riparian or upland position in the landscape will also affect the recharge potential, but in the case of this study, the site is in an upland position and will therefore be detrimental to potential recharge due to the vertical distance to the groundwater. At smaller scales, the texture and structure of the soil, as well as presence of impenetrable layers in the soil profile, will affect potential recharge.

The type of vegetation that exists and the community succession that propagates will have an affect on recharge, depending on the structure of the community and the way they forage for water resources below-ground. The scenario given in this paper hypothesizes that a change to grassland, by root-plowing of the woody shrubs will effectively increase the potential for recharge, since water is able to infiltrate past the majority of the roots and into the deeper subsoil during heavy rain, especially in cooler months of the year. If the soil texture is sandy, which is predominant in this landscape, and caliche horizons fragmented, the recharge has positive potential. When combined with a conversion of shrub to grass vegetation, given that grasses allow water to move deeper into the soil profile than shrubs, deep drainage and subsequent groundwater recharge is possible.

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Impacts of Texas Interbasin Water Transfers on the Water Dependent Economy and the Environment

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Economic, Hydrologic and Environmental Appraisal of Texas Inter-basin Water Transfers: Model Development and Initial Appraisal

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1 Introduction

Water scarcity is becoming a pervasive and persistent problem in Texas particularly in the drier regions containing cities like San Antonio, Austin, and Corpus Christi while growth causes emerging problems in Dallas, Fort Worth and Houston. A number of options are being considered including Inter-basin water transfers (IBTs) shifting water from surplus to deficit regions. Potential water transfers can have unforeseen or negative impacts on basin of origin, regional economies, and or on the environment including water quality. The Texas water Code mandates that water transfers should consider economic, environmental and water quality impacts (in section 11.085, (K), (F)) demanding projections of impacts on water quality, aquatic and riparian habitat in all affected basins. While there are 51 proposed Texas Inter-basin water transfers in 2006 Texas Water Plan, there is no comprehensive evaluation of or even evaluation methodology proposed for these transfers.

The water models available in Texas have various limitations that affect their usefulness in evaluating IBT induced economic impacts and water quality changes. Water-related models that deal with hydrologic and environmental issues commonly focus on the quantity issues such as water supply and water flow but do not have economic or water quality dimensions (Wurbs, 2003). Models with economic considerations tend to cover only restricted areas, for example, the Edwards aquifer and Nueces, Frio and Guadalupe-Blanco basin regions (Gillig et al, 2001; Watkins Jr & McKinney, 2000). Much of the research has been localized looking at only single or a couple of basins without looking at broader statewide issues.

This research is designed to build a statewide model integrating economic, hydrologic, and environment components. Such a model will be used to examine Texas water scarcity issues and socially optimal water allocation along with the effects of inter-basin water transfers.

We developed an integrated economic, hydrologic, and environment model covering 21 Texas riverbasins: Colorado, Brazos-Colorado, Brazos, Brazos-San Jacinto, Canadian, Red, Sabine, Guadalupe, San Antonio, Sulphur, Cypress, Neches, Neches-Trinity, Trinity, Trinity-San Jacinto, San Jacinto, Colorado-Lavaca, Lavaca, Lavaca-Guadalupe, San Antonio-Nueces, and Nueces.

The model is designed to yield information to support effective public water policy making for state agencies, water management authorities and regional water planning groups.

The surface water aspects of this project are summarized in this report. Future research work will be focused on combining surface and ground water by integrating the Edwards Aquifer Groundwater and River System Simulation Model (EDSIMR).

2 Modeling framework

Economic theory indicates that water should be allocated to the highest valued users in order to achieve economic efficiency. Maximizing the economic efficiency of water allocation involves maximizing the economic value gained from the use of the allocated water. The value of water is classified into (1) the direct value of water to the water user, and (2) the value that would accrue to producers and consumers that are affected by activity of water users and (3) the future value of water. The value of water and the indirect effects must be considered in the economic analysis of water (Castle, 1968). An inter-basin transfer can involve significant costs to the basin of origin along with the benefits to the receiving basin. One cost can involve the opportunity cost to the basin of origin of potentially reduced future economic growth and prosperity (Keeler, et al, 2002).

While desirable it is difficult to quantify the indirect value, and the future value of water, here the analytical and conceptual model only considers the direct use value of water under a projection of the future adjusted for the construction cost of IBTs.

(1)

$$
\begin{aligned}
ENB = \\
& \sum_{s} \overline{prob(s)} * \left(\sum_{c} \sum_{t} \sum_{m} \int_{0}^{Qs,c,t,m} \left[P_{s,c,t,m}\left(Q_{s,c,t,m}\right) - MC_{s,c,t,m}\left(Q_{s,c,t,m}\right) \right] d\left(Q_{s,c,t,m}\right) \right) \\
& - \sum_{i} \left(\overline{FC_i} * B_i - \overline{VC_i} * \sum_{s} \left(\overline{prob(s)} * \sum_{t} \sum_{m} TQ_{s,i,t,m} \right) \right)
\end{aligned}
$$

St.

(2) $$Q_{s,c,t,m} = \sum_d DQ_{s,c,t,m,d} + \sum_d \sum_i DTQ_{s,i,c,d,t,m}$$

(3) $$DQ_{s,c,t,m,d} \le \overline{DQ_{c,t,m,d}}$$

(4) $$\sum_t \sum_c (DQ_{s,c,t,m,d} + \sum_i DTQ_{s,i,c,d,t,m}) + FLOWout_{s,d,m} + STOREafter_{s,d,m} + TOBAY_{s,d,m}$$
$$\le \overline{INFLOW}_{s,d,m} + RETURN_{s,d,m} + FLOWin_{s,d,m} + STOREbefore_{s,d,m}$$

(5) $$TQ_{s,i,t,m} = \sum_c \sum_d DTQ_{s,i,c,d,t,m}$$

(6) $$\sum_t \sum_m TQ_{s,i,t,m} \le B_i * \overline{capacity_i}$$

(7) $$STOREafter_{s,d,m} \le \overline{STORAGE_d} \text{ and } STOREbefore_{s,d,m} \le \overline{STORAGE_d}$$

(8) $$\sum_s \overline{prob(s)} * (\sum_m (STOREafter_{s,d,m} - STOREbefore_{s,d,m})) = 0$$

Where,

s	State of nature
c	City or county
t	Type of user, or sector including municipal, industrial, agricultural, recreational and other water uses, as well as fresh water flowing into bays and estuaries
m	Month
i or j	Inter-basin water transfer project
d	River place where water is withdrawn
ENB	Expected net benefit from water uses
$\overline{prob(s)}$	Probability of a flow state of nature

$P_{s,c,t,m}$	Inverse water demand function in month M as it varies by state of nature, user type and place
$Q_{s,c,t,m}$	Quantity of water used as it also varies by state of nature, type and place
$MC_{s,c,t,m}$	Marginal cost function of supplied water as it varies by state of nature, type and place
FCi	Annualized fixed cost of a proposed inter-basin water transfer project
VCi	Annual operating cost per unit transferred for a proposed water transfer project
$TQ_{s,i,t,m}$	Amount of water transferred from an IBT and used by sector t in month m
B_i	Binary variable indicating whether an IBT in constructed or not
$DQ_{s,c,t,m,d}$	Amount of monthly water withdrawn from a diverter by sector t in place c
$DTQ_{s,i,c,d,t,m}$	Amount of water transferred from a diverter
$\overline{DQ_{c,t,m,d}}$	Maximum amount of water can be withdrawn from a diverter permitted by water authority
$\overline{INFLOW}_{s,d,m}$	Amount of water supplied by the nature at a river place
$FLOWout_{s,d,m}$	Amount of water flow out from the river place to down stream
$FLOWin_{s,d,m}$	Amount of water flow in from upstream river places to this river place

$STOREafter_{s,d,m}$ Amount of water stored at the end of a month in a reservoir

$STOREbefore_{s,d,m}$ Amount of water stored at the beginning of a month in a reservoir

$TOBAY_{s,d,m}$ Amount of water flow to bay or estuary

$RETURN_{s,d,m}$ Amount of water returned to the river place

$\overline{STORAGE_d}$ Maximum storage capacity in a reservoir

$\overline{capacity_i}$ Maximum yield of an IBT

Equation (1) is the objective function and gives the annual expected net benefit accrued from municipal, industrial, agricultural, and recreational usage as well as a minimal value for the fresh water escaping to bays and estuaries less the fixed costs of constructed IBT projects and the variable costs of the water transferred using the constructed IBTs.

The problem includes a number of constraints. Equation (2) is a water supply and demand balance linking the economic component to the hydrological component. The water demand for each city or county for different type of use $Q_{s,c,t,m}$ will be supplied from various diverters in a riverbasin $DQ_{s,c,t,m,d}$ and water transferred from other riverbasins $DTQ_{s,i,c,d,t,m}$. If d is a source diverter, $DTQ_{s,i,c,d,t,m}$ will be negative; if d is a destination diverter, $DTQ_{s,i,c,d,t,m}$ will be positive.

Equation (3) indicates that the water withdraw from a diverter for a particular type of use $DQ_{s,c,t,m,d}$ should not exceed the permitted amount $\overline{DQ_{c,t,m,d}}$. This constraint links the institutional regulation to the water supply.

Equation (4) is the instream flow balance depicting at each river place, total inflow must be in balance with total outflows by state of nature and month. The left side of the equation is the total outflows, equaling to the sum of water diverted by human activities $DQ_{s,c,t,m,d}$, water transferred in $DTQ_{s,i,c,d,t,m}$, and water flow to down stream $FLOWout_{s,d,m}$. If d is a source diverter for an

IBT, $DTQ_{s,i,c,d,t,m}$ will be negative; otherwise, $DTQ_{s,i,c,d,t,m}$ will be positive. If d is a reservoir or end river place in a riverbasin, then total inflows should also include reservoir storage at the end of the month $STOREafter_{s,d,m}$ and outflows would include retention for storage. If d is last river place on a riverbasin, outflows will include water flow out to bays and estuaries $TOBAY_{s,d,m}$. The right hand side is the total inflows at this river place, equal to the sum of water supplied by the nature $\overline{INFLOW}_{s,d,m}$, water flow from upstream $FLOWin_{s,d,m}$, and return flow $RETURN_{s,d,m}$. Again, if d is a reservoir, then total inflows should include water stored in the reservoir at the beginning of the month after discounting reservoir evaporation loss. Return flows come from upstream diverted water and once we add groundwater from groundwater diversions.

Equation (5) states the amount of water transferred from an IBT will be equal to the sum of the amount of water transferred to various destinations by this IBT.

Equation (6) states that the amount of water transferred from an IBT is restricted by the capacity. B_i is a binary variable indicator. If an IBT is built, B_i=1 and this constraint become working, and fixed cost for its construction incurs and will be considered in the objective function. If an IBT is not built, B_i=0, then no water will be transferred and fixed cost for its construction will not incur and thus not be considered in the objective function.

Equation (7) specifies that water stored at a reservoir in any time and any states of nature are limited by its storage capacity. Therefore, $STOREbefore_{s,d,m}$ and $STOREafter_{s,d,m}$ will not exceed the maximum storage capacity.

Equation (8) is a storage balance constraint for a reservoir. The states of nature-weighted sum of water stored at end of the month will be in balance of weighted sum of water stored at the beginning of the month in a reservoir.

3 Empirical model specification

The empirical TEXRIVERSIM model is a two stage stochastic programming with recourse model implemented using the General Algebraic Modeling System (GAMS). The model maximizes net statewide welfare while simultaneously considering environmental, hydrological, institutional, stochastic climate conditions and annualized IBT fixed and unit variable costs. In doing this, it chooses optimal IBTs and water allocation, instream flows, return flows, reservoir storage, bays and estuary freshwater outflows. It contains 21 riverbasins (see table 1), 46 major municipal water use cities, 25 major industrial water use counties, and all of the agricultural counties. 51 IBTs are introduced in the model: 10 river-to-river IBTs and 41 river-to-user IBTs (see table 20 in appendix).

Table 1: Riverbasins covered in the model

Basin name in GAMS	**Original basin name(s)**
Brazos	Brazos and Brazos-San Jacinto rive basins
Colorado	Colorado riverbasin and Brazos-Colorado
Canadian	Canadian riverbasin
Red	Red riverbasin
Sabine	Sabine riverbasin
Guadsan	Guadalupe-San Antonio riverbasin
Sulphur	Sulphur riverbasin
Cypress	Cypress riverbasin
Neches	Neches riverbasin
NechTrinity	Neches-trinity riverbasin
Trinity	Trinity riverbasin
TrinitySanJac	Trinity-San Jacinto riverbasin
SanJacinto	San Jacinto riverbasin
ColLavaca	Colorado-Lavaca riverbasin
Lavaca	Lavaca riverbasin
LavaGuadl	Lavaca-Guadalupe riverbasin
SanioNues	San Antonio-Nueces riverbasin
Nueces	Nueces riverbasin

The model TEXRIVERSIM maximizes expected welfare accumulated from municipal and industrial (M&I) consumers' surplus, recreational benefits and net farm income less the cost from IBTs. Based on the analysis of historical instream flows, nine states of nature ranging from very dry to very wet are defined in the model to reflect climate variability with probabilities reflective of historical frequency in a 50-year period. In turn, these probabilities serve as weights in the objective function. Therefore, the model is stochastic reflecting nine states of nature for water flows following the historical climate patterns.

Municipal water uses are divided into two classes: water in major cities where we introduce explicit demand curves and water from the small cities, which we treat as having constant net marginal benefit from using water up to a maximum quantity. Municipal water demand for major cities has constant price elasticity ε_1 while municipal water demand for small cities is infinitely price elastic but cannot exceed historical water use. Major cities' water demand is shifted up and down depending on the rainfall and climatic conditions characterizing each state of nature (See figure 1). The climate shifter is introduced as monthly average temperature (F) times the number of days without rainfall in a month divided by 1000 (W) as in Griffin and Bell (2006). The climate elasticity ε_2 is represented as the percentage change in quantity of water demand given 1 % change in climate shifter. Therefore, the major cities' water demand function is follows:

$$Q_c = \gamma_c P_c^{\varepsilon_1} W_c^{\varepsilon_2}$$

Industrial water demand is also separated into two types: 25 major industrial counties with explicit demand curve (McCarl, 1999); and small industry counties with constant marginal net water benefit using water up to a maximum amount. Municipal and industrial prices are set as the first block and last block price following Bell and Griffin (2006). Marginal cost is assumed to be 50% of the corresponding water price.

Benefits from water use for major cities or major industrial counties are measured as consumer surplus, the area below a constant elasticity demand curve and above the marginal cost curve. Benefits from water use for small cities or small industrial counties will be the constant net marginal net benefit times the amount of water used.

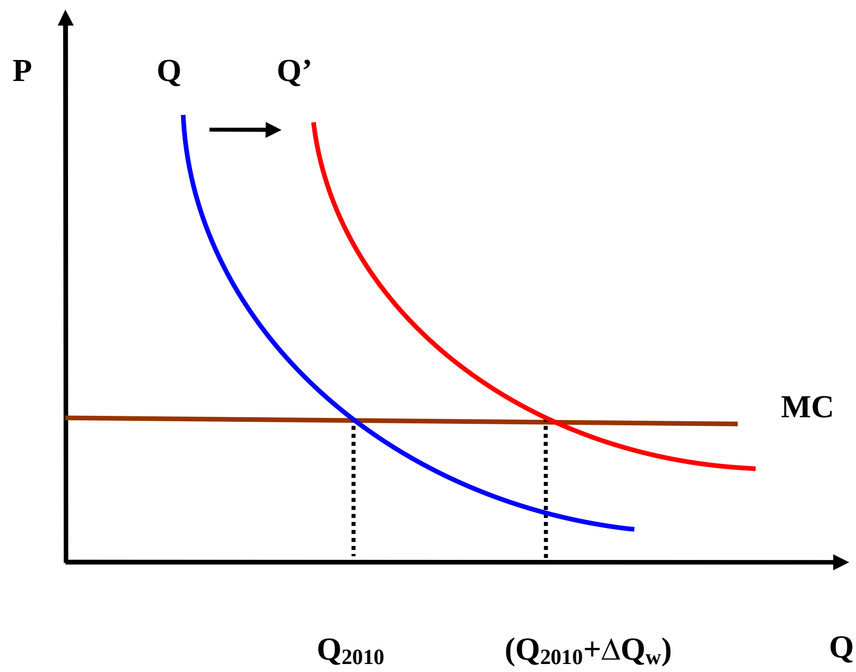

Figure 1: A major city’ water demand curve & its climate shift factor

Benefits from agricultural water use are represented using a linear programming crop mix representation. Net agricultural income from irrigated and dry land crop production is considered. Irrigated and dryland crop yields along with irrigation water requirements differ by state of nature, and are developed by using the Blaney-Criddle procedure (Doorenbos and Pruitt, 1977). The model employs a two-stage stochastic programming with recourse formulation. The choice of the crops to grow is decided early in the year at the first stage when the state of nature is unknown. At the second stage, harvest and irrigation water use can be adjusted when the amount of water available and state of nature are known. Cropland use across the crop mix patterns employed is restricted to the land available.

Recreational water use is gaining importance. The travel cost method is widely used to estimate the value of recreational water use, but this is beyond our scope. In this project, we assume recreational water withdraws have constant marginal net benefit in all riverbasins. Freshwater inflows to bays and estuaries are valuable and thus we include a term for this in the objective function. We did not find appropriate values for freshwater inflows to bays and estuaries. Currently we assign a net value of $0.01 per ac-ft to water which flows out. Higher values may well be in order.

4 Data specification

The model involves huge amount of data. The data sets used mainly involve water demand, including water prices and consumption, climate data, crop data, IBT data, hydrological data and state of nature data. Each is described below:

4.1 Water demand

Water is used by various sectors. Water demand quantities for municipal and industrial interests in 2010 are drawn from the “2006 Regional Water Plan” from the Texas Water Development Board (TWDB) website at (http://www.twdb.state.tx.us/data/popwaterdemand/2003Projections/DemandProjections.asp). Major municipal cities and industrial counties are designated as those with annual water use greater than 2000 and 3000 ac-ft respectively. This results in 46 cities and 25 major industrial counties being designated.

Municipal and industrial water prices in 2003 are drawn from a survey of over 2000 communities in Texas that was done by Bell and Griffin (2006). Municipal prices through which demand curves will be passed are the first block prices, and industrial water prices are the last block prices. We assume water prices in year 2010 are real prices same as the nominal prices in 2003. Monthly price elasticity for major cities’ water demand is from the same survey by Bell and Griffin (2006) while price elasticity for industrial water demand is from Renzetti (1988).

Marginal cost including treatment and operating cost for each city or county is assumed to be 50% of the water prices.

4.2 Climate data

Major cities water demand is sensitive to the climate. A climate-driven demand shifter is defined as monthly average temperature (F) times the number of days without rainfall in a month then divided by 1000 (W) as developed in Griffin and Bell (2006). Monthly average temperature and precipitation data for identified major cities for the period 1950-2004 are collected from National

Climatic Data Center (NCDC). Climate elasticity is adopted from the survey results by Bell and Griffin (2006). Therefore, we could identify the climate effects on major cities' water demand.

4.3 Crop data

TEXRIVERSIM models agricultural water use and crop management choice, so crop data are needed in the form of crop budgets, crop mix and surface water irrigated lands in Texas.

Crop budget data including crop yield, price and cost are adapted from Texas Cooperative Extension data on the website (http://agecoext.tamu.edu/). Crop irrigation water requirements and crop dryland yield are also sensitive to the climate. Therefore, monthly average temperature and precipitation data for all agriculture counties for the period 1950-2004 are obtained from the same source of NCDC. The Blaney-Criddle formula (Doorenbos and Pruitt, 1977) is used to obtain the climate-driven crop water requirements. A dryland crop yield is assumed proportional to the irrigated crop yield depending on how much rainfall is available. For example, if rainfall available is 70% of crop irrigation water requirement, then 70% of irrigated crop yield is assigned to the dryland crop yield.

Available agriculture land is defined as acreage of irrigated land available in a county in 2003 and drawn from the NASS, which serves as an upper limit that the optimal cropland use across the crop mix patterns can not exceed.

Historical crop mix is extracted from USDA county level statistics as developed by NASS (ftp://www.nass.usda.gov/pub/nass/county/byyear/) and will provide information for agricultural land constraints with land for irrigated and dryland uses having to be a convex combination of historic crop mix following McCarl(1982), McCarl and Onal(1989, 1991) and Gillig et al (2001). 21 crops from the historical crop mix are therefore included in the model (see table 19 in Appendix)

4.4 Hydrologic network structure

TEXRIVERSIM model is an integrated economic, hydrological model. When defining the model it is necessary to introduce a network flow structure that represents water flow in the various rivers dividing each basin into a set of reaches and nodes then linking the reaches to depict water flows from upstream to downstream as well as points of diversion. This is defined as follows:

A primary control point in Water Availability Modeling (WAM) (by Texas Commission on Environmental Quality –TCEQ) and Water Rights Analysis Package (WRAP) (Wurbs) is named as a "river place" in the TEXRIVERSIM model. River place is the most important unit in this model and used to define reaches, reach members, and river flow linkages. All the calculations are made with reference to the river place.

A secondary control point in WRAP is named as a "diverter" in the TEXRIVERSIM model. A diverter is the actual place that water users divert some amount of water for particular type of use and all usages in a reach are assigned to the downstream river place.. Diverter is one of the most fundamental units in the model as well as river place, and most of hydrological data such as historical water use and permitted diversion are based on it.

The area between two adjacent river places is defined as a reach. Diverters located in that reach are considered reach members of the down stream river place. A river place can contain many reach members. The diverter-river place mapping builds a link between a diverter and down stream river place, which enables us to aggregate diverter based data into the river flow model features.

The riverbasins contain many reservoirs. A reservoir is treated as both a diverter and a river place since it is an actual water diversion point. 175 major reservoirs with a capacity more than 5000 ac-ft are covered in the model. The normal storage capacity $\overline{STORAGE_d}$ for the major reservoirs is obtained from Texas Water Development Board (http://www.twdb.state.tx.us/publications/reports/waterconditions/twc_pdf_archives/latest.pdf)

Modeling the riverbasins involves representing the rivers with a series of river places and connecting them in sequence according to the river flow. The mapping between upstream river place and its consequent down stream river place is very important in modeling water flow sequence and instream flow balance particularly to determine how $FLOWin_{s,d,m}$, $FLOWout_{s,d,m}$ and $RETURN_{s,d,m}$ enter the model.

The tuple sector-diverter mapping is directly extracted from WRAP output and represents a particular diverter and type of water use.

4.5 Hydrological data

The hydrological data including naturalized flows, historical water use, and permitted diversion mainly obtained from the input data used within the WRAP and WAM.

Naturalized stream inflows represent water inflows that would have occurred in the absence of today's water uses, water management facilities etc. The naturalized inflow is used to calculate $\overline{INFLOW}_{s,d,m}$ for the instream water flow balance constraint.

Historical water use is used to identify the level of demand by the major industrial and municipal counties and set a limit for water withdrawn for recreational or other use.

Texas Commission on Environmental Quality issues permits to water right holders and specifies the maximum amount of water that can be diverted. Permitted diversions for a diverter serve as an upper bound $\overline{DQ_{c,t,m,d}}$ that the diverter can actually withdraw before IBT transfers.

Evaporation loss is defined as the percentage of water evaporating per unit water stored for a reservoir. Reservoir evaporation takes away a part of the available supply for diversion and eventually affects the variables $STOREbefore_{s,d,m}$ and $STOREafter_{s,d,m}$.

The model reflects the difference between diversions and consumptive use where a given proportion of diverted water return flows into a river. Once water is diverted for use, some percentage of water will return to the river and add water supply for the downstream users. This is represented as $RETURN_{s,d,m}$ in the instream flow balance constraint. Water returns to different locations after certain period. Recreational use has a 100% return flow since there is no consumptive use. The return flow percentage is obtained from the EDSIMR model (Gillig, 2001) (see table 22 in Appendix). It is assumed that water diverted from one river place will return to the next downstream river place and no time delay is considered in the model.

4.6 IBT data

Inter-basin water transfer is the key component and major focus in the TEXRIVERSIM model. Inter-basin water transfer related data includes the project name, corresponding fixed, and variable cost, capacity and as well as the IBT source and destination locations. These data are drawn from the Texas Water Plan 2002, 2006 along with regional water planning group reports (http://www.twdb.state.tx.us/RWPG/main-docs/2006RWPindex.asp).

Two types of IBTs are included in the model. An IBT associated with more than one diverter is treated as a River IBT (RIBT), where transferred water is not directly dedicated to a user but rather is placed in the instream flow of the destination basin that is used by downstream diverters. An IBT where the water is dedicated to only one diverter is treated as User IBT (UIBT) in which transferred water is assumed dedicated to that diverter. The source and destination river places are mapped according to their physical places. 51 possible inter-basin water transfers (10 RIBTs and 41 UIBTs) are included in the model (see table 20 in Appendix).

4.7 State of nature data

Inter-basin water transfers will not only operate in dry years when water is highly needed but also would operate in wet years when they may not be needed and in fact will operate across the spectrum of water availability years. Consequently, for accurate modeling and IBT appraisal we need to depict the full variety of water flow possibilities and their relative frequencies of occurrence. The states of nature define the stochastic part of the model.

Nine states of nature are defined based on the WRAP input historical river flow and climate data from the years 1949 to 1998 so they depicted conditions ranging from very dry to very wet. Years with similar flow and climate condition are grouped into the nine states and their relative incidence is used to define the probability $\overline{prob(s)}$. Weighted averages of all of the data with each of the states describing temperature, precipitation, and naturalized flows are then formed.

In turn given the definitions of the nine states of nature and the associated climate condition, the stochastic element of the model is defined. Nine secondary states of nature are defined within a stochastic programming with recourse formulation with varying levels of

- naturalized inflows for each river place and month
- agricultural water use, and crop yield for each irrigated crop that is defined in the major agricultural counties, for each water use month
- agricultural crop yield for each dryland crop that is defined in the major agricultural counties
- water demand quantity through which a constant elasticity demand curve will be passed for each major municipal water demand city based on a climate shift elasticity approach developed by Griffin and Chang (1990) and later updated by Bell and Griffin (2006)
- water demand quantity for minor cities

5 Model results and discussion

5.1 Optimal water allocation without IBTs

Once TEXRIVERSIM is constructed, a baseline scenario is run through the model. The "base" model is defined as a model without IBTs being built. The consequent results are discussed in the following sections.

5.1.1 Expected net benefit

Table 2 lists the expected net benefits for each riverbasin. The expected annual net benefits accruing from Texas surface water use across all riverbasins is $8,450 billion. Municipal water benefit ("mun") is the largest component of this accounting 99.88% of the above total benefits. Agricultural water benefits ("ag") are $2.44 million, while industrial water benefit ("ind") accounts for 0.11% of total benefits and reaches a value of $9.76 billion. The water benefits from recreation ("rec"), other ("other") and the value of fresh water inflows to a bay ("TOBAY") are $99, 7.01, 0.47 million respectively. The net benefit value from municipal and industrial water use must be carefully interpreted since their benefits are measured as area below a constant elasticity demand curve and above the marginal cost curve. That measure is large as price approaches infinity then the quantity of water approaches zero yielding very large areas. However, the net benefits from agriculture, recreational, other and value of fresh water inflows to bays and estuaries have real meaning. They are the real net income either from agriculture production or from other activities. Value from fresh water flows inflows to bays and estuaries is very small due to the assumption that its marginal net value is $0.01/acft.

Trinity, San Jacinto, Guadalupe-San Antonio and Brazos are four biggest components of the net benefit, accounting for 80%. This is not surprising since municipal water use is the dominant contributor and Dallas, and Forth Worth are in the Trinity basin, while Houston is in the San Jacinto basin, and San Antonio in the Guadalupe-San Antonio riverbasin. The total benefit from Trinity-San Jacinto, San Antonio-Nueces, Colorado-Lavaca, Lavaca, Neches-trinity fiver riverbasins are less than $0.8 million, reflecting the result that little water is used for municipal purpose.

Municipal water benefit ("mun") comes from two parts: from 46 major cities ("mun-city") and from other minor cities ("mun-other"). In Texas, there are around 960 cities with a range of population spanning from 1000 to 1 million. The projected surface water demand for the 46 major cities totals 1.146 million ac-ft, accounting for 49.1% of total municipal demand projection. Therefore, ignoring the small cities is not appropriate. These small cities are assigned to have constant marginal water benefit of $280.23/ac-ft, which is the lowest price from major cities.

The results shows that benefit from the small cities are relatively small, ranging from $0.21 million in Nuces basin to $105 million in Brazos Basin. Trinity, San Jacinto, Guadalupe-San Antonio and Brazos again are four big players in the municipal water benefit from major cities, followed by Neches, Red, Colorado, Nueces, and Sabine. Meanwhile, Trinity-San Jacinto, San Antonio-Nueces, Colorado-Lavaca, Lavaca and Neches-Trinity do not contribute greatly in terms of net welfare.

Industrial water benefit ("ind") are also composed of two parts: a major industrial part arising from explicit demands by 25 major industrial counties ("ind-main") and an other industrial part arising from the other 230 counties in Texas ("ind-other"). The projected water demand for these 25 major industrial counties accounts for 55% of total industrial demand. Therefore, it is necessary to include the small industrial counties in the model. The net benefits from these major counties accounts for 96.2% of the welfare, having a value of $9.39 billion. It does make sense since the marginal benefit for the rest counties are assumed constant to be the lowest ind. price from major counties ($570/ac-ft). San Jacinto, Brazos, Guadalupe-San Antonio and Sabine are four big players in both “ind” and “ind-main” categories, and contribute for 86% and 88% respectively, while Trinity-San Jacinto, San Antonio-Nueces and Colorado-Lavaca have zero net benefits.

The agricultural water benefits for all riverbasins totals $2.44 million. The major agriculture basins are Guadalupe-San Antonio, Colorado, Brazos and Nueces with net farm income ranging from $1.22 to $0.16 million, while Canada, Cypress, Lavaca, Neches, Neches-Trinity, Sabine, San Jacinto, Sulphur, Trinity, and Trinity-San Jacinto do not have any irrigated agricultural income. In the San Antonio and Guadalupe Riverbasin, surface water resources currently supply about 12% and 52% of the water used for all purpose (WAM- Guadalupe-San Antonio). In the Colorado Riverbasin, only 25% of water is for irrigation, 66% is for municipal supplies, 8% is for industrial purposes (WAM-Colorado). In the Brazos Riverbasin, surface water resources only supply for 18% of water use for all purposes while irrigated agriculture accounts for 77% of all water used and is concentrated in the High Plains and supplied largely from the Ogallala Aquifer (WAM-Brazos). This implies that majority of irrigation water are from ground water source (which is not depicted in TEXRIVERSIM), which means to only small percentage of agriculture production are covered in the model.

Benefits from recreational, other and fresh water flows to bays and estuaries are trivial in most basins. Recreational benefit in Guadalupe-San Antonio reaches $95.44 million, indicating that recreational use is an important competitor therein.

Table 2: Expected net benefit by basin ($ million)

Riverbasin	ag	ind	ind-main	ind-other	mun	mun-city	mun-other	other	outtobay	rec	sum
Brazos	0.5	2,526	2,452	74	532,061	531,955	106	0.1	0.07	0.3	534,587
Canadian	-	63	63	-	24	-	24	-	-	-	87
ColLavaca	0.01	-	-	-	-	-	-	-	0.005	0.0	.01
Colorado	0.6	136	90	47	365,940	365,915	25	0.7	0.03	0.4	366,079
Cypress	-	145	112	33	23,084	23,068	16	-	0.02	-	23,229
Guadsan	1.2	1,333	1,330	3.6	918,595	918,559	36	5.4	0.02	95	920,031
Lavaca	-	0.2	-	0.2	-	-	-	-	-	-	0.2
Neches	-	508	506	2	453,710	453,704	6	0.0	0.06	0.0	454
NechTrinity	-	0.2	-	0.2	-	-	-	0.4	0.01	-	0.6
Nueces	0.2	0.02	-	0.0	278,786	278,786	0.2	0.1	-	-	278,787
Red	0.0	53	46	7	414,803	414,789	14	0.2	0.10	-	414,856
Sabine	-	1,249	1,212	37	108,058	108,049	9.1	-	0.06	2.8	109,310
SanioNues	0.0	-	-	-	-	-	-	-	0.006	-	0.01
SanJacinto	-	3,289	3,289	-	1,584,368	1,584,368	-	0.0	0.02	0.0	1,587,657
Sulphur	-	15	15	0.1	44,825	44,820	5	-	0.02	-	44,841
Trinity	-	440	276	163	3,716,093	3,716,002	91	0.0	0.06	-	3,716,532
TrinitySanJac	-	-	-	-	-	-	-	-	0.002	-	0.00
Total	**2.4**	**9,758**	**9,391**	**367**	**8,440,348**	**8,440,016**	**332**	**7.0**	**0.47**	**99**	**8,450,215**

Table 3: Expected water use by basin (thousand ac-ft)

Basin	ag	ind	ind-main	ind-other	mun	mun-city	mun-other	other	outtobay	rec	sum
Brazos	46.02	308.21	178.63	129.58	462.22	84.13	378.09	1.35	6,683.83	3.6	821.40
Canadian	0.87	7.62	7.62	-	84.65	-	84.65	0.03	199.75	-	93.17
ColLavaca	-	-	-	-	-	-	-	0.07	78.04	-	0.06
Colorado	127.47	94.35	12.55	81.81	258.12	168.21	89.91	8.77	2,661.51	4.58	493.30
Cypress	-	68.81	11.69	57.12	59.07	3.29	55.79	-	1,570.23	-	127.88
Guadsan	45.3	142.44	136.18	6.26	269.44	140.03	129.42	67.56	1,848.07	1,060.45	1,585.20
Lavaca	1.8	0.37	-	0.37	-	-	-	-	784.63	-	2.17
Neches	-	106.48	102.54	3.94	69.16	46.25	22.92	0.47	5,501.06	0.13	176.24
NechTrinity	-	0.26	-	0.26	-	-	-	4.89	1,118.00	-	5.16
Nueces	9.32	0.04	-	0.04	62.68	61.94	0.74	0.75	524.24	-	72.79
Red	3.1	17.77	5.59	12.18	141.88	92.49	49.39	2.97	9,542.54	-	165.71
Sabine	-	145.05	80.23	64.82	49.38	17.01	32.37	-	6,295.28	30.54	224.97
SanioNues	0.21	-	-	-	-	-	-	-	565.43	-	0.21
SanJacinto	-	377.99	377.99	0.01	399.61	399.61	-	0.32	1,649.17	0.15	778.07
Sulphur	-	2.81	2.7	0.1	25.22	6.49	18.73	-	2,382.21	-	28.02
Trinity	-	307.81	21.27	286.54	1,169.51	845.35	324.15	0.45	5,696.40	0.08	1,477.85
TrinitySanJac	-	-	-	-	-	-	-	-	173.19	-	0
Total	**234.1**	**1,580.00**	**936.99**	**643.01**	**3,050.95**	**1,864.79**	**1,186.15**	**87.63**	**47,273.59**	**1,099.53**	**6,052.19**

5.1.2 Expected water use by basins and sectors

Socially optimal water allocation states that water should be allocated to highest value users to achieve economic efficiency. Generally, municipal and industrial water use creates higher value than other sectors, so the water demand from these sectors should be satisfied first.

The expected water use in each riverbasin is listed in table 3. The “sum” is defined as the total water use from all sectors (excluding fresh water flows to the bay). There are total of 6.05 million ac-ft of water used across all riverbasins. Approximately 3.9% of the water (234,100 ac-ft) supplies are used in the agricultural sector, 26.1% (1580,000 ac-ft) by industry, 50.5% (3051,000 ac-ft) in municipalities, while recreational water use accounts for 18.5% (1100,000 ac-ft).

Water use from the small cities is 1186,000 ac-ft, or 38.9% of the municipal total. Meanwhile, water use from the other small industrial counties is 403,000 ac-ft, accounting for 40.7% of total industrial water use. The results verify that it is necessary to include them in the model even though they do not create high welfare; otherwise, the results will be biased. On the other hand, 47.3 million ac-ft of water escapes to bays and estuaries, approximately 8 times the actual water use by all sectors.

Guadalupe-San Antonio, Trinity, Brazos, and San Jacinto are four biggest basins with total of 4.66 million ac-ft water used by all sectors, accounting for 77% of total water use. Water use in Neches-Trinity, Lavaca, San Antonio-Nueces, Colorado-Lavaca, Trinity-San Jacinto totals less than 10,000 ac-ft.

Water distribution among sectors varies significantly across riverbasins. In Guadalupe-San Antonio, recreational water use plays an important role, reaches 1067,000 ac-ft and is equivalent to 4 times of municipal consumption, 7.5 times of industrial consumption, 23 times of irrigational water use. Note a large portion of the San Antonio use is mainly supplied from the Edwards Aquifer that is out of our current modeling scope.

In the Trinity, water use totals 1477,000 ac-ft, while 79.1% are for municipal, 20.8% are for industrial. Recreation, other and agriculture use very small amount of water.

In the Brazos, water use totals 821,000 ac-ft, where agricultural, industrial, municipal, recreational water use account for 5.6%, 37.5%, 56.3% and 0.4% respectively, indicating that water are mainly used for municipal. This is consistent with the WRAP inputs.

In the San Jacinto, total water use reaches 778,000 ac-ft, which is exclusively used for major cities (51.4%) and major industrial counties (48.6%). The results do make sense since Houston and Harris County where Houston is are in San Jacinto riverbasins.

In the Colorado, water use totals 493,000 ac-ft. Among it, 25.8% are for agricultural purpose, 19.1% for industrial use, and 52.3% for municipal purpose. Therefore, agricultural water use has relatively larger portion in Colorado than in other riverbasin.

5.1.3 Major cities water use

Table 3 displays socially optimal water allocation by riverbasin. Table 4, 5, and 6 show details of water allocation for the major cities, major industrial counties and agricultural counties respectively.

Forty-six major cities are classified based on the historical municipal surface water use data from WRAP. Cities like College Station using ground water as main source are excluded in the model. However, San Antonio is an exception. A large potential water shortage (78,467 ac-ft) is being faced by San Antonio due to Edwards Aquifer pumping limits and rapid population growth. It is likely the shortage will be supplied by surface water possibly from inter-basin water transfer. Therefore, it is important to include San Antonio in the model. The projected water demand for these 46 cities totals 1.146 million ac-ft, accounting for 49.1% of total municipal demand. Dallas, Houston, Fort Worth, Austin and San Antonio are the five largest cities, constituting 62.8% of the projected municipal water demand among the 46 cities.

The optimal water allocation (“Base”) less the projected water demand gives us the water shortage faced by each city. If the water shortage is large and no ground water source available, then an inter-basin water transfer may become an option. The results show that Houston, Austin, and Dallas water demand is largely met if water is optimally allocated. However, San Antonio, Arlington, Fort Worth, Tyler, San Angelo, and Round Rock still face large shortages especially San Antonio and Arlington. This is why entities like San Antonio Water System (supplies water for San Antonio), Tarrant Regional Water District (serves Fort Worth and surrounding communities in ten counties), North Texas Municipal Water District (supplies water to cities such as Plano, Farmersville, Forney, Garland, McKinney, Mesquite, Princeton, Rockwall, Royse City, Wylie and Richardson) and Dallas Water Utilities (supplies water to Dallas and surrounding cities) are actively participating in many proposed inter-basin water transfer projects.

Table 4: Major Municipal City Water Use (thousand ac-ft)

City	Base*	Pre-demand**	Difference***
Abilene	22.93	22.87	0.06
Allen	22.25	23.62	-1.37
Arlington	13	79.73	-66.73
Austin	150.82	153.69	-2.87
Beaumont	27.09	26.97	0.12
Bonham	2.2	2.74	-0.54
Cedar Park	3.33	10.92	-7.59
Center	1.64	1.63	0.01
Cleburne	5.7	5.75	-0.05
Coleman	1.26	1.28	-0.02
Conroe	9.34	9.33	0.01
Corpus Christi	61.94	61.83	0.11
Corsicana	0.66	5.83	-5.17
Dallas	388.56	389.34	-0.78
Denison	5.52	5.5	0.02
Denton	29.46	29.6	-0.14
Fort Worth	100.77	149.57	-48.8
Frisco	45.82	45.58	0.24
Garland	40.12	42.85	-2.73
Georgetown	2.69	8.6	-5.91
Gonzales	1.55	1.54	0.01
Graham	1.53	1.53	0

Grapevine	13.45	13.5	-0.05
Greenville	5.56	5.55	0.01
Houston	390.27	388.93	1.34
Irving	55.23	55.41	-0.18
Liberty Hill	0.14	0.45	-0.31
Mansfield	9.36	13.54	-4.18
Marlin	2.51	2.65	-0.14
Marshall	3.29	3.26	0.03
McKinney	22.54	24.67	-2.13
Nacogdoches	7.71	7.65	0.06
Paris	6.24	6.25	-0.01
Plano	64.98	72.62	-7.64
Richardson	32.71	32.46	0.25
Round Rock	5.78	19.63	-13.85
San Angelo	10.31	20.78	-10.47
San Antonio	138.48	216.07	-77.59
Snyder	2.8	2.8	0
Sweetwater	3.02	3.01	0.01
Temple	14.66	20.89	-6.23
Terrell	3.58	3.58	0
Texarkana	6.49	6.47	0.02
Tyler	11.45	25.88	-14.43
Waco	25	24.89	0.11
Weatherford	2.85	5.2	-2.35

** "Base"gives the optimal water allocation under baseline scenario;*

*** "Pre-demand" gives the projected water demand;*

**** "difference" is the gap between the "Base" and the "pre-demand"*

5.1.4 Major industrial counties' water use

Industrial water counties with average historical surface water use greater than 3000 ac-ft are classified as major industrial counties. 25 counties fall in this category accounting for 55% of total industrial demand projection. Brazoria, Harris, Harrison and Jasper are the four largest industrial counties, using 70.8% of the water in this category.

The optimal level of water use by the major industrial counties is listed within the "base" column of Table 5. Again optimal water allocation is often less the projected water demand as in the "difference" column. This shows problems in Brazoria, Nueces, Harris, Dallas, Hutchinson, Tarrant, Harrison, Live Oak and Victoria counties. The water shortage is largest in Brazoria County with a shortage of 111,000 ac-ft. Therefore, interests within these counties may well seek alternative strategies to solve the water shortage issue including IBTs.

Table 5: Major industrial counties' water use (thousand ac-ft)

County	Pre-demand	Base	Difference
Angelina	30.28	30.28	0
Bastrop	5.13	5.13	0
Bell	1.14	1.13	-0.01
Bexar	29.53	29.53	0
Bowie	2.33	2.33	0
Brazoria	264.34	153.33	-111.01
Calhoun	49.82	79.76	29.94
Dallas	37.03	11.83	-25.2
Fort Bend	9.87	9.86	-0.01
Harris	397.28	375.46	-21.82
Harrison	85.24	78.33	-6.91
Hutchinson	24.06	7.62	-16.44
Jasper	64.27	64.27	0
Lamar	5.6	5.59	-0.01
Live Oak	5.84	0	-5.84
McLennan	3.94	3.94	0
Montgomery	2.53	2.53	0
Nueces	47.98	0	-47.98
Robertson	10.39	10.37	-0.02

Rusk	1.62	3.24	1.62
Smith	4.55	7.99	3.44
Tarrant	17.69	9.44	-8.25
Titus	10.71	10.71	0
Tom Green	2.3	2.3	0
Victoria	32.67	26.89	-5.78

** The column labeled "Base" gives the optimal model base scenario water allocation*

*** The column labeled "Pre-demand" gives the level of projected water demand*

**** The column labeled "difference" gives the gap between the optimal level and the level of projected demand*

5.1.5 Agriculture water use and production

Table 6 lists agricultural water use by county under different state of nature. Table 7 and 8 list the irrigated and dryland crop acres planted. Total agriculture water use averages 220,000 ac-ft. Agriculture water use is sensitive to state of nature and water use under drier conditions is more than water use in wet years. Wharton, Medina, Tom Green, Comanche, and Robertson are the five largest irrigation water using counties, accounting for 85% of total agricultural water use and 82.3% of total irrigated land. Crop mix differs across counties. In Wharton County, 100,000 ac-ft of water is used largely for rice production (3,695 acres) and upland cotton ("CottonU" 205 acres). In Medina, pima cotton ("cottonP"), upland cotton, peanuts and grain sorghum ("Sorghum") share 39,000 ac-ft of water. In Tom Green, upland cotton is the major crop accompanied with a few acres of grain sorghum, wheat and winter wheat (Winwht). In Comanche, peanuts are the principal irrigated crop using 15,000 ac-feet of water, while in Robertson upland cotton is the dominant irrigated crop.

Total dryland acres reach 2042,000 acres, which is 201 times larger than the total irrigated land (10,100 acres). Crop dryland acres in each county are much larger than the irrigated acres. One reason is that most irrigation water is from ground water source, while it is not covered in our current surface model. Therefore, majority of land will be converted to dryland if there is not enough surface water available. It also verifies that the agriculture water creates lowest value and will be first sacrificed once there is water shortage problem in a region in a social optimal point of view.

5.1.6 Instream water flows and fresh water inflows to bays and estuaries

Table 9 shows average instream flows at a river place in a riverbasin. It can be seen that Sabine, Neches and Trinity have the largest average instream water flows above 700,000 ac-ft, while Trinity-San Jacinto have the lowest instream flow less than 30,000 ac-ft. Monthly instream flows vary by basin. In the Brazos basin, instream flow is higher in December, January, May, while lower in July, August. In Sabine, instream flows are higher from January to July, while lower from August to December. Instream flow depends on the naturalized stream flow, diversion amount, return flow, so there is no clear pattern.

Table 6: Agricultural counties' water use under different state of nature (thousand ac-ft)

County	Average	HDry	MDry	Dry	Dnormal	Normal	Wnormal	Wet	MWet	HWet
Wharton	99.76	126.06	113.12	107.78	105.91	95.22	98.51	89.96	89.00	78.63
Medina	38.86	48.12	40.35	44.63	41.59	37.23	40.55	35.43	32.74	27.94
Tom Green	18.02	20.41	20.16	19.90	19.50	16.90	18.38	16.43	16.91	15.28
Comanche	15.21	18.01	15.13	16.68	17.23	14.55	13.98	14.38	13.45	14.45
Robertson	15.00	19.79	16.69	16.76	17.22	13.91	13.67	13.35	13.92	12.21
Wilson	7.93	8.66	8.50	8.22	8.50	7.73	7.79	7.39	7.51	7.62
Zavala	7.80	7.97	7.94	8.19	8.02	7.74	8.38	7.23	7.04	7.51
Concho	6.02	6.65	6.14	6.75	6.72	5.58	6.29	5.73	5.74	5.29
Mason	2.29	2.64	2.37	2.44	2.57	2.21	2.32	2.08	1.84	2.18
Runnels	2.21	2.47	2.44	2.41	2.39	2.12	2.23	1.98	2.05	1.85
Nolan	1.27	1.41	1.30	1.43	1.42	1.18	1.33	1.21	1.22	1.12
Wilbarger	1.04	1.33	1.07	1.21	1.31	1.05	0.75	0.82	0.72	0.96
Castro	0.46	0.58	0.46	0.52	0.47	0.44	0.50	0.45	0.39	0.35
Baylor	0.42	0.52	0.47	0.50	0.46	0.39	0.46	0.34	0.40	0.31
Hale	0.41	0.43	0.39	0.45	0.47	0.39	0.45	0.39	0.38	0.30
Haskell	0.38	0.45	0.42	0.42	0.44	0.37	0.36	0.35	0.33	0.32
Roberts	0.34	0.47	0.32	0.40	0.38	0.32	0.37	0.30	0.27	0.26
Donley	0.26	0.30	0.27	0.26	0.32	0.27	0.19	0.24	0.21	0.23
Deaf Smith	0.26	0.28	0.25	0.30	0.25	0.25	0.27	0.25	0.22	0.21
Hansford	0.25	0.33	0.24	0.28	0.23	0.25	0.26	0.23	0.23	0.19
San Patricio	0.22	0.24	0.24	0.24	0.23	0.21	0.24	0.19	0.19	0.19

Randall	0.20	0.23	0.20	0.24	0.20	0.20	0.22	0.19	0.17	0.17
Carson	0.19	0.24	0.18	0.21	0.21	0.18	0.19	0.17	0.15	0.15
Fisher	0.18	0.20	0.19	0.21	0.21	0.17	0.19	0.18	0.18	0.16
Swisher	0.17	0.20	0.16	0.19	0.18	0.16	0.18	0.16	0.15	0.13
Moore	0.16	0.20	0.15	0.18	0.15	0.16	0.16	0.14	0.15	0.12
Wheeler	0.15	0.17	0.15	0.15	0.18	0.15	0.12	0.14	0.12	0.13
Dallam	0.12	0.18	0.11	0.13	0.12	0.13	0.10	0.11	0.11	0.11
Dickens	0.12	0.14	0.13	0.13	0.13	0.11	0.11	0.10	0.12	0.09
Parmer	0.12	0.14	0.12	0.13	0.11	0.11	0.12	0.12	0.10	0.09
Crosby	0.09	0.10	0.10	0.10	0.10	0.08	0.09	0.09	0.09	0.08
Motley	0.05	0.06	0.05	0.05	0.06	0.05	0.04	0.04	0.04	0.04
Cottle	0.03	0.04	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.03
Atascosa	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Collingsworth	0.01	0.02	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01
Hardeman	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00
Total	**220.01**	**269.04**	**239.87**	**241.55**	**237.34**	**209.87**	**218.88**	**200.25**	**196.20**	**178.72**

Table 7: Agricultural counties' irrigated crop acres (acre)

County	Corng	CottonP	CottonU	Peanuts	Rice	Sorghum	Soybeans	Wheat	Winwht	Sum
Wharton			204.6		3695.4					3900.0
Medina		1071.0	318.4	289.5		173.7				1852.5
Comanche				950.8						950.8
Tom Green			685.1			52.4		43.6	43.6	824.7
Robertson			770.9							770.9
Wilson				411.5						411.5
Zavala		95.0	176.7					15.8	15.8	303.4
Concho			284.4							284.4
Mason				133.4						133.4
Runnels			100.9							100.9
Wilbarger				62.4						62.4
Nolan			60.2							60.2
Baylor								24.4	24.4	48.9
Castro	14.1		5.5			2.7	0.7	12.7	12.7	48.4
Roberts								23.0	23.0	45.9
Hale	8.0		12.0			3.5		3.9	3.9	31.4
Hansford						3.2		13.2	13.2	29.6
Deaf Smith			0.5			3.5		10.5	10.5	25.0
Haskell			4.0	13.1				3.8	3.8	24.6
Carson			1.9			3.2		8.1	8.1	21.3
Donley				20.7						20.7

Moore						2.4		9.0	9.0	20.5
Randall						1.8	0.4	9.1	9.1	20.3
Dallam						0.3		9.1	9.1	18.5
Swisher	1.9		3.1			2.0		4.6	4.6	16.1
Parmer			1.1			1.3		4.9	4.9	12.3
Wheeler			6.0	4.3						10.3
San Patricio			9.0							9.0
Fisher			8.7							8.7
Dickens			3.1			0.7		1.8	1.8	7.5
Crosby			4.9	0.1		0.1				5.1
Motley				2.7						2.7
Cottle			0.4	1.2						1.6
Collingsworth			0.1	0.7		0.0		0.1	0.1	1.0
Atascosa				1.0						1.0
Hardeman			0.1					0.2	0.2	0.5

Table 8: Agricultural counties' dryland crop acres (acre)

County	Barley	Corng	CottonU	Oats	Peanuts	Sorghum	Soybeans	Wheat	Winwht	Sum
Hale		1987.0	128491.9			163122.3	33305.7	25830.8	25830.8	378568.6
Parmer	602.2	11459.3	27519.0	83.6		111163.3	3680.4	37639.9	37639.9	229787.7
Castro	368.5	21870.5	33326.5	600.8		72501.1	9733.6	32525.3	32525.3	203451.6
Crosby		247.0	85050.5			52936.0	4834.8	14963.2	14963.2	172994.9
Deaf Smith	1642.2	2758.8	3678.4	144.5		60168.7	3547.1	45717.7	45717.7	163375.0
Swisher	197.4	3477.3	19501.0			59959.6	6061.7	26643.5	26643.5	142483.9
Sherman		3454.4				34283.0	945.1	38258.8	38258.8	115200.0
Dallam		3089.1		51.5		59797.1		24271.9	24271.9	111481.5
Hansford	201.8	4237.1		84.1		28751.8	168.1	32013.7	32013.7	97470.4
Moore	685.2	9235.7		521.4		20169.7	149.0	21659.3	21659.3	74079.5
Carson	126.2	97.1				10816.8	87.4	14875.6	14875.6	40878.7
Briscoe		192.9	7293.0	19.3		11653.3	1234.8	8103.3	8103.3	36600.0
Collingsworth		53.9	11432.9	251.7		10066.7		3846.9	3846.9	29499.0
Haskell	233.4		12147.1	1449.3		4949.7		4347.9	4347.9	27475.4
Tom Green	104.9		9507.4	2644.4		11375.3		671.6	671.6	24975.3
Uvalde	84.3	2190.5	315.9	4296.8		10236.5		2338.0	2338.0	21800.0
Hutchinson	80.2	951.0				4963.1		7102.8	7102.8	20200.0
Robertson		2449.8	10301.9	565.3	458.6	5653.5				19429.1
Randall	89.0	331.0	147.9	33.1		5296.4	206.9	6237.7	6237.7	18579.7
Zavala		2438.7	1927.4	531.0		7158.8		570.3	570.3	13196.6
Gray			190.6	84.7		2361.0		5081.9	5081.9	12800.0

Medina	13.3	1322.0	95.1	1559.8	190.2	5240.5		1413.3	1413.3	11247.5
Donley			3417.6			4430.2		1265.8	1265.8	10379.3
Burleson		1454.5	5030.3	363.6		1651.5				8500.0
Frio		416.3	327.1	148.7	2721.1	3434.8		226.0	226.0	7500.0
San Patricio			1238.2	3.0		5733.8		8.0	8.0	6991.0
Wilbarger	394.4		961.7	240.4		108.1		1916.6	1916.6	5537.6
Motley			1860.5	22.2	106.7	1220.4		443.8	443.8	4097.3
Hardeman	327.1		494.4	150.0		59.0		1484.4	1484.4	3999.5
Roberts						294.5		1579.8	1579.8	3454.1
Dickens	9.2		1471.8	52.3		689.9		384.7	384.7	2992.5
Wheeler	42.4		705.6			859.4		541.1	541.1	2689.7
Mason			105.3	157.9	2157.8	245.6				2666.6
Nolan			1226.6	101.0		487.0		262.6	262.6	2339.8
Howard			1729.2	6.5		501.5		31.3	31.3	2300.0
Comanche		16.7	30.7	315.2	1567.6	163.2		27.9	27.9	2149.2
Concho	42.3		410.4	450.6		385.0		413.6	413.6	2115.6
Cottle	30.0		1186.0	66.4		253.0		281.5	281.5	2098.4
Fisher	3.5		1123.5	65.4		143.6		327.6	327.6	1991.3
Atascosa		69.4	39.2	16.6	697.4	637.1		19.6	19.6	1499.0
Baylor	25.5		144.4	93.4		73.8		457.0	457.0	1251.1
Runnels	3.7		406.5	160.5		363.4		132.4	132.4	1199.1
Wilson		58.7		3.1	127.4	203.7		97.8	97.8	588.5

Table 9: Instream flows by basins (thousand ac-ft)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Brazos	70.79	47.38	24.54	32.56	71.22	32.10	12.17	9.62	16.50	47.44	38.20	67.56	470.08
Canadian	0.02	0.02	0.04	0.14	0.39	10.64	10.30	1.31	0.27	0.14	6.67	0.02	29.96
Colorado	23.74	64.16	18.79	29.22	34.57	26.38	12.62	10.62	27.25	89.69	34.37	18.50	389.90
Cypress	8.68	17.12	11.45	14.07	26.37	20.07	15.52	22.60	18.22	2.08	4.22	19.77	180.19
Guadsan	16.75	15.68	14.10	18.59	26.53	30.96	13.13	10.31	15.93	22.83	13.98	13.27	212.04
Lavaca	9.42	11.08	5.99	11.82	17.38	15.65	2.66	1.54	11.15	9.71	7.06	7.28	110.76
Neches	97.74	154.16	58.05	96.46	61.56	57.90	43.46	69.01	16.65	16.74	87.52	46.36	805.61
Nueces	6.26	6.56	6.91	10.31	10.64	19.52	7.63	10.26	13.36	16.03	5.46	3.49	116.45
Red	29.06	78.10	24.63	21.74	40.15	39.93	35.57	13.08	13.97	122.83	11.07	13.73	443.86
Sabine	133.98	115.81	71.94	138.96	137.93	139.55	140.01	5.08	38.33	69.39	18.75	32.96	1042.68
SanJacinto	30.41	33.58	19.91	29.54	25.24	23.10	10.11	11.38	12.70	24.23	14.20	23.23	257.63
Sulphur	36.48	63.30	66.90	57.88	99.50	25.59	14.57	26.89	15.60	27.95	48.06	57.55	540.28
Trinity	45.70	15.60	101.11	78.48	65.11	55.71	54.69	64.70	41.01	76.84	43.29	69.44	711.67
TrinitySanJac	2.45	2.27	1.53	2.18	2.59	3.15	1.30	0.69	1.12	1.87	1.51	2.09	22.75

6 Evaluation of inter-basin water transfers

Now we turn to the IBT appraisal examining implications for source basins, destination basins as well as other basins. Three scenarios are run within the model:

- Baseline: This scenario (“base”) assumes that no IBT is built.
- Optimal IBTs: In this scenario (“Opt”), all of the 51 IBT projects are candidates so the socially optimal IBT solution will be obtained.
- Environmental Restriction “env”: In this scenario, IBTs with medium-high or high environmental impact are ruled out of solution. 15 out of 51 IBTs are so classified (Table 10), where 4 of these are River IBTs and 11 are User IBTs.
- Permitted IBT's only(“pert”): Five IBTs (table 11) are already permitted in Texas, including the Water Project LCRA/BRA Alliance User IBT projects transferring water from Lake Travis in the Colorado Riverbasin to Cities in Williamson County within the Brazos Riverbasin. In this scenario, these already permitted IBT projects are the only candidates.

Table 10: Environmentally Sensitive IBTs

IBT names in GAMS	Option	Source basin	Destination Basin
Marvin_SulToTrin	Opt1	Sulphur	Trinity
Marvin_SulToTrin	Opt2	Sulphur	Trinity
BoisdArc_RedToTrin	Opt1	Red	Trinity
Parkhouse_SulToTrin	Opt1	Sulphur	Trinity
Parkhouse_SulToTrin	Opt2	Sulphur	Trinity
Fastrill_NecToTrin	Opt1	Neches	Trinity
Parkhouse_SulToTrin	Opt3	Sulphur	Trinity
RalphHall_SulToTrin	Opt1	Sulphur	Trinity
Columbia_NecToTrin	Opt1	Neches	Trinity
LCRASAWS_ColToGdsn	Opt1	Colorado	Guadsan
LCRASAWS_ColToGdsn	Opt2	Colorado	Guadsan

Bayou_TriToSan	Opt1	Trinity	SanJacinto
Bedias_TriToSan	Opt1	Trinity	SanJacinto
ETWT_SabNecToTri	Opt1	Sabine	Trinity
ETWT_SabNecToTri	Opt1	Neches	Trinity
Livingston_TriToSan	Opt1	Trinity	SanJacinto

Table 11: Permitted IBTs

IBT names in GAMS	Option	Source basin	Destination Basin
Marcoshays_GdsnToCol	Opt1	Guadsan	Colorado
Marcoshays_GdsnToCol	Opt2	Guadsan	Colorado
LCRABRA_ColToBrz	Opt1	Colorado	Brazos
LCRABRA_ColToBrz	Opt2	Colorado	Brazos
LCRABRA_ColToBrz	Opt3	Colorado	Brazos

6.1 Optimal IBTs chosen

An IBT is justified if the benefit it brings is greater than the total cost. The cost may include opportunity cost or environmental impacts, while the latter is hard to quantify. Here only the construction, operation and water opportunity costs are considered in the model.

The results (table 12) show that 7 out of 51 IBTs are economically attractive under "Opt" scenario.

- Luce Bayou Channel project (Bayou_TriToSan) originates from Lake Livingston on the Trinity Riverbasin and goes to Lake Houston in the San Jacinto River to supply water to north and northwest areas of Houston in Harris County. This IBT has the second largest yield of water (maximum 540,000 ac-ft in) and the lowest per ac-ft cost ($30/ac-ft fixed cost and $9.27/ac-ft variable cost) among the 51 IBTs. As implied by table 5, Harris County faces major industrial water shortage. It is an optimal strategy if no environmental consideration bringing 540000 ac-ft water to industrial sector in Harris County.
- LCRA/BRA Alliance (LCRABRA_ColToBrz with option 1 and option 2) are aimed to transfer water from Lake Travis in Colorado basin to Williamson Counties in Brazos basin to

supply cities such as Round Rock, George Town, and Cedar Park. These supply options are sized to meet 54 percent of water shortages in William County by 2060. The construction of a new intake structure on Lake Travis and transmission pipeline to Williamson County would entail low to moderate environmental effects, leaving it as optimal strategies under all the scenarios. Option 2 will transfer water of 20928 ac-ft municipally regardless of the state of nature, while Option 1 will serve municipal water use with range of 486 ac-ft to 3476 ac-ft depending on the state of nature. If it's wet year, less water will be transferred.

- LCRA-SAWS Water Project (LCRASAWS_ColToGdsn) with option 1: Under this IBT water will be transferred from Bay City on the Lower Colorado River and sent to Bexar County of the Guadalupe Riverbasin for municipal use in San Antonio. This IBT project is very expensive (fixed cost of $1326/ac-ft and variable cost of $302.85/ac-ft). Water transferred varies by state of nature with the range from 49,700 to 83,000 ac-ft to solve the water shortage faced in San Antonio due to pumping limits of Edwards Aquifer.
- George Parkhouse Lake N (Parkhouse_SulToTrin with option 1): water originates from George Parkhouse Lake in Sulfur basin and goes to Dallas surrounding region in Trinity basin. This IBT is relatively cheap with fixed cost of $248/ac-ft, variable cost of $77.8/ac-ft and yielding maximum of 112,000 ac-ft annually. It may bring medium high environment impact if it is built, so it is an optimal strategy only under "Opt" scenario, where 25,200 water will be used industrially regardless of state of nature while 54,600 ac-ft will be transferred municipally in the heavy dry state to solve water shortage problem faced by Dallas region.
- Cypress Basin Supplies project (Pines_CypToTrin with option 3): Water flows from Lake O' the Pines in the Cypress Riverbasin to the Trinity Riverbasin where its possible owner would be Tarrant Regional Water District with supplies dedicated to Fort Worth municipality and industrially. This user IBT is relatively more expensive than most other proposed IBTs (unit cost before amortization: $641 per acre-foot and a variable cost of $242.96). It is an optimal strategy under "Opt" and "evn" scenario while not under "pert" scenario, where 6479 ac-ft is used industrially regardless of state of nature and municipal transfer ranges from 31,040 to 59,657 ac-ft with less in wet year.
- Lake Texoma with desalination project (Texoma_RedToTrin with option 3) is to transfer water from Lake Taxoma and to supply water to multiple users such as Allen, Frisco and

Richardson. This IBT is relatively cheap with fixed cost of $476/ac-ft and variable cost of $231/ac-ft while transferring water municipally of 13,800 ac-ft under both "Opt" and "env" scenario.

Table 12: IBTs chosen under different scenarios

Names in Gams	Option	Desti place	sector	Opt	Env	Pert
Bayou_TriToSan	Opt1	Houston	ind	540000		
LCRABRA_ColToBrz	Opt1	Round Rock, Cedar Park, George Town	mun	2541.851	2541.851	2541.851
LCRABRA_ColToBrz	Opt2	Round Rock, Cedar Park, George Town	mun	20928	20928	20928
LCRASAWS_ColToGdsn	Opt1	San Antonio	mun	60694.46		
Parkhouse_SulToTrin	Opt1	Dallas, Iving	ind	25185.6		
Parkhouse_SulToTrin	Opt1	Dallas, Iving	mun	3278.877		
Pines_CypToTrin	Opt3	Forth Worth	ind	6478.716	6478.716	
Pines_CypToTrin	Opt3	Forth Worth	mun	41811.07	41811.07	
Texoma_RedToTrin	Opt3	Allen, Frisco, Richardson	mun	13830.79	13830.79	

6.2 Net benefit impacts of IBTs

Table 13 shows the IBTs impacts on net benefits under the three scenarios. The costs of constructing IBTs are assumed to be incurred by the destination basin.

Seven IBTs bring expected net benefits of $2,254 million statewide under "Opt" scenario, with $1,858 million arising in industrial benefits and $846 million from municipal benefits. Meanwhile, total annual construction and operation costs of $450 million are incurred. In the destination basins the

- Brazos basin realizes municipal benefit of $479 million less a cost of $17.4 million. The gains come from two IBT projects: LCRABRA_ColToBrz with option 1 and 2.
- Guadalupe-San Antonio faces a net loss of $63.4 million even though water brings a benefit of $262 million.
- San Jacinto basin gains $1,752 million, most from water transferred to Harris County to lessen industrial water shortage.

- Trinity receives benefits of $206 million, where $91 million is from industrial and $105 million from municipalities. This basin serves as destination basin of multiple IBT projects (Parkhouse_SulToTrin, Pines_CypToTrin, and Texoma_RedToTrin).

Under the “env” scenario, four IBTs are economically optimal,

- LCRABRA_ColToBrz with option 1
- LCRABRA_ColToBrz with option 2,
- Pines_CypToTrin with option 3,
- Texoma_RedToTrin with option 3

Leading to expected municipal benefit of $583 million and industrial benefit of $9 million while incurring IBT cost of $78.8 million. The annual net gain from these four IBTs is $513 million, of which $462 million are from Brazos Basin and $51 million are from Trinity Basin.

Under “pert” scenario, only two IBTs

- LCRABRA_ColToBrz with option 1
- LCRABRA_ColToBrz with option 2

are optimal, creating benefit of $479 million exclusively municipally for Brazos while exposed to IBTs costs of $17.4 million.

The impact of IBTs on other sectors for the destination basins is negligible. As we can see, municipal and industry are two beneficiaries in terms of net benefit. Once water is transferred to a destination basin, the return flow generally increases the water availability downstream in the destination basin, which may generate some value if it is efficiently used. Guadalupe-San Antonio does realize a gain of $3,000 in agriculture, while the gain for San Jacinto $2,000 is from fresh water inflows to bays and estuaries. On the other hand, Trinity realizes a loss of $5000 in fresh water inflows to bays and estuaries.

The construction of IBTs projects has trivial impacts on the source basins and third basins under these three scenarios. Colorado, Cypress, Trinity, Sulphur, Red are source basins for the optimal IBT projects, however, the only impacts occurs in Cypress basin is $4,000 loss industrially under “Opt” scenario. As respect to third basins impacts, Lavaca experiences a loss of $1000, $3000, and $4000 in agriculture under these 3 scenarios respectively. Nueces suffers a loss of $3000 in agriculture under "opt" scenario. Sabine has a net gain of $4000 in the industry sector.

Table 13: Welfare impact by basin (million $)

Basin	Sector	Base	Opt-Base	Env-Base	Pert-Base
Brazos	IBTcost		-17.422	-17.422	-17.422
Brazos	mun	532060.85	478.923	478.923	478.923
Brazos	**sum**	**534587.4**	**461.5**	**461.5**	**461.5**
Cypress	ind	144.987	-0.004		
Cypress	**sum**	**23229**	**-0.004**		
Guadsan	ag	1.216	0.003		
Guadsan	IBTcost		-325.247		
Guadsan	mun	918595.018	261.864		
Guadsan	**sum**	**920030.501**	**-63.38**		
Lavaca	ag	0.006	-0.001	-0.003	-0.004
Lavaca	**sum**	**0.223**	**-0.001**	**-0.003**	**-0.004**
Nueces	ag	0.164	-0.003		
Nueces	**sum**	**278786.63**	**-0.003**		
Sabine	ind	1249.156	0.004		
Sabine	**sum**	**109310.073**	**0.004**		
SanJacinto	IBTcost		-16.178		
SanJacinto	ind	3288.917	1767.893		
SanJacinto	outtobay	0.016	0.002		
SanJacinto	**sum**	**1587657.436**	**1751.716**		
Trinity	IBTcost		-91.401	-61.399	
Trinity	ind	439.741	91.084	8.967	
Trinity	mun	3716092.555	104.811	103.903	
Trinity	outtobay	0.057	-0.005		
Trinity	**sum**	**3716532.395**	**104.489**	**51.472**	
Total	IBTcost		-450.248	-78.821	-17.422
Total	ind	9757.921	1858.976	8.967	
Total	mun	8440348.199	845.598	582.826	478.923
Total	outtobay	0.473	-0.004		
Total	**sum**	**8450214.998**	**2254.321**	**512.972**	**461.5**

6.3 Water allocation impacts of IBTs on riverbasins

Table 14 lists the water allocation impacts of IBTs on riverbasin base. Water is largely transferred from instream flow in the source basins to supply municipal or industrial purpose in the destination basins, while the reduction of instream flow leads to the reduction of fresh water inflows to bays and estuaries.

Under the "Opt" scenario, municipal and industrial water use increase by 143,000 and 572,000 ac-ft state wide, while fresh water inflows to bays and estuaries reduces by 445,000 ac-ft. The Colorado, Cypress, Sulfur and Red basins are the sources for the seven optimal IBTs. Each of these basins experiences a significant reduction in fresh water inflows to bays and estuaries. On the other side, the destination basins Brazos, Guadalupe-San Antonio, and San Jacinto incur a significant increase in either municipal or industrial use or fresh water inflows to bays and estuaries.

The Trinity serves as both a source basin for Bayou_TriToSan and destination basin for Parkhouse_SulToTrin, Pines_CypToTrin, and Texoma_RedToTrin, therefore the impacts on water allocation is mixed. Water use in Trinity for municipal and industry increases by 59,000 and 32,000 ac-ft while showing a loss of 493,000 ac-ft in fresh water flow to bay, so we can see that Bayou_TriToSan project transferring water 540,000 ac-ft to San Jacinto plays a more important role.

Under "env" scenario, municipal and industrial water use increase by 79,000 and 6,500 ac-ft state wide, while fresh water inflows to bays and estuaries is reduced by 40,000 ac-ft. Under "pert" scenario, municipal water use will increase by 23,000 ac-ft while the loss of fresh water inflows to bays and estuaries is 10,700 ac-ft.

Overall three scenario analysis implies that source of water transfer is surplus of instream flows in the source basins while beneficiary is the municipal or industry sector. The impact of IBTs on other sectors for example agricultural sector for both source basin and destination basin or third basins are trivial.

Table 14: Water use impact (thousand ac-ft)

Basin	Sector	Base	Opt-Base	Env-Base	Pert-Base
Brazos	ag	46.021	0.004	-0.001	-0.023
Brazos	mun	462.220	23.47	23.47	23.47
Brazos	outtobay	6683.833	8.413	13.553	13.786
Brazos	**sum**	**7505.233**	**31.887**	**37.021**	**37.234**
Colorado	ag	127.470	0.456	1.015	1.168
Colorado	outtobay	2661.514	-84.353	-24.303	-24.517
Colorado	**sum**	**3154.809**	**-83.897**	**-23.287**	**-23.349**
Cypress	outtobay	1570.228	-48.29	-48.29	
Cypress	**sum**	**1698.107**	**-48.29**	**-48.29**	
Guadsan	ag	45.302	0.072	-0.008	-0.008
Guadsan	mun	130.966	60.694		
Guadsan	outtobay	1848.070	33.055	0.008	0.008
Guadsan	**sum**	**3294.789**	**93.821**	**-0.001**	**-0.001**
Lavaca	ag	1.803	-0.46	-1.017	-1.155
Lavaca	outtobay	784.632	0.431	0.952	1.081
Lavaca	**sum**	**786.801**	**-0.029**	**-0.065**	**-0.074**
Neches	outtobay	5501.057	-0.051		
Neches	**sum**	**5677.301**	**-0.051**		
Nueces	ag	9.317	-0.072	0.008	0.008
Nueces	outtobay	524.243	0.067	-0.008	-0.008
Nueces	**sum**	**597.031**	**-0.005**	**0.001**	**0.001**
Red	outtobay	9542.540	-10.332	-13.793	1.998
Red	**sum**	**9708.254**	**-10.332**	**-13.79**	**2.008**
Sabine	outtobay	6295.282	0.051		
Sabine	sum	6520.255	0.051		
SanJacinto	ind	377.990	540		
SanJacinto	outtobay	1649.174	181.332		
SanJacinto	**sum**	**2427.242**	**721.332**		
Sulphur	outtobay	2382.205	-31.948	-0.144	-2.111
Sulphur	**sum**	**2410.227**	**-31.948**	**-0.144**	**-2.111**
Trinity	ind	307.811	31.664	6.479	

Trinity	mun	1169.508	58.921	55.642	
Trinity	outtobay	5696.402	-493.117	31.743	-0.91
Trinity	**sum**	**7174.247**	**-402.532**	**93.864**	**-0.91**
Total	ind	1579.996	571.664	6.479	
Total	mun	2912.467	143.085	79.112	23.47
Total	outtobay	47273.587	-444.742	-40.281	-10.672
Total	**sum**	**53187.302**	**270.008**	**45.309**	**12.797**

6.4 Water allocation impacts of IBTs on major cities

The above sections discussed the impacts of IBTs on water allocation on riverbasins and results imply that water is mainly transferred for municipal and industrial purpose. This section will discuss the detailed impacts on major cities (table 15). The next section will discuss the impacts on major industrial counties (table 16).

San Antonio, Arlington, Fort Worth, Tyler, San Angelo, Round rock, Plano, Cedar Park, Georgetown, Corsicana, Mansfield and McKinney are major cities where water allocation is less than the projected demand under the baseline model in section 4.1.3. If there is no ground water available, these cities will face a water shortage issue, but we lack sufficient information to identify cities having ground water source. Here we only list the impacts of IBTs on the major cities' water allocation. Under the "opt" scenario, total city water allocation increases by 143,000 ac-ft, where

- 61,000 ac-ft is for San Antonio via LCRASAWS_ColToGdsn,
- 39,000 ac-ft is for Fort Worth via Pines_CypToTrin,
- 23,000 ac-ft is for Round Rock, Cedar Park and George Town via LCRABRA_ColToBrz.

The water shortages in San Antonio, Fort Worth are greatly relaxed while in other cities listed in the table 14, the water shortage is eliminated.

Under the "env" scenario, LCRASAWS_ColToGdsn and Parkhouse_SulToTrin are ruled out of solution, resulting in an increase of 79,000 ac-ft in water allocation in major cities. This includes

- 39,000 ac-ft for Fort Worth via Pines_CypToTrin,
- 23,000 ac-ft for Round Rock, Cedar Park and George Town via LCRABRA_ColToBrz.

Under the "pert" scenario, only LCRABRA_ColToBrz with option 1 and option 2 are optimal, realizing an increasing of 23,000 ac-ft for Round Rock, Cedar Park and George Town.

Overall, if no restriction on IBTs is applied, the IBTs will greatly solve cities water shortage issues especially for San Antonio and the Fort Worth region. Therefore, inter-basin water transfer is one prominent option that a policy maker should take into consideration.

Table 15: Cities' water allocation (thousand ac-ft)

City	Pre-demand	Base	Opt-Base	Env-Base	Pert-base
Allen	23.616	22.252	1.332	1.332	
Cedar Park	10.924	3.330	6.547	6.547	6.547
Dallas	389.338	388.565	2.607		
Denton	29.599	29.460	0.199		
Fort Worth	149.572	100.769	38.555	38.555	
Garland	42.850	40.123	2.997	2.997	
George Town	8.604	2.690	5.088	5.088	5.088
Grapevine	13.496	13.451	0.093		
Irving	55.410	55.226	0.381		
Mansfield	13.537	9.358	3.256	3.256	
McKinney	24.672	22.544	2.086	2.086	
Plano	72.619	64.982	7.415	7.415	
Round Rock	19.627	5.782	11.835	11.835	11.835
San Antonio	216.073	138.480	60.694		
Total	**1069.937**	**897.012**	**143.085**	**79.111**	**23.47**

6.5 Water allocation impacts of IBTs on major industrial counties

In section 4.1.4, Brazoria, Nueces, Harris, Dallas, Hutchinson, Tarrant, Harrison, Live Oak and Victoria are counties facing major water shortage problems. Table 16 shows the optimal water allocations for major industrial counties by IBT scenario.

Water transferred through Bayou_TriToSan is exclusively used by Harris County making the water use in Harris County greater than the projected demand. This is because optimal water transfers will be where marginal benefit equals marginal cost.

Parkhouse_SulToTrin brings 25,000 ac-ft to Dallas County under "opt" scenario and is optimal under both "opt" and "env" scenarios, realizing 6,500 ac-ft of water to Tarrant County. Under "pert" scenario, no IBTs are feasible for industrial water transfer.

Table 16: Major industrial counties water allocation (thousand ac-ft)

ind counties	**Pre-demand**	**Base**	**Opt-Base**	**Env-Base**	**Pert -Base**
Dallas	37.025	11.832	25.186		
Tarrant	17.691	9.44	6.479	6.479	
Harris	397.279	375.46	540		

6.6 Instream impacts of IBTs

Table 17 shows the impacts of IBTs on instream flows. Our interests are to see how IBTs affect the instream flows for source basins, destination basins as well as the third parties. In particular, Colorado, Sulphur, Cypress, and Red basins are source basins, while Guadalupe-San Antonio, Brazos and San Jacinto are destination basins. The Trinity basin serves as both a source and destination basin.

The average instream flows in all source basins decrease under the "Opt" scenario by about,

- 0.29% in the Colorado,
- 0.19% in the Red,

- 1.29% in the Sulphur, and
- 1.28% in Cypress.

Instream flows for all destination basins increases, where stream flow increases by 1.26% in Guadalupe-San Antonio, 0.19% in Brazos, 0.61% in San Jacinto.

As both a source and destination basin, Trinity realized a net loss of 0.37% instream flow under “Opt” scenario since the effect of Bayou_TriToSan outweighs the other two IBTs. However, under “env” scenario, it becomes a sole destination, realizing a rise of 0.71% instream flows.

Instream flows in third basins may increase or decrease or do not change. For example, instream flows in Lavaca, Nueces will increase by 0.36%, 0.10%, while decrease slightly in Neches by 0.05% and have no effect in Canadian, Trinity-San Jacinto Basin.

Table 17: Annual Instream flows under scenarios

	Base (thousand ac-ft)	**Opt-base (%)**	**Env-base (%)**	**Pert-base (%)**
Brazos	470,083	0.19	0.17	0.30
Colorado	389,904	-0.29	-0.23	-0.26
Canadian	29,955			
Red	443,857	-0.19	-0.02	-0.03
Sabine	1,042,680	-0.02	-0.01	-0.02
Guadsan	212,044	1.26	0.20	0.54
Sulphur	540,280	-1.29	-0.21	0.08
Cypress	180,188	-1.28	-1.44	0.02
Neches	805,612	-0.05	-0.04	
Trinity	711,669	-0.37	0.71	-0.19
TrinitySanJac	22,753			
SanJacinto	257,627	0.61	0.58	0.31
Lavaca	110,757	0.36	0.22	0.23
Nueces	116,448	0.10	0.01	0.10

7 Conclusions

This study develops an integrated economic-hydrological model to examine proposed inter-basin water transfer projects in Texas in the face of water scarcity issues while assuming efficient water allocation. The model includes 21 Texas riverbasins explicitly covering 46 major municipal cities, 25 major industrial counties, 44 agricultural counties, 175 major reservoirs and 51 proposed inter-basin water transfer projects. 21 agricultural crops are introduced in the model for analysis of agricultural activities.

The model maximizes regional expected net benefits of water use accrued from municipal, industrial, agricultural, recreational, others, and fresh water flowing to bays against the cost incurred from IBTs construction while subject to hydrological, financial, institutional constraints. Nine states of nature are introduced to simulate the future climate thereafter influencing water demand and water availability.

If no IBT is built, there are total of 6.05 million ac-ft water used for these sectors in Texas bringing a net benefit of $8,450 billion. Among this, 3.9% of water use is for agriculture, 26.1% for industry, 50.5% for municipal sector, and 18.5% for recreation. Municipal water use plays a dominant role in total net welfare. The value of municipal and industrial net benefits must be carefully interpreted since it values areas under the demand curves, containing consumer and producer surplus, unlike Gross Regional Product (GRP), which is measured only with producer surplus.

Total agriculture water use averages 220,000 ac-ft accounting for 3.9% of total water use for all sectors. Since a large portion of irrigation water is from ground source, which is not modeled in this model, resulting that irrigated crop acres are much smaller than dry land acres. Out of 46 modeled big cities, 19 cities face different degrees of water shortage problems totaling 281,400 ac-ft in 2010. San Antonio, Arlington, Fort Worth, Tyler, San Angelo, and Round Rock have larger shortages especially San Antonio. On the industrial side Arlington, Brazoria, Nueces, Harris, Dallas, Hutchinson, Tarrant, Harrison, Live Oak and Victoria counties faces water shortage problems. Among them, water shortage is most serious in Brazoria County with a shortage of up to 111,000 ac-ft. Therefore, inter-basin water transfer strategy becomes an option to solve the water shortage issue.

To examine IBTs four scenarios are examined with the model.

- A baseline scenario without IBTs allowed;
- An optimal scenario “Opt” that allows all IBTs;
- An environmentally motivated scenario “env”, wherein IBTs with above medium high environmental impact are ruled out of the solution;
- A permitted IBT scenario “pert” that only allow the model to choose the IBTs under current permits.

We find 7 IBTs are economically attractive under “Opt” scenario. They are:

- Bayou_TriToSan,
- LCRABRA_ColToBrz with option 1 and option 2,
- LCRASAWS_ColToGdsn,
- Parkhouse_SulToTrin,
- Pines_CypToTrin, and
- Texoma_RedToTrin.

Under the “env” scenario,

- LCRABRA_ColToBrz with option 1 and option 2,
- Pines_CypToTrin, and
- Texoma_RedToTrin.

are optimal.

In the “Pert” scenario, only LCRABRA_ColToBrz with option 1 and option 2 are constructed.

We find that when an IBT is optimally chosen, the amount of water transferred remains at its maximum level and does not vary by scenario. Water is transferred from instream flows to San Antonio, Fort Worth, Round Rock, Plano, and Georgetown along with industry in Harris, Dallas, and Tarrant counties, realizing the gains of $2254, 513, 462 million respectively under the opt, env and pert scenarios.

Agriculture production activities are not meaningfully affected by the IBTs. Destination basins Brazos, San Jacinto, Trinity, and Guadalupe-San Antonio are winners while the source basins Colorado, Cypress, Red and Sulphur are essentially unaffected.

The unrestricted set of IBTs alleviates the water shortage issues especially for large cities like San Antonio and the Fort Worth region. But implementing the IBTs generally reduces source basin instream flows and fresh water inflows but increases them in destination basins.

There are some limitations in our analysis. One is that the groundwater component is not introduced in our model with our modeling and analysis based on the surface water. This will restrict comprehensive understanding on water demand, instream flows, necessities of inter-basin water transfers and their resulting social welfare changes. More accurate information on IBT should be included. Furthermore, other than recreational value, the value of instream flows is ignored in the model and the value of bay and estuary inflows is held at a very low level. Future research will focus on incorporating ground water part into the model.

However, this research examined the water scarcity issue under optimal water allocation and developed an inter-basin water transfer evaluation system that integrates the effects of the proposed water transfer on the economic, hydrologic and environment in Texas. This system yields information on economic implications for municipal, industrial and agricultural water users by basin. Such information can support effective public water policy making for state agencies, water management authorities and regional water planning groups. It can help them to devise appropriate compensation rules for origin basin and loss of instream uses.

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9 Appendix

Table 18**:** State of nature

State of nature	Explanation	Years	Probability
HDry	Very dry	1956, 1963, 1954	0.06
MDry	Medium dry	1964, 1951, 1988, 1978, 1955	0.10
Dry	Dry	1998, 1996, 1952, 1967, 1972, 1962, 1971	0.14
Dnormal	Dry-normal	1984, 1965, 1980, 1970	0.08
Normal	Normal	1977, 1976, 1966, 1959, 1997, 1953, 1983, 1982, 1981, 1958, 1949, 1960, 1969, 1986, 1985	0.30
Wnormal	Normal-wet	1989, 1975, 1950, 1994	0.08
Wet	Wet	1995, 1961, 1987, 1974, 1993, 1990, 1968	0.14
MWet	Medium wet	1979, 1991	0.04
HWet	Very wet	1992, 1973, 1957	0.06

Table 19: Crops covered in the model

Crop name	Explanation (units)
Barley	Barley All
Corng	Corn For Grain
Corns	Corn for silage (tons)
CottonP	Pima cotton (lb)
CottonU	Cotton Upland
Alfalfa2	Hay Alfalfa Dry
Hy	Hay other than Sorghum Hay (ton)
HayOth	Hay Other Dry
Ots	Grazing Oats (days)
Peanuts	Spanish Peanuts (cwt)

Rice	Rice (cwt)
PeanutsR	Runner peanuts(ton)
Sorghum	grain sorghum (cwt)
Soybeans	(bu)
Sugarbeets	Sugar beets
Sugarcane	(tons)
Sunflower	(cwt)
SunflowerO	Sunflower seed for oil use
SunflowerNo	Sunflower seed for non oil use
Wheat	Wheat All
Winwht	Winter Wheat (bu)

Source: United States Department of Agriculture (USDA/NASS), "*Crops County Data Files*"

Table 20: Data on Inter-basin water transfers in the model

Status	IBT names	Option	Origin	Destination	Capacity	FC	VC
RIBT	Toledo_SabToTrin	Opt1	Sabine	Sabine	50000	1.36E+08	128.896
RIBT	Toledo_SabToTrin	Opt2	Sabine	Sabine	50000	2.15E+08	143.239
RIBT	Toledo_SabToTrin	Opt3	Sabine	Sabine	50000	1.73E+08	151.44
RIBT	Marvin_SulToTrin	Opt1	Sulphur	Trinity	172800	1.55E+08	115.189
RIBT	Marvin_SulToTrin	Opt2	Sulphur	Trinity	174840	1.6E+08	97.474
UIBT	Patman_SulToTrin	Opt1	Sulphur	Trinity	100000	35284600	203.334
UIBT	Patman_SulToTrin	Opt2	Sulphur	Trinity	100000	32025600	233.414
UIBT	Patman_SulToTrin	Opt3	Sulphur	Trinity	100000	32025600	233.414
UIBT	Patman_SulToTrin	Opt4	Sulphur	Trinity	112100	42465000	110.027
UIBT	Patman_SulToTrin	Opt5	Sulphur	Trinity	180000	68226000	110.522
UIBT	Patman_SulToTrin	Opt6	Sulphur	Trinity	180000	61349000	120.483
UIBT	Patman_SulToTrin	Opt7	Sulphur	Trinity	180000	77222200	165.754
UIBT	Patman_SulToTrin	Opt8	Sulphur	Trinity	130000	1.41E+08	180.237

UIBT	Texoma_RedToTrin	Opt1	Red	Trinity	113000	15023400	55.766
UIBT	Texoma_RedToTrin	Opt2	Red	Trinity	105000	43752600	222.347
UIBT	Texoma_RedToTrin	Opt3	Red	Trinity	50000	13616200	75.796
UIBT	Texoma_RedToTrin	Opt4	Red	Trinity	105000	49935400	230.996
UIBT	Rayburn_NecToTrin	Opt1	Neches	Trinity	200000	97276800	179.086
UIBT	Rayburn_NecToTrin	Opt2	Neches	Trinity	200000	1.05E+08	211.028
UIBT	Rayburn_NecToTrin	Opt3	Neches	Trinity	200000	97276800	179.086
UIBT	BoisdArc_RedToTrin	Opt1	Red	Trinity	123000	29606800	41.823
UIBT	Fork_SabToTri	Opt1	Sabine	Trinity	119900	27066600	48.89408
UIBT	Parkhouse_SulToTrin	Opt1	Sulphur	Trinity	112000	27786800	77.823
UIBT	Parkhouse_SulToTrin	Opt2	Sulphur	Trinity	118960	26932200	69.484
UIBT	Palestine_NecToTrin	Opt1	Neches	Trinity	111460	30993600	73.662
UIBT	Palestine_NecToTrin	Opt2	Neches	Trinity	133400	37158400	75.90405
UIBT	Fastrill_NecToTrin	Opt1	Neches	Trinity	112100	42248200	79.249
UIBT	Parkhouse_SulToTrin	Opt3	Sulphur	Trinity	108480	35541600	77.059
UIBT	Pines_CypToTrin	Opt1	Cypress	Trinity	89600	25708200	201.471
UIBT	Pines_CypToTrin	Opt2	Cypress	Trinity	87900	19227000	188.771
UIBT	Pines_CypToTrin	Opt3	Cypress	Trinity	87900	35002200	242.956
UIBT	RalphHall_SulToTrin	Opt1	Sulphur	Trinity	32940	15651200	75.252
UIBT	Columbia_NecToTrin	Opt1	Neches	Trinity	35800	16544120	80.581
UIBT	Marcoshays_GdsnToCol	Opt1	Guadsan	Colorado	1680	577162.2	354.73
UIBT	Marcoshays_GdsnToCol	Opt2	Guadsan	Colorado	1302	446339.2	353.96
UIBT	LCRASAWS_ColToGdsn	Opt1	Colorado	Guadsan	75000	1.53E+08	302.847
UIBT	LCRASAWS_ColToGdsn	Opt2	Colorado	Guadsan	18000	9598600	611.133
RIBT	AlanHenry_BrzToCol	Opt1	Brazos	Colorado	16800	17946000	130.595
UIBT	LCRABRA_ColToBrz	Opt1	Colorado	Brazos	3472	1478400	338.306
UIBT	LCRABRA_ColToBrz	Opt2	Colorado	Brazos	20928	8133600	332.11
UIBT	LCRABRA_ColToBrz	Opt3	Colorado	Brazos	1800	811400	338.667
UIBT	JoePool_TrinToBrz	Opt1	Trinity	Brazos	20000	6285380	285.891
UIBT	Bayou_TriToSan	Opt1	Trinity	SanJacinto	540000	11173010	9.269
RIBT	Bedias_TriToSan	Opt1	Trinity	SanJacinto	90700	5975025	135.303
RIBT	ETWT_SabNecToTri	Opt1	Sabine	Trinity	155646	23414010	15.6285
RIBT	ETWT_SabNecToTri	Opt1	Neches	Trinity	117305		

UIBT	Livingston_TriToSan	Opt1	Trinity	SanJacinto	59000		
UIBT	Garwood_ColToNus	Opt1	Colorado	Nueces	35000	5606400	399.931
UIBT	Garwood_ColToNus	Opt2	Colorado	Nueces	35000	471833	399.931
UIBT	Garwood_ColToNus	Opt3	Colorado	Nueces	35000	3624232	399.931

Capacity: ac-ft; FC: fixed cost ($); VC: variable unit cost ($/ac-ft)

*Source: Texas Water Development Board***, “***2006 Adopted Regional Water Plan***”**

Table 21: Return flow percentages by sector

Sector	**ag**	**ind**	**mun**	**rec**	**other**
Return flow percent (%)	0.0637	0.3358	0.5452	1	0.3358

Source: Gillig, McCarl, and Boadu (2001)

Estimation of Water Quality Parameters for Lake Kemp Texas Derived From Remotely Sensed Data

Basic Information

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Estimation of Water Quality Parameters for Lake Kemp Texas Derived From Remotely Sensed Data.

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Abstract:

Remote sensing of water quality would provide resource managers' with tools to monitor and maintain water bodies in a well-timed and cost-effective manner. The primary aim of this study was to estimate chlorophyll a, total Phosphorus (TP), and turbidity using remote sensing data derived from the Moderate Resolution Imaging Spectrometer (MODIS). Based on in situ measurements from Lake Kemp collected in June and October of 2006, and reflectance data collected from May 2001 to January 2002, spectral indicators for the above mentioned water quality parameters were calculated. Chlorophyll a and TP concentrations were quantified using the ratios of (MOD1- MOD14)/(MOD14 + MOD2) and MOD12/MOD13, respectively, which showed a linear relationship with in-situ data. Turbidity was quantified using the ratio of (MOD2 – MOD15)/(MOD13 × MOD12). Chlorophyll a and turbidity had the strongest correlation (r^2 = 0.81, r^2 = 0.82 respectively) with in situ measurements, while TP had the lowest correlation (r^2 = 0.56). Maps for chlorophyll a distribution as well as for TP and turbidity were generated from MODIS data.

Introduction

Inland water bodies are considered important ecological and sociological zones. Many lakes (natural and man-made) and rivers are the main sources for drinking water as well as for agricultural usage. According to Brooks et al. (2003) water quality standard refers to the physical, chemical, or biological characteristics of water in relation to a specific use.

Protection and maintenance of water quality is a primary objective for watershed or resource managers. Increase of chlorophyll a, turbidity, total suspended solids (TSS) and nutrients in lakes are symptomatic of eutrophic conditions (Shafique el al. 2002). Sediments also affect water quality and thus its suitability for drinking, recreation and other activities. It serves as a carrier and storage agent for nitrogen, phosphors and organic compounds that can be indicators of pollution (Jensen 2000).

The traditional measurement of water quality requires in situ sampling, which is a costly and time-consuming effort. Because of these limitations, it is impractical to cover the whole water body or obtain frequent repeat sampling at a site. This difficulty in achieving successive water quality sampling becomes a barrier to water quality monitoring and forecasting (Senay et al. 2001). It would be advantageous to watershed managers to be able to detect, maintain and improve water quality conditions at multiple river and lake sites without being dependent on field measurements (Shafique el al., 2002).

Remote sensing techniques has the potential to overcome these limitations by providing an alternative means of studying and monitoring water quality over a wide range of both temporal and spatial scales. Several studies have confirmed that remote sensing can meet the demand for the large sample sizes required for water quality studies conducted on the watershed scale (Senay el al., 2001). Hence, it is not surprising that a significant amount of research has been conducted to develop remote sensing methods and indices that can aid in obtaining reliable estimates of these important hydrological variables. These methods ranged from semi-empirical techniques to analytical methods for estimating and producing quantitative water quality maps.

Several researchers have developed regression formulas to predict several lake water quality parameters from satellite data by employing spectral ratios or indices. These water quality parameters have included chlorophyll a concentration, suspended matter concentration and turbidity.

In nature the upwelling radiance from lakes or rivers is the combination of all the constituents of the water column, that includes suspended organic, inorganic, and pigment (Han and Rundquist, 1997). The bottom of the shallow water can also contribute to the radiance leaving the water. Hence, determining which signal is attributable to a particular water quality parameter is not an easy task (Han and Rundquist, 1997). In general, the optics of water–sediment mixtures are highly nonlinear, while many factors such as suspended particle size, shape and color can have large influences on water–sediment optics (Warrick et al., 2004). Due to these optical complexities it is well known that there are no universal algorithms to remotely estimate sensed sediment concentrations (Warrick et al., 2004).

However, differentiating the influence of suspended sediment concentrations (SSC) and chlorophyll a on spectral reflectance characteristics when using coarse spectral resolution imagery such as Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) remains problematic (Svab et al., 2005). Lindell et al. (1999) concluded that chlorophyll a determination is not possible when SSC increases and is heterogeneously distributed.

Tyler et al (2006) used a mixed model to derive chlorophyll a concentration in lakes using Landsat TM images. Linear regression models were developed to estimate total suspended matter concentrations using Landsat TM data (Zhou et al., 2006). In addition, Svab et al. (2005) concluded that spectral mixture modeling can be used to estimate chlorophyll a concentration in water with high heterogeneous SSC distribution.

The purpose of this study was to estimate chlorophyll a concentration, total Phosphorus concentration, and turbidity using spectral indices. Spectral indices developed by Shafique et al, 2002 for hyperspectral data were modified in order to make them suitable for use with multispectral remote sensing, specifically the Moderate Resolution Imaging spectrometer (MODIS) onboard NASA's 'Terra' and 'Aqua' Earth observation satellites. We tested these modified indices to Lake Kemp, Texas. This included determination of the optical properties of the water parameters mentioned above and selection of spectral bands that are used in the indices. Remote sensing data were validated with field measurement to test the accuracy of the indices. The final objective was to present and provide sequential and spatial images of water quality estimates to provide decision makers with easily applicable information.

Materials and Methodology

Study area: Lake Kemp is located on Wichita River north of Seymour in Baylor County, Texas (Fig.1). It covers an area of 15,590 acres with a maximum depth of 53 feet, has a depth fluctuation of 6-8 feet annually and 4-6 feet depth visibility. The annual precipitation is 24 inches/year, average temperature is 63^{o} F and the elevation is 1,114 ft above mean sea level.

Data: We utilized MODIS imagery from May 2001 to January 2002, covering two periods of the dry and wet seasons for Lake Kemp, for our initial model development. Based on previous studies and spectral analysis, five MODIS reflectance bands were used in this study. Concurrent limnological data, collected by Wilde (2003) was used. These limnological data include chlorophyll a, total phosphorus and turbidity measurements collected from Lake Kemp during 2001-2002. MODIS data were available on a daily basis, and free for research use. After the initial development of 'spectral reflectance vs. limnological parameters' relationships, we collected data in June and October of 2006 to validate and refine our models. Five samples with three replications were collected from the lake during that period.

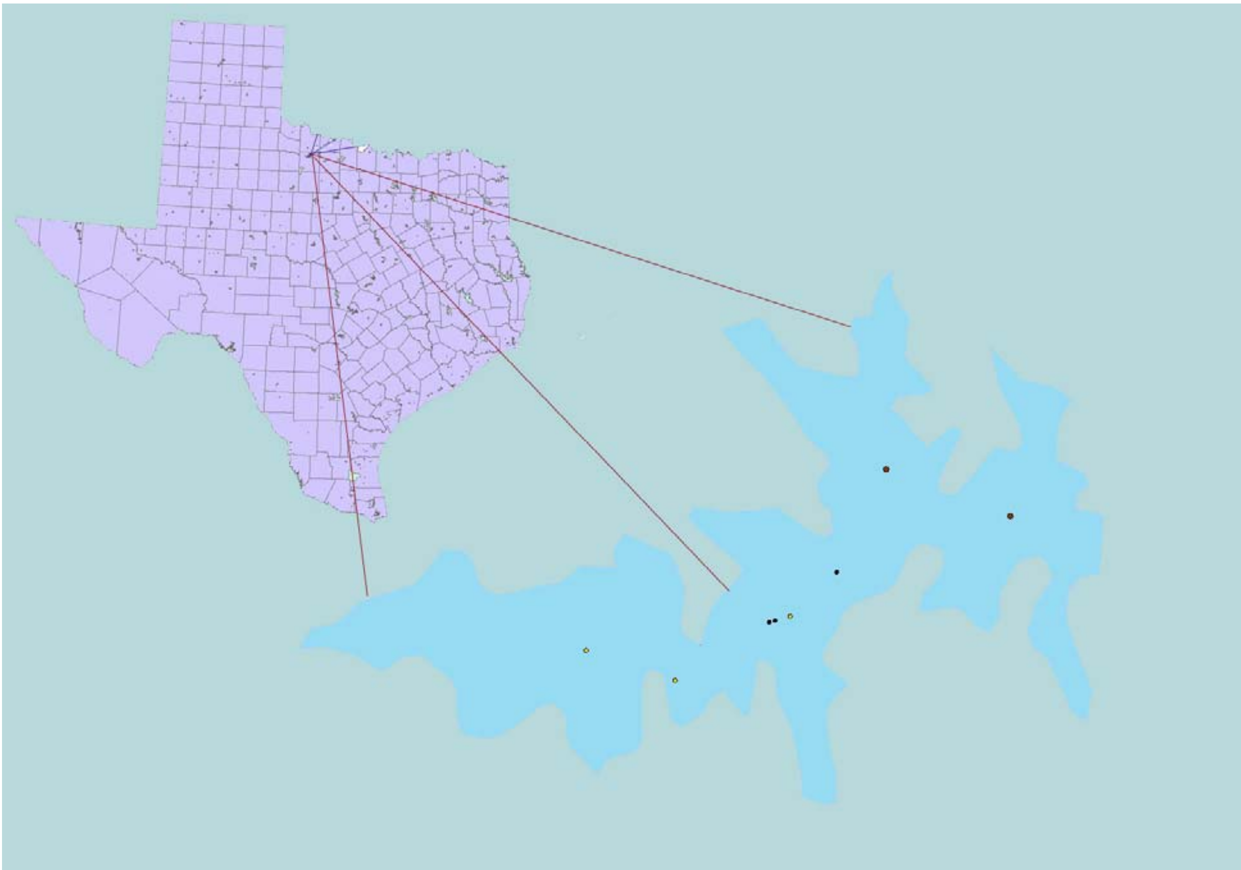

Fig.1. Map of the Lake Kemp, Baylor County, Texas showing where the samples were collected. The red circles represent samples that were collected on June and October. The yellow circles represent samples collected in June. The black circles represent samples collected in October.

Criteria of MODIS Band Selection:

The reflectance of a water body depends upon absorption and scattering of incoming radiation. This absorption and scattering is a function of the material present in the surface water (Senay et al., 2001). According to Jenson (2000), visible wavelengths between 580 – 690 nm may provide information on the type of suspended sediment in the surface water, while the near-infra red wavelength range of 714 – 880 nm can be useful for determining the amount of these materials. In addition, Gitelson (1992) and Rundquist et al. (1995) found that strong chlorophyll a absorption of red light is approximately at 675nm and the predominant reflectance peak is around 690 – 700nm. Thus the height of this peak above the baseline (670 – 750nm) can be used to measure chlorophyll amount (Rundquist et al., 1995).

Mittenzwey et al. (1992) found a high coefficient of determination (r^2) of 0.98 between chlorophyll a and the near-infrared (NIR)/red reflectance ratio (Sited in Han and Rundquist, 1997). Han and Rundquist (1997) and Rundquist et al. (1996) estimated the chlorophyll a pigment amount in surface water using the ratio of near-infra red (705nm)/ red (670nm) ratio when the concentration was low. On the other hand, the best result was derived from reflectance around 690nm when chlorophyll a concentration was high. Regions of the spectrum at wavelengths near 450-550nm, 675-750nm and 800-1000nm were found to be good estimators of turbidity (Senay et al., 2001).

Model Development:

Based on these above-mentioned assumptions, this study proposed modification of water quality indices developed using hyperspectral remote sensing by Shafique et al., (2002) to make them useable with multispectral sensors. The indices proposed by Shafique et al., (2002) were:

$$chlorophyll\ a = 48.849(R_{705} \div R_{675}) - 34.876 \quad (1)$$

$$Total\ Phosphorus\ (TP) = 0.18081 \times \log(R_{554} \div R_{675}) - 0.0371 \quad (2)$$

$$Turbidity = 186.59(R_{710} - R_{740}) + 8.5516 \quad (3)$$

where R is the reflectance at the spectral wavelength (nm) expressed by the subscript number.

We used reflectance values of MODIS bands #13 (662 – 672nm) and #14 (673 – 683nm) to estimate chlorophyll *a* concentration, #15 (743 – 753nm) and #16 (862- 877nm) to estimate turbidity, and #14 (673 – 683nm) and #12 (546 – 556nm) to estimate total phosphors (TP). Hence, the water quality indices modified for MODIS bands were proposed as:

$$chlorophyll\ a = 48.849(b14 \div b13) - 34.876 \tag{4}$$

$$Total\ Phosphorus\ (TP) = 0.18081 \times \log(b12 \div b14) - 0.0371 \tag{5}$$

$$Turbidity = 186.59(b16 - b15) + 8.5516 \tag{6}$$

where b and the subsequent numerals stand for MODIS band numbers.

Chlorophyll a, turbidity and total phosphorus were calculated using the indices 4, 5 and 6 and then correlated with the data collected in 2001. This analysis was performed in order to examine their capability to estimate water quality parameters using MODIS data. Low correlation between the indices 4, 5 and 6 and MODIS data was detected. The analysis of this correlation was the first step in the process to develop new indices and to validate them using the data collected in 2006.

Single spectral bands, ratios of bands, and combination of multiple bands were used to develop the indices. Scatter plots were created between spectral bands and ground truth data and spectral bands of interest against each other. Simple linear regression was used to determine the relationship between single and combinations of bands and water quality parameters. Then, the entire images were converted to water quality maps based on the indices developed.

MODIS reflectance bands 1 to 16 were used to test for relationship with water quality parameters to determine which bands and parameters correlated the most with better certainty. Scatter plots showed that the ratio of (b2 – b15)/ (b12 × b13) and (b1 – b14)/ (b14 + b2) can be used to estimate turbidity and chlorophyll a respectively. The ratio of b12/b13 was the best indicator for total Phosphorus. Also, it was found that MODIS b12 correlates well with b15 (r^2 = 0.57), and b13 and b4 correlated strongly (r^2 = 0.76). In the case where no data were available for b13 and b15 such as for June 2006, b4 and b12 were used instead. Hence, the new indices developed for this study were:

$$chlorophyll\ a = ABS[(b1 - b14)]/(b14 + b2) \quad (7)$$

$$Total\ Phosphorus\ (TP) = b12/b13 \quad (8)$$

$$Turbidity = ABS[(b2 - b15)]/(b12 \times b13) \quad (9)$$

where ABS[] indicates the absolute value.

Results

The evaluation of the band selection criteria led to the selection of particular bands that were used to developed spectral indices for the estimation of the desired water quality parameters. The correlation between MODIS developed indices and ground measurements varied between water quality parameters and seasons.

The values for the water quality parameters were higher in the dry season (October) compared to the wet season (June). Chlorophyll a was stable between the two seasons (mainly higher values in October) ranging from 6 - 10 ug/l, whereas turbidity showed huge variation from a mean of 0.114 NTU in June to 23.46 NTU in October. This variation was coupled with increase in TP variation and values from a mean of 0.05 mg/l in June to a mean of 0.06 mg/l in October.

The ratio of bands 1, 2, and 14 as shown in equation 7 produced a good correlation (r^2= 0.82) with chlorophyll a concentration in October 2006 (Fig.2). Where as, a week correlation (r^2= 0.3) was observed between the same index and chlorophyll a concentration in June 2006 (Fig.2). Turbidity and the ratio of bands 2, 12, 13, and 15 (equation 8) correlated strongly (r^2 = 0.72 and r^2 = 0.82) for both June and October 2006 respectively (Fig.3). The ratios of b12 and b13 had a good correlation (r^2 = 0.56) with TP in October of 2006, while the correlation was week (r^2 = 0.3) for June 2006 (Fig.4). Thus, TP had the weakest correlation with MODIS bands.

The MODIS images were transformed to water quality parameters maps by using the indices developed. This was done pixel by pixel through the development of modules using ERDAS Imagine software. The results were six maps for chlorophyll a, turbidity, and TP for both June and October. The spatial distributions of chlorophyll a showed variation between the wet and the dry seasons. The highest values can be observed on the north to north east of the lake (Fig.4 and Fig.5).

Meanwhile, Turbidity and TP had many pixels of missing data for the lake in June and October respectively. TP spatial distribution (June) was some how similar through out the lake with the highest values in the northwest of the lake (Fig. 6). This spatial distribution for TP can be detected in October especially in the west parts of the lake, in spite of the large number of missing data (Fig.7). On the other hand, the spatial distribution for turbidity showed a significant variation between June and October (Fig.8 and Fig.9). Moreover, the spatial variation within the lake was more obvious in October compared to June (Fig.8 and Fig.9). Turbidity was higher in the east and south of the lake compared to the north and west parts of the lake (Fig.8 and Fig.9).

Discussion and Conclusion

Lake Kemp experienced enormous fluctuation in water level during the study period, especially in the east part of the lake. On October 15, Lake Kemp received 82.5 mm of rainfall in one event (data from Lake Kemp weather station available on NOAA website: http://cdo.ncdc.noaa.gov/pls/plclimprod/somdmain.somdwrapper?datasetabbv=DS3220&countryabbv=US&georegionabbv=&forceoutside=), which is about one week prior to the samples collection.

Regardless of that, the water level in the lake was extremely low where the east part of the lake was approximately dry.

Our results revealed that there was an increase in turbidity values from June to October, which can be related to the extreme rainfall event mentioned above. Also, this sudden increase can be associated with high erosion event that characterized Wichita River drainage (Lake Kemp is a moderately large impoundment of Wichita River) (Greiner 1982, cited in Wilde, 2003). Most of the erosion (71%) in the basin is sheet and rill erosion, both of which are associated with overland runoff following rain events (Wilde, 2003). Over land flow caused by rainfall is considered one of the non-point sources that cause turbidity to increase (Senay et al., 2001). On the other hand, chlorophyll a and TP concentration were similar in both the dry and the wet season.

Apparently, the variation within the lake in water quality parameters values might have an effect on the correlation between those parameters and the indicators developed from MODIS data. This is noticeable through the comparison of the correlations for both June and October. The negative relation between turbidity and equation 9 in June might be related to the fact that band 15 was replaced by band 12 and that there exist a negative correlation between these two bands. Meanwhile, the result for the data collected for TP in June were constant across the lake (0.05 mg/l), thus 4 out of the 5 samples collected had the same value. This might be one of the reasons why the correlation could not be established between TP and equation 8 in June. Another reason could be related to sampling size limitations where 5 samples might not be enough to detect changes in Lake Kemp TP during that period where there might be a little variation in TP values.

Limited number of pixels (10 out of 442 pixels) for band 14 that had data in the June image might have contributed to the week correlation between chlorophyll a and the MODIS data. Moreover, there was a little variation in the chlorophyll a ground data in June compared to October and that might also caused that week correlation. Hence, this reveals the ability for the MODIS sensors to detect variation in water quality parameters during times when there exist variations within those parameters across the lake.

Mapping the water quality spectral indices revealed the ability of these indices to detect spatial and temporal variation in chlorophyll a, turbidity, and TP. For instance, higher values of turbidity can be observed beside the lakeshores (especially the south part), where most of the residential areas are located and the east side where Wichita River enters the lake. The higher values for chlorophyll a in the east and north parts of the lake can be related to the presence of aquatic plants. In addition, the spatial distribution for the calculated turbidity has east to west gradient that is consistent with the results for Lake Kemp limnological report by Wilde, 2003.

The study demonstrated a procedure for estimating and mapping specific water quality parameters for inland water using MODIS data. This was done through the development of water quality spectral indices and applying them to the MODIS data. Based on this study, we think chlorophyll a, turbidity, and TP of lake Kemp can be estimated and mapped using MODIS data. These methods may also be applied to estimate water quality parameters for other inland water bodies. Our results indicated that chlorophyll a (more than turbidity or TP) has a unique spectral signature that makes it possible to develop spectral indices to estimate its concentrations in lakes.

Mapping the spatial distribution for chlorophyll a, turbidity, and TP with remotely sensed data would be helpful for management of water bodies by determining the point and non point sources that are responsible for such spatial variability. Thus, we conclude that remote sensing can potentially be used as a tool for monitoring water quality throughout the seasons and thus provide natural resource managers and decision makers a crucial information. Future research should focus more on the use of remotely sensed data to estimate seasonal variations in water quality parameters.

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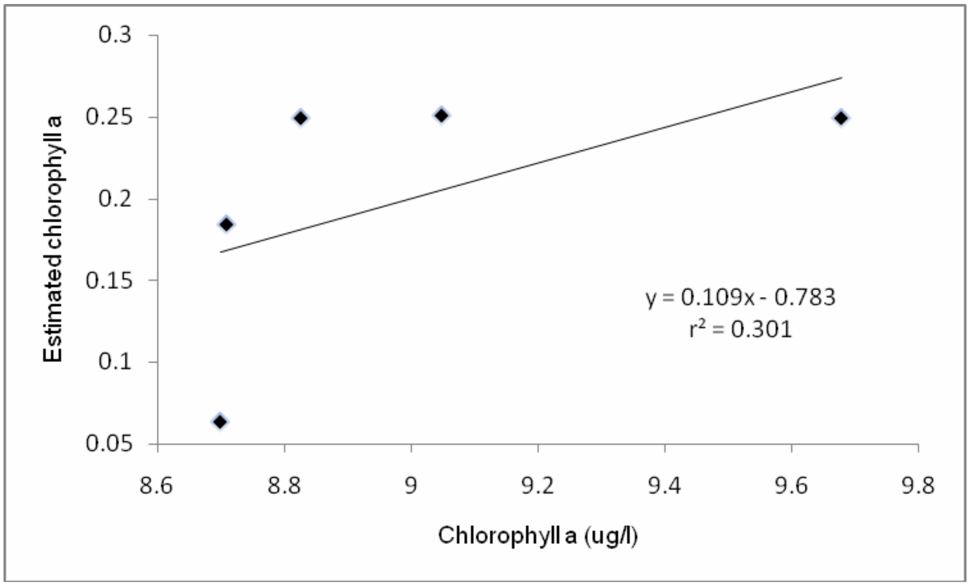
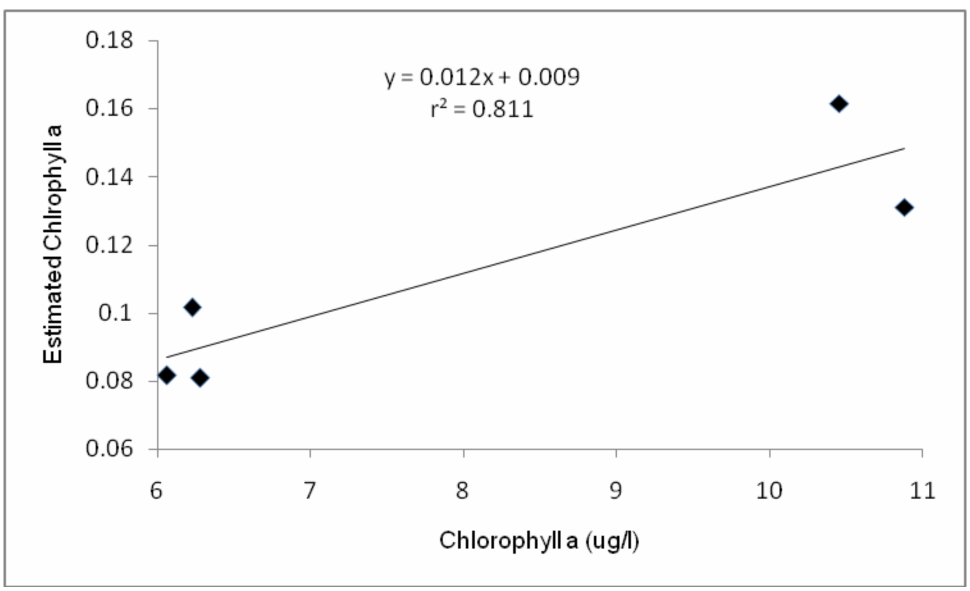
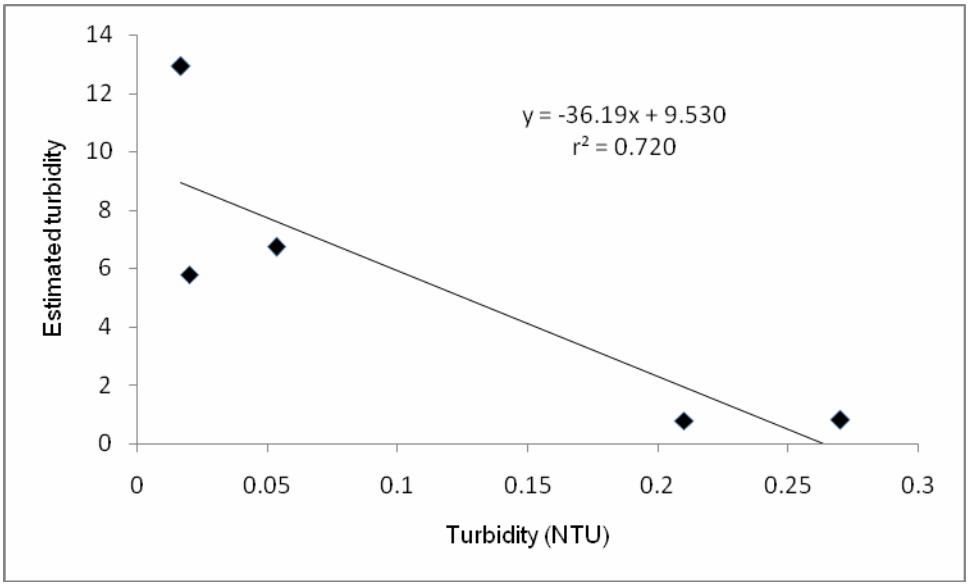


(a)



(b)

Fig.2. Observed and estimated chlorophyll a for (a) June , (b) October.



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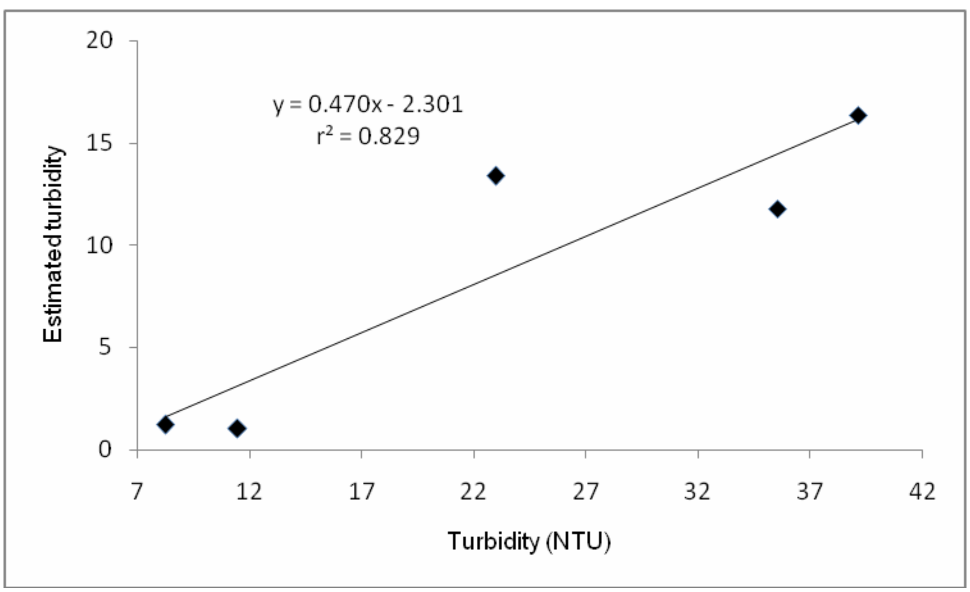
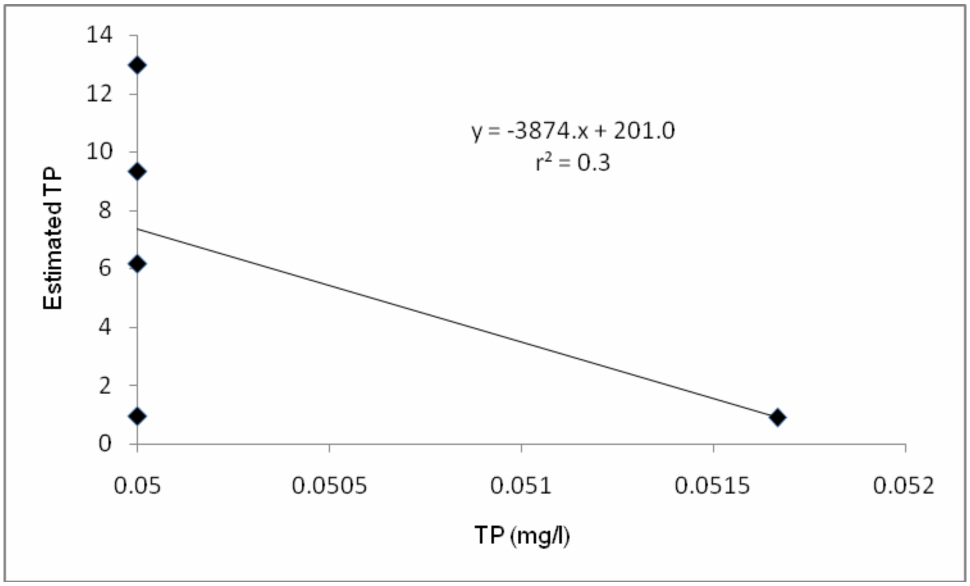


(b)

Fig.3. Observed and estimated turbidity for (a) June, (b) October.



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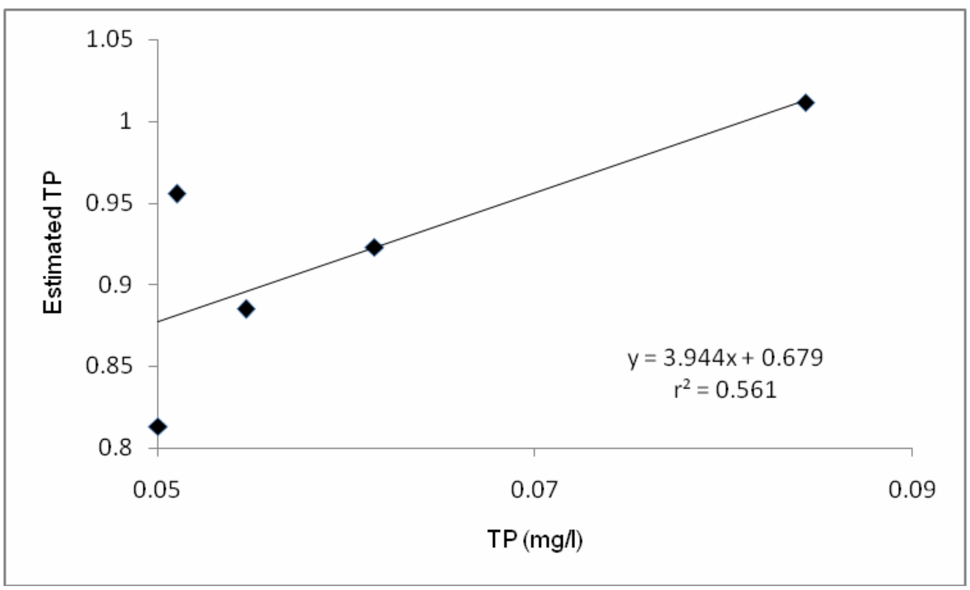

(b)

Fig.3. Observed and estimated total phosphorus (TP) for (a) June, (b) October.

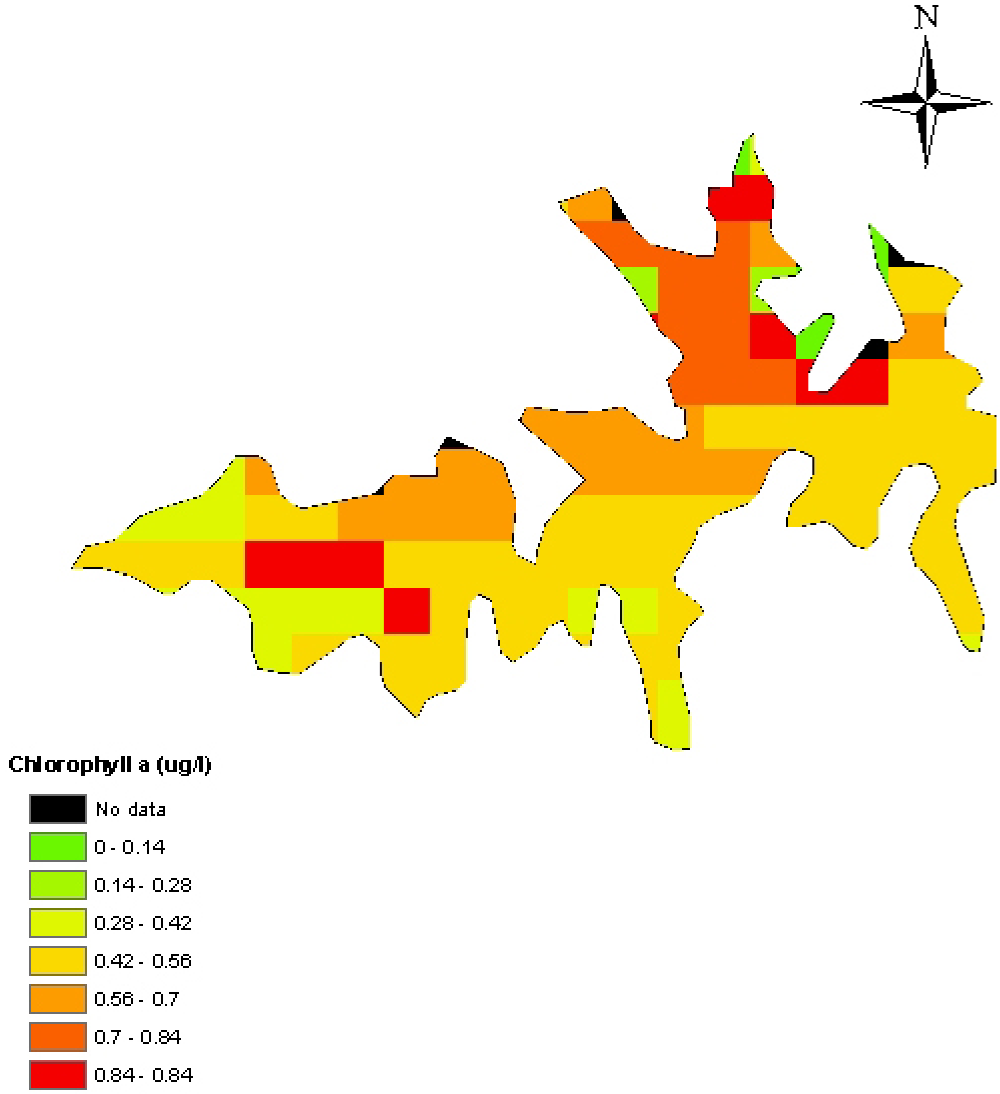

Fig.4. Chlorophyll a map for lake kemp for June 2006.

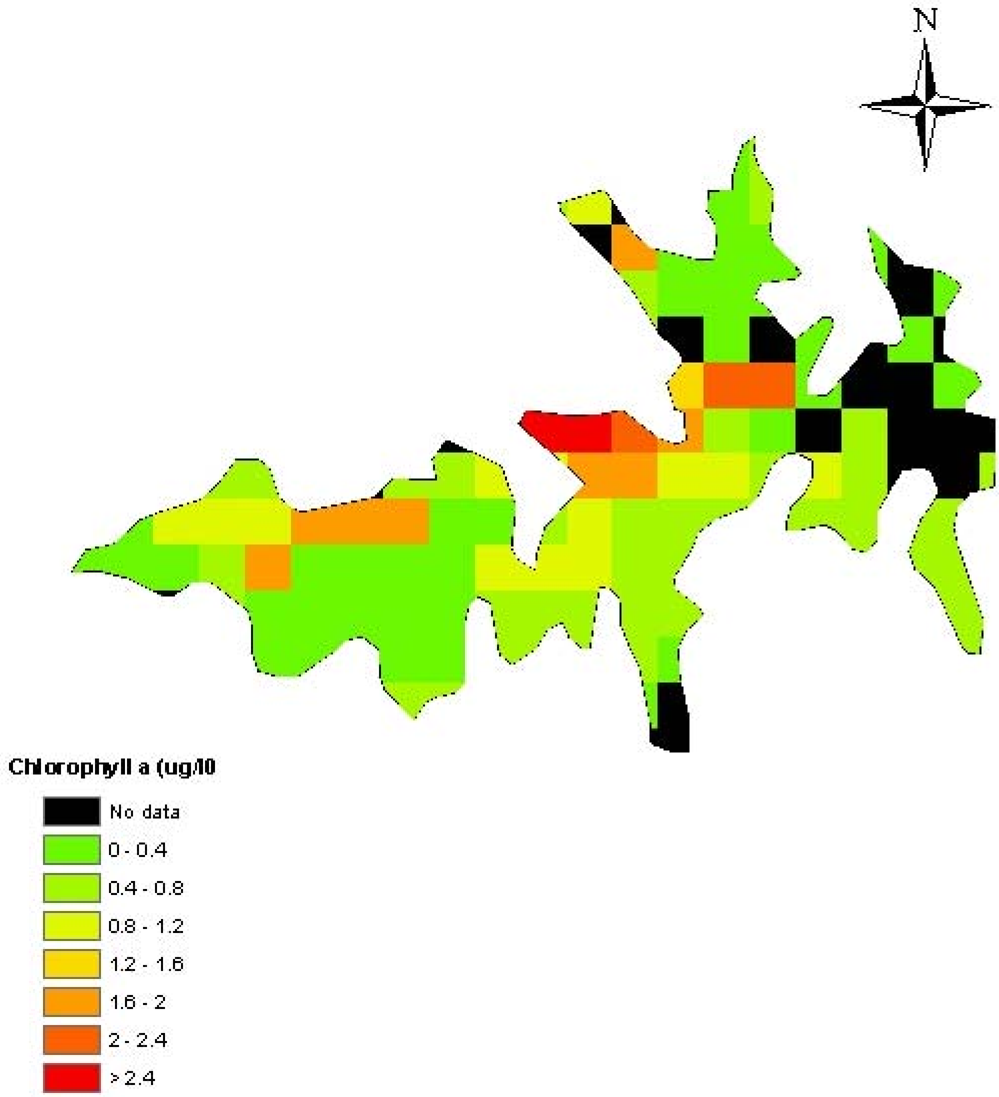

Fig.5. Chlorophyll a map for Lake Kemp for October 2006.

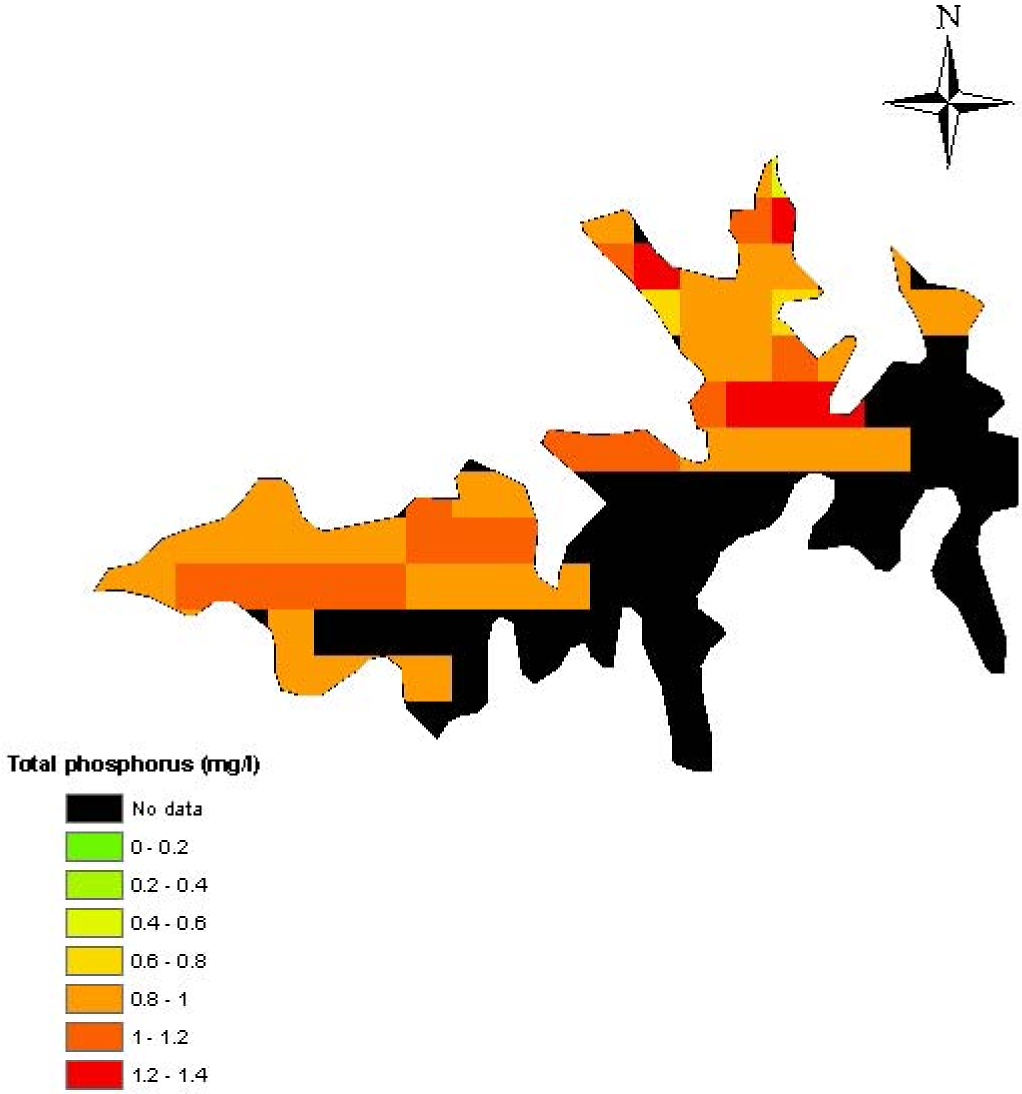

Fig.6. Total Phosphorus (TP) map for Lake Kemp for June 2006.

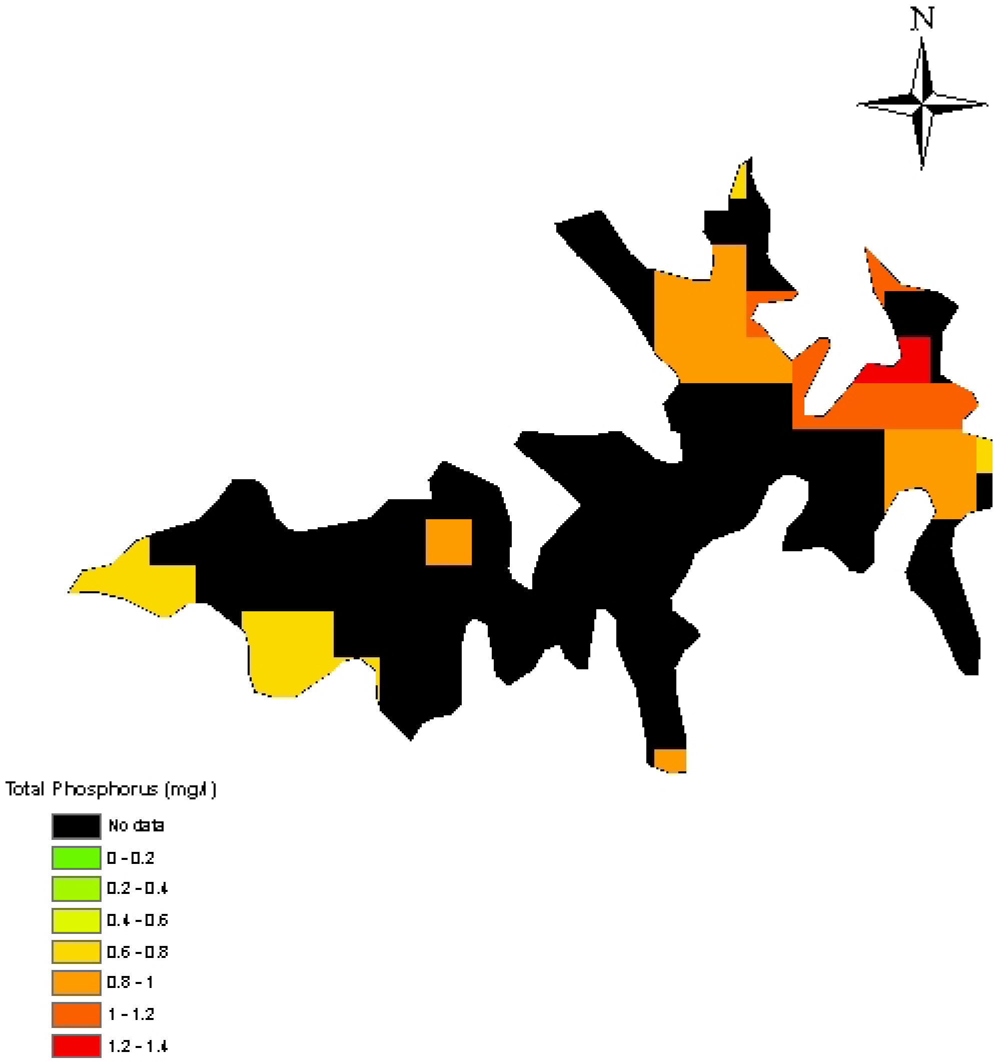

Fig.7. Total Phorsphorus (TP) map for Lake kemp for October 2006.

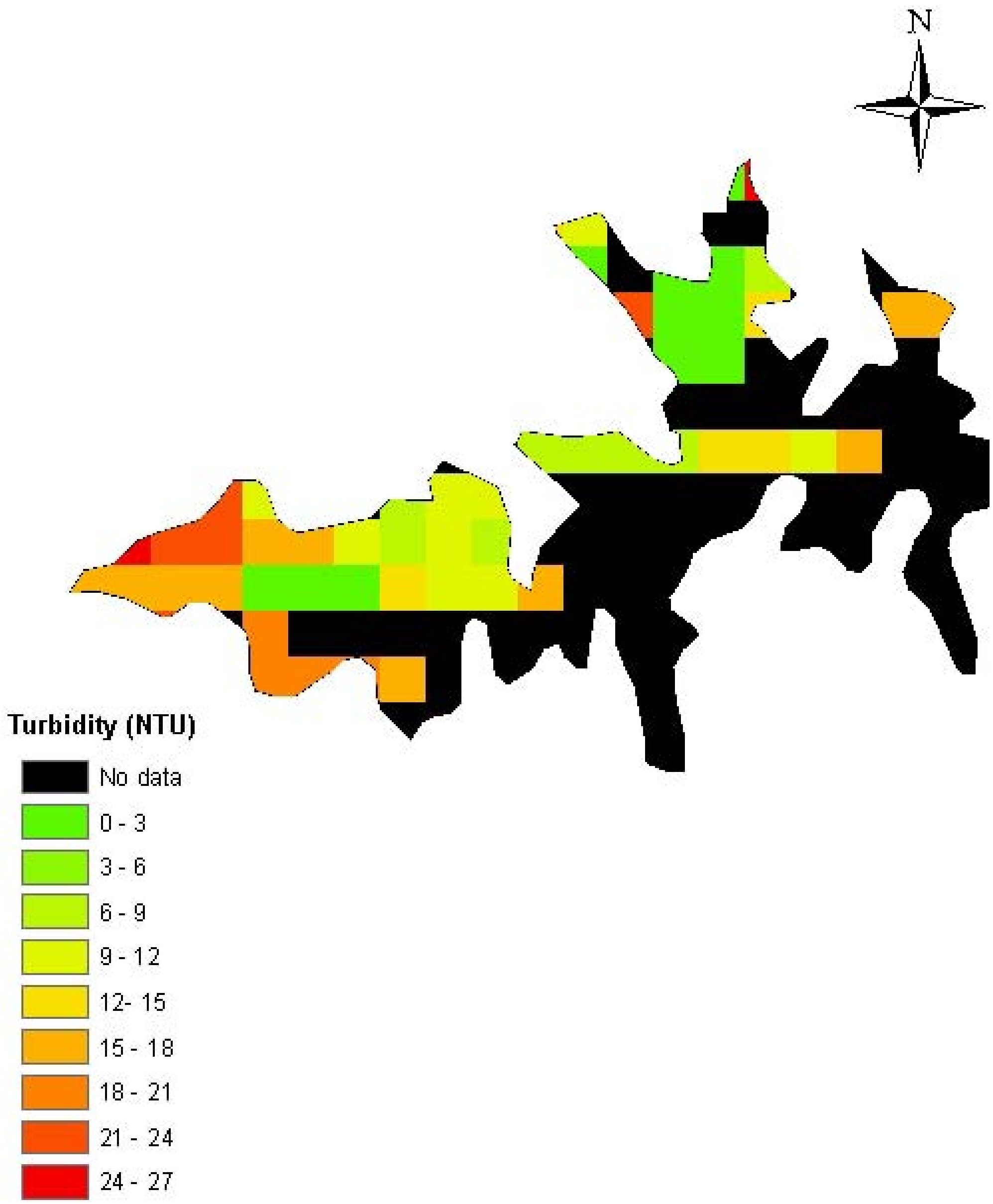

Fig. 8. Turbidity map for Lake Kemp for June 2006.

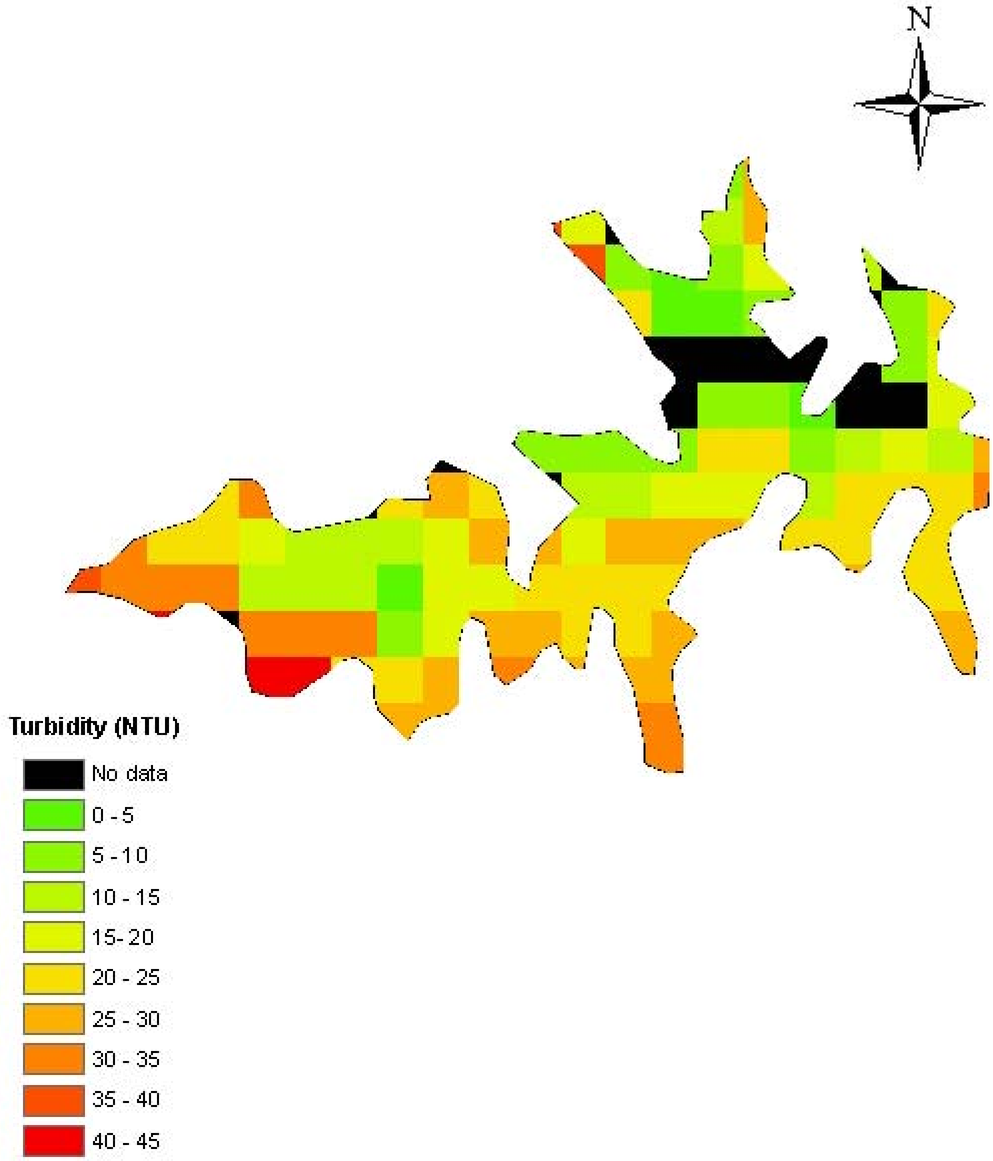

Fig.9. Turbidity map for Lake Kemp for October 2006.

Arsenic Removal by Novel Nanoporous Adsorbents-Kinetics, Equilibrium, and Regenerability

Basic Information

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- Kinetics, Equilibrium, and Regenerability -

Submitted to
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ABSTRACT

Arsenic contamination in groundwater is of major concern to many water treatment facilities in the world. Various treatment technologies have been applied to remove arsenic from drinking water. Among them, adsorption processes are often considered to be most effective forms of treatment for As(V), but they can be limited in their ability to remove As(III). To enhance removal efficiency of adsorption process for As(III) as well as As(V), this study has focused on developing highly ordered mesoporous silica solid (SBA-15) that can incorporate reactive titania sorption sites ($Ti_{(x)}$-SBA-15), and on synthesizing nanoporous titania (NT). XRD results showed that both $Ti_{(25)}$-SBA-15 and NT synthesized had surface property of anatase (TiO_2). From nitrogen adsorption/desorption tests, mesoporosity of these solids were observed by showing hysteresis loops which is representative of Type IV isotherm. However, TEM images showed that SBA-15 and $Ti_{(25)}$-SBA-15 have highly ordered hexagonal mesoporosity and titania nanostructured mesopores. However, NT has disordered wormhole-like mesopores that are caused by interparticle porosity. Based on q_{max} (μmol As/g) in the Langmuir isotherm, $Ti_{(25)}$-SBA-15 had more sorption capacity for As(III) than did $Ti_{(15,35)}$-SBA-15. It was also observed by FT-IR analysis that the peak intensity of the silanol (Si-OH) peak at 960 cm^{-1} was stronger for $Ti_{(25)}$-SBA-15. This indicates that $Ti_{(25)}$-SBA-15 has not exceeded its capacity to incorporate Ti. The rates of arsenic uptake were very fast and followed a bi-phasic sorption pattern where sorption was fast for the first 10 minutes, and then slowed until being almost completed within 200 minutes of contact. The Langmuir isotherm more accurately fitted experimental sorption data than did the Freundlich model. The order of maximum As(III) sorption capacity was NT (162 μmol/g) > $Ti_{(25)}$-SBA-15 (87 μmol/g) > $Ti_{(35)}$-SBA-15 (76 μmol/g) > $Ti_{(15)}$-SBA-15 (60 μmol/g). The order of sorption capacity for As(V) was NT (pH 9.5, 285 μmol/g) > NT (pH 7, 162 μmol/g) > $Ti_{(25)}$-SBA-15 (pH 4, 121 μmol/g) > $Ti_{(25)}$-SBA-15 (pH 7, 87 μmol/g) > NT (pH 4, 66 μmol/g) > $Ti_{(25)}$-SBA-15 (pH 9.5, 60 μmol/g). Distinct sorption maxima for As(III) removal were observed between pH 8 and pH 11 for NT and between pH 4 and pH 7 for $Ti_{(25)}$-SBA-15. The amount of As(V) adsorbed generally decreased as pH increased.

1. Introduction

Arsenic contamination in groundwater is serious threat to human health because of its toxicity and carcinogenicity. Arsenic contamination is found in many countries and has been caused by use of arsenical pesticides, activities related to mining, fallout from the atmosphere, and natural geologic weathering process [*1*]. In the US, arsenic has been ranked as the contaminant that poses the greatest risk to human health based on frequency of occurrence at NPL sites, toxicity, and potential for human exposure [*2*]. The toxicity and carcinogenicity of arsenic have compelled regulatory agencies in many countries to consider standard levels for arsenic in drinking water that are less than 10 ppb. Therefore, enhanced arsenic removal technologies are needed to meet these stringent standards for drinking water and to meet related standards for wastewater effluents.

Arsenite (As(III)) and arsenate (As(V)) are the oxidation states of arsenic that are generally found in subsurface environments. The distribution between different species of each valence state depends primarily on pH. Arsenous acid (H_3AsO_3) has pK_a values at 9.22, 12.13 and 13.40 while arsenic acid (H_3AsO_4) has pK_a values of 2.20, 6.97, and 11.53. In reduced environments at pH in the typical environmental pH range, nonionic arsenous acid (H_3AsO_3) is the primary species of arsenic [*3*]. In oxidized environments, on the other hand, two ionic arsenate species ($H_2AsO_4^-$ or $HAsO_4^{2-}$) exist, depending on the pH. Specifically, arsenite is more mobile, more toxic, and more difficult to remove due to its electro-neutrality.

The commonly applied processes for arsenic removal are chemical precipitation, co-precipitation, reverse osmosis, ion exchange, and oxidative filtration [*3*]. Adsorption is considered to be the most promising process, because of its safety, ease of handling and set-up, high removal efficiency with low cost, and potential for regeneration of materials [*4*]. Despite their wide availability, adsorption process may not be able to decrease As(III) concentrations to acceptable levels because of their physical limitations, although they are lowering As(V) concentration to acceptable levels. Traditional adsorbents have a relatively low density of surface sites with an affinity for As(III), which leads to low removal efficiency. Also, their irregular physical structure makes it difficult for arsenic to easily access internal sorption sites. To overcome these disadvantages, this study proposed novel nanostructured adsorbent media for removal of both As(III) and As(V).

Nanostructured mesoporous materials studied in this research project are widely used in many industries because they have improved physical, chemical, and biological properties. These solid materials include an ordered structural frame work, high surface area, high density of surface functional groups, large pore volume, and the ability to incorporate catalytic components [*5-7*]. Nevertheless, applications of mesoporous materials to environmental technology have not been studied extensively. Therefore, the purpose of this study is to develop highly ordered nanostructured mesoporous adsorbents (NMAs) for removing both As(III) and As(V) from water to low concentrations. Two types of NMAs were produced and characterized. The characteristics of these NMAs for sorption of As(III) and As(V) were evaluated by kinetic and equilibrium tests.

2. Methodology

2.1 Synthesis of nanostructured mesoporous adsorbents (NMAs)

2.1.1 Mesoporous silica molecular sieves (SBA-15)

SBA-15 was synthesized by modifying the procedure described by Zhao et al [*8*]. A portion (4 g) of Pluronic P123 triblock copolymer (poly(ethylene oxide)-poly(propylene oxide)-poly(ethylene oxide), $EO_{20}PO_{70}EO_{20}$, Aldrich) was dissolved in 2 M HCl solution and mixed for 30 minutes at room temperature. Then, 9 mL of tetraethyl orthosilicate (TEOS) were added and the mixture stirred using a rotary mixer for 20 hours at 45 °C. The resulting gel was allowed to age for 48 hours at 80 °C. The solid product was then filtered from the mixture with a 0.45 µm filter, washed with distilled water, and dried at room temperature. Finally, the solid was calcined at 550 °C for 6 hours to remove the polymer. Figure 1 shows synthesis procedure of SBA-15.

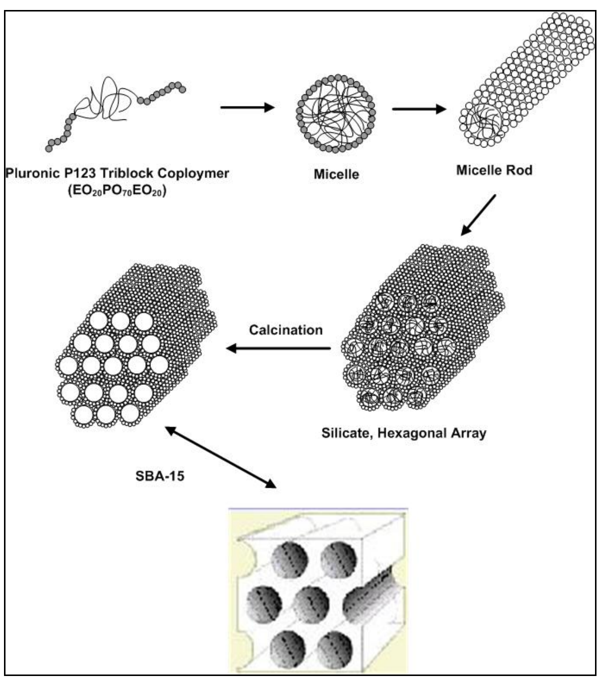

Figure 1. Schematic diagram for SBA-15 synthesis procedure

2.1.2 Nanoporous titania incorporated with SBA-15 ($Ti_{(x)}$-SBA-15)

Titanium was grafted on SBA-15 by following the general incipient impregnation method [*9*]. First, 1 g of SBA-15 was pretreated at 120 °C for 3 hours to remove adsorbed water. The pretreated SBA-15 was dispersed in 100 mL of anhydrous solvent (i.e., ethanol or isopropyl alcohol, Aldrich 99.8 %) and then the appropriate amount of titanium isopropoxide ($Ti(OPr)_4$, Aldrich, 97 %) was slowly added to achieve the desired loading of titanium. The mixture was stirred for 24 hours, followed by filtration and washing with ethanol. Then, the resulting solids were dried at 90 °C for 3 hours and finally calcined in furnace at 550 °C for 6 hours. The NMA produced was identified as "$Ti_{(x)}$-SBA-15", where the subscript x stands for the weight ratio of Ti to SBA-15.

2.1.3. Nanoporous titania (NT)

Nanoporous titania (NT) adsorbent was prepared with the procedure described by Huang et al [*10*]. A portion (6.65 mL) of titanium (IV) butoxide was added to ethanol as an anhydrous solvent with a weight ratio of 1/7 and then the system was vigorously stirred. After 30 min, 0.96 mL of 0.28 M phosphoric acid was added and stirred for 3 hours. Then, 72.4 mL of distilled water was added, the mixture was continuously stirred for 2 hours, and vaporized at 80 °C by an evaporator. The resulting solids were washed with ethanol, dried at 80 °C for 6 hours, and calcined at 550 °C for 6 hours. Figure 2 shows the synthetic final products for SBA-15, Ti-SBA-15, and NT.

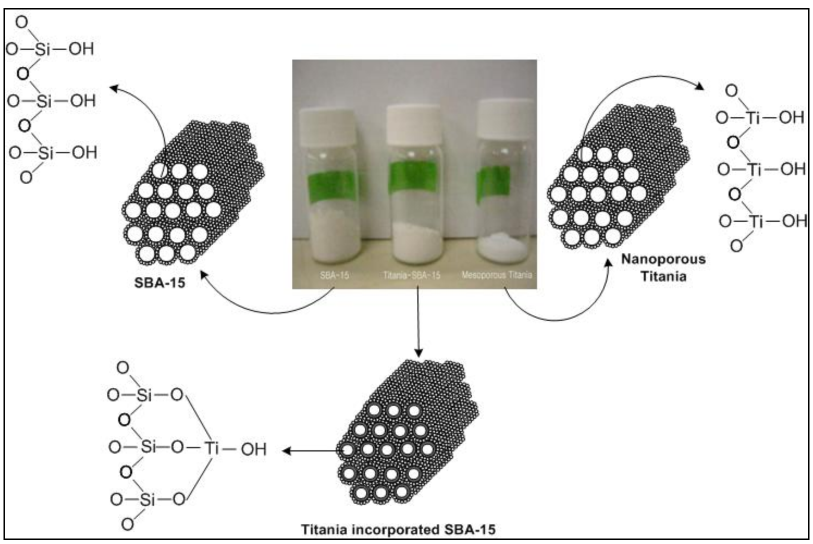

Figure 2. Schematic diagram of SBA-15, Ti-SBA-15, and NT

2.2 Kinetics experiment

Kinetic experiments for As(III) and As(V) uptake were performed by using a solids concentration of 1 g/L at pH 4, 7, and 9.5 in a solution of NaCl as background electrolyte to give an ionic strength of 0.01 M. The suspension was mixed for 2 hours and then that amount of arsenic stock solution was added to achieve an initial arsenic concentration of 13.3 μM. The desired initial pH was adjusted by adding 0.5 M HCl or 0.5 M NaOH. The reaction vessel was mixed by a reciprocal shaker with 200 rpm to promote arsenic uptake. At specified sampling times, approximately 10 mL of solid suspension was filtered by cellulose nitrate membrane filter (Whatman®) with a pore size of 0.2 μm. Approximately 12 samples were taken over the time period of 5 min to 1 day. All filtered samples were placed into an anaerobic chamber to avoid arsenic oxidation or pH change until atomic absorption spectroscopy (AAS) analysis.

2.3 Equilibrium experiment

Equilibrium experiments were conducted to evaluate sorption capacity of each adsorbent for As(III) and As(V). To start each equilibrium test, 10 mL of 2 g/L of adsorbent suspension was added to 20 mL of reaction vessels and then 10 mL of a mixture of de-ionized water and arsenic stock solution (200 ppm) was added to reach a solid concentration of 1 g/L and specified initial arsenic concentration. The desired pH was adjusted using 0.5 HCl or 0.5 M NaOH. The reaction vessels were mixed by a reciprocal shaker at 200 rpm. After 24 hours of reaction, all samples were filtered using cellulose nitrate membrane filter (Whatman®) with pore size of 0.2 μm. All filtered samples were placed into an anaerobic chamber to avoid arsenic oxidation or pH change until atomic absorption spectroscopy (AAS) analysis. In order to describe arsenic removal onto solids, two equilibrium isotherms were applied to the experimental data. One is the Langmuir model, which can be represented by

$$q_e = \frac{q_{\max} b C_e}{1 + b C_e} \qquad (1)$$

Where q_e is the equilibrium concentration of target compound on the solid (μmol/g), q_{max} is maximum concentration of target compound on the solid (*i.e.*, maximum sorption capacity, μmol/g), b is the Langmuir isotherm parameter (L/μmol). The other model is the Freundlich isotherm.

$$q_e = k_f C_e^{1/n} \qquad (2)$$

Where k_f is the Freundlich constant that is related to the capacity of adsorbent to adsorb adsorbate ($\mu mol^{1-1/n} \cdot L^{1/n}/g$) and n is also the Freundlich constant that expresses the affinity of adsorbate to the surface. As an extended equilibrium experiment, arsenic adsorption envelopes were conducted as a function of pH. Specific amounts of solid suspension and arsenic stock solution were added to 20 mL of reaction vessels to reach specified initial arsenic concentrations and a solids concentration of 1 g/L. The initial solution pH was adjusted to values between pH 4 and pH 12 with a pH increment of 0.5 unit by adding 0.5 HCl or 0.5 M NaOH. The samples were filtered and stored using the procedure described for kinetic experiments.

2.4 Arsenic analysis

Arsenic was analyzed with a model Solar M6 atomic absorption spectrometer equipped with a model V90 continuous hydride generator (Thermo Elemental). The procedure for measuring total arsenic (As(III) + As(V)) was based on Standard Method 3114C, which is a continuous hydride generation/atomic absorption spectrometer (HGAAS) method [*11*]. Total arsenic is determined by mixing a sample flow of 7 mL/min with an equal flow of strong acid (6 M HCl) and a 3.5 mL/min flow of sodium borohydride. With these flows and pH conditions, both As(III) and As(V) can be reduced by borohydride to arsine gas [*12*]. The arsine is transferred by argon gas with a 250 mL/min flow to the flame AA, where its absorbance is determined and used to calculate the arsenic concentration using a standard calibration curve.

2.5 XRD analysis

X-ray diffractograms were collected using a Riga automated X-ray diffractometer using CuKα radiation (40 kV, 20 mA) with a 0.05° step size and 3s step time over the range $6^o < 2\theta < 60^o$.

2.6 Nitrogen adsorption isotherm

Nitrogen adsorption experiments were performed on a Micrometrics ASAP 2010 micropore system using approximately 0.1 g of sample. The samples were degassed under vacuum at room temperature for 2 hours, then at 100^{o}C for 4 hours, and then at 300^{o}C for overnight prior to analysis. The surface area was calculated by the BET method. The micropore and mesopore volumes were determined using the alpha s-method [*13-14*]. The mesopore size distributions were calculated from the adsorption branch of the isotherm using the BJH method with a modified equation for the statistical film thickness [*15-16*].

2.7 TEM analysis

Transmission electron microscopy (TEM) was performed using a JEOL 2010 microscope with a lanthanum hexaboride filament and an excitation voltage of 200 kV. The solid samples were washed with ethanol (99.99 %, Aldrich) and dried as soon as possible, and then transferred to a 400-mesh copper grid, followed by dispersion of the solids by sonication.

2.8 FTIR analysis

Fourier transform infrared (FTIR) spectra were measured using the KBr wafer technique. Samples of 1 g were dried and KBr was mixed with 0.02 g portions of the dried sample. Appropriate amounts of the prepared samples were moved to sample chamber and their FTIR peaks were recorded in transmission mode using a Perkin Elmer 2000 FTIR spectrophotometer. A total 64 scans were collected with a triglycine sulfate (TGS) detector at a resolution of 1 cm^{-1}.

3. Results and discussion

3.1 XRD patterns of NMAs

Figure 3 shows the wide-angle XRD pattern of NT. Comparison of the measured d-spacings to the values in JCPDS card (i.e., 3.516, 1.892, 2.378, 1.700, 1.666, and 1.480 nm) shows that they are the same as those for anatase, which is a crystalline form of TiO_2. Figure 4 shows that the XRD patterns of SBA-15 and titanium-incorporated SBA-15 are very similar to those reported by other studies, indicating that the broad XRD reflection peak at 23^{o} is caused by the very small size of the solid [*17-18*]. Also, Figure 4 shows that the highest peak for $Ti_{(25)}$-SBA-15 is closest to 2θ equal to 25^{o}, which is similar to that observed for anatase, even though peaks for $Ti_{(15,35)}$-SBA-15 are also near 2θ equal to 25^{o} . In contrast, rutile has its highest peak at about 2θ equal to 54^{o} or 56^{o}. Therefore, it can be expected that $Ti_{(25)}$-SBA-15 has properties that are similar to those of anatase.

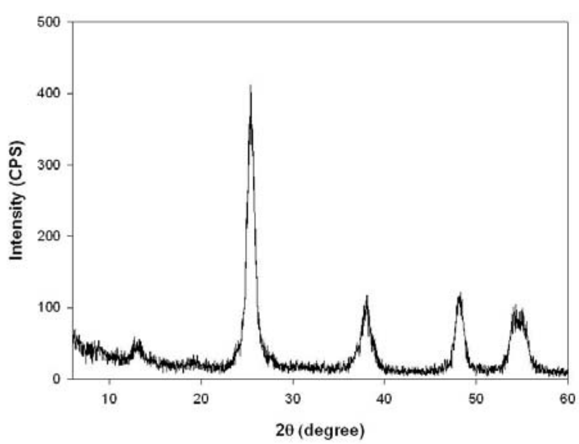

Figure 3. High angle XRD patterns for NT

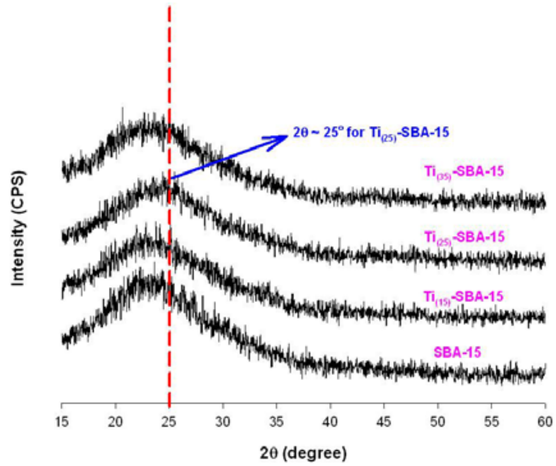

Figure 4. High-angle XRD patterns for SBA-15, $Ti_{(15)}$-SBA-15, $Ti_{(25)}$-SBA-15, and $Ti_{(35)}$-SBA-15 samples.

3.2 Porosity characterization of NMAs

Figure 5 shows nitrogen adsorption-desorption isotherms for NT and $Ti_{(25)}$-SBA-15. They follow the typical irreversible type IV model as designated by IUPAC (International Union of Pure and Applied Chemistry) classification [*14*]. These NMAs have a H1 hysteresis loop, which is representative of mesopores. The sharpness of the inflection step for $Ti_{(25)}$-SBA-15 was greater than that of NT, so it appears that $Ti_{(25)}$-SBA-15 has more uniformity in its mesopores than NT. Figure 6 shows the distribution of pore volume in these NMAs. It provides further evidence of the differences in porosities. It shows a sharp peak at 7.3 nm for $Ti_{(25)}$-SBA-15, whereas NT had broad peak at 9.4 nm. The specific surface areas (A_{BET}) and specific pore volumes (V_{BJH}) for NT were 114 m^2/g and 0.28 cm^3/g, respectively, and for $Ti_{(25)}$-SBA-15 were 588 m^2/g and 0.78 cm^3/g, respectively.

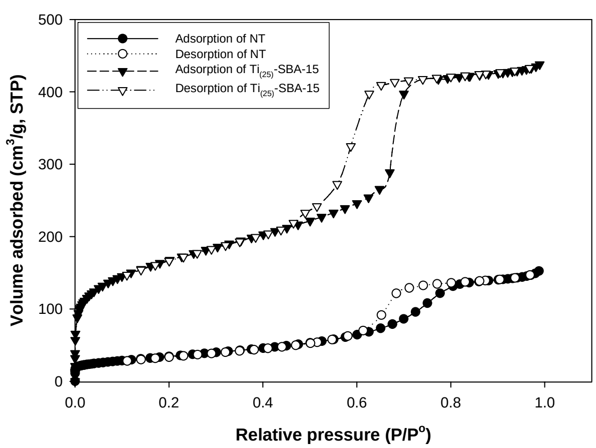

Figure 5. N_2 adsorption-desorption isotherms for NT and $Ti_{(25)}$-SBA-15

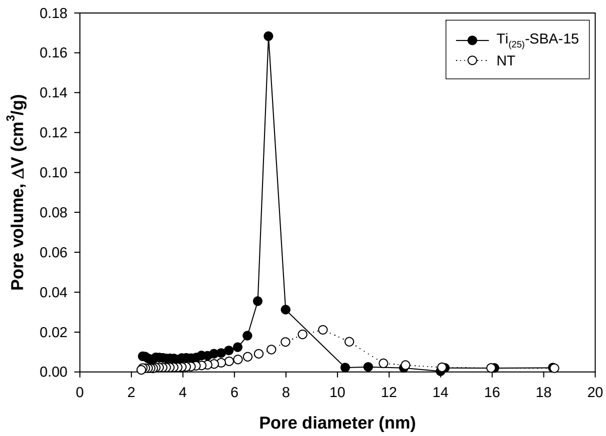

Figure 6. Pore size distribution for NT and $Ti_{(25)}$-SBA-15

3.3 Transmission element microscopy (TEM)

Figure 8 shows that SBA-15 and $Ti_{(25)}$-SBA-15 have highly ordered hexagonal pores with diameters of approximately 10 nm,. However, NT has a disordered wormhole-like pore structure with pore sizes in the range of 10 nm to 20 nm. This agrees with Huang et al. who reported that NT was formed by the agglomeration of TiO_2 nanoparticles and had its mesoporosity caused by interparticle porosity rather than intraparticle porosity [*10*]..

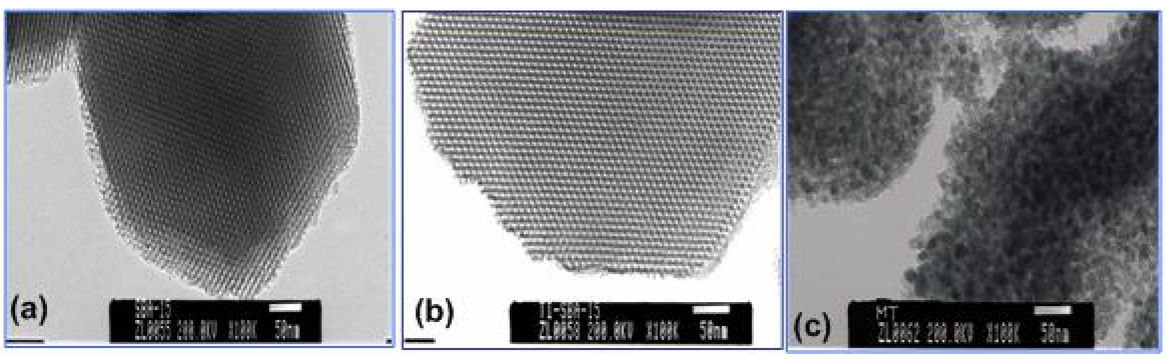

Figure 8. TEM images of a) SBA-15, b) $Ti_{(25)}$-SBA-15, and c) NT.

3.4 FT-IR spectroscopy analysis

Figure 8 shows FT-IR spectra for several NMA. The spectra show three peaks at 445, 795, and 1070 cm^{-1}, indicating rocking, bending (or symmetric stretching), and asymmetric stretching of the tetrahedral oxygen atoms in the SiO_2 structure [*19*]. In addition, the peak at 960 cm^{-1} is assigned to the silanol group (Si-OH) in the framework of SBA-15 by the stretching of nonbridging oxygen atoms [*19*]. As the extent of titanium incorporation increases, the peak at 960 cm^{-1} gradually decreases because of the interaction between titanium and the silanol groups. This peak can be also assigned to Ti-O-Si stretching vibration [*20*]. From this result, we can postulate that SBA-15 can incorporate more titanium into their frameworks, because the presence of peaks at 960 cm^{-1} indicates that the silanol groups have not been completely consumed. Furthermore, the decrease in intensity of the peak at 1070 cm^{-1} in $Ti_{(35)}$-SBA-15 indicates that O-Si-O bonding in the mesoporous SBA-15 framework was decreased by attack of titanium. Thus, excessive impregnation of titanium can destroy the pore structure of SBA-15. The peaks at around 3600 and 1615 cm^{-1} can be attributed to the stretching vibration of hydroxyl and water, caused by humidity of KBr used as a blank sample or humidity incorporation into sample in the process of sample preparation [*20*].

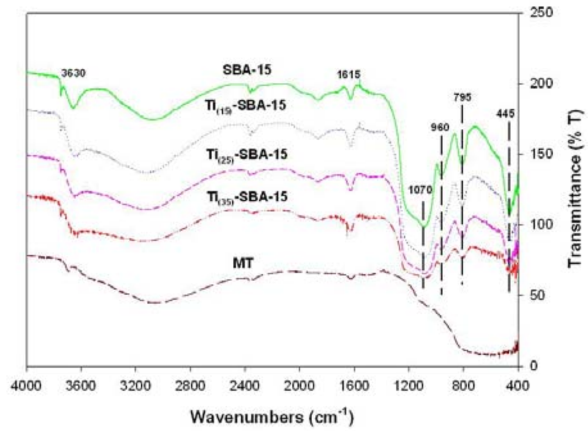

Figure 8. FT-IR spectra of SBA-15, $Ti_{(15,25,35)}$-SBA-15, and NT

3.5 Kinetics for arsenic uptake

Arsenic sorption kinetics by $Ti_{(25)}$-SBA-15 and NT were investigated in a batch system at three different initial pH (4, 7, 9.5). Figure 9 shows the experimental results for As(III) uptake by $Ti_{(25)}$-SBA-15 and NT where the solid concentration was 1 g/L and the initial As(III) concentration was 13.3 μM. Figure 9 (a) and (b) shows that adsorption of As(III) onto both adsorbents initially was very rapid with most being removed within the first 10 minutes of contact, and later was slower. This biphasic kinetics could be caused by transformation of arsenic species adsorbed or by other environmental factors. Specifically, the slower sorption reaction could be attributed to surface precipitation or polymerization, diffusion into interparticle or intraparticle pores, or changes in the type of surface complex (***i.e.***, monodentate adsorption followed by bidentate complex) as reported by other studies [*21*-*22*]. In this study, it could be postulated that slower adsorption of arsenic might be controlled by intraparticle diffusion because NMAs have a lot of pores and channels. The extent of As(III) uptake by NT increased with increasing pH over the range investigated, whereas the highest level of As(III) removal by $Ti_{(25)}$-SBA-15 was observed at pH 7. The amount adsorbed at pH 7 was and initially much greater than adsorbed at pH 4. However, after a longer time of reaction, the amount removed at pH 4 became nearly as high as that at pH 7. At pH 9.5, the removal efficiency of NT for As(III) was more than three times greater than that of $Ti_{(25)}$-SBA-15.

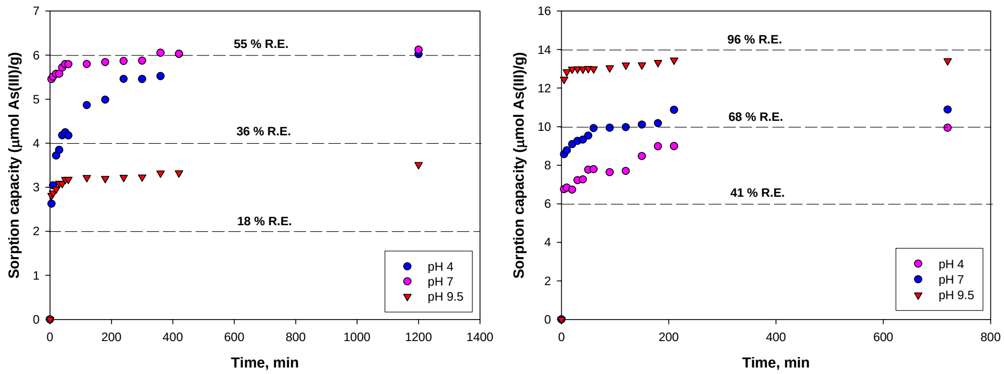

Figure 9. As(III) uptake rate by (a) $Ti_{(25)}$-SBA-15 (left) and (b) NT (right) as a function of pH

The kinetic experiments for As(V) removal were conducted in a similar manner. Figure 10 (a) and (b) show that the amount of As(V) removed depends strongly on solution pH. At lower pH, higher As(V) adsorption was observed, which can be caused by electrostatic attraction between As(V) species and positive surface functional groups. While at high pH, lower removal of As(V) was observed and this could be caused by electrostatic repulsion. In spite of the similar trends of As(V) removal by each adsorbent over the pH range investigated, the extent of As(V) uptake at a specified pH was very different. For instance, As(V) at pH 4 was completely removed by $Ti_{(25)}$-SBA-15, whereas only 91 % of As(V) was adsorbed by NT. However, at other pH, the extent of As(V) uptake by NT was much higher than that by $Ti_{(25)}$-SBA-15.

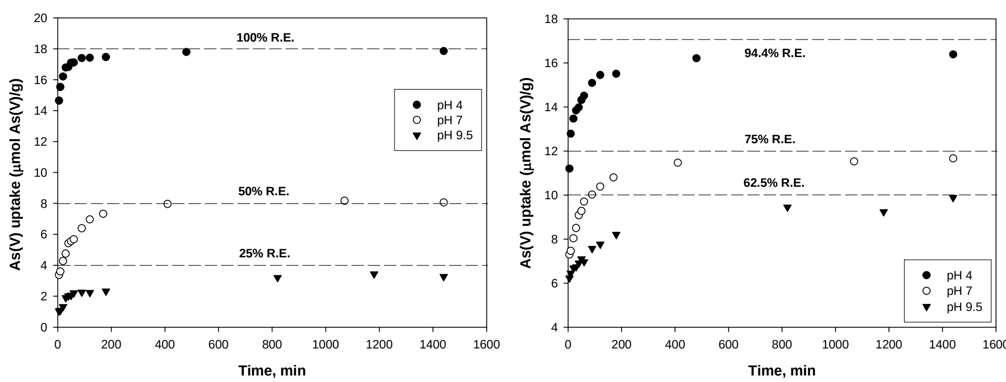

Figure 10. As(V) uptake rate by (a) $Ti_{(25)}$-SBA-15 (left) and (b) NT (right) as a function of pH

3.6 Nonlinear Equilibrium for arsenic uptake

Figure 11 shows As(III) adsorption isotherms for $Ti_{(15,25,35)}$-SBA-15 and NT with Figure 11(a) showing the Langmuir isotherm and Figure 11 (b) showing the Freundlich isotherms. These isotherms were obtained by non-linear regression using data for adsorption of As(III). Table 1 shows the fitting parameters for these isotherm models and the sum of squared residuals (SSR). These results show that the maximum sorption capacity for As(III) decrease as follows; NT (162 µmol/g) > $Ti_{(25)}$-SBA-15 (87 µmol/g) > $Ti_{(35)}$-SBA-15 (76 µmol/g) > $Ti_{(15)}$-SBA-15 (60 µmol/g). The SSR values in Table 1 show that the Langmuir isotherm model provided a better fit than the Freundlich isotherm model for both adsorbents. These results indicate that the optimal weight ratio of Ti to SBA-15 for As(III) adsorption is 25 %. As(III) sorption capacity decreased when the incorporation ratio increased from 25% to 35%, possibly due to incorporation of Ti into the silica framework. Ti that is in the silica framework would not function as reactive sorption sites for As(III) removal. Similar results have been observed in other studies that investigated $La_{(x)}$-SBA-15, $Al_{(x)}$-SBA-15, and $Fe_{(x)}$-SBA-15 [*23*]. In addition, NT had a higher sorption capacity than $Ti_{(25)}$-SBA-15, by a factor of 1.7.

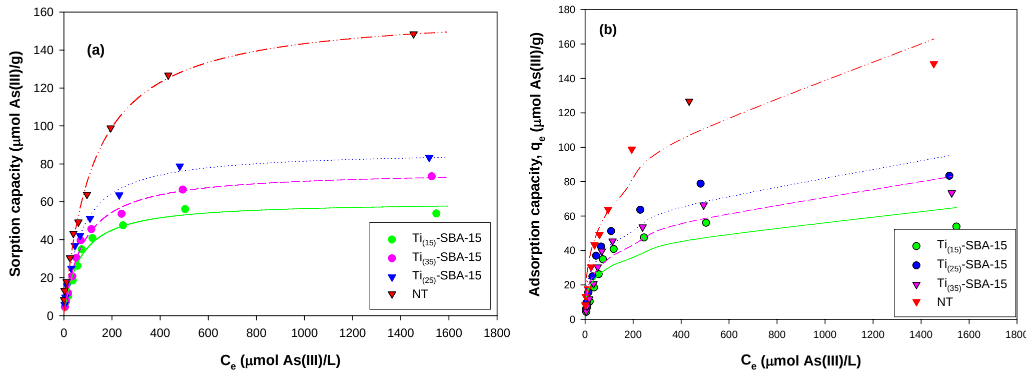

Figure 11. As(III) adsorption isotherm by $Ti_{(15,25,35)}$-SBA-15 and NT with solid concentration = 1g/L. The nonlinear fitting curves are obtained from (a) the Langmuir and (b) Freundlich isotherm model.

Table 1. Comparison of isotherm parameters ±95% confidence levels for As(III) adsorption

	$Ti_{(15)}$-SBA-15	$Ti_{(25)}$-SBA-15	$Ti_{(35)}$-SBA-15	NT
Langmuir				
b (L/µmol)	0.014±0.004	0.014±0.003	0.013±0.003	0.008±0.002
Q_{max} (µmol/g)	60±6	87±5	76±5	162±14
SSR	60	41	42	250
Freundlich				
K_f ($\mu mol^{1-1/n} \cdot L^{1/n}/g$)	8.3±6.4	11±6.3	8.6±5.5	12.7±6.8
n	3.6±1.7	3.4±1.1	3.3±1.1	2.8±0.6
SSR	650	710	600	1200

Experiments were conducted at three pH values (pH 4, 7, 9.5) in order to investigate the effect of pH on maximum sorption capacity of each adsorbent for As(III) and As(V). Figures 12, 13, 14, and 15 show adsorption isotherms fitted by the Langmuir and Freundlich model. Adsorption isotherm parameters are summarized in Table 2 and 3. In the case of As(III) removal, we can determine the order of maximum sorption capacity to be: NT (pH 9.5, 285 µmol/g) > NT (pH 7, 162 µmol/g) > $Ti_{(25)}$-SBA-15 (pH 4, 121 µmol/g) > $Ti_{(25)}$-SBA-15 (pH 7, 87 µmol/g) > NT (pH 4, 66 µmol/g) > $Ti_{(25)}$-SBA-15 (pH 9.5, 60 µmol/g). In addition, at all pH except for pH 9.5, the Langmuir model for As(III) sorption provided a better fit than the Freundlich model as measured by SSR.

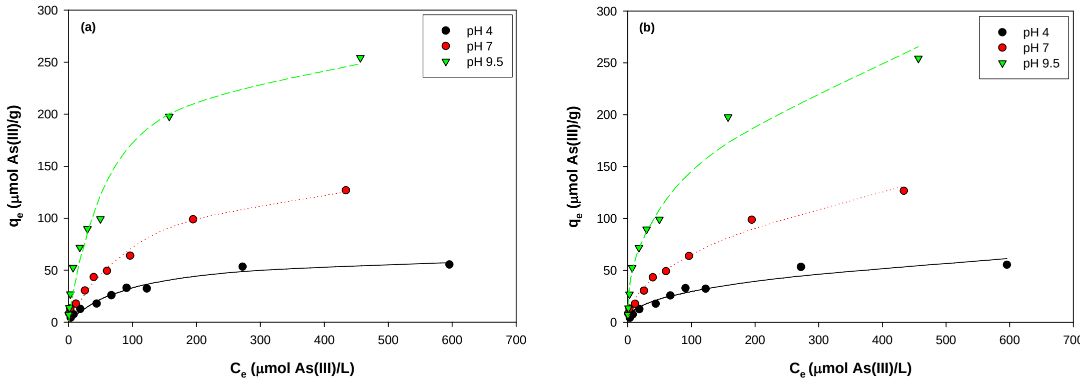

Figure 12. As(III) adsorption isotherms by NT as function of pH that are fitted to (a) the Langmuir and (b) Freundlich model by non-linear regressions using MATLAB®

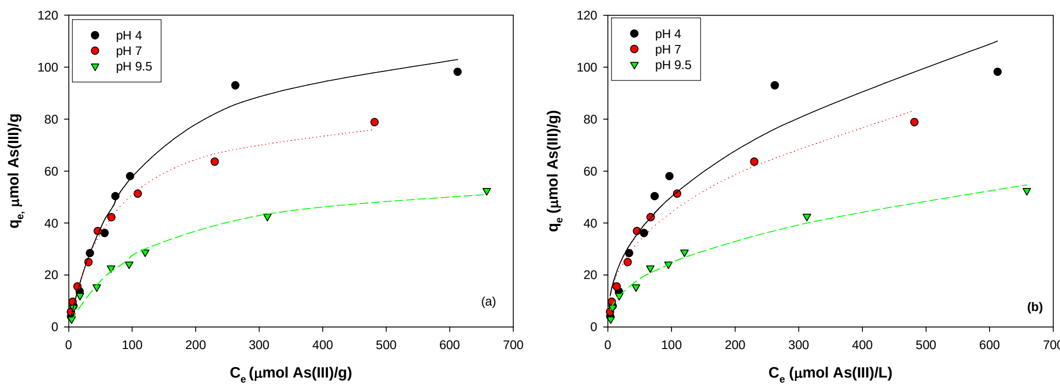

Figure 13. As(III) adsorption isotherms by $Ti_{(25)}$-SBA-15 as function of pH that are fitted to (a) the Langmuir and (b) Freundlich model by non-linear regressions using MATLAB®

Table 2. Comparison of As(III) adsorption isotherm parameters as a function of pH

NMAs	pH	*Langmuir*			*Freundlich*		
		b (L/µmol)	q_{max} (µmol/g)	SSR	k_f (µmol$^{1-1/n}$·L$^{1/n}$/g)	n	SSR
NT	4	0.01±0.004	66±11	69	4.71±2.86	2.5±0.7	167
	7	0.008±0.002	162±14	250	12.7±6.8	2.8±0.6	1200
	9.5	0.015±0.008	285±52	1705	22.4±7.8	2.48±0.4	1052
$Ti_{(25)}$-SBA-15	4	0.009±0.0027	121±14	117	6.79±5.34	2.3±0.7	783
	7	0.014±0.003	87±5	41	11±6.3	3.4±1.1	710
	9.5	0.0083±0.0031	60±9	48	3.59±1.37	2.4±0.4	38

The order of maximum sorption capacity for As(V) is: $Ti_{(25)}$-SBA-15 (pH 4, 193 µmol/g) > NT (pH 4, 173 µmol/g) > NT (pH 4, 116 µmol/g) > $Ti_{(25)}$-SBA-15 (pH 7, 72 µmol/g) > NT (pH 9.5, 56 µmol/g) > $Ti_{(25)}$-SBA-15 (pH 9.5, 30 µmol/g). Except for pH 9.5, the Langmuir model for As(V) provides the best fit to experimental isotherm data as measured by the SSR.

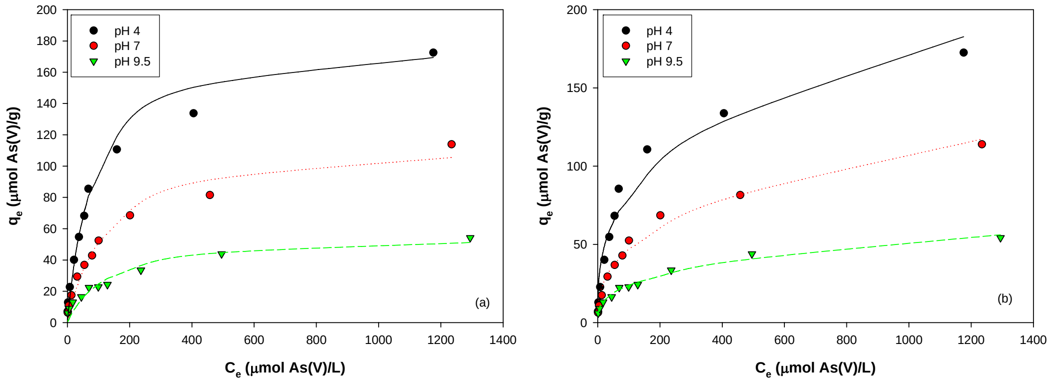

Figure 14. As(V) adsorption isotherms by NT as function of pH that are fitted to (a) the Langmuir and (b) Freundlich model by non-linear regressions using MATLAB

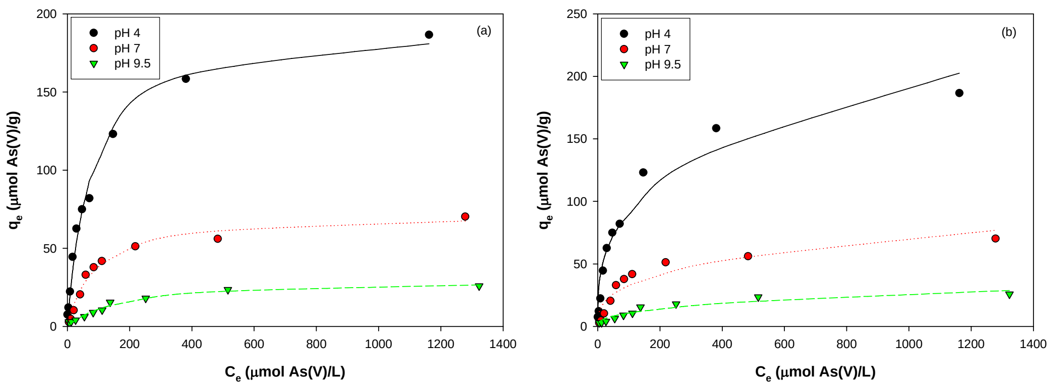

Figure 15. As(V) adsorption isotherms by $Ti_{(25)}$-SBA-15 as function of pH that are fitted to (a) the Langmuir and (b) the Freundlich model by non-linear regressions using MATLAB

Table 3. Comparison of As(V) adsorption isotherm parameters as a function of pH

NMAs	pH	*Langmuir* b (L/µmol)	q_{max} (µmol/g)	SSR	*Freundlich* k_f ($\mu mol^{1-1/n}\cdot L^{1/n}/g$)	n	SSR
NT	4	0.0128±0.0038	173±16	449	17.8±6.9	3.03±0.59	1013
	7	0.008±0.003	116±17	331	8.8±2.4	2.75±0.33	159
	9.5	0.0078±0.004	56±11	155	5.1±1.1	2.99±0.31	26
$Ti_{(25)}$-SBA-15	4	0.0081±0.0049	193±17	443	20.5±9.1	3.08±0.71	1649
	7	0.0031±0.0017	72±7.0	82	6.9±4.7	2.98±1.02	549
	9.5	0.0041±0.0013	30±4.0	15	1.85±1.27	2.62±0.76	55

3.7 Arsenic adsorption envelopes

To investigate the effect of pH and total As(III) concentration on the extent of adsorption onto solids over pH, three different As(III) concentration (*i.e.*, 7.82, 14.4, and 45.6 µM) were chosen. Figure 16(a) shows As(III) adsorption envelopes for NT in which a maximum is observed around pH 8-11. The percentage of As(III) adsorbed decreases with increasing total As(III) concentration. Figure 16(b) shows that As(III) removal by $Ti_{(25)}$-SBA-15 was somewhat constant over the pH range between pH 4 and pH 7, but decreased as pH increased about pH 8.5. The decrease as high pH may be caused by increased electrostatic repulsion between negative arsenite species

($H_2AsO_3^-$) and negative surface functional groups. Figure 17 (a) and (b) show the effect of total As(V) concentration on the extent of adsorption by NT and $Ti_{(25)}$-SBA-15. As shown in Figure 17(a), As(V) adsorption was pH dependent and the extent of As(V) adsorption decreased with increasing total As(V) concentration over all pH values investigated. Figure 17(b) shows that As(V) sorption to $Ti_{(25)}$-SBA-15 was more strongly dependent on pH rather than was sorption of As(III). As(V) adsorption to NT showed the highest percent adsorbed at low pH, compared to As(III) which showed decreasing removal at the lowest pH.

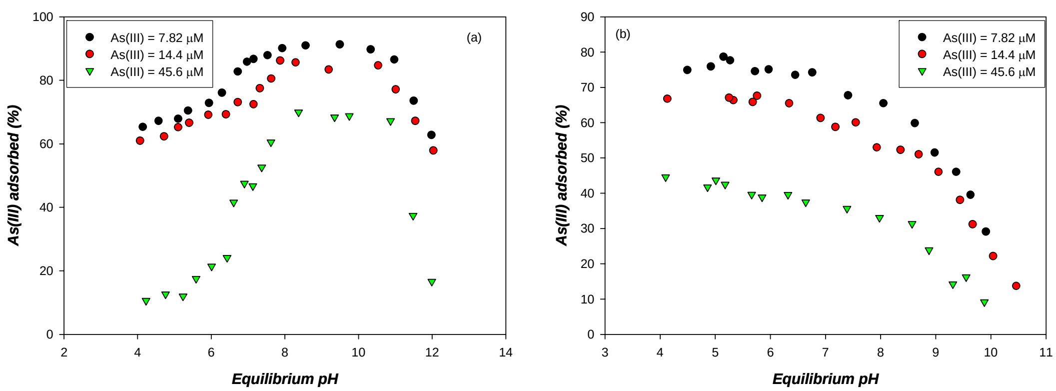

Figure 16. Adsorption envelope of As(III) by (a) NT and (b) $Ti_{(25)}$-SBA-15 as a function of pH; Solid concentration = 1 g/L, ionic strength = 0.01 M as NaCl, equilibration time = 24 hrs, total As(III) concentration added = 7.82, 14.4, and 45.6 µM, respectively.

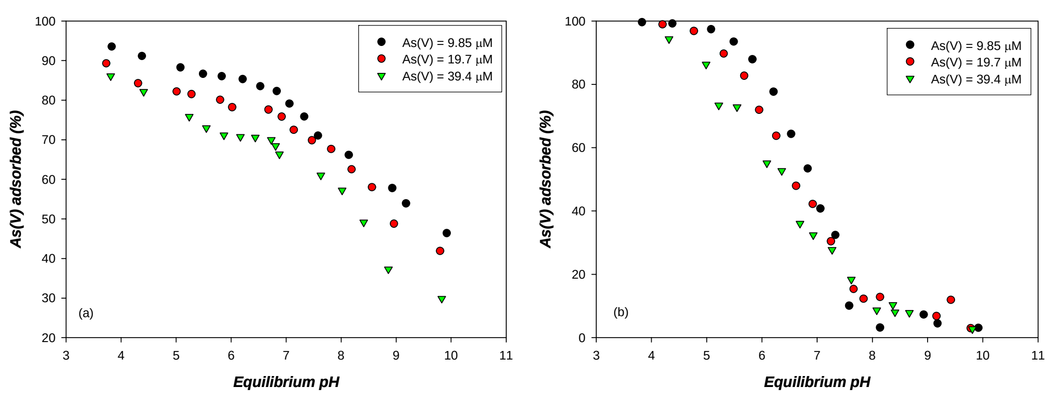

Figure. 17. Adsorption envelope of As(V) by (a) NT and (b) $Ti_{(25)}$-SBA-15 as a function of pH; solid concentration = 1 g/L, ionic strength = 0.01 M as NaCl, equilibration time = 24 hrs, total As(V) concentration added = 9.85, 19.7, and 39.4 µM, respectively.

4. Conclusions

Both As(III) and As(V) showed rapid removal during the first 10 minutes and then slower sorption until 200 minutes. After 24 hours of reaction, the extent of arsenic removal by $Ti_{(25)}$-SBA-15 and NT and how they were affected by pH were observed to be different. In the case of $Ti_{(25)}$-SBA-15, the amount of As(III) uptake became greater as pH shifted to pH 4 or pH 7, while in the case of NT, increasing pH enhanced As(III) sorption capacity over the entire range. NT had a higher equilibrium As(III) sorption capacity than $Ti_{(25)}$-SBA-15 over all pH ranges investigated. For As(V) uptake, high sorption capacity was observed at low pH, probably due to strong electrostatic attraction. The extent of As(V) sorption onto both solids decreased with increasing pH.

Adsorption data for both As(III) and As(V) on $Ti_{(25)}$-SBA-15 and NT were more accurately modeled by the Langmuir isotherm than by the Freundlich isotherm. These results support the hypothesis that the affinity of the adsorbate for the surface sorption sites of NMAs is similar and that there is a maximum sorption capacity. Thus, the surface sorption sites on $Ti_{(25)}$-SBA-15 and NT have similar affinities for As(III) and As(V). However, pH can affect the maximum sorption capacity (q_{max}, μmol As/g) of each solid for As(III) and As(V). For As(III) sorption onto NT, higher sorption capacity was observed at pH 7 to 9.5, whereas for As(III) sorption onto $Ti_{(25)}$-SBA-15, higher capacities were seen at low pH. At environmental pH conditions, it could be expected that NT can achieve higher As(III) removal. In the case of As(V) removal, both solids had higher As(V) removal capacity at low pH and this is probably due to electrostatic attraction.

The extent of arsenic adsorption onto $Ti_{(25)}$-SBA-15 and NT showed a regular pattern with pH. This pattern was not affected by total arsenic concentration, but the percentages of As(III) and As(V) adsorbed decreased with increasing total arsenic concentration. Optimal pH ranges for As(III) removal were between pH 8 and pH 11 for NT and between pH 4 and pH 7 for $Ti_{(25)}$-SBA-15. Maximum removal efficiencies for As(V) by $Ti_{(25)}$-SBA-15 was observed in the pH range between pH 4 and pH 7 and the maximum for NT was close to pH 4. However, at environmental pH near pH 7 to pH 8, the extent of removal efficiencies for As(III) and As(V) by NT was greater than those by $Ti_{(25)}$-SBA-15. Consequently, it can be concluded that at environmental pH, NT could be a better adsorbent for removal of both As(III) and As(V).

The incorporation ratio of titanium that resulted in the highest maximum adsorption capacities was 25 %, *i.e,* $Ti_{(25)}$-SBA-15. Also, analyses by XRD, TEM, and FT-IR provided evidence that $Ti_{(25)}$-SBA-15 is a selective adsorbent with nanostructured titania surface properties. XRD analysis indicated that the peaks of synthetic NT were in accordance with those of anatase. In addition, nitrogen adsorption/desorption results showed that SBA-15, $Ti_{(25)}$-SBA-15, and NT follow typical irreversible type IV model as designated by IUPAC, which is indicative of mesoporous materials. Based on TEM results, however, the mesopores of NT could be related to interparticle porosity, unlike SBA-15 and $Ti_{(25)}$-SBA-15 which showed a highly regular hexagonal intraparticle porosity.

5. Research in the future works

We will continue to conduct experiments and develop theoretical mechanisms for arsenic removal to achieve the following objectives.

1) Develop sorption kinetics models to describe adsorptive and diffusive sorption removal mechanisms, and to predict sorption removal rates
2) Develop modified equilibrium models to predict sorption capacity more precisely
3) Determine optimum solution conditions as affected by competing anions (e.g., PO_4^{3-} and SO_4^{2-})
4) Characterize electrostatic surface properties of solids by potentiometric titration or electrophoretic mobility
5) Develop surface complexation model (SCM) using computer program software such as FITEQL and V-MINTEQ
6) Determine regenerability of solids for arsenic removal to predict life-cycle and cost-effectiveness

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Development of Coastal Margin Observation and Assessment System to Monitor the Water Quality in the Corpus Christi Bay

Basic Information

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Principal Investigators:	Mohammad Islam, James Bonner

Publication

Real Time Monitoring of Water Quality Parameters in Corpus Christi Bay to Understand Hypoxia

Mohammad Shahidul Islam, James S. Bonner, Temitope Ojo, and Cheryl Page
(Texas A & M University, College Station, Texas, USA)

Abstract- **Corpus Christi Bay (Texas, USA) is home to the nation's seventh largest port with numerous petrochemical facilities. This shallow wind-driven bay (average depth 3m) is very dynamic, and is typically a well-mixed system. However, the water column becomes stratified during the summer months in the south-east portion of the bay, and so dissolved oxygen (DO) in the upper-layer water column is not able to mix with the lower-layer water column. Therefore, an hypoxic condition can develop at the lower portion of the water column in the bay, and as this bay is very stochastic in nature, this condition lasts on the order of hours. It is difficult to 'capture' this kind of episodic events through discrete sampling at limited locations in the bay. Our research group has developed an integrated data acquisition system which can measure horizontal and vertical variation of various water quality parameters 'synchronically' over a highly-resolved spatial regime. Also, software has been developed in our laboratory which can display the horizontal and vertical variation of these parameters in real time and thereby, guides in determining the spatial extent of the water quality parameters of interest. As part of our routine monitoring of Corpus Christi (CC) Bay, we conducted an east-west transect of the bay's ship channel on November 29, 2006 and March 22, 2007. The data collected by our system suggests that the inverse estuary situation exists in the ship channel, i.e., the water becomes more saline and dense as we moved away from the mouth of the Gulf of Mexico towards the bay interior. The prevailing south-east wind on those days 'pushed' the high saline water from the mouth of the Laguna Madre and Oso Bay toward the ship channel. The preliminary results of the hydrodynamic model developed by our research collaborators showed the similar circulation pattern. Integrating the model with the observed data will help us in characterizing the stratification pattern of the bay and therefore, greater understanding of the hypoxic phenomena. Also, particle concentrations measured by a particle sizer (one of the instruments in our suite of instruments) are well correlated with the acoustic backscatter intensity measured by our acoustic Doppler current profiler. This kind of relationship is very important because it provides a greater capability to characterize the particle dynamics of the bay. Particles can transport 'particulate BOD' (biochemical oxygen demand), thus affecting hypoxia. Quantification of the particle influx/outflux to the Gulf of Mexico through the ship channel may help us to understand the contribution of the ship channel effects on hypoxia in the bay.**

Keywords- hypoxia, inverse estuary, water quality and real time monitoring

I. INTRODUCTION

Hypoxia develops when the concentration of dissolved oxygen (DO) in a water body dips below 2 mg/l; most aquatic organisms cannot survive under this condition. In the summer months, portions of Corpus Christi (CC) Bay (Texas, USA) routinely experience hypoxic events. Various factors such as eutrophication, water column stratification, geomorphology of the bay, meteorology etc. may contribute to the development of hypoxia [1]. Texas researchers have concluded that eutrophication is not the likely cause for hypoxia in this particular bay since, over the past 14 years, freshwater inflow rates into the bay have decreased and nutrient levels have not changed significantly [2]. Although water column stratification is a possible cause for hypoxia, CC Bay would not be considered a likely candidate for stratification because it is a shallow wind-driven bay (average depth 3m) with an expected high-level of mixing. However, hypoxic events occur in the southeast portion of the bay, near the Laguna Madre and at the mouth of nearby Oso Bay [3]. On closer inspection, quiescent periods, when combined with tidal cycling and inflows of hypersaline water (up to 60 psu) from these two adjoining water bodies can lead to conditions favorable to stratification in Corpus Christi Bay.

A stratified water column can become mixed through several mechanisms, including double-diffusive instabilities driven by unstable salinity or unstable temperature, shear or Kelvin-Helmholz instabilities, and advective instabilities. The relative importance and distribution of these instability mechanisms in controlling stratification of CC Bay could help in predicting the spatial and temporal extent of an hypoxic event. Analyzing parameters such as temperature, salinity, particle concentration and vertical shear structure of the water column can aid in understanding these mechanisms. However, monitoring of water quality parameters and environmental indicators poses a challenge due to the spatial extent and dynamics involved, and since CC Bay is a dynamic system, it is not possible to fully capture the conditions that lead to episodic events (such as hypoxia) through discrete sampling. As such, it is necessary to measure these parameters at higher spatial and temporal resolution.

Over the past several years, our research group has been expanding our monitoring system in CC Bay. This system consists of observational remote, fixed and mobile platforms equipped with real-time sensors. A vertical profiling robot is installed on each of the fixed platforms and can measure the vertical variation of various water quality parameters (e.g., dissolved oxygen, particle size/concentration, chlorophyll-a, salinity, temperature, etc). One of the fixed platforms is located where hypoxia has been observed every summer since 1988 [4]. Our mobile platform (i.e., research boat) is equipped with an integrated data acquisition system that can measure a similar spectrum of environmental parameters 'synchronically' over a highly-resolved spatial regime in an undulating (vertical sinusoidal) pattern.

In this paper, we discuss the use of our mobile system to capture the water quality parameter variation in CC Bay's ship channel. Included is an acoustic Doppler current profiler (ADCP), which can determine vertical shear structure of the water column. Particle influx and outflux between the bay and the Gulf of Mexico (through the ship channel) can transport significant amounts of particulate BOD (biochemical oxygen demand), thus potentially affecting hypoxia. Therefore, it is necessary to characterize the particle dynamics of the bay to better understand hypoxia and other environmental phenomena. Past researchers have observed the positive correlation between acoustic backscatter intensity measured by an ADCP and particulate concentrations in the water column [5, 6, 7]. One of the objectives of this research is to correlate the acoustic backscatter intensity with the particle concentration measured and thereby aid in understanding of the particle dynamics in CC Bay.

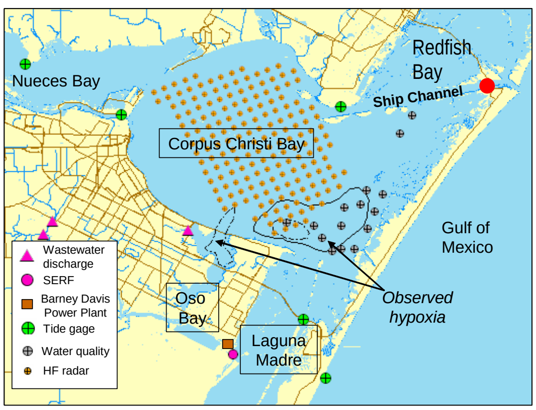

Figure 1. Characteristic Features of Corpus Christi Bay

II. SITE DESCRIPTION

Corpus Christi Bay is located on the Gulf of Mexico (approximately 200 miles southwest of Houston, TX) and has an area of 434 sq. km [8]. It is surrounded by four water bodies, namely Oso Bay in the southwest, Nueces Bay in the northwest, Upper Laguna Madre in the south and Redfish Bay in the northeast. This bay has almost uniform depth (~3m) except in the 15-meter ship channel, which runs east-west in the northern portion of the bay. CC Bay is connected to the Gulf of Mexico through the ship channel. Figure 1 shows the characteristic features of CC Bay. Hypoxia has been reported to occur at the mouth of the Oso Bay and near the Laguna Madre. As the Upper Laguna Madre is very shallow (~2m), it brings highly saline water into CC Bay during the summer time. The red circle in Figure 1 shows one of the locations of the Texas Coastal Ocean Observation Network (TCOON) platform in Port Aransas, TX. The wind data measured at this platform is used in our data analysis.

III. MATERIALS AND METHODS

A. Research Cruise Objective

On November 29, 2006 and March 22, 2007, we conducted east-to-west transect cruises along the Corpus Christi Bay Ship Channel. The objective was to measure various water quality parameters and begin to address their effects on naturally-occurring phenomena such as hypoxia. We also attempted to identify the relationship between particle concentrations measured by the particle size analyzer and the intensity of acoustic backscatter measured by the ADCP. This kind of relationship will help us in better understanding the particle dynamics of the bay because the ADCP can measure acoustical backscatter (ABS) intensity at highly resolved spatial and temporal regime. Also, since particle flux can carry significant amounts of particulate BOD, this relationship will help to better characterize the DO variation in the bay.

B. Integrated Data Acquisition, Communication and Control (IDACC) System

For these cruises, our research group has previously developed an Integrated Data Acquisition, Communication and Control (IDACC) system which can measure vertical variation of various water quality parameters 'synchronically' over a highly-resolved spatial regime. This unit is capable of adaptive sampling to facilitate and guide data acquisition exercises and has been used successfully in several deployments in simulated emergency spill response, routine bay profiling as well as dye-tracer experiments [9]. Instruments currently included in this system are a particle size analyzer (LISST-100 by Sequoia Scientific), a dissolved oxygen sensor (Optode by Aanderaa), a fluorosensor (Eco-FL3 by WETLabs), a GPS (Global Positioning System) and a CTD (Conductivity, Temperature and Depth) sensor. This integrated instrument suite is towed by our research vessel in a vertically-undulating fashion within the water column. Along with this system, an ADCP has been installed on the research vessel to determine water currents, acoustic backscatter intensity and the vertical shear structure within the water column.

We have performed quality assurance and quality control tests (within 5% error limit) for each instrument of the IDACC system. All instruments are pre- and post-calibrated for each research cruise. Cycle time of each set of synchronized measurements is determined by considering the fastest stable response time for all sensors in the instrument suite.

C. Multi-Parameter Instrument Array and Control System (MPIACS) software

In addition to the IDACC system, Multi-Parameter Instrument Array and Control System (MPIACS) software was also developed in our laboratory for the real-time data acquisition and display of the horizontal variation of intensities of the parameter (measured value relative to a pre-set peak value). It aids in locating "cold" and "hot" spots for the constituent of interest along the transect route. Since CC Bay is very dynamic in nature, significant vertical gradients can also exist. Therefore, we have recently modified our MPIACS software to also display the vertical variation of water quality parameters along the transect route. Figure 2 presents a snapshot of the graphical user interface (GUI) from one of our routine monitoring activities of CC Bay. The lower left portion of the GUI gives the user the option to select the type/number of instruments to be used in each monitoring activities. At present, a maximum of six instruments can be included for synchronized measurements, and more instruments can easily be added in future. The user also has the option to select the area to be monitored. Currently, Corpus Christi Bay, Matagorda Bay, Galveston Bay, Galveston Offshore area have been loaded in the software so that user can use them directly as reference boundary of their monitoring activities. The lower middle panel of the GUI displays the color-coded trace line of the travel route whereas the upper middle panel shows the vertical variation of a water quality parameter along that route. In this snapshot, it shows the DO variation along the travel route but the user can select other monitored parameters to be displayed (e.g., temperature, salinity, total particle concentration (totvol), etc.). This software also displays the numerical values of the other synchronized measurements of various water quality parameters, and latitude and longitude of the measurement location in the edit boxes at the lower right side of the GUI. The real time display of each parameter helps the user to identify the transect route for the determination of the spatial extent of water quality parameter of interest.

IV. RESULTS

In both of our cruises, we started our transect from the mouth of the ship channel where it is connected with the Gulf of Mexico (to the east) and moved towards the bay in a westerly fashion along the ship channel. Wind was blowing from south-east during both of our cruises (Fig. 3). Figure 4 presents the color-coded (magenta-to-cyan) east-to-west trace line of the November cruise in the Corpus Christi Bay Ship Channel. This color-coded trace line is also presented in the subsequent data plots to help visually link the data with the location of measurement. On each figure, the solid black line represents the seabed profile. Figures 5 and 6 present the vertical variation of salinity along the IDACC route on the November and March cruises, respectively. The color coded (magenta-to-cyan) trace line in the CC Bay map of Figure 6 shows the track line of travel on the March cruise. As we moved from east to the west over time, we expected a lower-salinity condition; however, our observed data from both cruises indicated the opposite profile (Fig. 5 and Fig.6). The persistent south-east wind prior to our cruises may bring highly saline water from the mouth of the Oso Bay and upper Laguna Madre into the ship channel. Low freshwater flow and the dominance of evaporation over rainfall tends to increase the salinity levels in the

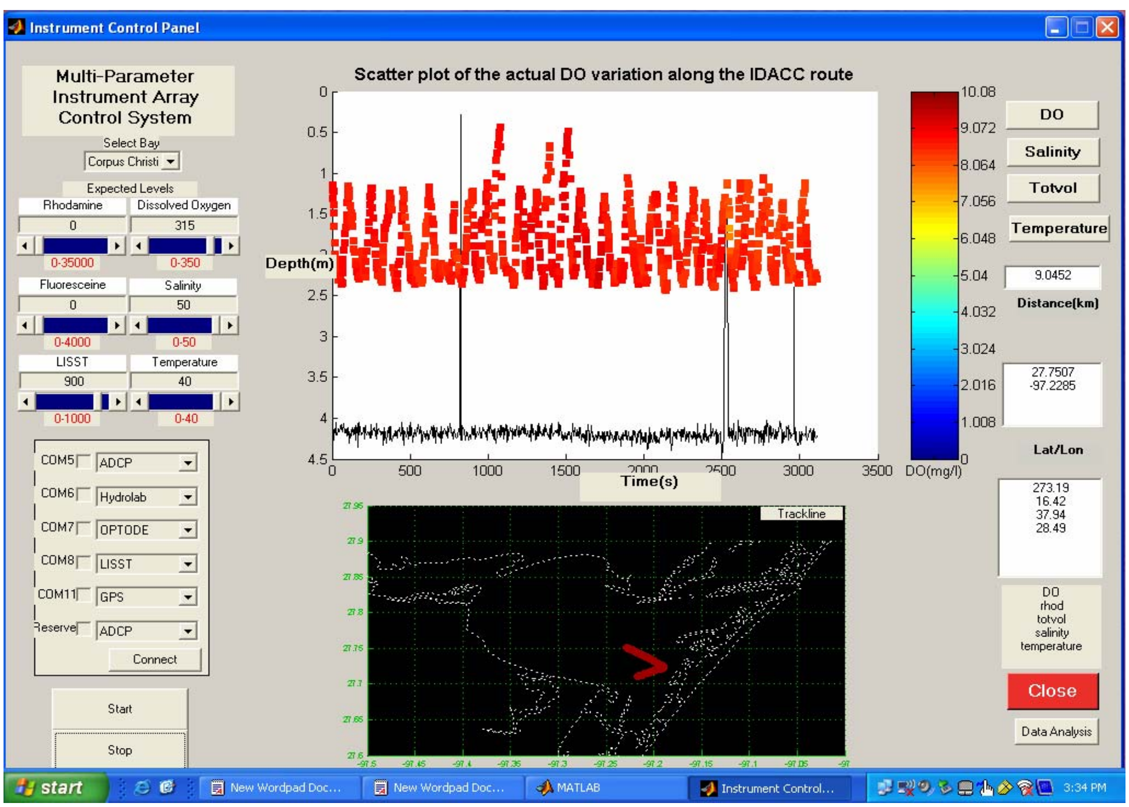

Figure 2. Snapshot of Graphical User Interface (GUI) generated by our real time data acquisition and visualization software (MPIACS-II) in one of our routine monitoring activities of the CC Bay.

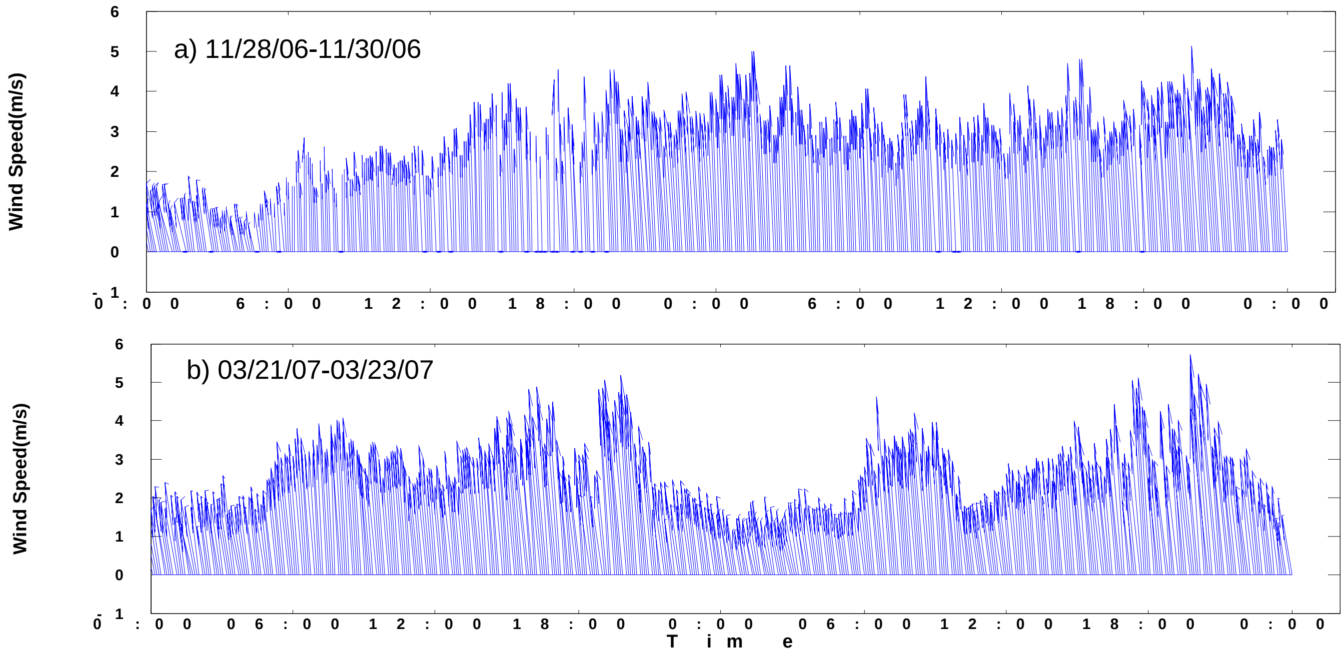

Figure 3. Six-minute averaged wind vectors at Port Aransas in the Corpus Christi Bay for the (a) November cruise and (b) March cruise. Positive vectors represent the wind is blowing from south.

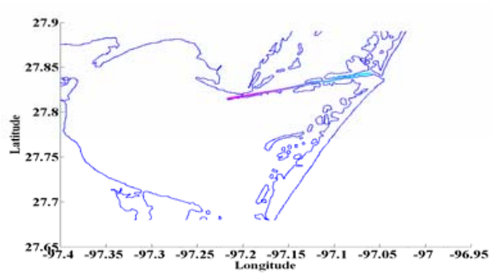

Figure 4. IDACC transect route (in ship channel in CC Bay) on Nov 29, 2006 (Note: direction of transect was east-to-west).

shallow upper Laguna Madre and the mouth of the Oso Bay as compared to the rest of the bay. The preliminary results of the hydrodynamic model developed by our research collaborator (Dr. Ben Hodges, University of Texas Austin, personal communications) finds the similar circulation pattern., i.e., higher salinity water from the Laguna Madre (shallow water body~2m depth) moves along the south-east coastline towards the ship channel. Integration of the model with observed data will provide more insight into the circulation pattern of the bay and thereby, help in

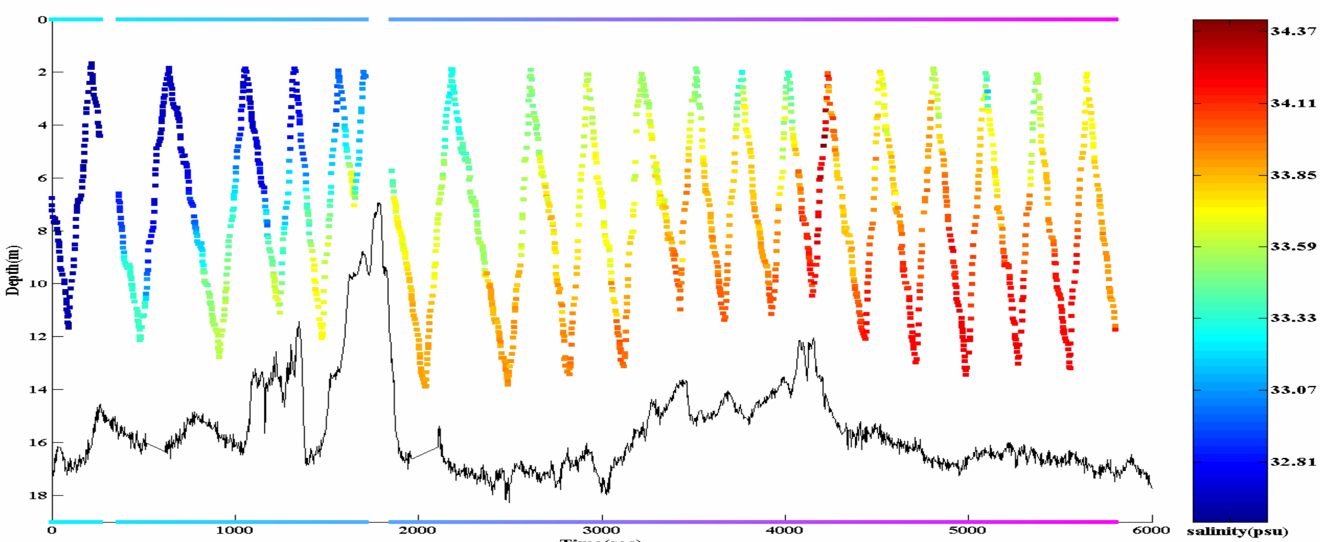

Figure 5. Salinity variation along the IDACC route on Nov. 29, 2006. (Note: the colored horizontal lines at the top/bottom of the figure correlate to the transect route as presented in Figure 4).

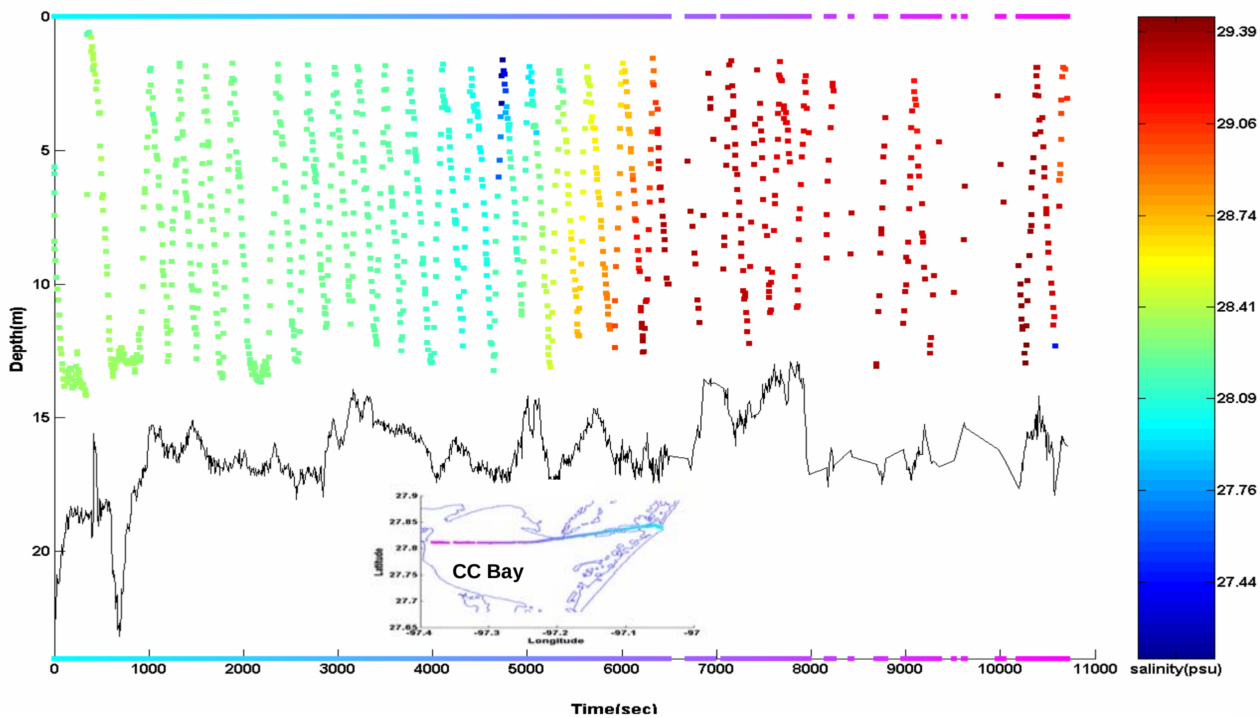

Figure 6. Salinity variations along the IDACC route on March 22, 2006. Note map insertion showing east-to-west trace line of the cruise.

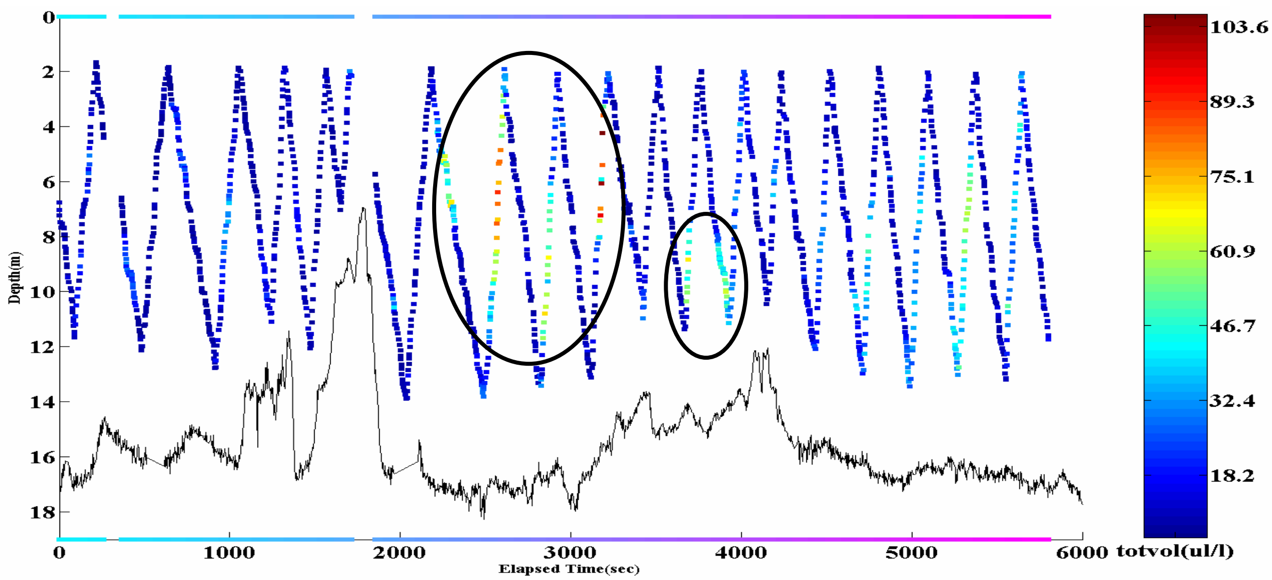

Figure 7. Particle concentration variation along the Nov. 29, 2006 cruise transect. (Note: the colored horizontal lines at the top/bottom of the figure correlate to the transect route as presented in Figure 4).

understanding the frequency and extent of hypoxic events in CC Bay.

Figure 7 presents the particle concentration while Figure 8 presents the acoustic backscatter intensity variation along the transect route on Nov. 29, 2006. Note that Figure 8 presents only a portion of the transect data for the ADCP (from T=2100 sec through T=4800 sec). Comparing Figures 7 & 8, it is clearly visible that higher particle concentrations (encircled in black, Figure 7) correspond to the higher acoustic backscatter intensity data (encircled in black, Figure 8). In order to interpret and understand a quantitative relationship between acoustic backscatter intensity with the actual particle concentration, it is necessary to analyze other water quality parameter measurements such as salinity, temperature, particle type and size distribution in the water column. Future research will provide more insight in clarifying the relationship between acoustic backscatter intensity and particle concentration with all the water quality parameter measurements by our IDACC system and therefore, will help in better understanding the particle dynamics of the CC Bay. Particles can transport ‘particulate BOD’ (biochemical oxygen demand), thus affecting hypoxia. Quantification of the particle influx/outflux to the Gulf of Mexico through ship channel may help us to understand the contribution of ship channel in controlling hypoxia of the bay.

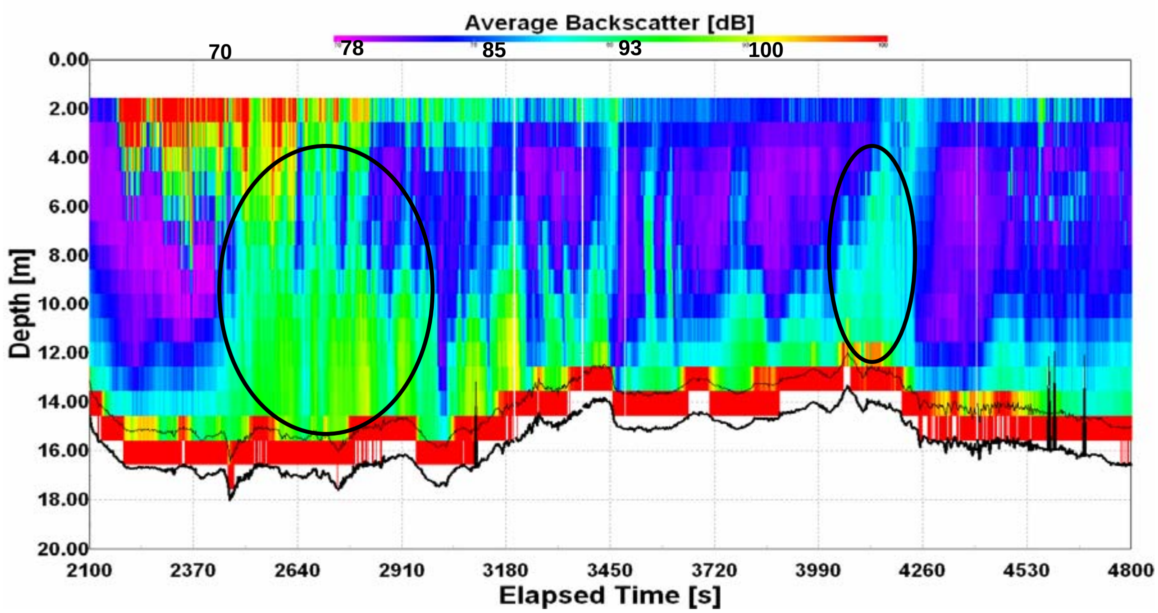

Figure 8. Average acoustic backscatter intensity variation along the IDACC transect route on Nov 29, 2006.

V. CONCLUSIONS

As presented in this paper, the observed data from two of our field monitoring activities proved the capability of our IDACC system as an aid in capturing the dynamics of the bay. Inflows of the hypersaline water from the Laguna Madre and Oso Bay may be responsible for the observed inverse estuary situation captured by our IDACC system. Understanding the circulation pattern of the bay with the observed data will help us to better predict the stratification event that causes the hypoxia in bay through preventing vertical mixing of water column. As oxygen-consuming organisms and particulates in the stratified water column can not move to upper surface layer, they will consume all the available oxygen in the lower layer of the water column and make the water hypoxic. The positive correlation between acoustic backscatter intensity measured by the ADCP and particle concentration measured by the LISST-100 will allow us to develop a quantitative relationship between these two parameters and potentially with the other observed data as measured by our IDACC system. The development of these kinds of quantitative relationships is the subject of our future research, which will then facilitate better understanding the particle dynamics of the bay that significantly affect the hypoxia through the transport of the particulate BOD in/out of the bay. Also the development of water quality and three-dimensional hydrodynamic models with observed-data integration will assist in greater understanding of the processes that control hypoxia in this shallow wind-driven bay.

ACKNOWLEDGMENTS

Funding for this work was provided by the Texas General Land Office, the National Science Foundation, Texas Water Research Institute and the Office of Naval Research. Thanks also go to the staff members of the Shoreline Environmental Research Facility (SERF) for their support in the data collection effort.

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Using Numerical Modeling and Direct Observation to Investigate Hypoxia in a Shallow Wind-Driven Bay

Mohammad Shahidul Islam, James S. Bonner, Temitope Ojo, and Cheryl Page
(Texas A & M University, College Station, Texas, USA)

***Abstract*- Corpus Christi (CC) Bay, Texas, USA is a shallow (average depth around 3m) wind-driven bay that is subjected to diurnal wind variation. However, our observations suggests that this bay becomes stratified during the summer time and hypoxic (<2mg/l dissolved oxygen [DO]) condition develops in the south-east part of it, near the Laguna Madre and at the mouth of Oso Bay. As this system is very energetic, it is not possible to capture or fully understand the dynamic patterns of DO concentrations through spatially- or temporally-limited sampling schemes typical of discrete sampling or continuous monitoring at limited locations. Therefore, in this study, a system is being developed to measure various water quality parameters at higher spatial and temporal resolution. To get the vertical variation of different water quality parameters, a vertical profiling robot has been installed at one of our fixed monitoring platforms in the bay. Four more platforms/profilers are targeted for installation in the near future. This profiler's instrumentation suite measures DO, temperature, salinity, chlorophyll concentration and particle size. The same spectrum of environmental parameters is measured 'synchronically' over a highly-resolved spatial regime through our mobile platform equipped with an IDACC (Integrated Data Acquisition, Communication and Control) system. Short time analysis of observed data indicates the potential of these observation systems in identifying the factors that may affect hypoxia. In addition, a 2-dimensional hydrodynamic model which produces water surface elevation and depth-averaged velocity variation with time has been developed for CC Bay using the ADCIRC (ADvanced CIRCulation) model. This model will be extended into a 3-dimensional model which is then coupled to a water quality model for dissolved oxygen. Integrating model output with observed data will contribute into the understanding of processes that lead to the development of hypoxia and other environmental phenomena.**

I. INTRODUCTION

Dissolved oxygen is an important water quality parameter that indicates the status of the life of an aquatic ecosystem. Hypoxia develops when the concentration of dissolved oxygen (DO) in the water column dips below 2 mg/l and most aerobic aquatic organisms cannot survive under this condition. Various factors like eutrophication, water column stratification, geomorphology of the bay, meteorology etc. may contribute to the development of hypoxia [1]. According to Ritter, Montagna and Applebaum, 2005, eutrophication does not cause hypoxia in CC Bay because over the last fourteen years, freshwater inflows rates have decreased and nutrient levels also have not changed significantly [2]. Ritter and Montagna also observed the hypoxia at relatively stagnant portion of the CC Bay where the vertical salinity gradient is very high [3]. But since Corpus Christi (CC) Bay is very shallow and predominantly wind driven, it ordinarily would not be expected to become stratified. However, this phenomenon does occur during the summer time in the south-east portion of the bay, near the Laguna Madre and at the mouth of nearby Oso Bay [3]. Therefore, it is necessary to identify the circulation pattern of CC Bay to contribute to the understanding of how/why hypoxic events occur in this bay. In this study, a 2-dimensional (2D) hydrodynamic model which produces water surface elevation and depth-averaged velocities variation with time has been developed for CC Bay using the ADCIRC (ADvanced CIRCulation) model [4]. This model will be extended into a 3-dimensional model which will give detailed hydrodynamic information including the circulation pattern and stratification structure.

Spatial extent, frequency and duration of hypoxia determine the level of disturbance it causes to the ecosystem. As CC Bay is very dynamic system, it is not possible to fully capture the extent of a hypoxia event through discrete sampling or continuous monitoring at one or very few locations. Therefore, in this study, an observational system has been developed that will supply surface current maps, vertical profiles of currents, DO, temperature, salinity and other chemical and biological water quality parameters at higher spatial and temporal resolution. This system consists of observational fixed and mobile platforms equipped with water quality measuring instruments which will be guided by the output of the water quality and 3D hydrodynamic model. A vertical profiling robot installed on a fixed platform can measure vertical variation of various water quality parameters whereas our mobile platform (i.e., research boat) equipped with an IDACC (Integrated Data Acquisition, Communication and Control) system can measure the same spectrum of environmental parameters 'synchronically' over a highly-resolved spatial regime in an undulating(vertical sinusoidal) pattern.

II. MATERIALS AND METHODS

A. Vertical Profiler (with Instrumentation Suite) on Fixed Platform

An automated vertical profiler system, which lowers an instrument package periodically through the water column and houses it above the water between profiles, is well suited to measure the vertical water quality parameters continuously over long time period. This profiler consists of three main parts: the payload, which houses the instruments, the profiler, which raises and lowers the payload, and the control software, which operates the previous two components. The payload is suspended from the profiler by two cables, with a single power/data cable connecting the instruments to the control software. The profiler is deployed off a tall pylon with an arm reaching over the side of the platform overlooking the water. Two suspension cables connect the payload to this arm, and from there to an electric motor responsible for winching the payload up and down. This motor is operated by an electronic controller module, which in turn is operated by control software developed as part of this research effort. The control software operates the profiler and payload to provide a vertical profile of the water to raise and lower the payload and runs the instruments in the payload to gather data. The payload capacity of the profiler is such that we will be able to deploy a minimum of up to four instruments. The instruments deployed on this profiler are a particle sizer (LISST 100X, by Sequoia Sciences), a DO sensor (Optode, by Aanderra), a CTD (Conductivity, Temperature and Depth) sensor (SBE 37 SIP, by Sea-Bird Electronics, Inc.) and a flurometer (Eco-FL3, by WETLabs). The profiler lowers the instrument from mean low-water level to the bottom of the bay within 2.5 minutes and measures water quality parameters at five equi-distant depth levels. It then pulls the instrument suite out of the water and dries them through the exposure to the sunlight. This helps in reducing the bio-fouling of the instruments. The cycle time of profiler is 15 minutes. The optimal cycle time and data collection time will be determined through due consideration of the time scale of the variation of the actual water quality parameters and the response time of each instruments.

B. IDACC System on Mobile Platform

The IDACC system has been previously developed in our research group to measure various water quality parameters ‘synchronically’ over a highly-resolved spatial regime [5]. This unit is capable of adaptive sampling to facilitate and guide data acquisition exercises and has been used successfully in several deployments in simulated emergency spill response, routine bay profiling as well as dye-tracer experiments. Instruments included in this system are a particle size analyzer (LISST 100X), a flurosensor (Eco-FL3, GPS (Global Positioning System) and a CTD (Conductivity, Temperature and Depth) sensor (SBE 37 SIP). A DO sensor has been newly added with this instrumentation suite to measure DO variation. The output of the water quality model and in-situ water quality parameters measured by the vertical profiler will aid in determining the time and route of future mobile platform (IDACC) transects designed to capture a hypoxia event or phenomena of interest.

C. Hydrodynamic Model

The hydrodynamic model developed for Corpus Christi Bay is the ADvanced CIRCulation (ADCIRC) Model for Coasts, Shelves, and Estuaries [4]. It is a two-dimensional depth-integrated finite-element model. The original grid developed by Scheffner, Carson, Rhee and Mark [6] is modified in the area of interest with details added using Surface Modeling System (SMS) software. Coastline data and bathymetric data were obtained from Geophysical Data System (GeoDas), National Oceanic and Atmospheric Administration (NOAA) database and U.S. Army Corps of Engineers (USACE)

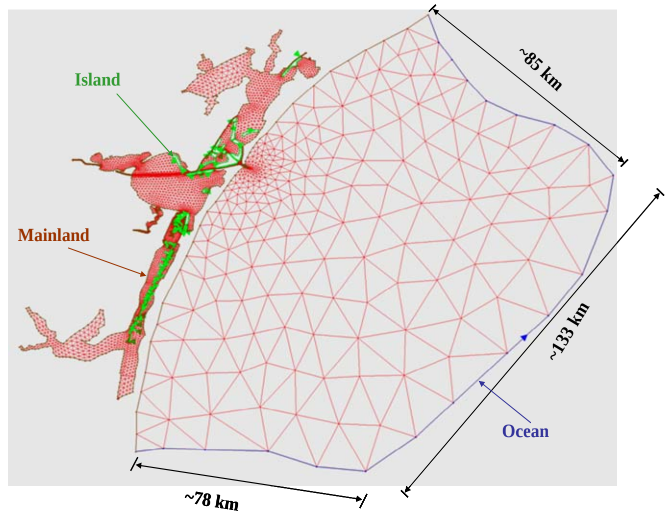

Figure 1 Computational Domain

surveys. The computational domain for this model is presented in Fig. 1. Three types of boundary are considered, namely mainland, island (no flux condition), and Open Ocean (tidal flux only). Atmospheric and wind forcing information, collected from Windbird instrumentation (by R.M. Young Company) at our nearby Oso Bay monitoring platform, were applied at the whole computational domain. The amplitude, frequency and other parameters of tidal potential constituents were determined for a specified time that the model ran using the Le Provost Database [7]. Eight constituents for the tidal forcing frequencies and five constituents for tidal potential were used in this model. The optimal time step (6 seconds) was calculated based on Courant number criteria. Our research group at Shoreline Environmental Research Facility (SERF) has deployed and operates two HF (High Frequency)-Radar unit to monitor real time hydrodynamic information of the Corpus Christi (CC) Bay [8]. This unit has coverage of 600 square km at 1 square km grid spacing. Radar measurements are hourly averages of 10 min time series data obtained using the Bragg scattering principle applied to incident radio waves. These hourly current vectors are coincident temporally with model output which was interpolated spatially into radar grid space.

III. RESULTS AND DISCUSSION

The dynamic pattern of dissolved oxygen variation depends on the complex interplay of physical, chemical and biological processes. The robotic profiler equipped with various instruments measure various water quality parameters at five equidistant levels from the surface to the bottom of the bay. An example of a series of vertical profiles on June 15, 2006 is presented in Figure 2. Fig. 2(a) presents the depth variation of the sea levels over this 24-hour time period, while Figures 2(b), 2(c) and 2(d) depict corresponding vertical dissolved oxygen, salinity and total particle concentration variations with time, respectively. All measurements are referenced with GMT time. These synchronized measurements may aid in understanding various phenomena. For example, from Figures

2(b), 2(c) and 2(d), it is clearly visible that a sediment re-suspension event occurred between 10:00 and 15:00 (GMT). Both salinity and total particle concentration levels noticeably increased during that time frame. The decreased DO levels shortly thereafter suggest that the bottom hypoxic or anoxic sediments may have consumed a portion of the oxygen from the water column (Fig 2(b)). Long term analysis of these water quality parameters will facilitate in exploring various important environmental phenomena that contribute to the hypoxia.

In recent years, Ritter and Montagna [3] have observed hypoxia in the southeast portion of CC Bay during the months of July and August. Thus, we are in the process of deploying a fixed platform (for vertical profiling) in that region to collect data that will aid in the study of hypoxia. Moreover, we can use these water quality parameter data as the input of our water quality model. The model output will help in determining the location and timing of subsequent field transect runs using our mobile platform equipped with IDACC system. The IDACC system measures various water quality parameters at higher spatial resolution but lesser temporal resolution. These runs may help in determining the spatial extent of a hypoxic event. On 7 April 2006, we conducted a south-to-north transect of the bay to investigate the spatial variation of salinity. We found slightly higher salinity levels at the south end of the bay (near the opening to the Laguna Madre) and the northern end of the bay (near the ship channel (Fig 3)). Salinity levels at the southern portion could be affected by the shallower depths, which can lead to the higher evaporation rates. This spatial profile of salinity concentration shows how these types of monitoring activities with the

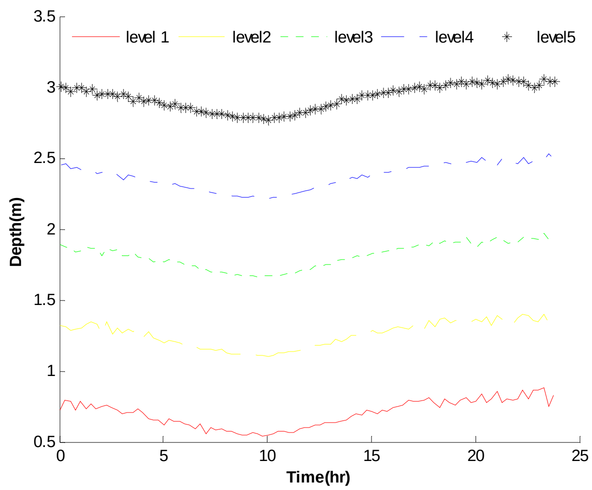

Figure 2(a) Depth variation of different level with time on June 15, 2006(GMT).

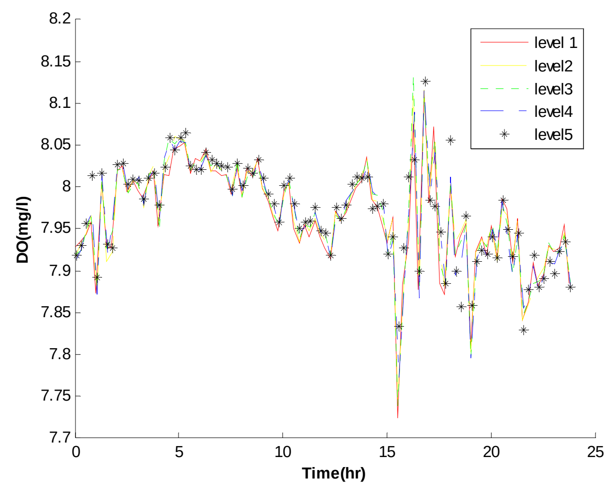

Figure 2(b) Vertical dissolved oxygen variation with time on June 15, 2006(GMT).

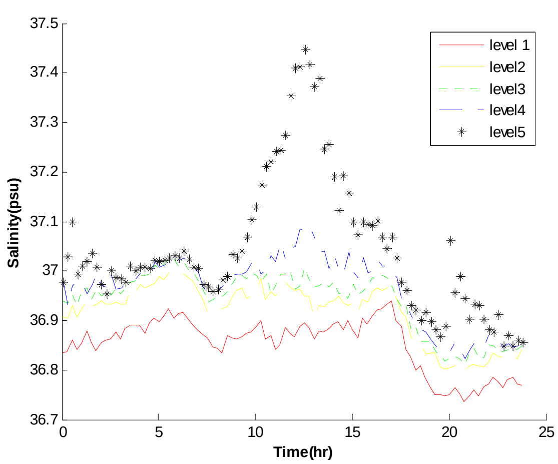

Figure 2(c) Vertical salinity variation with time on June 15, 2006(GMT).

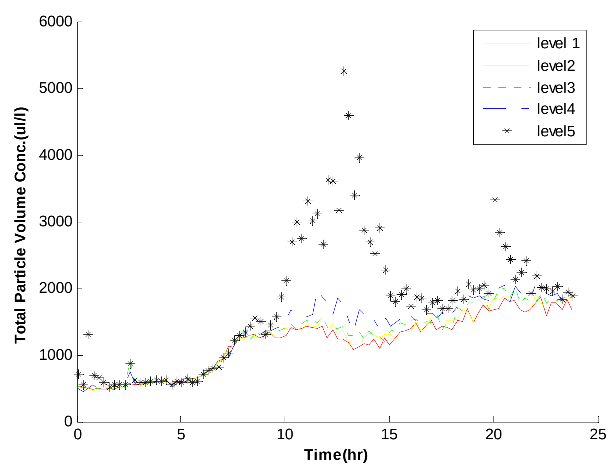

Figure 2(d) Vertical variation of total particle concentration with time on June 15, 2006(GMT).

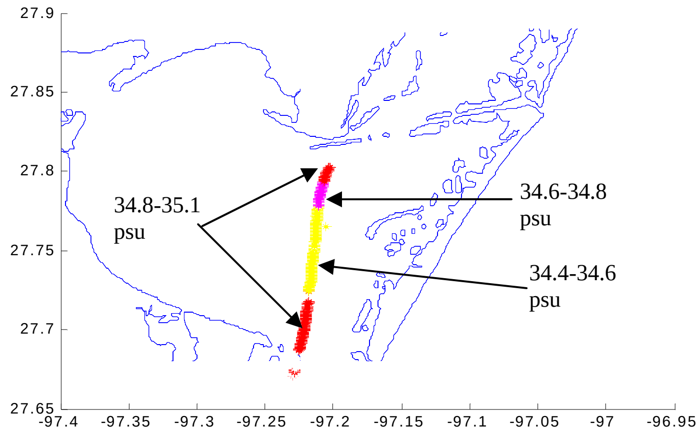

Figure 3 Salinity variation along the transect route of the IDACC run on April 7, 2006.

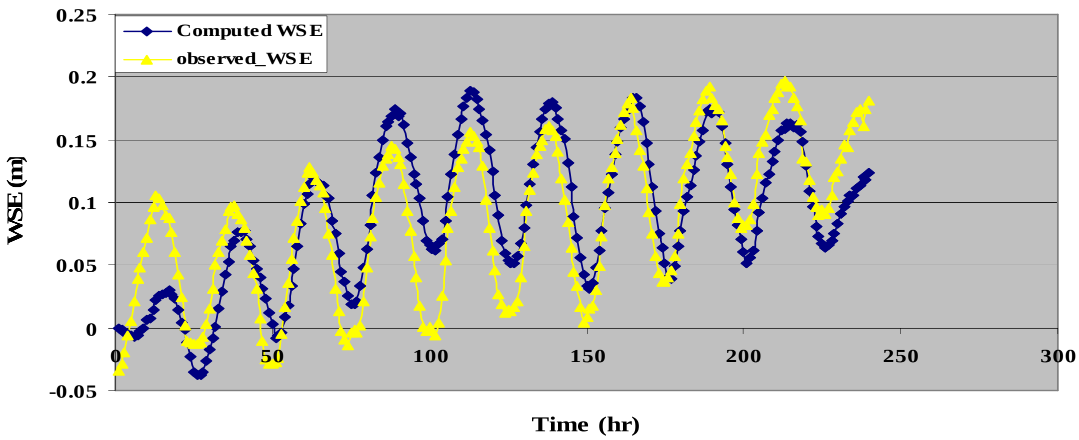

Figure 4 Observed vs computed Water Surface Elevation (WSE) at Packery Channel.

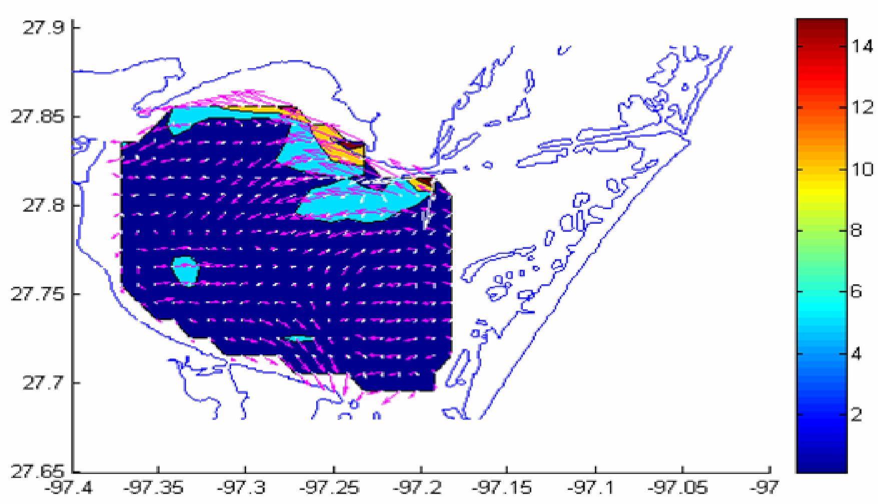

Figure 5 Velocity magnitude residual plots for observed and model-computed velocities;
Note: Observed radar measured current (pink arrows), Model-computed current (white arrows); range is 0 cm/s to 14 cm/s.

IDACC system can aid in providing various water quality parameters at greater spatial resolution.

A 2-dimensional hydrodynamic model, which produces water surface elevation and depth-averaged velocities variation with time, was developed for Corpus Christi Bay using the ADCIRC (ADvanced CIRCulation model). The model was calibrated with observed water surface elevation and surface current data. Once calibrated, the model was verified by another set of observed data (Windbird instrumentation).The comparison between observed and model-computed water surface elevation (WSE) variation at Packery Channel (southern portion of CC Bay), as presented in Fig. 4, are in good agreement. Fig. 5 illustrates the residual plot between model-computed current velocities and observed surface currents by HF (High Frequency) radar. From the velocity magnitude residual plot (Fig. 5), it is inferred that differences between the observed- and model-computed velocity magnitudes are usually within the range of 8 cm/s. Chapman et al., 1997 showed the error in measuring current velocities by HF radar to be in the range of 7 to 8 cm/s [9]. So this model captures the dynamics of the bay within tolerable limits. This model will be extended into a 3-dimensional model, which is then coupled to a water quality model for dissolved oxygen. All the data collected by our observational systems will be fed into our water quality model, and model parameters will be adjusted through the comparison of model-predicted data with the observed data. The prediction of the modified model will then guide the sampling strategies and route of our observational systems. This mutual adjustment between the observational system and the model will help in better understanding of the dynamic system in Corpus Christi Bay and thereby, further clarify this critical hypoxia phenomenon.

IV CONCLUSION

Corpus Christi Bay, which can be described as a stochastic pulsed system, has very complex hydrodynamic and water quality conditions. The dynamic patterns of DO concentration variation in this dynamic system can be explored through the integration of real time observation systems that can measure various water quality parameters at a higher spatial and temporal resolution with water quality models. Our observational system consists of fixed and mobile platforms equipped with various water quality measuring instruments. A robotic profiler, installed at our fixed platform, can measure the vertical variation of various water quality parameters. The IDACC system, towed by our mobile platform, can determine the same spectrum of environmental parameters 'synchronically' over a highly-resolved spatial regime. Short-time analysis of observed data proved the potential of these observation systems in identifying the factors that may affect hypoxia. Long time analysis of the observed data will clarify many factors that contribute to hypoxia and help us understand this critical phenomenon. All the data collected by our observational systems will be fed into our water quality model, and model parameters will be adjusted through the comparison of model-predicted data with the observed data. The prediction of the modified model will then guide the sampling strategies and route of our observational systems. At the first stage of this endeavor, we developed 2D hydrodynamic model for the CC Bay that can determine water surface elevation and depth-averaged velocity variation with reasonable accuracy. This model needs to be extended into a 3-dimensional model for getting the detail hydrodynamic information and will then be coupled to a water quality model for dissolved oxygen. The integration of this model with our observational system will aid in understanding hypoxia and other natural phenomena observed in the CC Bay, Texas.

ACKNOWLEDGMENTS

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A Socio-Technical Case Study of Sustainable Stormwater Management in Austin, Texas

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THE CULTURAL APPROPRIATION OF WATER QUALITY IN AUSTIN, TEXAS
Politics, Infrastructure, and Urban Nature

Andrew Karvonen, The University of Texas at Austin
1 May 2007

In this paper, I examine the historic and current meaning of water to different social groups in Austin, Texas. Beginning in the early 1970s, water quality became a central concern in the divisive political debate over the benefits and drawbacks of urban growth. Environmental and community activists used stormwater management as a proxy for the declining health of the ecosystem and by extension, the decline of Austin's community character. Development and property owners were concerned that environmental regulations to protect water quality would infringe on their development rights. The debate came to a head with the passage of the Save Our Springs Ordinance in 1992, a particularly important piece of municipal legislation that imposed strict impervious cover limits over environmentally sensitive areas of the region, further fueling the debate over urban growth in Austin.

This urban case study is based on information collected from in-depth interviews with key stakeholders (technical experts, developers, politicians, environmental activists, journalists, and concerned citizens) as well as historical documents on the development of stormwater practices and the environmental culture of Austin. I employ notions from the field of Urban Political Ecology to highlight the political nature of infrastructure development and the tensions that exist between urban expansion and ecosystem function. The study emphasizes the intertwined material and social conditions that form the "water culture" of Austin and suggests the need for a new understanding of the relationship of water flows to urban residents.

I am grateful to the Texas Water Resources Institute at Texas A&M University for their generous funding support for this research.

Introduction: The Emergence of Water Quality as an Urban Issue

Since the nineteenth century, municipal governments have been charged with planning, constructing and maintaining centralized sewerage systems for stormwater and sanitary waste to support transportation networks, reduce flooding incidents, and protect the public health.[1] To a great extent, municipal engineers and infrastructure managers have followed a systematic logic of "expand-and-upgrade" to develop extensive physical networks based on scientific principles as well as technical and economic feasibility.[2] In the 1970s, this logic was expanded as the U.S. government began to focus on water quality aspects of stormwater in addition to water quantity. A number of significant federal regulations prompted state and local authorities to reduce the water quality impacts of urban drainage.[3] The focus on water quality resulted in the proliferation of technical approaches–notably detention and retention ponds–on both public and private properties to slow down stormwater flows and remove contaminants before release to downstream waterbodies.

Today, protection of water quality is a common practice in many U.S. cities. However, a few communities exhibit a heightened political dialogue on stormwater issues due to issues of threatened or endangered species, the failure of antiquated network components, perceived or real threats to the waterborne tourist industry or public health, and declining water quality. In places such as Austin, Denver, Portland, Seattle, Washington, D.C., and Philadelphia, urban hydrology is not merely an issue for municipal engineers to tackle but serves as a lightning rod for political controversy, influencing election outcomes, changing land development patterns, and even reshaping the hydrologic functioning of urban environments. These public dialogues on stormwater management have resulted in the emergence of new approaches such as Low Impact Development, Better Site Design, and ecological engineering based on demand-side management of urban waterflows. Developed by a wide range of technical and non-technical stakeholders including civil engineers, landscape architects, environmental activists, and municipal program managers, these approaches challenge the expand-and-upgrade logic of conventional stormwater management in the pursuit of improved environmental quality and aesthetics, as well as reduced infrastructure costs.[4]

In this paper, I examine stormwater issues in Austin, Texas, a city where highly contentious political debates have revolved around water quality since the 1970s. Beyond the municipality's reputation as a progressive manager of stormwater flows (see commendations from the U.S. Environmental Protection Agency and the Natural Resources Defense Council[5]), the most important issues of water quality have involved public dialogues over future growth of the metropolitan region. These debates demonstrate the intertwining of nature, society, and technology in modern societies and the challenges that communities face in appropriating new conceptions of environmental quality.

Interpreting Urban Water Flows

This study is founded in the new field of Urban Political Ecology (UPE) where scholars from a wide range of disciplines have come together to focus on the complex

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1 Tarr and Konvitz 1987
2 Moss 2001
3 Notable stormwater regulations include the Water Pollution Control Act of 1972, the Clean Water Act of 1977, the Water Quality Act of 1987, and the National Pollutant Discharge Elimination System (NPDES) regulations of the 1990s.
4 For example, Schueler 2000, France 2002, and Hough 2004.
5 See U.S. EPA 2006 and NRDC 1999.

relationships between the material and social aspects of the built environment. The discourse emerged in the 1990s from political ecology as well as various forms of critical ecology studies (eco-Marxism, eco-feminism, eco-anarchism), critical geography, ecological planning, science and technology studies, and urban sustainability.[6] UPE scholars interpret the built environment in a variety of different ways but a common theme is to reject modern dualisms of nature/society, urban/rural, and natural/artificial. Keil notes that "the material and symbolic, the natural and cultural, the pristine and the urban are not dual and separate realities but rather intertwined and inseparable aspects of the world we inhabit."[7] These hybrids or collectives are what Donna Haraway refers to as "cyborgs" and Bruno Latour calls "quasi-objects" to reflect both their natural and social attributes.[8]

From a UPE perspective, the urban landscape can be understood as a hybrid complex of overlapping material and social processes. The process of urbanization is not understood as a progression from natural environments (the natural pole) to built environments (the social pole) but is a process in which complex political relationships are formed between the social and the natural.[9] With respect to stormwater management, the UPE approach opens the discourse to many social actors and takes into account the importance of material aspects of the city.[10] Politics thus transcends its social roots and becomes embedded in its material context.

Water is increasingly a central issue in the constitution of urban spatial relations and urban political regimes.[11] Urban water flows are multivalent and cannot be reduced to technical or cultural explanations. As Geographer Matthew Gandy argues, "Water plays an important role in reconstructing the urban space with its closely choreographed intersection between technology, space, and society."[12] Tracing the social and material relationships embodied in stormwater networks allows for a more nuanced understanding of the relationships between nature and culture, opening the political discussion to reflect on how communities want to live within their surroundings. Such a perspective suggests that the control and modification of urban water flows is not merely a technical and economic issue but is rife with political meaning, like any social process.

Austin as Urban Growth Machine

The capital city of Austin is located in Central Texas, within the metropolitan triangle of Dallas/Fort Worth, San Antonio, and Houston (**Figure 1**). It is the fourth largest city in the state with a population of 650,000 in the city limits and another 600,000 in the larger metropolitan area. Similar to other cities, the location of Austin was chosen for its proximity to water resources. An 1839 map of the region (**Figure 2**) presents Austin as a 640-acre settlement on the banks of the Colorado River where "the new city is shown nestling, as it were, between the sheltering arms of the two creeks, Shoal and Waller."[13]

6 Keil 2003
7 Ibid., p. 728
8 Swyngedouw 2006
9 Whatmore 1999, Keil 2003
10 See Latour 1998
11 Examples of UPE literature on urban waterflows include Desfor and Keil 2004, Gandy 2003, Swyngedouw 2004, and Kaika 2005.
12 Gandy 2004, p. 366
13 Hart 1974, p. 24

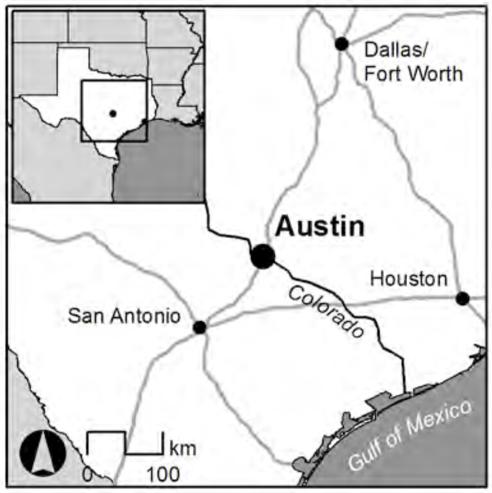

Figure 1 Location map of Austin, Texas

Despite its proximity to water resources, Austin grew slowly because it lacked a manufacturing sector and instead, relied on the slow-growing industries of state government and higher education.[14] A recurring problem for residents of the capital city was how to harness the Colorado River with minimal public funds. Austin floundered in the late nineteenth and early twentieth century with an inadequate water supply, unreliable electricity service, and periodic floods that devastated the community. The municipal government was successful in building a dam on the Colorado River in 1893 to generate electricity and provide a consistent source of water but the dam collapsed in 1900, propelling the city into fiscal crisis.[15] Between 1900 and 1913, Austin residents suffered through 17 floods that claimed 61 lives while causing $61.4 million in damage.[16]

It wasn't until the 1930s that Austin finally overcame its battle with the Colorado River, thanks in large part to financial assistance from the U.S. government. The federal government's New Deal programs provided vital infrastructure development projects to spur commerce and development in many U.S. cities.[17] Austin was very fortunate, receiving more funding for municipal construction projects from the Public Works Administration than any other Texas city in the 1930s.[18] U.S. Senator Lyndon Johnson was instrumental in bringing New Deal projects to Central Texas, including several dams on the Colorado River that created a chain of waterbodies known as the Highland Lakes. The dam projects created jobs and provided city residents with much needed water and electricity services as well as flood control. The harnessing of the river thus became central to the future growth of Austin.[19]

With stable municipal services and a burgeoning recreation economy from the Highland Lakes, the Austin population surged. From 1940 to 2000, the Austin population grew at an average rate of 40 percent per decade.[20] Much of this growth can be attributed to the rapid expansion of government and education, but after World War II, Austin's Chamber

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[14] Orum 1987
[15] Humphrey 2001
[16] Orum 1987
[17] Tarr and Konvitz 1987
[18] Humphrey 2001
[19] Banks and Babcock 1988, Pipkin 1995
[20] Humphrey 2001

Figure 2 An 1839 map of Austin nestled between Shoal and Waller Creeks

of Commerce and the municipal government laid the groundwork for a new economy based on the high-tech industry. A consortium of university administrators, municipal officials, and local entrepreneurs recognized an opportunity to transform the city into a regional center for the growing computer industry. After several decades of planning, the consortium finally succeeded in wooing IBM to Austin in 1967. Other companies followed, including Texas Instruments in 1969, Motorola in 1974, and in the 1980s, Microelectronics & Computer Technology Corporation and Sematech.[21] Whereas the growth of Austin before the 1950s was fueled by significant Federal funding, the economy after World War II was increasingly dependent on the private marketplace for urban expansion, specifically high tech companies.[22]

The arrival of the high tech industry transformed Austin into an 'urban growth machine'[23] that was desirable to landholders and developers but was unwelcome by many Austin residents who perceived the influx of people and the expansion of the city as a detriment to their quality of life. The roots of Austin's liberal population are based on the

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21 Humphrey 2001
22 Austin is frequently referred to as the "Silicon Hills," a nod to Silicon Valley in Northern California.
23 See Jonas and Wilson 1999

employment opportunities of the state government and university that created a community of highly educated middle class residents. The University of Texas fueled the populist sentiment of Austinites as early as the 1940s when university professors and students railed against the Austin establishment on contentious social issues, notably segregation.

In the 1970s, neighborhood groups became a prominent fixture in municipal politics, focusing on urban growth and expansion issues which threatened the perceived character of Austin.[24] Neighborhood activists fought battles over new apartment complexes and traffic congestion to protect the integrity of their neighborhoods from new development. By 1983, there were more that 150 neighborhood groups active in Austin. Among the populist groups, environmentalists became a powerful force in protecting streams, lakes, watersheds, and undeveloped areas from environmental degradation.[25] To this day, most city elections can be characterized as contests between pro-growth candidates and pro-environment/community candidates.

The Importance of Urban Water in Austin

The water features of Austin have long been embraced by its citizens as a defining characteristic of the city. The City Plans of 1928, 1961, and 1980 consistently called for protection of the urban creeks and waterways through integration of greenbelts or linear parks to protect these natural resources.[26] In 1976, Austin's Bicentennial Gift to the Nation created the Creeks Project, designating all urban creeks as multimodal recreation and transportation spaces.[27] The focal point of the "water culture" of Austin is Barton Springs Pool, a spring-fed public pool in the Barton Creek watershed in southwest Austin (**Figure 3**). Since the late 1800s, the springs have served as a public meeting place for recreation and community building. The City of Austin acquired the springs in 1918 and built a dam just below the springs to create Barton Springs Pool, solidifying the springs as the city's communal meeting place.

The cultural importance of Barton Springs to Austin residents cannot be understated. The springs are often referred to as the "soul of Austin" and reflect the egalitarian values of the community. As one longtime swimmer of Barton Springs notes, the springs have "a social leveling influence that is unique. When you strip down to a bathing suit, everyone is equal."[28] Thus, the springs serve as a totem for the Austin community, simultaneously creating a connection between Austin residents and the landscape while also promoting a sense of community within that space.[29] Here, the social, natural and technical combine to create a distinct local identity. Former Texas agriculture commission and nationally-known political commentator Jim Hightower observed that:

> The glory of Barton Springs–and similar jewels around the world–is not simply its passive pleasures and the pureness of its existence but also its power to pool individuals into a genuine community of activist citizens....the Springs refresh, but they also empower those who love them.[30]

[24] Orum 1987
[25] Humphrey 2001
[26] City of Austin 1928, 1961, 1980
[27] Horizons Committee 1976
[28] Quoted in Pipkin and Frech 1993, p. 69
[29] Swearingen 1997
[30] Quoted in Pipkin and Frech 1993, p. 105

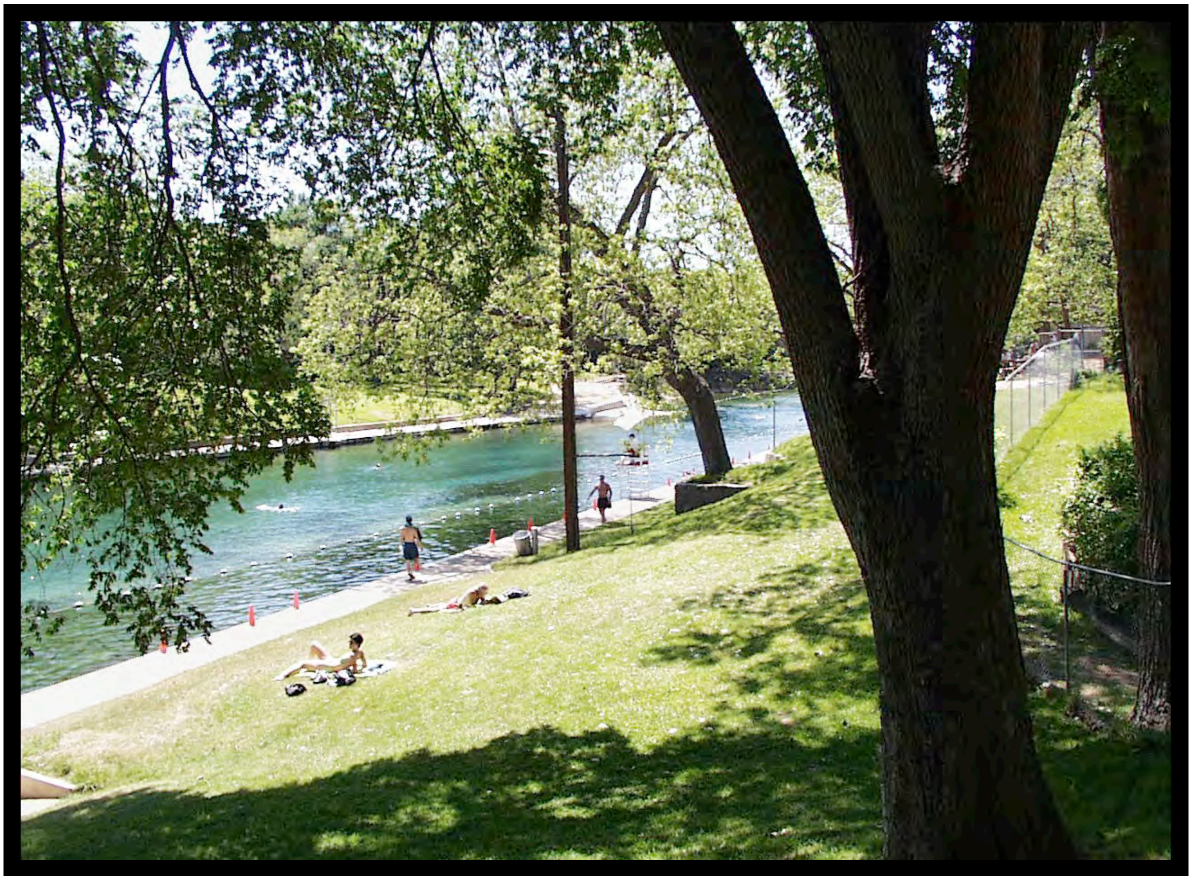

Figure 3 Barton Springs Pool, often referred to as the "soul of Austin"

The springs embody more than cultural and political significance, they also serve as a gauge for water quality conditions of the region. The springs are the outlet of the Barton Springs section of the Edwards Aquifer, a karst aquifer that is highly porous and thus, is susceptible to contamination from land development. Unlike sand aquifers that tend to slow down and filter stormwater, karst aquifers tend to transport water and contaminants quickly. Scientists began examining the complex conditions of the Edwards Aquifer in the 1960s and characterizing the mechanics of karst aquifer hydraulics with respect to urbanization and increasing levels of impervious cover.[31] These studies showed that the aquifer's water quality was highly susceptible to development processes.

The municipal government recognized the environmental sensitivity of the aquifer and passed ordinances to protect water quality. For instance, the 1980 City Plan called for limited development in the Barton Creek Watershed (City of Austin 1980). In 1985, the City of Austin completed a 7.9 mile greenbelt in the watershed encompassing 809 acres of land to serve as a recreation destination for hikers, mountain bikers, rock climbers, and swimmers as well as protect the water quality of Barton Creek, Barton Springs, and the underlying aquifer (**Figure 4**). The Barton Creek Watershed is one of the least developed in the region–79% of the land area is undeveloped–and consequently has the lowest ecological impairment.[32]

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[31] For example, see Woodruff and Slade 1986.
[32] City of Austin 2005

Figure 4 Barton Creek Greenbelt with Barton Springs Pool at the upper right

Beyond its hydrologic attributes, Barton Springs has biological significance to the regional ecosystem. Of particular importance to the Barton Springs story was the 1993 discovery of an indigenous species, the Barton Springs Salamander (*Eurycea sosorum*), which resides in Barton Springs Pool. In 1997, the U.S. Fish and Wildlife Service added the salamander to its list of endangered and threatened wildlife to receive protection under the Endangered Species Act.[33] As such, the role of Barton Springs as an indicator of the ecological health of the aquifer was further solidified.

Political Contests over Urban Water Flows, 1970s to present

Public battles over water quality in Austin erupted in the 1970s when real estate developers chose the Barton Springs zone of the Edwards Aquifer as a prime location for new development. In addition to its unique hydrologic characteristics, the region contains some of the most picturesque landscape in close proximity to the city. The struggle between environmental protection and urban growth continued to escalate, with the City passing a succession of comprehensive water quality ordinances to protect the aquifer and urban waterways.[34] These ordinances were significant because they introduced stormwater management and water quality protection as a municipal mandate. Between 1980 and 1992, the city adopted eight water quality ordinances along with several amendments that addressed impervious cover, density, transfer of impervious cover or development rights, stormwater treatment and detention requirements, construction site management, and stream setbacks or buffer zones.[35] These regulations formalized the city's commitment to protecting the region's natural

[33] Lieberknecht 2000
[34] City of Austin 2006a
[35] Ibid.

resources using "Best Management Practices" and were an attempt to direct urban growth off of the sensitive aquifer. Unfortunately, they only achieved mixed success because the City offered exemptions to many developments over the aquifer. Furthermore, State law allowed developers to create Municipal Utility Districts that superceded local regulations and allowed for development over the aquifer.[36]

Frustrated over the City's inability to protect the aquifer, politically active Austinites rallied for further water quality regulations to curtail urban development. The political conflict over water quality and urban growth came to a head on June 7, 1990 at an infamous all-night meeting of the City Council where over 600 citizens spoke about the threats of a new 4,000-acre development being proposed over the aquifer. The momentum from that meeting propelled a number of local environmental groups to form the Save Our Springs Coalition (later renamed the Save Our Springs Alliance and frequently referred to as SOS) to focus specifically on protection of Barton Springs and the Barton Springs segment of the Edwards Aquifer. The coalition wrote its own water quality ordinance and in 1992, after contentious political debates, the ordinance was passed as a citizen referendum by a two-to-one margin.

The Save Our Springs Ordinance addressed land use development over 112 square miles in sensitive portions of the Barton Springs section of the Edwards Aquifer (some inside the city limits and some in the 2-mile and 5-mile Extra Territorial Jurisdictions) and further codified the community's commitment to water quality. The ordinance established strict impervious cover limits of 15 to 25 percent depending on a property's location over the aquifer and also included a non-degradation policy and construction setbacks. By comparison, typical urban development consists of 40 to 95% impervious cover. Environmental activist Helen Bellew states, "With the SOS vote, Austin made it clear that Barton Springs is where we draw the line."[37] In subsequent years, the development community has waged numerous court battles and influenced the State legislature to grandfather existing site plans and weaken the ordinance to some extent but it continues to be a formidable piece of municipal legislation.[38]

The story of Barton Springs and the S.O.S. Ordinance is founded on cultural politics and to some extent, mirrors the environmental debates in the U.S. in the late nineteenth and early twentieth centuries over preservation versus conservation of undeveloped lands. Citizens are portrayed as defenders of the environment and the desired quality of life that natural areas provide. Developers are described as outsiders who represent capitalist values that run counter to both the Austin culture of environmental quality and middle class lifestyle.[39] Moreover, Barton Springs serves as a symbol of the larger meaning of Austin as a unique place, one that is opposed to the ideology of unchecked land development patterns.[40] The debate over the springs and the health of the aquifer is at heart a public deliberation over how the city will grow in the future, the very stuff of urban politics.

[36] See Staff 1999. It is important to recognize the municipality's dual role as promoter of economic development and protector of the natural environment. The water quality debates in Austin often center around the City's ability or inability to achieve both of these missions simultaneously.
[37] Quoted in Pipkin and Frech 1993, p. 86
[38] Shea 2006
[39] Since 2000, the unofficial motto of Austin has been "Keep Austin Weird," reflecting the desire by many Austin residents to maintain the characteristics that make the city a unique place. See Kanter 2004 for the origin of the motto.
[40] Swearingen 1997

Framing Nature as Non-Urban

In the political debate over stormwater management and protection of the aquifer and springs, nature is frequently framed as an entity outside of the social world. The landscape is considered as a place to protect from human influence and preserve in its sacred state or as a platform on which to expand the city and accommodate the growing population. Bill Bunch, executive director of the S.O.S. Alliance states succinctly: "You can't both pave and save the watershed."[41] Neither perspective embraces nature as integral and inseparable from the community and instead, voters and politicians are restricted to two options: protect or destroy (**Figure 5**).

By ignoring the hybridity of the springs and the aquifer, urban growth is subjected to the ebb and tide of election cycles and by extension, the power of activist citizen organizations to remain a vigilant and influential political force to counter the insistent activities of developers to expand the urban boundaries via development. Since the S.O.S. Ordinance was passed in 1992, the S.O.S. Alliance and other organizations have struggled to maintain their momentum.[42] Of particular importance has been the splintering of the S.O.S. Alliance in the mid- to late-1990s over the future direction of

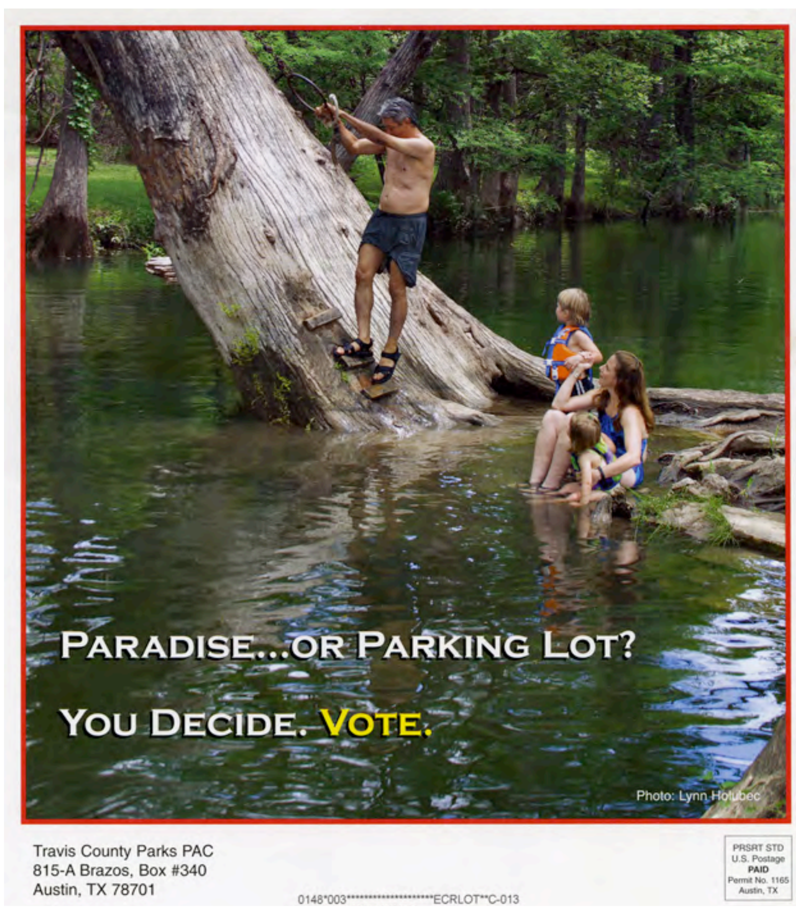

Figure 5 A 2006 political advertisement from the Travis County Parks Political Action Committee

41 Alexander 2006

42 Clark-Madison 2002

environmental activism. Many of the major players in the organization left to found a new organization, Liveable City, that addresses a wider palette of community and environmental issues including affordable housing, transportation, regional planning, and economic development.[43] In short, these defectors found the uncompromising political approach and singular focus of the S.O.S. Alliance to be unworkable, and instead adopted new, more conciliatory notions of sustainable development that tie together multiple urban issues.[44]

Another problem with the dualist nature of the stormwater debates in Austin is that there is little opportunity for design intervention by municipal engineers and property developers who are attempting to mitigate water quality impacts due to urbanization. Emerging drainage approaches such as Low Impact Development and Better Site Design are not part of the water quality conversation in Austin because any manipulation of the environment from land development is portrayed as negative. Instead, the work of municipal engineers is restricted to characterizing the flow conditions of the aquifer and monitoring water quality conditions as opposed to being actively involved in design interventions that could work towards mitigating the environmental impacts of urban development. To be sure, stormwater experts have been employed on both sides of the political debate to argue about the technical aspects of impervious cover, the effectiveness of particular Best Management Practices, and so on. But scientific and technical knowledge tends to be wielded as a political weapon to forward the partisan agendas of the development community or the environmental community rather than develop solutions to the seemingly intractable contradiction between environmental quality and urban growth.

The limited geographic focus of water politics in Austin has also been problematic. Barton Springs has been framed as *the* indicator of water quality and urban growth of the region while the rest of the city has been left out of the debate. In the late 1990s, the City Council adopted the Smart Growth Initiative as a partial solution to the impasse between environmentalists and developers over urban development. The intent of the initiative was for the municipality to use incentives to simultaneously protect the land from development over the sensitive aquifer in the southwest portion of the city while spurring development in desirable locations of Austin, notably downtown and East Austin.[45] The explicit message of the initiative was that urban development is desirable as long as it is done in the proper location. The initiative included a map designating a Water Quality Protection Zone (in West Austin) and a Desired Development Zone (for underdeveloped lands in downtown and East Austin) (**Figure 6**). The approach was characterized as a politically astute way to resolve a political dispute using geographic delineation and reflects the win-win approach of sustainability advocates by combining environmental protection with economic development to reduce sprawl, protect environmental quality, and develop a vibrant urban core.[46]

While the Smart Growth Initiative was received positively by much of the Austin community, it generated fierce criticism from East Austin residents whose neighborhoods were targeted for increased development. Since the early twentieth century, East Austin has been the home to the majority of African American and Latino residents who were effectively removed from Austin proper via formal and informal

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[43] Rather 2006
[44] Price 2007
[45] City of Austin 2006b
[46] Ibid.

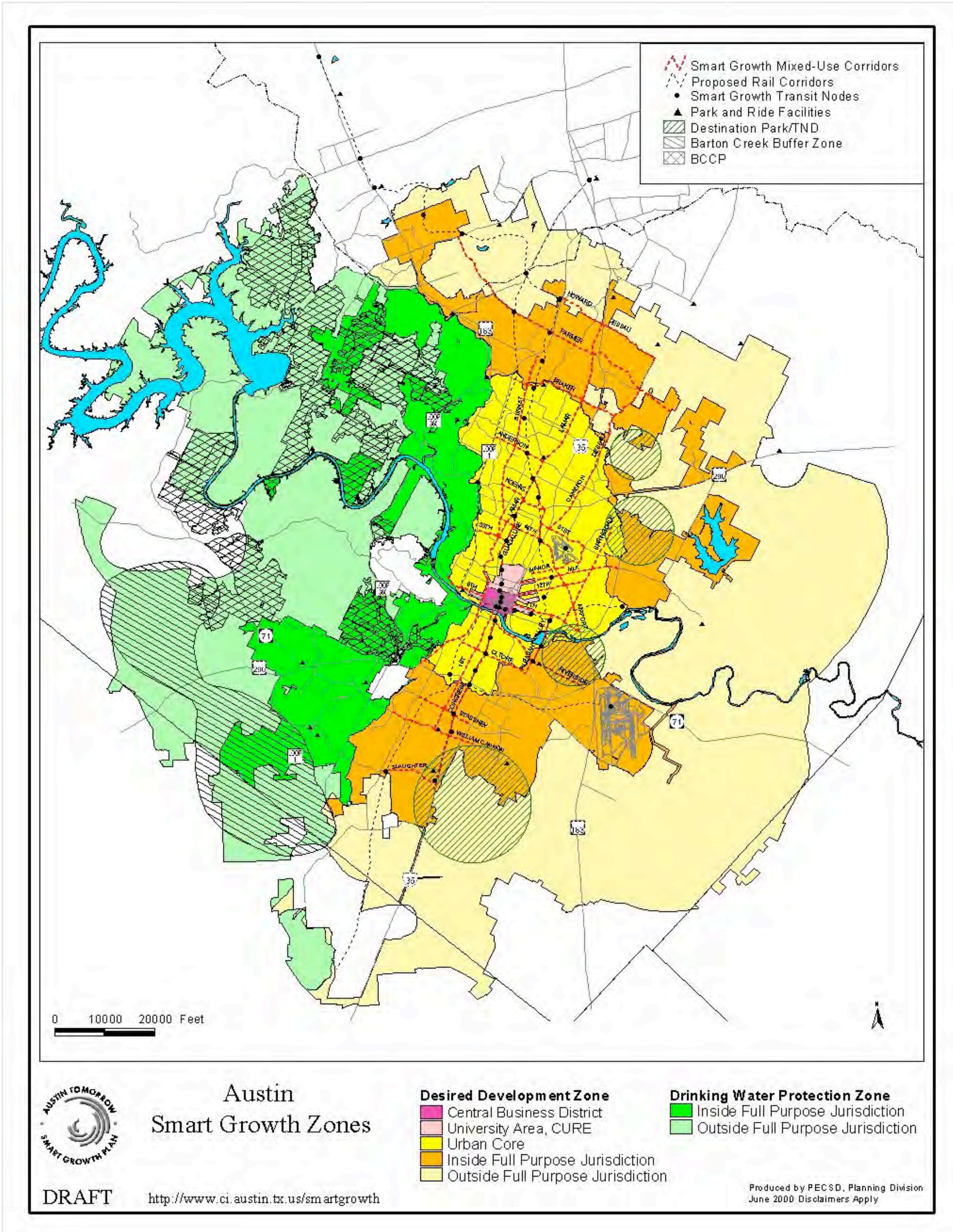

Figure 6 The Smart Growth Initiative proposed a Water Quality Protection Zone and a Desired Development Zone

mechanisms.[47] Fears of gentrification and rising property values as a result of the Smart Growth Initiative served to increase the division between East Austin residents and the rest of Austin.[48] While the Smart Growth Initiative may have been effective at partially diffusing the tension between environmental quality and economic development, it came at the expense of social equity.[49] The splinterization of the community has not only been within environmental groups but also in other community groups, particularly those interested in inequitable distribution of wealth, gentrification, and race relations.

The singular focus on Barton Springs has also had ramifications for other waterways in the city. Despite the numerous City documents that call for the protection of Austin's streams, the streams are all but forgotten in the urban landscape. Stormwater flows have eroded the stream banks and water quality has suffered (see **Figure 7**).[50] In short, the emphasis on the water quality of Barton Springs has not transferred over to these urban waterways. The streams of East Austin are perhaps the worst in terms of biological health and hydrological function, many having been channelized in previous decades by the Army Corps of Engineers to reduce flooding while ignoring biological and aesthetic concerns.

Concluding Remarks: Potential for Hybrid Nature in Austin

The debate over Barton Springs has shaped the political arena by creating a forum where a diverse group of residents have discussed how the region should grow. Austin's attempts to deal with the competing demands of environmental protection and economic growth take place in land development politics and a struggle to maintain a sustainable form of urban growth. As such, the sustainability of places is related to the spatial patterns in which they develop.[51] However, the discourse has been binary and uneven. In the Barton Springs segment of the Edwards Aquifer, the politics have been reduced to a choice of "paving or saving" the fragile water resources. Opportunities for design intervention and finding ways to integrate new development with the sensitive hydrologic conditions have been marginal to nonexistent. Instead, unbuilt land has been portrayed as either too fragile for any form of development (thus the highly restrictive development regulations) or as an opportunity for developers and property owners.

An alternative to the modern dualisms of city vs. nature, natural vs. artificial, and social vs. material would demonstrate that human relationships with nature are ineluctable and inherently subversive of the nature-society dualism.[52] Such a perspective has the potential to broaden the political choices beyond preservation or conservation by focusing on how nature is transformed by actors and the intertwined social and ecological consequences. Perhaps a first step for community members in Austin is to recognize that the springs and the aquifer are not pristine natural entities but are constructed as much as the urban areas of the city. The politics of water quality and urban growth might then transcend the contest of political wills between environmental activists and developers to become an integral part of the urban fabric, just like Barton Springs. Gandy offers the following prescription for a new conception of urban politics:

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[47] For example, a formal mechanism to locate minorities in East Austin is the 1928 City Plan that restricted city services such as water, electricity, sewer, and garbage collection for African Americans to East Austin.
[48] Clark-Madison 1999
[49] See Campbell 1996 for a discussion of the conflicts between economic development, environmental protection, and social equity.
[50] See Tom Hegemeir's 1997 technical assessments of Austin's creeks for the City of Austin Drainage Utility.
[51] Throgmorton 2003
[52] Castree and Braun 1998

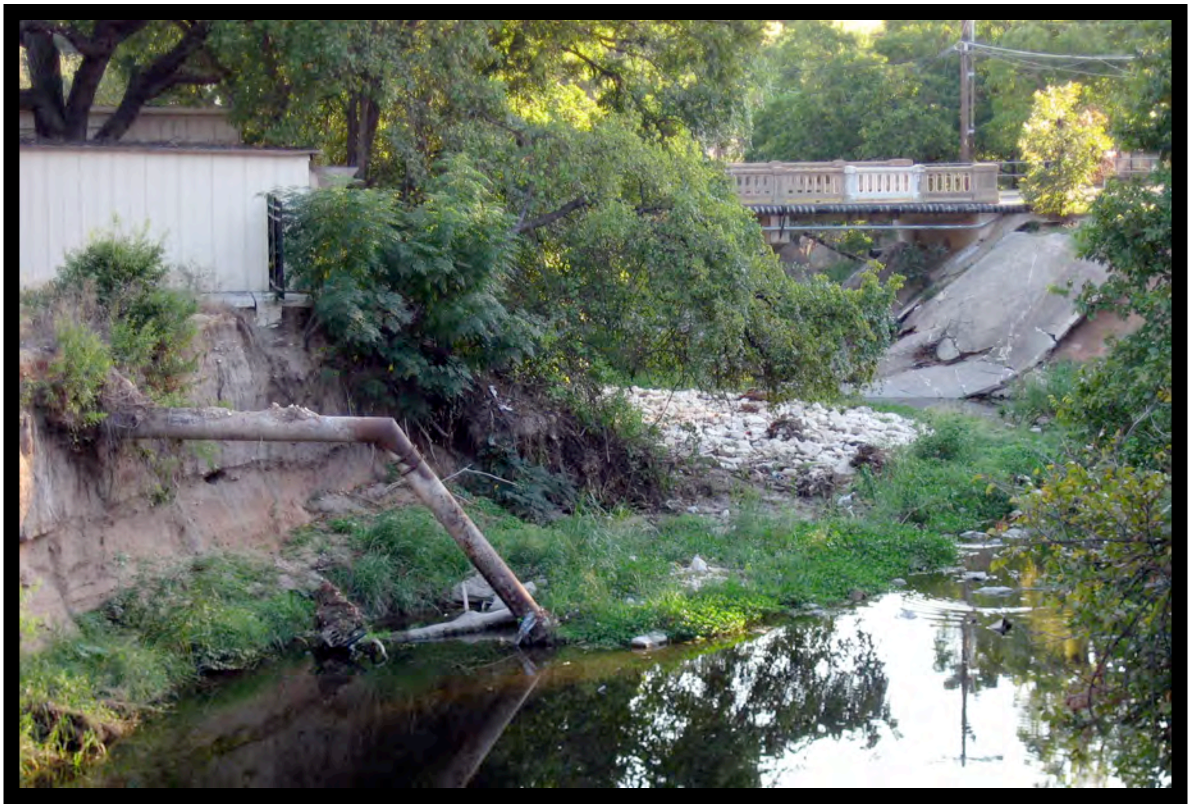

Figure 7 Waller Creek in Downtown Austin

> The urban ecology of the contemporary city remains in a state of flux and awaits a new kind of environmental politics that can respond to the co-evolutionary dynamics of social and bio-physical systems without resorting to the reactionary discourses of the past. By moving away from the idea of the city as the antithesis of an imagined bucolic ideal we can begin to explore the production of urban space as a synthesis between nature and culture in which long-standing ideological antimonies lose their analytical utility and political resonance.[53]

A first step in creating a new form of politics based on a "material constructivist" form of politics is to reimagine infrastructure networks such as stormwater systems to be hybrid and partial and focus on how to best structure these socio-natural systems to accommodate both humans and non-humans.[54] This lets us consider infrastructure networks or water flows as "boundary objects" between citizens and their surroundings.[55] Such a conception when combined with a strongly democratic form of urban decision-making can potentially return the city to its citizens.[56] Engagement in practices such as urban creek restoration, trail building, and more environmentally benign forms of landscaping are potential pathways to further pursue water quality in Austin culture.

In 2004, the City opened a new City Hall building with a design that reflects the geology of the Edwards Aquifer. The importance of the city's environmental setting is literally embedded in municipal politics. However, battles over land development in the sensitive

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53 Gandy 2006, p. 72-3
54 Demeritt 1998
55 Star and Griesemer 1989
56 Swyngedouw 2006

portions of the aquifer will likely continue as the region expands. Perhaps future community leaders will build upon the history of Austin and expand water politics to include both social and natural elements. Such an approach might prove to be a lasting way for the city's residents to maintain the environmental quality of the region while simultaneously accommodating a growing population.

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Post-Restoration Evaluation of Urban Streams in Central Texas

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Principal Investigators:	Megan Meier, Anne Chin

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POST-RESTORATION EVALUATION OF URBAN STREAMS IN CENTRAL TEXAS

Megan D. Meier and Anne Chin

INTRODUCTION

Research over the past few decades have revealed the impacts of urbanization on stream channels. Even though this knowledge is increasingly used to restore degraded urban streams, few studies have investigated what occurs post-restoration. In this study, physical and biological characteristics of three restored reaches in the Colorado River basin in Austin, Texas, are analyzed during a "one-shot" post-project evaluation[1]. These characteristics are compared with pre-restoration data to test the hypothesis that restoration has improved stream stability and health. This research is significant in that it is the first comprehensive analysis of restoration efforts on urban streams in Texas, and one of the few in the United States.

OBJECTIVES

The research questions are:

(1) How effective are stream restoration efforts in improving stream stability in the Colorado River watershed in Austin, Texas?

(2) How effective is stream restoration in improving ecological conditions?

Testable hypotheses are as follows:

(1) Because restoration increases channel bank and bed resistance, increased channel stability is expected through an increase in channel capacity and a

reduction in slope and stability parameter scores from the Pfankuch channel stability evaluation protocol[2].

(2) Through the introduction of vegetation and bank protection measures, leading to a reduction in erosion, enhanced habitat conditions are expected to result in higher habitat scores and improvements in the benthic macroinvertebrate community, such as an increase in taxa richness.

STUDY AREA

The city of Austin, located in central Texas, has developed around the Colorado River and its tributaries (Fig. 1). Rapid urban development over the past decade has increased stormwater runoff, leading to greater erosion within these steep-sloped stream channels. By 1995, Austin had identified 947 cases of localized stream erosion, with 160 channel reaches classified as unstable. To minimize the threat of property damage from stream erosion, the City of Austin has restored approximately 30 channel reaches since the late 1990s. This study evaluates three of these reaches, with the following characteristics:

Bartholomew Park Site

- Drainage area is approximately 10 km^2 (Fig. 1)
- Main land use is residential.
- The restored reach is ~ 710 m.
- The lower reach was restored in 2001 and an upper reach was completed in 2006.

- The channel was reconstructed using rock to armor banks and to provide grade control within the channel. Native vegetation was also planted (Fig. 2)

Lovell Site

- Site is located next to Morris Williams Golf Course on Lovell Drive (Fig. 1).
- Restoration of a ~100 m reach was completed in 2005.
    - The channel was reconstructed using rock armor along the meander bend and installation of a pool-riffle system. Native vegetation was also planted (Fig. 3)

Shipe Park Site

- This site is located within one of the most urbanized watersheds in Austin, containing the University of Texas and the State Capitol building (Fig. 1)
- Drainage area is approximately 16 km^2
- Restoration of a 95 m reach was completed in 1998.
    - Rock armor and native vegetation stabilized channel banks. A pool-riffle system was also constructed to protect the stream bed (Fig. 4).

METHODS

The analysis consists of the following components:

(1) Collect morphological data from restored reaches and compare to topographic surveys conducted before restoration by the City of Austin;

(2) Collect bed sediment samples at restored reaches and analyze particle size distributions; compare with pre-restoration data;

(3) Evaluate channel stability using Pfankuch channel stability evaluation protocol[2] at restored reaches and adjacent reaches; compare to pre-restoration stability scores from adjacent reaches (available from the City of Austin);

(4) Evaluate habitat condition of the restored reaches and adjacent reaches using the Rapid Bioassessment Protocol of the United States Environmental Protection Agency[3];

(5) Collect benthic macroinvertebrate samples from selected riffles within the restored reaches and adjacent reaches. Identify organisms and calculate biological metrics (such as taxa richness); compare to pre-restoration biological data from adjacent reaches, available from the City of Austin.

PRELIMINARY RESULTS

Channel Morphology

Preliminary results indicate:

- Enlargement of channel capacity, with most changes in the width dimension (Fig. 5)

Bed Sediment

Data thus far reveal:

- Bartholomew Park average sediment size was coarser in the lower end of the reach than the upper part of the reach

- Lovell and Shipe Park average sediment size was coarse (> 2mm) at all sites

CONTINUING RESEARCH

Continuing research includes collection and analysis of biological data as well as further analysis of morphological changes in the restored reaches. The information gained from this one-shot post-project evaluation provides the basis upon which longer-term monitoring and assessment can be conducted. These data will augment knowledge of geomorphological and ecological adjustments of urban stream restoration practices in Texas and in the United States. Such knowledge will improve future restoration projects, thus leading to more successful mitigation of flood hazards and enhancement of aquatic ecosystems.

ACKNOWLEDGEMENTS

The Texas Water Resources Institute and the United States Geological Survey provided funding for this research. The city of Austin (Mikeproviding valuable data and background to the restoration projects. Adriana Martinez and Russell Meier served as able field assistants

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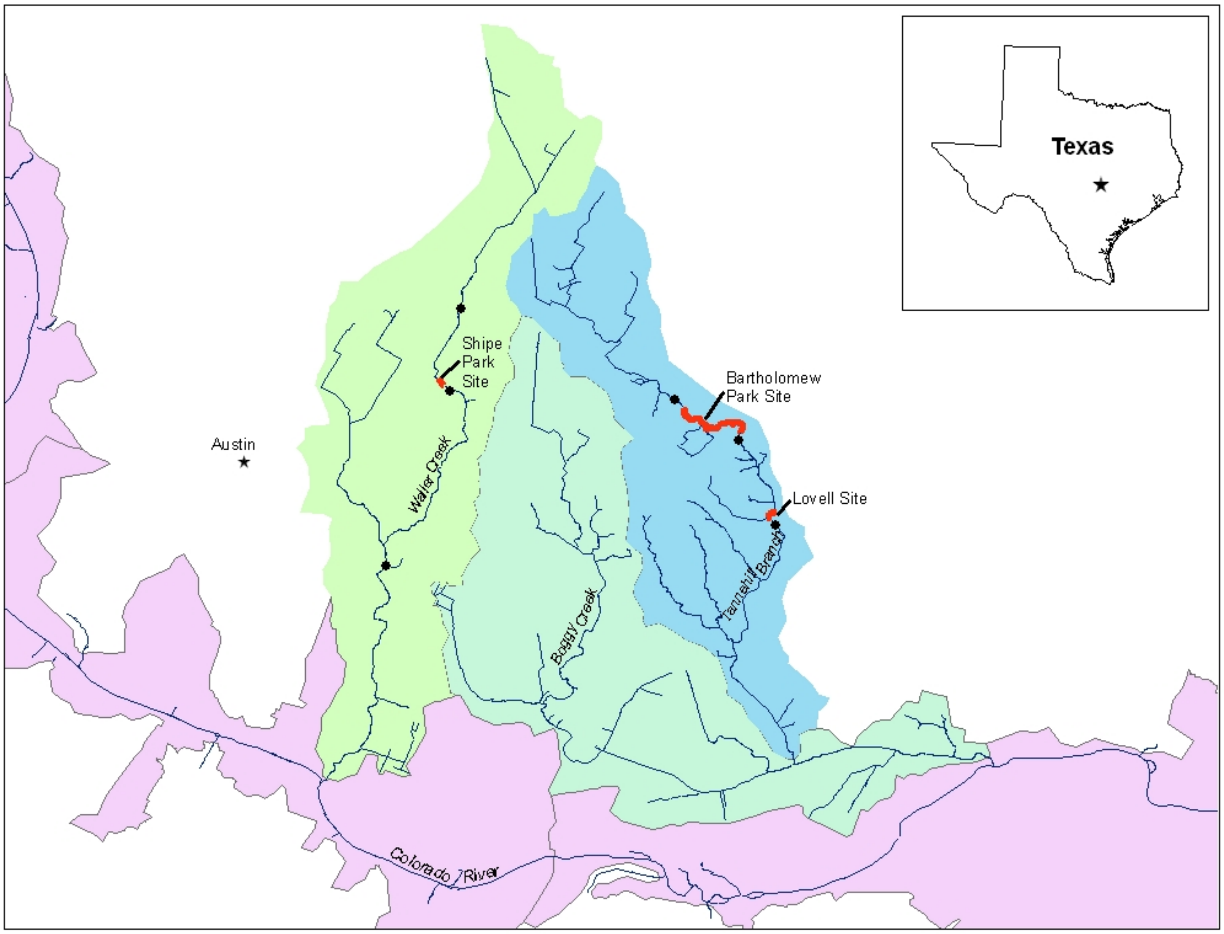


Figure 1. Location of restoration study sites and City of Austin water quality study sites (represented by ●).

a)

b)

Figure 2. Tannehill Branch Creek at Bartholomew Park a) before restoration in 2003 (M. Rotar) and b) after restoration in 2007.

a)

b)

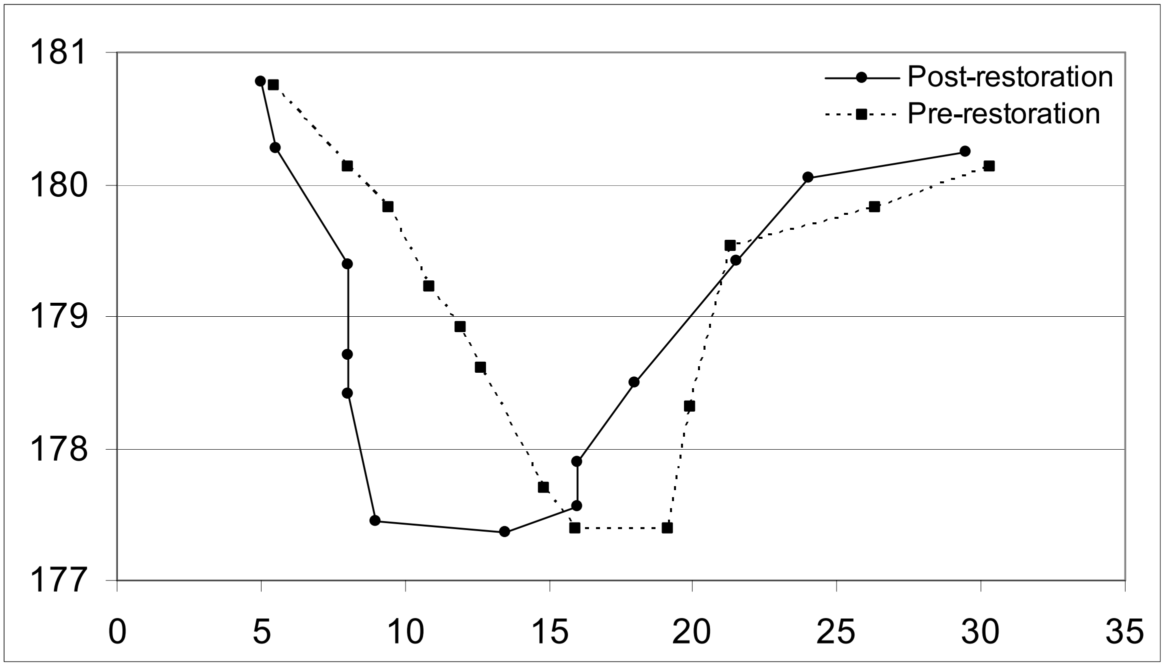
Figure 3. Tannehill Branch Creek at Lovell Drive a) before restoration and b) after restoration, both from 2005 (City of Austin, 2001b).

a)

b)

Figure 4. Waller Creek at Shipe Park a) before restoration in 1997 (City of Austin, 2001b) and b) after restoration in 2007.

a)



b)

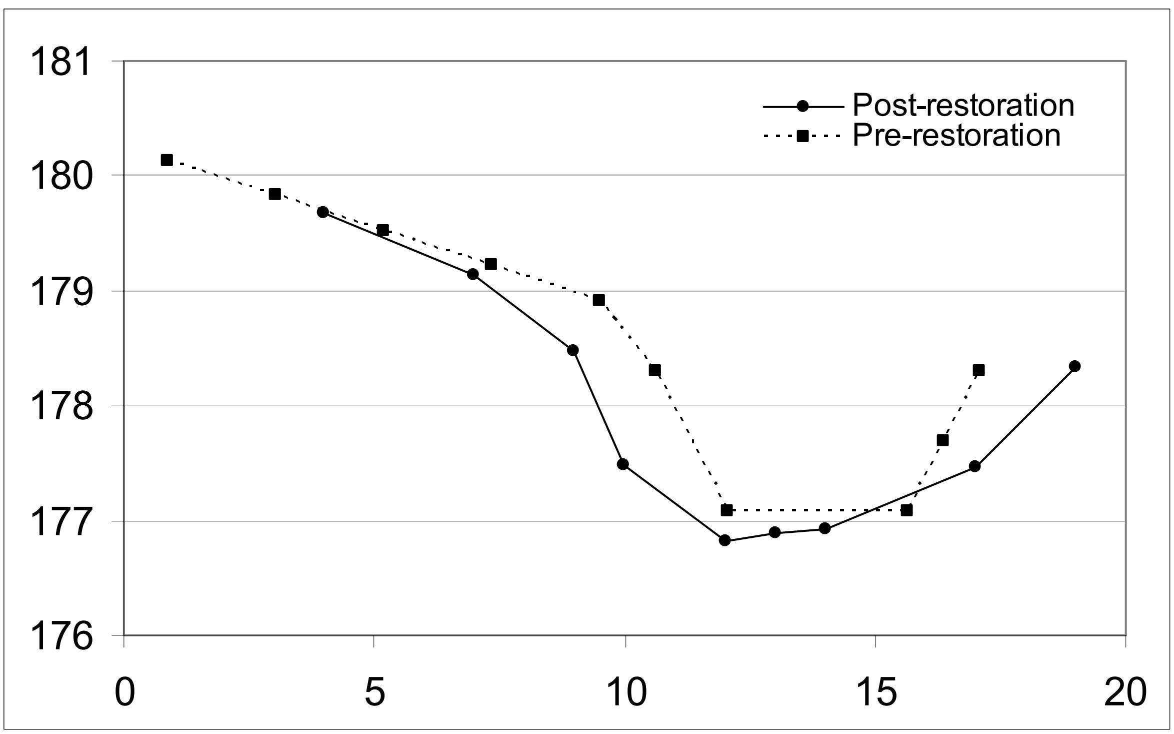


Figure 5. Channel cross-sections from a) Bartholomew Park Pool 1, and b) Bartholomew Park Riffle 1.

Property-Based Management and Optimization of Water Usage and Discharge in Industrial Facilities

Basic Information

Title:	Property-Based Management and Optimization of Water Usage and Discharge in Industrial Facilities
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Publication

PROPERTY BASED MANAGEMENT AND OPTIMIZATION OF WATER USAGE AND DISCHARGE IN INDUSTRIAL FACILITIES

BY

ARWA RABIE

ABSTRACT

This work is aimed at developing a generally-applicable methodology for the optimal design of water recycle networks in batch processes. This is a challenging problem that requires the identification of network configuration, fresh-water usage, recycle assignments from sources to sinks, wastewater discharge, and a scheduling scheme. Previous research efforts have suffered from three primary limitations: restricted recycle within the same cycle, lumped balances that may not lead to feasible solutions, and unrealistic objective functions. These limitations are overcome by this work. A new source-tank-sink representation is developed to allow for storage and dispatch tanks. A hierarchical procedure is developed to solve the problem in interconnected stages. Benchmarks for minimum usage of fresh water and wastewater discharge are determined by eliminating scheduling constraints. An iterative procedure is formulated to minimize the total annualized cost of the system by trading off capital versus operating costs. A case study is solved to illustrate the usefulness of the devised procedure.

INTRODUCTION, MOTIVATION, AND SIGNIFICANCE

Industries around the world are seeking efficient methods to conserve natural resources. Consequently, there is an ongoing drive towards increasing the utilization of process resources to decrease consumption of external resources. One of the most widely and extensively used resources in industry is water. In addition to its impact on natural resources and cost, excessive usage of water also leads to the discharge of significant quantities of wastewater. Consequently, responsible industries have begun to take considerable actions to identify ways to reduce fresh water consumption and wastewater generation. One effective approach has been to maximizing water reuse and recycle within the process plant. The numerous water sources and users must be simultaneously addressed. This leads to the need for efficient techniques to design water recycle networks to optimize the use of fresh water, recycle of process water, and discharge of wastewater.

Recently, significant contributions have been made in developing systematic techniques for the synthesis of industrial water networks. To date, the majority of the water-network research has focused on continuous, steady-state processes. Recent reviews of steady-state water networks can be found in literature (e.g., El-Halwagi, 2006; El-Halwagi et al., 2003; Mann and Liu, 2000; Bagajewicz, 2000). Much less attention has been given to batch water processes. Given that batch systems are common within industry, it is important to develop batch water recycle networks that minimize fresh water consumption, and wastewater discharge.

Wang and Smith (1995) developed a time-pinch analysis method which uses graphical techniques to synthesize batch water networks. This technique treats time as the primary constraint and concentration as the secondary constraint. Majozi et al. (2005) also devised a graphical technique which is an extension of the time-pinch analysis technique. Both of these techniques were limited to water-using units that are modeled as mass exchangers and deal with single-contaminant systems. Foo et al. (2005) devised a graphical method known as water cascade analysis which is limited to single contaminant systems. Also, mixing of water sources at different impurities in the same tank was not allowed. Kim and Smith (2004) and Majozi (2005a, b) developed mathematical formulations that optimize water usage and network configuration. These formulations are limited to mass transfer based water units and single contaminant systems. Chang and Li (2006) also developed a mathematical formulation for batch networks that are not limited to mass transfer based water units.

The previous research efforts have provided valuable tools and insights for batch water-network design. Nonetheless, they suffer from one or more of the following assumptions and limitations:

- Recycle within the same cycle: According to this assumption, water recycle is limited to units that require water later in the same cycle (i.e., no recycle from one batch cycle to another). In many cases, it may be beneficial to recycle water from a source which is available later in a cycle to a user which demands water earlier in the cycle. This can be achieved by storing water from one cycle and using it in another cycle.
- Lumped usage of water over a cycle: This assumption accounts for a total quantity and quality of water supply and demand. Such an assumption can lead to wrong results when the demand overlaps with the supply. As an illustration, consider the case shown by Fig. 1 with two water sources that are mixed and recycled to a water-demanding unit. Suppose that the first source is available from time t_1 to t_3 while the second source is available from time t_2 to t_5. The quantities and compositions for sources I and II are given by W_I, W_{II}, y_I, and y_{II}, respectively.

The sink demands a total quantity of W_I+W_{II} of water. The maximum admissible composition to the sink is given by:

$$Z^{\max} = \frac{W_I y_I + W_{II} y_{II}}{W_I + W_{II}} \qquad (1)$$

The two sources may be stored in a tank and used to provide feed to the sink. On a cycle basis, the stored mixture satisfies the sinks demand for water quantity and composition. However, there is a problem with implementation. When the sink begins to draw water at time t_4, the composition of the stored mixture (of all source I and the quantity of source II generated from t_2 to t_4), will initially be satisfactory since it is less than Z^{max}. However, as time progresses the concentration of the mixture will continually increase (since only higher-composition source II is contributing to the storage tank). Therefore, before reaching t_6, the stored mixture will have a composition exceeding Z^{max}. Since cycle-based averages do not capture such violation, this example underscores the need for detailed scheduling.

- Fresh-water minimization: The overwhelming majority of research on water-recycle networks has focused on the objective of minimizing fresh water usage and wastewater discharge. While this is a useful objective from an operating-cost perspective, it is also important to consider a more comprehensive objective dealing with the fixed cost in addition to the operating cost.

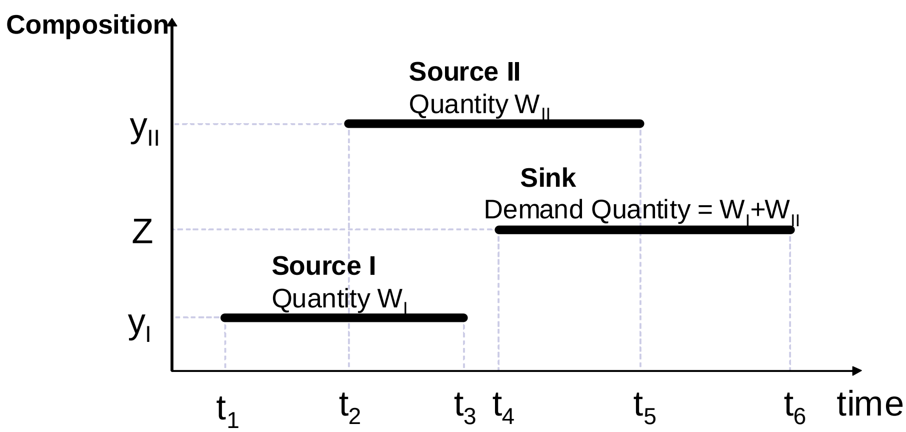

Fig. 1. Illustrating Example for Limitation of Averaging Supply

The objective of this paper is to develop a systematic procedure to synthesize and schedule an optimal batch water network of a minimum total annualized cost while meeting all process constraints. The aforementioned limitations of previous research efforts are overcome. A source-tank-sink structural representation is developed to account for the potential configurations of the water network. This representation allows for separate tanks to be used for storage and dispatch over alternating cycles. A hierarchical procedure is developed to solve the problem in interconnected stages. First, the target for minimum fresh usage and waste discharge is identified. Next, a minimum fixed-cost network is synthesized using dispatch and storage tanks to meet the fresh and wastewater targets and to devise a scheduling scheme. Next, trade off occurs between capital and operating costs with the objective of minimizing total annualized cost. A case study is solved to illustrate the merits of the developed approach.

PROBLEM STATEMENT

The batch water network problem to be addressed in this work may be stated as follows:
During a batch process with a cycle time (τ), there are a number of water sources and sinks characterized by the following:

- Sources: There is a set SOURCES = $\{v|v=1,2,\ldots, N_{SR}\}$ of process water streams. The dynamic profiles for the flowrate and composition of each source, v, are known and given by $w_v(t)$ and $y_{v,u}(t)$ where u is an index for components and t is the time from the beginning of the cycle ($0 \le t \le \tau$).
- Sinks: There is a set SINKS = $\{s|s=1,2,\ldots, N_{SK}\}$ of process units that require water. Constraints on dynamic profiles for the flowrate and maximum admissible composition of impurity of each sink s are known and given by $g_s(t)$ and $z_{s,u}^{\max}(t)$.

Available for service are:

- A number of fresh water streams; each fresh stream r has an impurity concentration of x_r.

It is desired to develop a systematic procedure to synthesize and schedule a batch water network in which water from sources may be stored in tanks then recycled to sinks when needed or released as waste. The water network must meet the minimum total annualized cost and meet all process constraints. The synthesis and scheduling tasks require the identification of the following:

- What is the optimum network configuration including assignment of sources and sinks?
- Which fresh stream(s) should be used? How much of each?
- How many tanks should be used? What are their sizes? What are their feeds?
- How should the synthesized network be scheduled for operation?

APPROACH

The following approach will be used to synthesize an optimal batch water network of minimum total annualized cost:

1. Reformulation of sources and sinks into discrete events
2. Target minimum usage of fresh water and minimum wastewater discharge
3. Synthesize a direct-recycle water network using storage and dispatch tanks to achieve the target
4. Schedule an optimum operating scheme to achieve the target
5. Tradeoff water usage, discharge, fixed and operating cost to obtain minimum total annualized cost

Due to the dynamic variation of both the sources and the sinks, the process sources and the sink constraints are discretized over time. Each source is discretized into a number of sources with a given composition and a given water quantity. The sink constraints are also discretized; each having a given water demand and a given maximum inlet impurity composition, i.e.

For the sources, the time domain is decomposed into $N_{t\_Sources}$ time intervals (large enough to capture significant changes in composition). The discretization index is referred to as q. The q^{th} time interval between indices q-1 and q is described by t_{q-1} and t_q. The flowrate profile of each source, v, is transformed into a discrete set of flows per cycle (water quantities per cycle not continuous flowrates). For the q^{th} time interval, the quantity of the v^{th} source is given by:

$$W_{v,q} = \int_{t_{q-1}}^{t_q} w_v(t)dt \tag{2}$$

and the composition is given by:

$$y_{v,q,u} = \frac{\int_{t_{q-1}}^{t_q} w_v(t) y_{v,u}(t)dt}{W_{v,q}} \tag{3}$$

To simplify the terminology, a single index, i, will be used for all discretized source such that i=1 corresponds to v=1 and q = 1. i=2 corresponds to v=1, q=2, i=N_q +1 corresponds to v=2, q=1, and so on until i= $N_{Sources}$ corresponds to v=N_{SR} and q=$N_{t\_Sources}$. For each discretized source i, the flow and composition are referred to by W_i and $Y_{i,u}$.

Similarly, for the sinks, the time domain is decomposed into N_{t_Sinks} time intervals. An index p is used for discretization and the pth time interval is described by t_{p-1} and t_p. The constraint for flowrate profile of each sink, s, is transformed into a discrete set of constraints on flows as follows:

$$G_{s,p} = \int_{t_{p-1}}^{t_p} g_s(t)dt \qquad (4)$$

and the composition constraints are given by:

$$z_{s,p,u}^{\max} = \frac{\int_{t_{p-1}}^{t_p} g_s(t) z_{s,u}^{\max}(t)dt}{G_{s,p}} \qquad (5)$$

Again, to simplify the index terminology, a single index, j, will be used for all discretized sink constraints such that j=1 corresponds to s=1 and p = 1 until j= N_{Sinks} which corresponds to s=N_{SK} and p=N_{t_Sinks}. For each discretized sink j, the flow and composition constraints are referred to by G_j and $Z_{j,u}^{\max}$.

The foregoing discretization and reformulation are carried out as pre-synthesis tasks. Therefore, the problem formulation will involve algebraic equations instead of the simultaneous algebraic and differential equations.

STRUCTURAL REPRESENTATION

The next step in designing a batch water network is developing a structural representation which embeds all potential configurations of the network and enables proper scheduling. As mentioned before, earlier approaches have been restricted by two limitations: recycle within the same cycle and lumped usage of water over a cycle. These limitations can be overcome by the source-tank-sink representation shown in Fig. 2. According to this new representation, two sets of tanks are used: one set for storage and another for dispatch. Every cycle, the role of each set of tanks will alternate. During one cycle, the storage tanks will be collecting water from sources and in the next cycle, these tanks will be used to dispatch the stored water to the sinks. This arrangement shown by Fig. 2 allows the assignment of sources from one cycle to be allocated to sinks in the subsequent cycle. This is important in cases when a source available at time t_1 is to be assigned to a sink at time t_2 with $t_2 < t_1$. The storage-dispatch arrangement also insures proper satisfaction of sink constraints even when source supply and sink demand overlap (as was shown by Fig. 1).

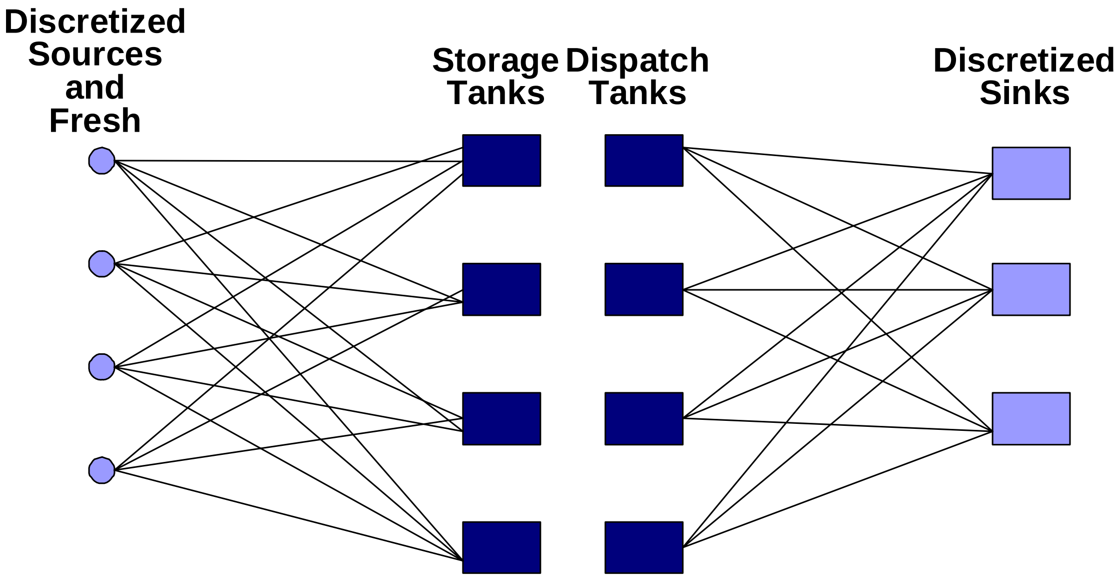

Fig. 2. Source-Sink Representation with Storage and Dispatch Tanks

Each source is split into several fractions that are allocated to storage tanks. The stored water are drawn from the dispatch tanks and assigned to sinks. One of the sinks is designated as the "waste sink" and it is intended to collect the unallocated sources.

TARGETING FOR MINIMUM FRESH USAGE AND WASTEWATER DISCHARGE

In order to determine benchmarks for the operating cost of the network, it is beneficial to identify lower bounds for the usage of fresh water and the discharge of wastewater. A particularly useful observation is that one of the key conditions for attaining minimum fresh usage is when there are no scheduling limitations for assigning any source to any sink. Eliminating scheduling limitations may be achieved by allowing the use of infinite number of storage and dispatch tanks. This arrangement allows all the sources to be available whenever any of the sinks demand them. Equivalently, the targeting problem can be dealt with by assigning sources directly to sinks. Therefore, the following mathematical formulation can be used to determine the water targets. One target is to determine the minimum flow of the fresh (which also corresponds to minimum discharge of the wastewater):

$$\text{Minimize } \sum_{r=1}^{N_{Fresh}} \sum_{j=1}^{N_{\sin ks}} f_{r,j} \tag{6a}$$

Where $f_{r,j}$ is the flowrate of the r^{th} fresh assigned to the j^{th} sink. Another objective is to determine the minimum cost of the fresh as follows:

$$\text{Minimize } \sum_{r=1}^{N_{Fresh}} \sum_{j=1}^{N_{\sin ks}} C_r \, f_{r,j} \tag{6b}$$

Subject to

Splitting of sources:

$$W_i = \sum_{j=1}^{N_{Sinks}} w_{i,j} + w_{i,waste} \qquad i=1, 2,\ldots,N_{Sources} \tag{7}$$

Waste flow:

$$Waste = \sum_{i=1}^{N_{Sources}} w_{i,waste} \tag{8}$$

Sink balances:

$$G_j = \sum_{i=1}^{N_{Sources}} w_{i,j} + \sum_{r=1}^{N_{Fresh}} f_{r,j} \qquad j=1, 2,\ldots,N_{Sinks} \tag{9}$$

$$G_j Z_{j,u} = \sum_{i=1}^{N_{Sources}} w_{i,j} Y_{i,u} + \sum_{r=1}^{N_{Fresh}} f_{r,j} x_{r,u} \qquad j=1,2,\ldots,N_{Sinks} \text{ and } u=1,2,\ldots,N_{Components} \tag{10}$$

Composition constraints for the Sinks:

$$Z_{j,u} \le Z_{j,u}^{\max} \qquad j=1,2,\ldots,N_{Sinks} \text{ and } u=1,2,\ldots,N_{Components} \tag{11}$$

The source-splitting constraints distribute the flows from the sources to the sinks and the waste. The waste flow is the sum of the unallocated sources. The sink balances account for the flow and component balances for the fresh water streams and the source streams.

MINIMIZING FIXED COST

The next step is to synthesize and schedule a batch water network in which the fixed cost is minimized while still meeting the water targets determined in the previous step. The items which dominate the fixed cost are the storage and dispatch tanks. Therefore, the quantity of tanks is minimized using the following objective function:

$$\text{Minimize} \sum_{k=1}^{N_{Tanks}} 2I_k \qquad (12)$$

where I_k is a zero/one binary integer variable designating the absence/existence of a tank,
The following constraints are used:

Splitting of Sources:

$$W_i = \sum_{k=1}^{N_{Tanks}} w_{i,k} \qquad \text{i=1,2,…,N}_{\text{Sources}} \qquad (13)$$

Storage-tank balances:

$$T_k = \sum_{i=1}^{N_{Sources}} w_{i,k} \qquad \text{k=1,2,…,N}_{\text{Tanks}} \qquad (14)$$

$$T_k y_{k,u}^{Tank} = \sum_{i=1}^{N_{Sources}} w_{i,k} Y_{i,u} \qquad \text{k=1,2,…,N}_{\text{Tanks}} \text{ and u=1,2,…,N}_{\text{Components}} \qquad (15)$$

$$T_k = \sum_{j=1}^{N_{\sin ks}} t_{k,j} + t_{k,waste} \qquad \text{k=1,2,…,N}_{\text{Tanks}} \qquad (16)$$

Waste flow:

$$Waste = \sum_{k=1}^{N_{Tanks}} t_{k,waste} \qquad (17)$$

Sink balances:

$$G_j = \sum_{k=1}^{N_{Tanks}} t_{k,j} + \sum_{r=1}^{N_{Fresh}} f_{r,j} \qquad \text{j=1,2,…,N}_{\text{Sinks}} \qquad (18)$$

$$G_j Z_{j,u} = \sum_{k=1}^{N_{Tanks}} t_{k,j} y_{k,u}^{Tank} + \sum_{r=1}^{N_{Fresh}} f_{r,j} x_{r,u} \qquad \text{j=1,2,…,N}_{\text{Sinks}} \text{ and u=1,2,…,N}_{\text{Components}} \qquad (19)$$

Composition constraints for the Sinks:

$$Z_{j,u} \le Z_{j,u}^{\max} \qquad \text{j=1,2,…,N}_{\text{Sinks}} \text{ and u=1,2,…,N}_{\text{Components}} \qquad (20)$$

Furthermore, two more sets of constraints are needed:

Assigning the integer values to used tanks: since the variable $I_k \in \{0,1\}$, it is necessary to add a constraint which assigns the value zero when there is no feed to the tank and one when there is feed to the tank. This can be accomplished by the following constraint:

$$T_k \leq U_k I_k \qquad \text{k=1,2,…,N}_{\text{Tanks}} \qquad (21)$$

Where U_k is a given upper bound on the maximum capacity of the tank. When there is positive flow (T_k) to tank k, the variable I_k is forced to be one. On the other hand, when T_k is zero, the constraint is satisfied by I_k being zero or one. However, the zero value will be picked in order to minimize the objective function.

Finally, a constraint is added to include the value of the operating cost (either the minimum fresh cost target identified earlier or an iterative target for trading off fixed versus operating costs as will be described in the next section). Hence,

$$\sum_{r=1}^{N_{Fresh}} \sum_{j=1}^{N_{\sin ks}} C_r \, f_{r,j} = \text{Cost} \qquad (22)$$

MINIMIZING TOTAL ANNUALIZED COST (TAC)

The last step in attaining an optimal batch water network is to achieve the minimal TAC of the system by trading off fixed and operating costs. The proposed approach is shown by Fig. 3. First, the problem of minimizing the operating cost (minimizing fresh water consumption) is solved. The solution of this program provides the targets for fresh flow and wastewater discharge. Next, the fixed-cost minimization problem is solved subject to the identified fresh target. The solution identifies the assignment of sources to tanks and tanks to sinks, the associated flows, and the scheduling scheme. Inspection of the new design is done to try to further simplify the network. The solution is inspected to see if the two sets of tanks are needed for each assignment. If scheduling of any assignment can be done in one tank, the second tank is eliminated. Now that the network configuration has been determined, the TAC corresponding to this system can be calculated. Next, tradeoff of operating cost with fixed cost is done by decreasing the quantity of tanks used in the network by two. Then, the minimum operating cost (fresh water consumption) subject to the new tank constraint is determined. Further inspection of the new design is done to try to simplify the network. Comparison of the original TAC and the new TAC is carried out. If the new annualized cost is lower than the original, it will replace the original total annualized cost as the current minimum. If not, the original TAC remains as the current minimum. Iterations are continued until a system of zero tanks is achieved (corresponding to the minimum fixed cost and maximum operating cost). The minimum stored value of the TAC is the global minimum TAC for the system and its associated configuration and scheduling are the optimum schemes.

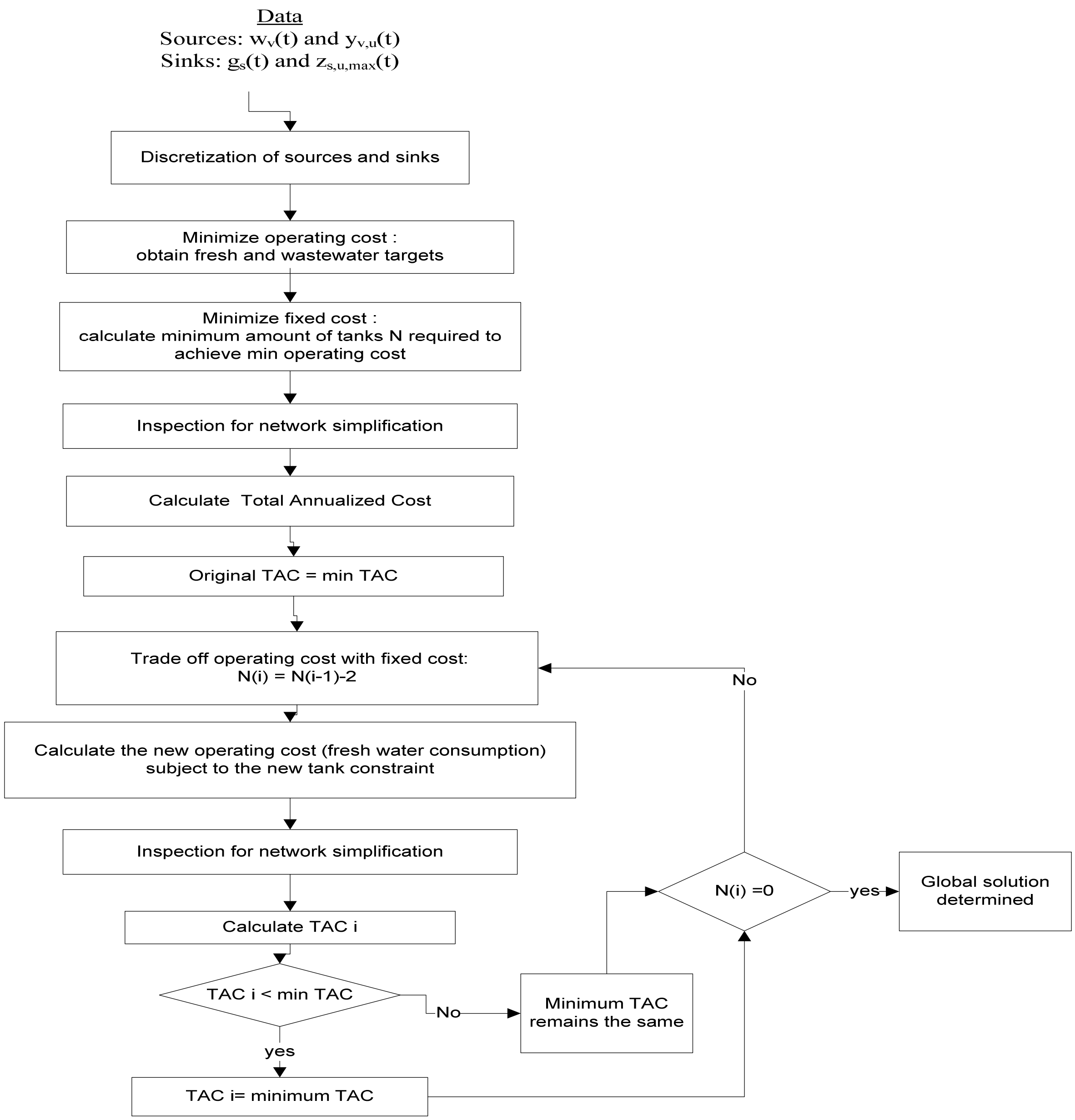

Fig. 3. Minimum TAC Approach

CASE STUDY

A batch water network in a manufacturing plant has a batch cycle of eight hours. It is a single contaminant system which consists of two water sources and two water sinks. Both the sources and sinks exhibit dynamic behavior. Available for use is one fresh water stream with a cost of \$.21/kg of water. Also available are storage and dispatch tanks. The tanks cost \$1000/m^3 and have an installation and yearly maintenance cost of \$1,000 and \$500 per tank respectively. The discretized source and sink data for this network is represented by the following tables.

Source Data:

Source	Hour	Yi	Wi (kg)
1	1-2	0.00	0.0
	3-4	0.00	0.0
	5-6	0.05	20
	7-8	0.10	30
2	1-2	0.00	0.0
	3-4	0.85	30
	5-6	0.90	40
	7-8	0.00	0.0

Sink Data:

Sink	Hour	Zjmax	Gj (kg)
1	2	0.50	50
	7	0.60	50
2	1	0.40	50
	8	0.70	50

Following the above procedure, the next step in synthesizing a batch water network is determining the minimum operating cost using the first mathematical formulation. The formulation is a linear program consisting of 22 constraints and 27 linear variables. A solution of 80 kg of fresh water and 0 kg of wastewater with a yearly operating cost of \$18,396 was found. Next, using the second mathematical formulation, the minimum fixed cost subject to the minimum operating cost must be determined. The formulation is a mixed integer non-linear program consisting of 41 constraints, 58 variables, 24 non-linear variables, and 4 integers. The solution of two tanks was found with a total annualized cost of $21,182. Using the iterative procedure presented above, $21,182 is the minimum total annualized cost.

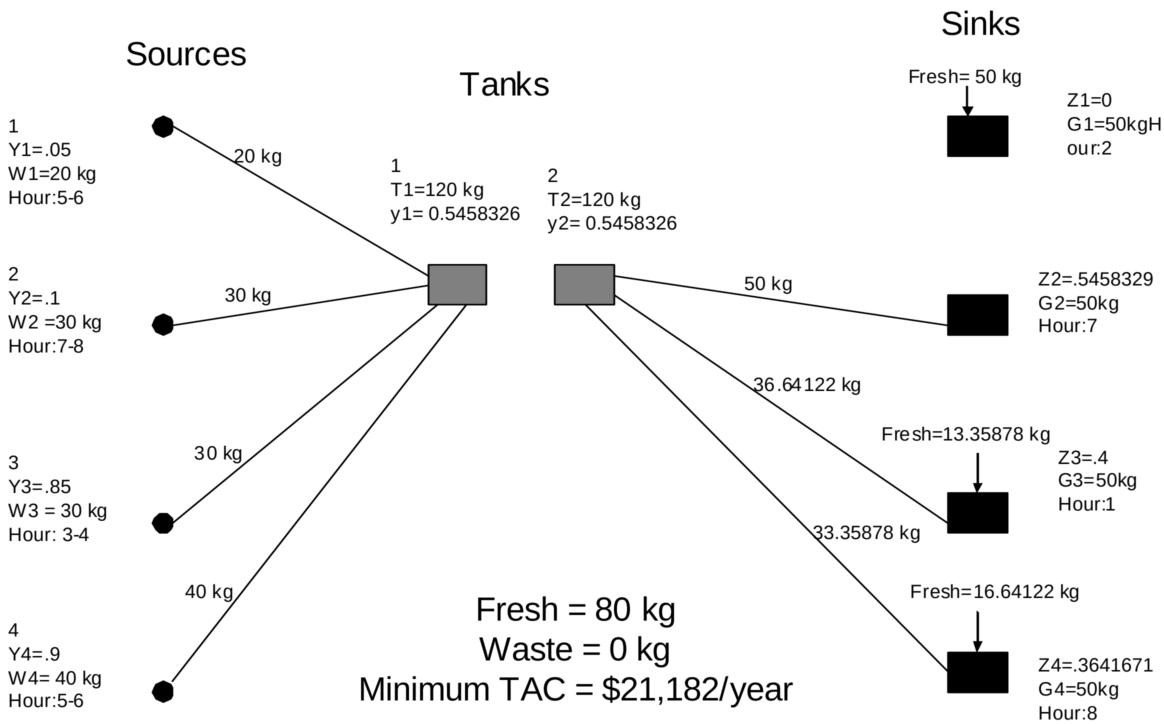

Fig. 4. Optimal Network for the Case Study

As illustrated above, two tanks are required to achieve the optimal batch water network. The storage tank will collect all the water from the four discretized sources. It will have an impurity composition of 0.5458, and will require a capacity of at least 120 kg. The dispatch tank will have the same impurity composition, and require the same capacity as the storage tank. It will begin by dispersing 36.64 kg of water to sink 3 at hour one of the cycle. Then it will disperse 50.00 kg of water to sink 2 at hour seven, and 33.36 kg of water to sink 4 at hour eight of the cycle. Sink 1 will acquire all of its water demand (50.00 kg) from the fresh source at hour two of the cycle. Overall, 80.00 kg of fresh water per cycle is required and no wastewater is generated.

CONCLUSIONS

This work has developed a novel systematic procedure to synthesize and schedule an optimum batch water network. First, a structural representation has been developed to embed potential configurations. In addition to sources and sinks, two sets of tanks have been introduced for storage and dispatch. This new arrangement overcomes previous-research limitations that restricted assignment within the same batch cycle and were not capable of insuring sink feasibility when supply and demand overlap. Sources and sinks have been reformulated through discretization into meaningful events to transform simultaneous differential and algebraic equations into algebraic equations. Then, water targets for both fresh water and wastewater have been determined by developing a representation with no scheduling limitations. This representation involves the use of infinite tanks which has been mathematically transformed into direct assignment of sources to sinks. Next, the problem of determining the minimum fixed cost or the minimum number of tanks has been formulated. Finally, an iterative procedure has been established to trade off operating and fixed costs (e.g., by iteratively trading off fresh water consumption and number of tanks) until the minimum TAC is identified.

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Will be presented in 2007 AIChE meeting

Property based management and optimization of water usage and discharge in industrial facilities

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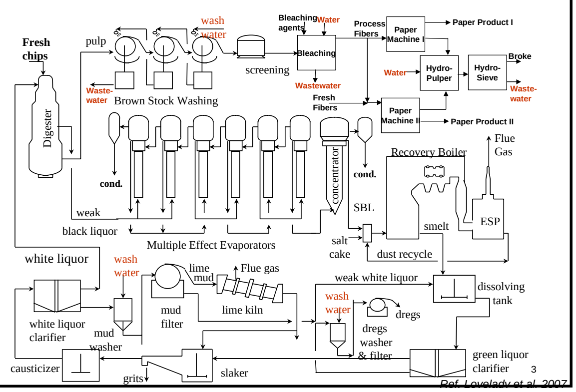
Outline

- Motivation
- Problem Scope
- Literature Survey
- Problem Statement &Representation
- Novel Approach
- Case Study
- Conclusions

Motivating Example



Ref. Lovelady et al. 2007

Motivation

- Industrial facilities significantly use fresh water and discharge wastewater
- Growing public concern as well as environmental regulations
- Conservation of resources
- Enhanced market competitiveness

Problem Scope

Given: a batch process with a number of

- water sources whose composition and flow rate vary over time
- sinks whose water demand and maximum admissible composition vary over time

Objectives: Develop a systematic procedure to

- Synthesize an optimal batch water network
- Schedule an operating network of a minimum total annualized cost while meeting all process constraints

Examples of Previous Literature

- Wang and Smith(1995), Majozi (2005)
  - Graphical method limited to mass transfer based utilities
  - Limited to single contaminant systems
  - Used storage tanks
  - Water sources were not recycled to lower concentration utilities or in previous times of the cycle.
- Foo, Manan& Tan(2005)-Water Cascade Analysis
  - Graphical method for non-mass transfer based utilities
  - Limited to single contaminant systems
  - Water sources were not recycled to utilities that required water in previous times of the cycle.
  - Mixing of water sources at different impurities in the same tank was not allowed

Examples of Previous Literature

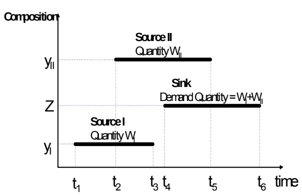
- Kim and Smith(2004), Majozi(2005a),Majozi(2005b)
  - Mathematical formulation limited to mass transfer based water units
  - Limited to single contaminant systems
  - Used storage tanks
  - Water sources were not recycled to utilities that required water in previous times of the cycle.
- Chang & Li(2006)
  - Mathematical formulation not limited to mass transfer based water units
  - Used storage tanks
  - Water sources were not recycled to utilities that required water in previous times of the cycle.

Limitations of Previous Work

One of more of the following limitations:

- Recycle within the same cycle: water recycle is limited to units that require water later in the same cycle
- Lumped usage of water over a cycle: this assumption accounts for a total quantity and quality of water supply
- The objective of minimizing fresh water usage: it is important to consider an objective dealing with fixed cost in addition of operating cost.
- Lack of global solution procedure

Lumped usage of water



$$Gj = W_I + W_{II}$$

$$Z^{max} = \frac{W_I y_I + W_{II} y_{II}}{W_I + W_{II}}$$

Problem Statement

During a batch cycle (τ) of a given batch process there is a number of:

-Sources; process streams

- impurity concentration of $y_{v,u}(t)$
- flow of $w_v(t)$
- $0 \le t \le \tau$

-Sinks; process units that are in need of water

- maximum inlet impurity composition $z_{s,u}(t)$
- flow rate requirement $g_s(t)$
- $0 \le t \le \tau$

Available for service are:

-Tanks; used for water storage and dispatch

-Fresh water streams

- Impurity composition x_r
- cost of C_r

Optimization Formulation

- Dynamic variation of sources and sinks
- Synthesis:
  - Numerous source and sink constraints
  - Tanks selection and assignment
- Scheduling:
  - When to store sources and when to dispatch them to sinks

Mathematical programming approach

Characteristics and Features:

- Mathematical programs can tackle complex systems
- Need to handle multiple sources
- Need to handle multiple sink requirements
- Need to incorporate storage and dispatch tanks

Novel Approach

- Reformulate sources and sinks into discrete events
- Determine target for minimum usage of fresh water and minimum waste water discharge
- Synthesize a direct-recycle water network using storage and dispatch tanks to achieve the water target
- Schedule an optimum operating scheme to achieve the target
- Use insight to further simplify network design
- Tradeoff water usage, discharge, fixed and operating costs to obtain minimum TAC

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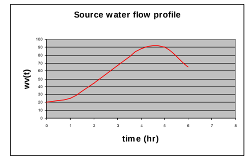
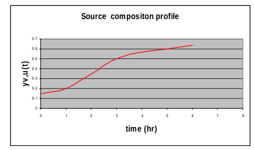
Source Reformulation

During a batch cycle τ, the profile for both $w_v(t)$ and $y_{v,u}(t)$ are known ($0 \le t \le \tau$).

- $Wi = \int_{t_{q-1}}^{t_q} w_v(t)\,dt$
- $Y_{i,u} = \dfrac{\int_{t_{q-1}}^{t_q} w_v(t)\, y_{v,u}(t)\,dt}{W_i}$





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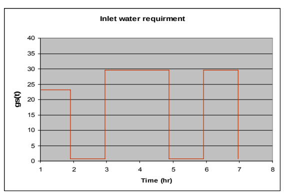
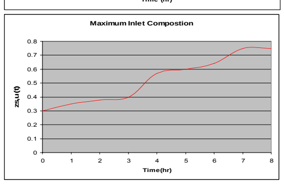
Sink Reformulation

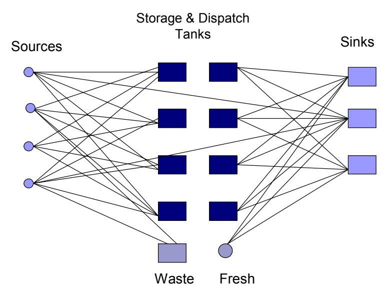
During a batch cycle τ, the profile for both $g_s(t)$ and $z_{s,u}(t)$ are known ($0 \le t \le \tau$).

- $G_j = \int_{t_{p-1}}^{t_p} g_s(t)\,dt$
- $z_{j,u}^{\max} = \dfrac{\int_{t_{p-1}}^{t_p} g_s(t) z_{s,u}^{\max}(t)\,dt}{G_j}$





Water Recycle Network Representation



- Availability and demand are not concurrent.
- Assumption: two sets of tanks will be used one for storage and one for dispatch

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Targeting Mathematical Formulation

- **Minimize** $\sum_{r=1}^{N_{Fresh}} \sum_{j=1}^{N_{\sin ks}} C_r f_{r,j}$

Subject to:

- **Splitting of Sources**

$W_i = \sum_{j=1}^{N_{Sinks}} w_{i,j} + w_{i,waste}$ i=1, 2,…,NSources

- **Waste flow**

$Waste = \sum_{i=1}^{N_{Sources}} w_{i,waste}$

- **Sink Balances**

$G_j = \sum_{i=1}^{N_{Sources}} w_{i,j} + \sum_{r=1}^{N_{Fresh}} f_{r,j}$ j=1, 2,…,NSinks

$G_j Z_{j,u} = \sum_{i=1}^{N_{Sources}} w_{i,j} Y_{i,u} + \sum_{r=1}^{N_{Fresh}} f_{r,j} x_{r,u}$ j=1,2,…,NSinks and u=1,2,…,NComponents

$Z_{j,u} \le Z_{j,u}^{\max}$ j=1,2,…,NSinks and u=1,2,…,NComponents

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Synthesis & Scheduling Mathematical Formulation

- **Minimize** $2N_k$

Subject to:

$N_k = \sum_{k=1}^{N_{Tanks}} I_k$

$I_k \in \{0,1\}$

$T_k \le U_k I_k$

- **Splitting of Sources**

$W_i = \sum_{k=1}^{N_{Tanks}} w_{i,k} + w_{i,waste}$ i=1,2,…,NSources

- **Storage Tank Balances**

$T_k = \sum_{i=1}^{N_{Sources}} w_{i,k}$ k=1,2,…,NTanks

$T_k y_{k,u}^{Tank} = \sum_{i=1}^{N_{Sources}} w_{i,k} Y_{i,u}$ k=1,2,…,NTanks and u=1,2,…,NComponents

$T_k = \sum_{j=1}^{N_{\sin ks}} t_{k,j}$ k=1,2,…,NTanks

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Synthesis & Scheduling Formulation Continued

- **Waste Flow**

$$Waste = \sum_{i=1}^{Nsources} w_{i,waste}$$

- **Sink Balances**

$$G_j = \sum_{k=1}^{N_{Tanks}} t_{k,j} + \sum_{r=1}^{N_{Fresh}} f_{r,j}$$ j=1,2,…,NSinks

$$G_j Z_{j,u} = \sum_{k=1}^{N_{Tanks}} t_{k,j} y_{k,u}^{Tank} + \sum_{r=1}^{N_{Fresh}} f_{r,j} x_{r,u}$$ j=1,2,…,NSinks and u=1,2,…,NComponents

$$Z_{j,u} \le Z_{j,u}^{\max}$$ j=1,2,…,NSinks and u=1,2,…,NComponents

- **Operating Cost Constraint**

$$\sum_{r=1}^{N_{Fresh}} \sum_{j=1}^{N_{\sin ks}} C_r f_{r,j}$$ = Cost

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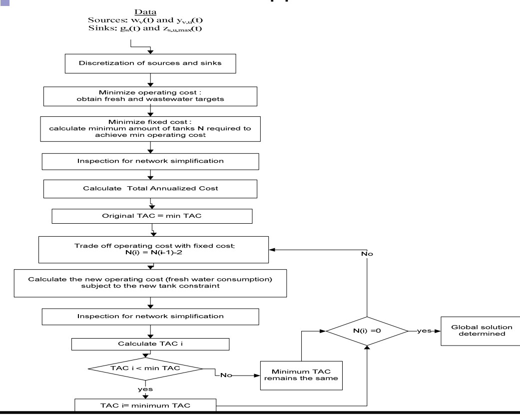
Approach



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Case Study

Batch water network

- 2 process sources
- 2 sinks
- 1 contaminant present in water from sources
- 1 fresh water stream
  -x_r=0
  -cost: $0.21/kg
- Available tanks
  -cost: $1000/m^3
  -instillation cost: $1,000 per tank
  -yearly maintenance: $500 per tank
- Batch cycle = 8 hours

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Case Study

Source	Hour	Yi	Wi (kg)
1	1-2	0.0	0
	3-4	0.0	0
	5-6	0.05	20
	7-8	0.10	30
2	1-2	0.0	0
	3-4	0.85	30
	5-6	0.90	40
	7-8	0.0	0

Sink	Hour	Zjmax	Gj (kg)
1	2	.5	50
	7	.6	50
2	1	.4	50
	8	.7	50

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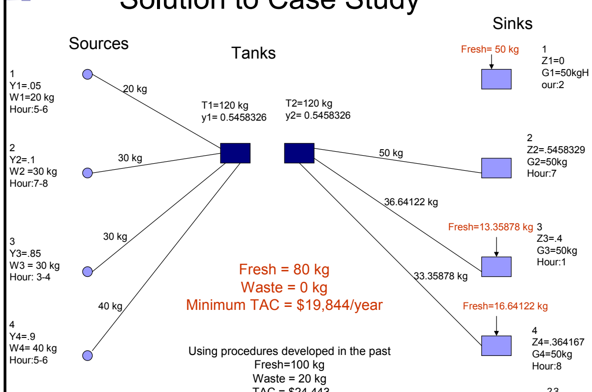
Solution to Case Study



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Conclusion

- Developed a systematic procedure to synthesize and schedule a batch water network
- Properly discretized batch cycle into meaningful events
- Targeting of water usage and discharge ahead of synthesis and scheduling
- Devised an iterative scheme to achieve total minimum annualized cost

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Modeling the Effect of Urbanization and Optimizing Land Use For Estuarine Environmental Flows

Basic Information

Title:	Modeling the Effect of Urbanization and Optimizing Land Use For Estuarine Environmental Flows
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End Date:	2/28/2007
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Focus Category:	Models, Water Quantity, Hydrology
Descriptors:	None
Principal Investigators:	Debabrata Sahoo, Patricia Haan

Publication

Monitoring the Effect of Urban Growth on Freshwater Inflows using Wavelet Analysis

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H23D-01

Introduction

Estuaries are the connecting link between terrestrial and marine ecosystems, and provide a critical coastal habitat that is essential ecologically and economically to the world economy. Therefore, it is important to maintain the productivity and ecological integrity of estuarine ecosystems. The productivity of these systems depends on the timing and magnitude of freshwater inflow (NRC, 2005) along with the associated nutrients such as N and P, metals, and organic matter from the terrestrial environment. Freshwater inflows help in ecological processes such as dilution of salt water that creates a unique environment; creation of habitats for several species; regulation of bay water temperature and are essential for marine bio-geochemical cycles. Variations in freshwater inflows can alter the ecology of estuarine environment, potentially hampering productivity. Freshwater inflow, nutrient, and metal delivery are influenced by the land use/land cover and water management practices in the contributing watershed, particularly in watersheds that are experiencing rapid human induced disturbances. San Antonio, TX, the 8th largest city in the US, is situated in the San Antonio River basin. The San Antonio River Basin encompasses 4180 square miles from the headwaters to the point at which this river joins with the Guadalupe River, before draining into Gulf of Mexico. Rapid urbanization has changed the land use and land cover in this river basin. Studies in the river basin suggest that change in land use has primarily been an increase in impervious surface. Increase in impervious surface can change the flow regime by altering timing, magnitude, scale, and frequency of freshwater inflows.

This study used continuous wavelet transformation (CWT) on the geo-physical signal (environmental flow) to analyze changes in frequency and scale in the San Antonio River flow regime (seasonal flows in particular) using 63 years (1940-2003) of average daily discharge obtained from USGS gauging station number 8188500 situated most downstream in the river. This study also applied similar technology on seasonal baseflow, which was separated from total flow.

Wavelet analysis of the hydrologic stream flow data helps to understand the cyclic changes and patterns present in the time series. It helps to link these cyclic changes to river basin water management to maintain estuarine ecological health.

Methodology

Data from daily average flow were aggregated into three distinct seasonal periods (Dec-Mar, Apr-Jul, and Aug-Nov), for each year. From this aggregated datasets, maximum, minimum, and total seasonal flows were calculated. Baseflow was estimated from total flow using a baseflow separation program (digital filter technique) developed by Arnold, and Allen, 1999. Similar analysis was conducted on baseflow.

Wavelet analysis was conducted using MATLAB. For the current analysis, a complex Morlet wavelet function was used. The wavelet transformation *Wn* is the convolution of a vector *x* (with time dimension n) with a wavelet function *ψ*

$$W_{n(s)} = \sum_{n'=0}^{N-1} x_n \psi^{*}\left[\frac{(n'-n)\delta t}{s}\right] \quad (1)$$

where *s* is the scale, or dilation, n' – n shows the number of points from time series origin (translation), *δt* is the time interval, *N* is the number of points, and the overbar designates the complex conjugate. Scale is the width of the wavelet; a larger scale means that more of the time series is included in the calculation and that finer details are ignored. Scale is approximately equal to the Fourier period (inverse of frequency). Translation of the wavelet is accomplished by calculating the convolution from n' = 0….. N-1. In other words, a wavelet of varying width (scale) is moved, or translated, through the entire time series. The wavelet transformation is therefore localized in both time (through the translation) and frequency (through the range of scales). Wavelets are advantageous in that they simultaneously localize frequency and time, allowing for the detection of variations in the amplitude and timing of periodic signals present in the time series (White et al., 2005).

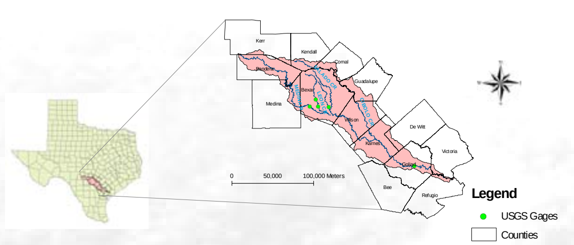
In this analysis, a complex Morlet wavelet function *ψ0(η)*, which is commonly used for signals with strong wave-like features (such as streamflow data), was used and is calculated as:

$$\psi(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2} \quad (2)$$

where *ω0* is the non-dimensional wave number and *η* is a time parameter (non-dimensional, also could represent other metrics such as distance).

The continuous wavelet transform can then be calculated using a fast Fourier transform (FFT). The wavelet power spectrum (WPS), as for the Fourier power spectrum, is defined as | *Wn(s)* |². In addition to viewing the entire wavelet power spectrum, wavelets can be averaged in time and space.

San Antonio River Basin showing major streams, and USGS gauging stations



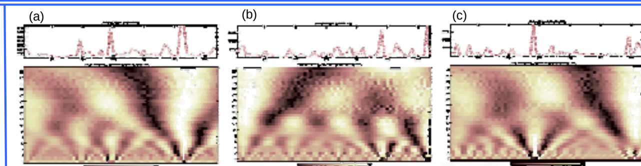


Figure 6: (a) Dec-Mar Maximum Baseflow, (b) Apr-Jul Maximum Baseflow, (c) Aug-Nov Maximum Baseflow

Results and Discussion

The x-axis in the figures show wavelet location in time (Time Translation) and y-axis is the wavelet period in years (Scale Dilation). Total seasonal flow analysis (Figure 1) suggested the presence of highest magnitude at 11-17 year scale in Dec-Mar and Apr-Jul, with a 10 year cycle (oscillation). Total minimum flow (Figure 2) for each of the season suggested the presence of highest magnitude at 11-17 year scale across all seasons before 1980. However, after 1980 higher magnitudes are observed at the lower scale. Total maximum flow (Figure 3a and Figure 3b) suggested presence of some dominant features at 11-15 year scale with 10 years of oscillation prior to 1980. Analysis of total baseflow (Figure 4a and Figure 4b) suggested that signals have become erratic after 1980. Highest magnitude dominated 11-15 years scale with 10 years oscillation. However, that magnitude is not observed at 11-15 years scale after 1980. Higher frequencies are observed in smaller scale. This may suggest that the baseflow is affected by the continuous discharge from waste water treatment plants. These plants being established between 1972 and 1980, following the Clean Water Act. Similar signatures were observed in Minimum and Maximum baseflow of Dec-Mar, and Apr-July seasons (Figure 5a, 5b and Figure 6a, 6b).

Further analysis will include wavelet analysis of rainfall, and spectral analysis of total flow, baseflow, and rainfall.

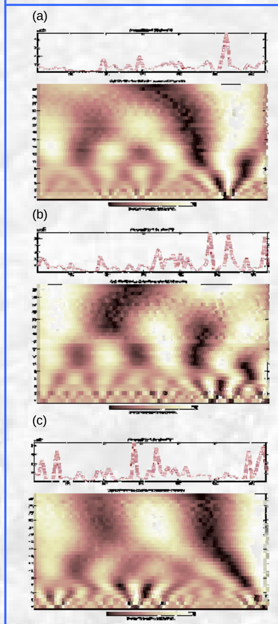


Figure 1: (a) Dec-Mar Total Flow, (b) Apr-Jul Total Flow, (c) Aug-Nov Total Flow

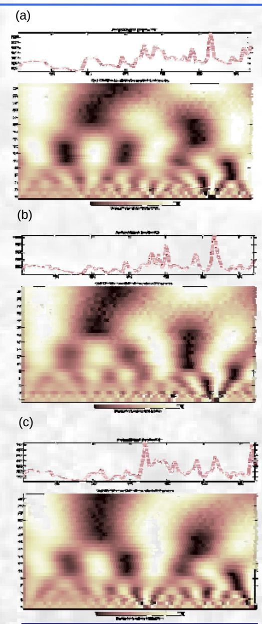


Figure 2: (a) Dec-Mar Total Minimum Flow, (b) Apr-Jul Total Minimum Flow, (c) Aug-Nov Total Minimum Flow

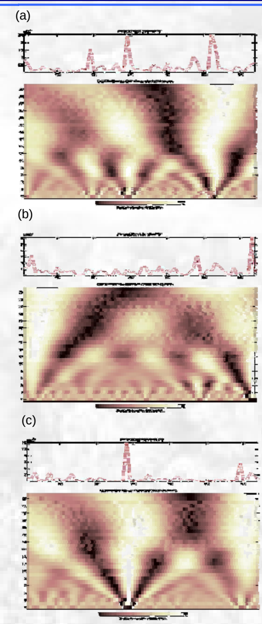


Figure 3: (a) Dec-Mar Total Maximum Flow, (b) Apr-Jul Total Maximum Flow, (c) Aug-Nov Total Maximum Flow

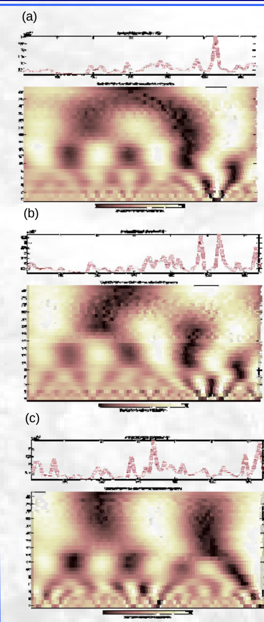


Figure 4: (a) Dec-Mar Total Baseflow, (b) Apr-Jul Total Baseflow, (c) Aug-Nov Total Baseflow

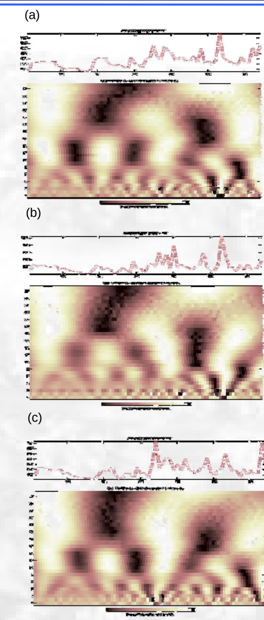


Figure 5: (a) Dec-Mar Minimum Baseflow, (b) Apr-Jul Minimum Baseflow, (c) Aug-Nov Minimum Baseflow

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Evaluating the Effect of Land Use Land Cover Change in a Rapidly Urbanizing Semi-Arid Watershed on Estuarine Freshwater Inflows

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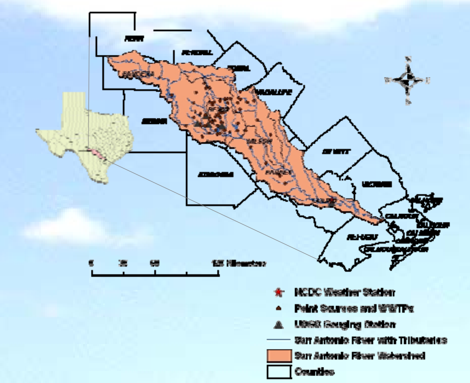

Figure 1: San Antonio River Basin showing major streams, and USGS gauging stations

Introduction:

The study of environmental inflows is an evolving science (NRC, 2005). Adequate environmental inflows are needed for proper ecological maintenance of aquatic ecosystems such as estuaries. Estuarine freshwater inflows along with their associated nutrient and metal delivery are influenced by the land use/land cover (LULC) and water management practices in the contributing watershed, particularly in watersheds that are experiencing rapid human induced disturbances. San Antonio, TX, the 8th largest city in the US, is situated in the San Antonio River basin. The San Antonio River Basin encompasses 4180 square miles from the headwaters to the point at which this river joins with the Guadalupe River, before draining into Gulf of Mexico. Rapid urbanization has changed the land use and land cover in this river basin. Studies in the river basin suggest that change in land use has primarily been an increase in impervious surface. Increase in impervious surface can change the flow regime by altering timing, magnitude, scale, and frequency of freshwater inflows.

Methodology:

LULC data set were obtained from LANDSAT TM satellite imageries for the years 1987, 1999, and 2003 from USGS and Texas View. Four row/path combinations: 2839, 2739, 2740, and 2640 covered the entire watershed area. ENVI 4. 2 was used for image processing. Images with 28.5 m resolution were resampled for 30 m resolution. Unsupervised ISODATA classification was conducted on the images. Approximately 20 classes were used initially. These 20 classes were lumped into 4 classes. Each classified scene was then mosaiced for the required watershed area. ArcGIS 9.1 and Arcinfo were used for spatial analysis.

This study used 63 years (1940-2003) of daily average flow data from the most downstream USGS gauging station number 08188500 (Figure 1), and rainfall from NCDC COOP ID 413618 situated near the USGS gauging station (Figure 1). Average daily data was aggregated to estimate seasonal flow and seasonal rainfall (December-March, April-July, and August-November). A baseflow separation filter (Arnold, and Allen, 1999) was used to separate baseflow. Non parametric time series analysis was performed on all these hydroclimatic variables.

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Sahoo, D., P. Smith, and F. Zhang. 2006. (Submitted to Estuarine Coastal and Shelf Science) Characterization of freshwater inflows draining to a gulf coast estuary in a rapidly urbanizing coastal watershed using wavelet techniques.

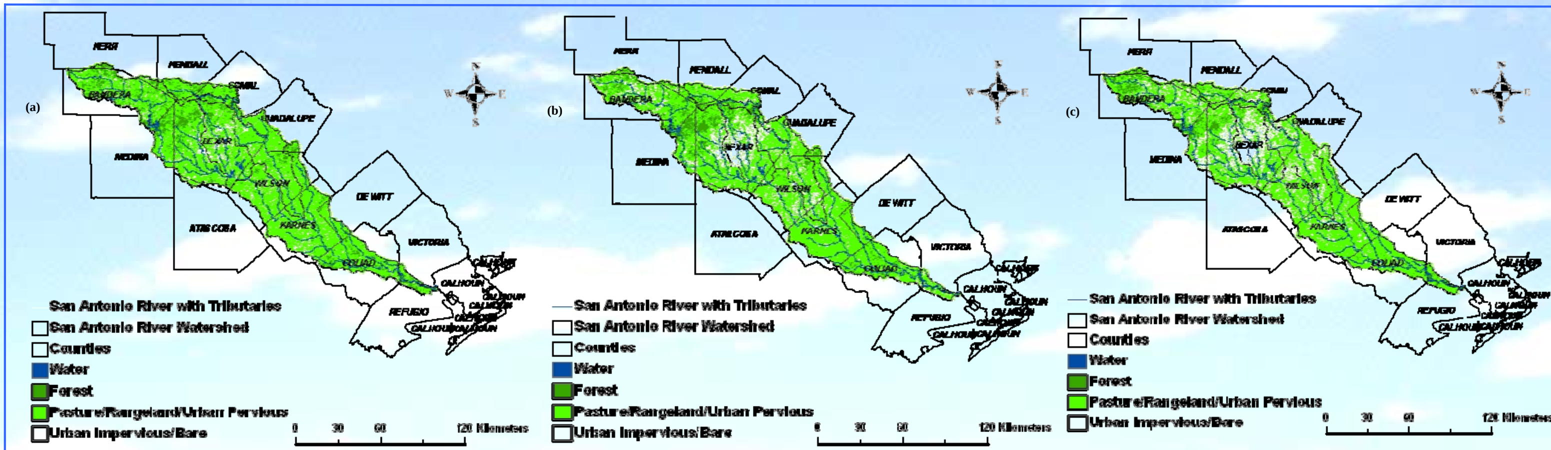

Figure 2: Land use land cover in San Antonio Watershed; (a) 1987, (b) 1999, and (c) 2003

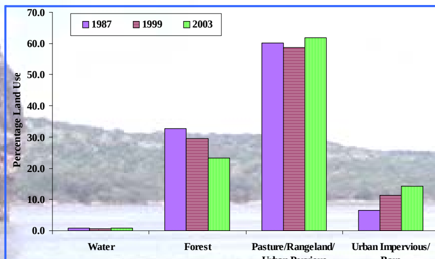

Figure 3: LULC percentage in San Antonio Watershed

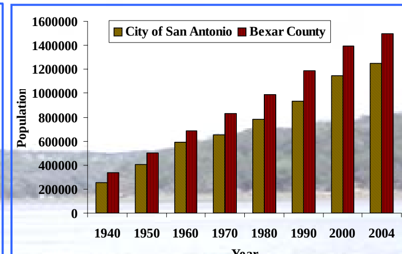

Figure 4:Population in the City of San Antonio and Bexar County

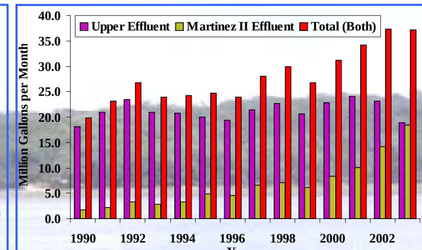

Figure 5: Two WWTPs discharge in San Antonio River Basin

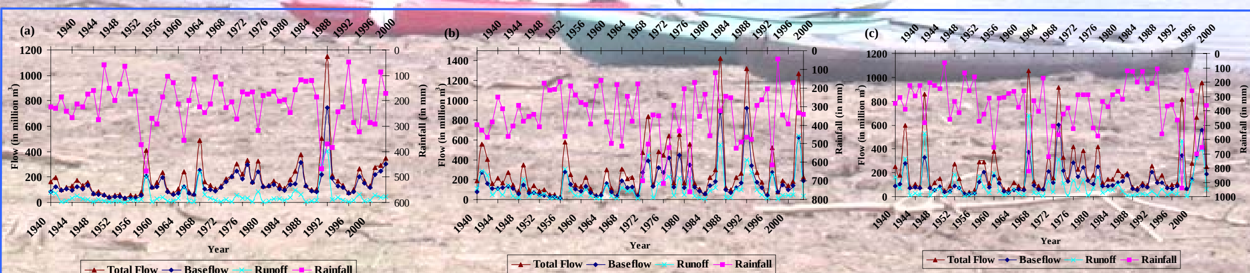

Figure 6: Comparison of seasonal Total flow, Baseflow, Runoff, and Rainfall (a) Dec-Mar, (b) Apr-Jul, and (c) Aug-Nov

Results and Discussion:

LULC analysis suggested Pasture/Rangeland/Urban impervious to be the dominant land use in all the three years (Figure 2). Forest area decreased in the analysis period (Figure 3). Decrease in forest area could be attributed to an increase in urban impervious/bare land (Figure 3). Population has also increased in last two decades, particularly in Bexar County (Figure 4). Urban impervious/bare cover increased in Bexar County from 9% in 1987 to 21% in 2003.

With increase in population, increase in impervious surface, there has been an increase in WWTPs discharges (Figure 5). Analysis of environmental flow suggested an increasing trend in total seasonal flow (Dec-Mar, Apr-Jul, Aug-Nov), and total seasonal baseflow (Figure 6) (Sahoo and Smith, unpublished). Also analysis of these variables suggested presence of dominant frequency in 8 years cycle (Sahoo et al., unpublished). However, no increasing trend was observed in seasonal rainfall or seasonal runoff. Analysis of similar rainfall events from 1950s and from 1990s and corresponding seasonal total flow, baseflow and runoff suggested seasonal total flow increased substantially in 1990s. Baseflow contributed more to total flow than runoff. Increasing trend in baseflow could be attributed to WWTPs discharge (Figure 1 and Figure 5).

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A Pricing Model to Assess the Effect of Groundwater Availability on Land Valuation

Basic Information

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Project Number:	2006TX231B
Start Date:	3/1/2006
End Date:	2/28/2007
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Congressional District:	13
Research Category:	Social Sciences
Focus Category:	Law, Institutions, and Policy, Groundwater, Conservation
Descriptors:	None
Principal Investigators:	Robert Taylor, Lal Almas

Publication

A Pricing Model to Assess the Effect of Groundwater Availability on Land Valuation

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Abstract:

The Ogallala Aquifer provides 90% of the water used for irrigated agriculture in the Texas Panhandle. Due to this reliance on groundwater, pumping for irrigation purposes has had a significant impact on the amount of water available for agriculture over the years. While the adoption of new technology has resulted in an efficient use of groundwater, the region still is faced with declining groundwater availability. This is due primarily to the slow or non-existent recharge rate of the aquifer in the High Plains and the increased levels of irrigation by producers. Land valuation by both taxing entities and purchasers or sellers of property should reflect the amount of water available under the land being valued, but often times the valuation does not fully or accurately reflect the availability of groundwater. Adding to the problem more recently is the purchasing of "water rights" in the region, which has raised further issues concerning how the value of the available water should be considered, both for tax purposes (regionally in the form of property tax and nationally in the form of capital gains and losses taxes).

This study sought to determine the price being paid for irrigated, dryland, grassland, and CRP acreage in order to determine the value purchasers are placing on each factor. It also looked at the importance that purchasers of agricultural land place on such variables as saturated thickness, well capacity, and pump lift. This yielded a hedonic pricing model that incorporates land usage as well as water availability that can be used to estimate the sales price for agricultural land in the region. The study results can be used to help landowners, tax authorities, credit institutions, and potential purchasers to better understand the effect that water availability currently has on land values. The results can also provide a basis for determining the value for water buyout programs for management, conservation, and planning purposes.

Introduction:

The availability of water in the Texas Panhandle is a major concern, as is the conservation of the limited supply of water in the region. The Texas High Plains area has a semi-arid climate and average low rainfalls which results in little surface water being available year-round for agriculture. Thus, more than 90% of the water used in agriculture in the High Plains area comes from the Ogallala Aquifer (Stewart, 2003 and Jenson, 2004). The aquifer covers about 36,080 square miles and it currently has a supply of water of approximately 6.1 million acre feet of water, which is expected to decline to 4.8 million acre feet by 2060 (Jenson, 2004). From 1994 to 2004, the aquifer declined at an average of 1.28 feet per year (Jenson, 2004). Adding to the problem is the low recharge rate of the aquifer in the High Plains area (Postel, 1998). In the southern region, the recharge rate has been reported to be as low as 0.024 inches per year from precipitation (Ryder, 1996).

The use of low-energy-application (LEPA) and low-energy-spray-application (LESA) have allowed for more efficient use of water in the region (Howell, 2001). However, producers have had the benefit of increased technology in drilling and installing these systems, which has led to increased irrigation use. In the southern High Plains, which uses intense irrigation, the decline in the water table has been estimated to be between 50 and 100 feet (Ryder, 1996). A contributing factor to the increased use of groundwater comes from the state laws covering the right of capture of ground water beneath the land, by which the land owner may capture the water beneath the land regardless of the effect on nearby or distant users of the water supply (Stewart, 2003). A survey conducted in 2003 showed that of 63,602 operating wells, only 4,530 wells had a meter installed (NASS, 2004). Finally, recent trends in purchasing “water rights” and the potential uses of the water associated with these rights threaten to result in further depletion.

The importance of irrigation in the area can also be seen by the difference in the price being paid for dryland acreage versus that paid for irrigated acreage. Land prices in the region have remained stable despite higher energy costs over the last seven years (Texas ASFMRA, 2005). This stability has partially been caused by the amount of good irrigated land available for sale gradually declining and the continued demand for irrigated acreage in the area. Other contributing factors in stabilizing irrigated acreage prices in spite of the rising cost to irrigate include an increased number of cotton crops in the region and the marketing of water rights (Gilliland and Klassen, 2006).

Hedonic pricing models are most commonly used in valuing real estate in housing markets, incorporating such factors as number of bathrooms, bedrooms, square footage, garage capacity, and living areas. However, several researchers have been incorporating the hedonic approach to valuing agricultural land in recent years to analyze such factors as easement payments (Lynch and Lovell, 2002), the level of accessibility and remoteness (Sengupta and Osgood, 2002), and the importance of irrigation in light of global warming (Schlenker, Hanemann, and Fisher, 2004).

Objectives:

This project was aimed at evaluating the effect that the availability of groundwater in the Texas High Plains area has on the value of the property overlying the aquifer. This is critical for a number of reasons, including possible reductions in tax bases for property tax evaluation, the value of land in purchase and sale transactions, the taxes associated with capital gains and losses for federal tax purposes, and to provide a possible further incentive to encourage greater conservation of ground water.

The specific objectives of this study were as under:

- ❖ To develop a pricing model to determine the price per acre paid for irrigated, dryland, grassland, and CRP acreage in the Texas Panhandle.
- ❖ To determine the value placed on the availability of ground water in terms of saturated thickness, depth to the aquifer (pump lift), well capacity (in gallons per minute), and acreage type (irrigated, dryland, CRP, and grassland) by purchasers of agricultural land in the region.
- ❖ To integrate the results of the first two objectives into a hedonic pricing model that accurately estimated the sales price (net of any improvements) with respect to the availability of water for irrigated acres and the value of dryland, grassland, and CRP acres.

These results provide the basis for determining the value that is added by the amount of available water, which then can be compared to the rates being paid per acre for "water rights" as well as a means for estimating the changes in land value due to future declines in the level of the Ogallala Aquifer.

Data and Methods:

Actual sales data was collected from the Panhandle Groundwater District, which includes Carson, Donley, Wheeler, Gray, Roberts, and Armstrong Counties, and the North Plains Water District, which covers Dallam, Hartley, Hansford, Hutchinson, Lipscomb, Moore, Ochiltree, and Sherman Counties. The data obtained from these two districts included the total price paid for each parcel sold, the value of any improvements to the land such as buildings, irrigation wells and equipment conveyed with the real estate sale, the legal description of the property sold, and the total acres included in the sale during a two year period covering the last half of 2004, all of 2005, and the first half of 2006. Purchaser and seller surveys conducted by the water development boards also provided information relating to the number of irrigated acres, dryland acres, grassland acres, CRP acres, the acres of unusable land (roads, easements, etc.), estimated well capacities, and price paid for each irrigated acre. Water development board records also provided information on the estimated saturated thickness, depth to the aquifer, and additional well capacity estimates for each parcel sold.

A total of 71 observations, 28 of which included irrigated acreage, and the supporting data associated with each sale was obtained for the 14 counties represented by the North Plains and Panhandle Water Districts were collected. The first phase of building the model involved regressing the net sales price, which was derived by subtracting the value of improvements from the total sales price, against the total irrigated acres, total dryland acres, total grassland acres, and total CRP acres for each sale using SAS software. This gave the contribution of each acreage type to the total price. The second phase in building the model involved regressing the actual price paid per irrigated acre against the estimated saturated thickness in feet, estimated depth to the aquifer in feet, and the estimated well capacity in gallons per minute, both individually and with the others, for each parcel sold that included irrigated acreage using SAS software. This provided the significance and the value contributed by each variable.

Results and Discussion:

The first objective was to determine the price that was paid for each acre of irrigated cropland, dryland cropland, grassland, and each acre in CRP. The net price paid for a parcel can be defined as being a function of the number of acres each type of acreage multiplied by the price per acre for each type. The SAS results presented in Table 1 show the SAS regression of the Net Sales Price (the total price paid minus the value of any improvements to the land), and the associated coefficients for the value of irrigated, dryland, grassland, and CRP acreage. The estimated equation for the total purchase price for a parcel can be shown by the equation:

Total Sales Price=$17,118.83 + $526.45(Number of Irrigated Acres) + $335.64(Number of Dryland Acres) + $359.57(Number of CRP Acres) + $207.19(Number of Grassland Acres)

The SAS results for the 71 observations of land sales showed an R^2 of 0.9247, reflecting that the variables adequately explain the variation in the total price paid for each sale. The F-value for the model was 202.55 with a p-value of <0.001, reflecting that the independent variables are significant to the model. The results also show that each variable included in the model had a p-value of less than 0.001, showing that all of the variables are significant. Finally, the Variance Inflation Factor for each independent variable was less than 10, meaning that multicolinearity does not exist in the model.

The second objective was to analyze the effect that water availability had on the price paid for each acre of irrigated cropland. It is often assumed that the saturated thickness of the Ogallala Aquifer below the surface of irrigated cropland is the best measure of water availability and as such would be a dominant deciding factor (along with the depth to the aquifer in terms of pump lift) in a purchaser's decision on how much to pay for irrigated cropland. However, it appears that purchasers do not consider saturated thickness at all when deciding to buy a parcel. Figure 1 shows a scatter plot of the actual price paid for irrigated cropland versus the saturated thickness in feet for each of the 28 observations for irrigated cropland sales in the study region. The trend line showed an R^2 of 0.0011, which signifies that purchasers do not consider the saturated thickness in their decision on how much to pay for irrigated acreage.

The next logical variable to consider is the well capacity of existing wells on the parcel. As Figure 2 shows, well capacity in gallons per minute is a better explanatory variable for the price of irrigated acreage than saturated thickness. The trend line shows an R^2 of 0.3153, representing that well capacity represents 31.53% of the variability in price. The independent variable also was significant, with a t-value of 3.46 and an associated p-value of less than 0.002. However, the scatter plot also shows the possible presence of heteroscedasticity, which is evidenced by the data points diverging from the trend line as well capacity increases. One of the key assumptions in regression is that the variance of the errors is constant across all observations. When the variance of the errors is not constant, standard estimation methods can yield inaccurate results. As a result, a test for heteroscedasticity was also performed.

The model procedure in SAS provides the ability to test for heteroscedasticity using Whit's test, which is a general test that does not make any assumptions about the form of heteroscedasticity, and the Modified Breusch-Pagan test, which is less sensitive to the assumption of normality than the original test. The null hypothesis for both tests is that the error variances are constant (no heteroscedasticity). Table 2 gives the SAS model test statistics for both White's and the Breusch-Pagan tests Calculated in SAS for well capacity.

The test statistic for White's was 2.57 with a p-value of 0.2761 and the Modified Breusch-Pagan statistic was a 1.12 with a p-value of 0.2892. This means that the null hypothesis can not be rejected and thus heteroscedasticity does not exist. This was also confirmed by conducting a standard Breusch-Pagan test by regressing the squared residuals against the independent variable which gave a F-test statistic of 0.857 and a p-value of 0.363, meaning that the independent variables are not jointly significant and thus the null hypothesis of no heteroscedasticity can not be rejected, or the model is homoscedastic.

Another factor to be considered in building the model is the effect that pump lift may have on price. As the pump lift increases, the cost to irrigate also increases. This means that a purchaser of irrigated cropland should consider what it will cost to irrigate the acreage. Figure 3 shows a plot of the price per irrigated acre versus pump lift in feet for the 28 observations of irrigated acreage sales. As the plot shows, the pump lift has a negative impact on irrigated acreage prices. The R^2 associated with the trend line in the scatter plot was a 0.4054, which signifies that pump lift does describe some of the variability in irrigated land prices. Here again, however, it appears that heteroscedasticity may be present, necessitating the need to conduct a White's and a Modified Breusch-Pagan test.

Table 3 gives the SAS model results for the irrigated price per acre against pump lift in feet and the associated heteroscedasticity tests. The statisitic for the White's test was 8.59 with an associated p-value of 0.0136, and the statisitic for the Modified Breusch-Pagan test was 8.55 with an associated p-value of 0.0035. Both tests show that the hypothesis of no heteroscedasticity can be rejected, meaning that heteroscedasticity is present with pump lift. A standard Breusch-Pagan test confirmed these findings, yielding an F-value of 14.54 and an associated p-value less than 0.001, meaning that the independent variables are jointly significant and thus the null hypothesis is rejected, resulting in the conclusion that heteroscedasticity does exist. This means that any model using pump lift will require transforming the pump lift variable. Figure 4 shows the plot of dividing negative 1 by the pump lift and plotting against the price per irrigated acre. It is clearly apparent by the plot that this corrects for the heteroscedasticity, and increases the R^2 to 0.47.

Due to the fact that both well capacity and pump lift were found to be significant to purchasers' decisions, both are included in the final model on water availability. Table 4 presents the SAS regression output for the combined model with the two independent variables. The heteroscedastic situation with pump lift was corrected in the model by dividing negative one by the pump lift in feet, then running the regression is SAS along with well capacity and irrigated acre price. The overall model returned an R^2 of 0.6304, which was significantly better than either of the two models with individual independent variables. The F-value for the overall model was 21.32 with a p-value less than 0.001, signifying that the independent variables are significant to the model. The overall model can thus be expressed as:

Price per Irrigated Acre = \$166.17 + \$0.49(Well Capacity in GPM) +

-1/(– 26541.90(Pump Lift in Feet))

The coefficient associated with well capacity had a t-value of 3.29 and an associated p-value of 0.002, and the coefficient associated with pump lift had a t-value of -4.62 and a p-value of less than 0.001. This shows that that both independent variables are significant to the overall model and thus should be included. One possible concern with using both well capacity and pump lift is the possibility of multicolinearity, as there is it is possible for pump capacity to be affected by pump lift. However, the Variance Inflation Factor for both variables was less than 10, showing that multicolinearity does not exist in the model.

The final hedonic price model can now be derived by combining the two models developed previously:

Total Price = \$17,118.83 + (\$166.17 + \$0.49(Well Capacity in GPM) + -1/(– 26541.90(Pump Lift in Feet)) +

\$335.64(Number of Dryland Acres) + \$359.57(Number of CRP Acres) +

\$207.19(Number of Grassland Acres)

The total sales price is a function of the individual prices for irrigated cropland, dryland cropland, grass land, and acreage in CRP, and the price for irrigated cropland is a function of well capacity and pump lift.

Conclusion:

The model for total sales price as a function of each type of acreage was shown to be a significant model. However, in order to incorporate the full effect that water availability has on land valuation, a separate model had to be developed to account for the variables that contribute to the amount of water available for irrigation. This was accomplished by developing a second model for that sole purpose. The result is a hedonic pricing model for valuing agricultural land that is more accurate in terms of the effect of water availability, while retaining non-irrigation variables. This model allows for assessors, appraisers, purchasers, and policy makers to better understand what buyers of agricultural land are actually paying for irrigated farm land as well as for non-irrigated acreage.

Future research endeavors will seek to acquire more observations, as well as more accurate data from other groundwater districts not included in this study. Additional observations are available as data exists for land sales prior to 2004, though this study did not utilize them in order to avoid complications due to inflationary issues. One possible method for correcting for price changes over time would be the development of an index based in part on the Consumer Price Index. Additional research will also focus on adding variables for soil type and climatic changes, though preliminary results showed that climate may have a minimal effect as there is not a lot of variability from one county in the region to another.

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Exhibits:

Table 1: SAS Regression Results, Net Parcel Price against Acres by Type.

Dependent Variable: price

Number of Observations Read	71
Number of Observations Used	71

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	1.125005E12	2.812512E11	202.55	<.0001
Error	66	91642405151	1388521290		
Corrected Total	70	1.216647E12			

Root MSE	37263	R-Square	0.9247
Dependent Mean	176003	Adj R-Sq	0.9201
Coeff Var	21.17173		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|	Variance Inflation
Intercept	1	17119	7742.16271	2.21	0.0305	0
irrigated	1	526.44747	23.13958	22.75	<.0001	1.19938
dryland	1	335.63837	23.80685	14.10	<.0001	1.06788
crp	1	359.57293	45.13412	7.97	<.0001	1.14745
grass	1	207.19266	53.96070	3.84	0.0003	1.17659

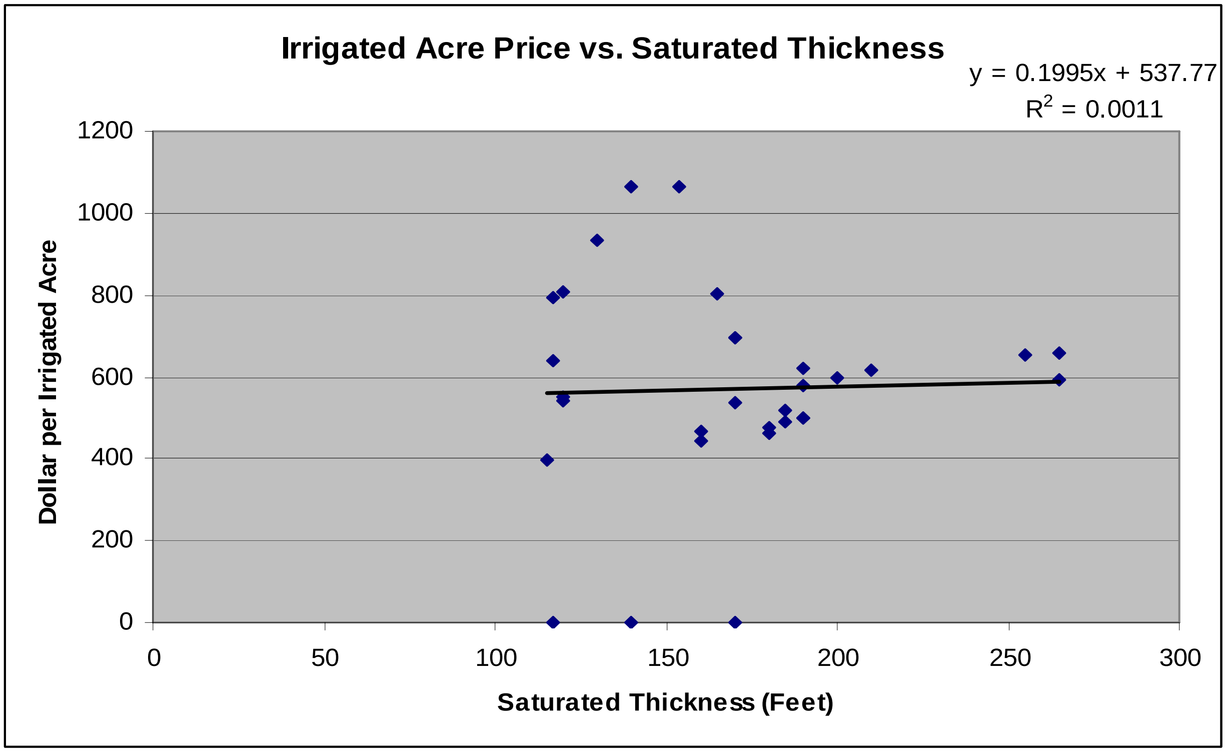


Figure 1: Plot of Actual Price Paid for Irrigated Acreage versus Saturated Thickness in Feet.

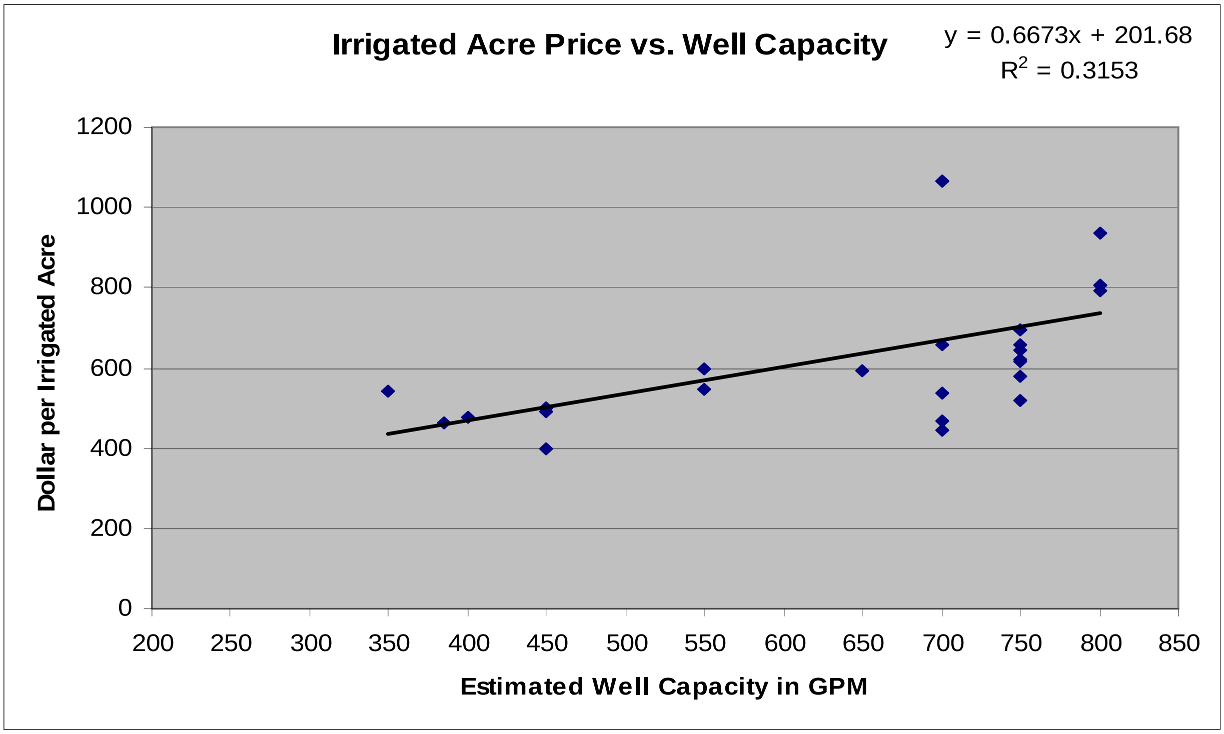


Figure 2: Plot of Actual Price Paid for Irrigated Acreage versus Well Capacity in Gallons per minute.

Table 2: SAS Model Results with White's and Breusch-Pagan Tests for Heteroscedasticity, Net Parcel Price against Well Capacity in Gallons per Minute.

Model R^2	0.3153			
Observations	28			
DF Model	2			
DF Error	26			
Parameter	Estimate	Standard Error	t-Value	p-Value
Intercept	201.68	127.7000	1.58	0.126
GPM	0.667	0.193	3.46	< 0.002
Test	Statistic	DF	Pr > ChiSq	Variables
White's	2.57	2	0.2761	All
Breusch-Pagan	1.12	1	0.2892	GPM

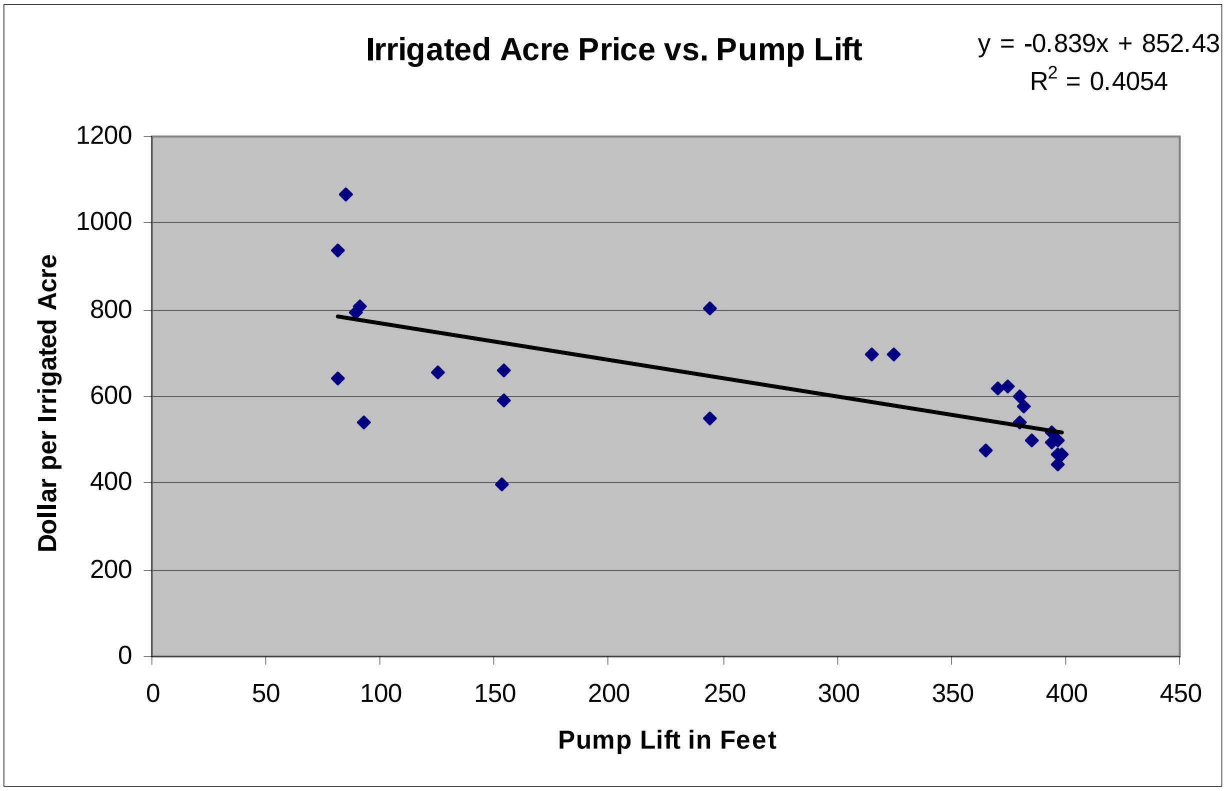


Figure 3: Plot of Actual Price Paid for Irrigated Acreage versus Pump Lift in Feet.

Table3: SAS Model Results with White's and Breusch-Pagan Tests for Heteroscedasticity, Net Parcel Price against Pump Lift in Feet.

Model R^2	0.4054			
Observations	28			
DF Model	2			
DF Error	26			
Parameter	Estimate	Standard Error	t-Value	p-Value
Intercept	852.43	58.315	14.62	< 0.001
GPM	-0.84	0.193	3.46	< 0.001
Test	Statistic	DF	Pr > ChiSq	Variables
White's	8.59	2	0.0136	All
Breusch-Pagan	8.55	1	0.0035	Lift

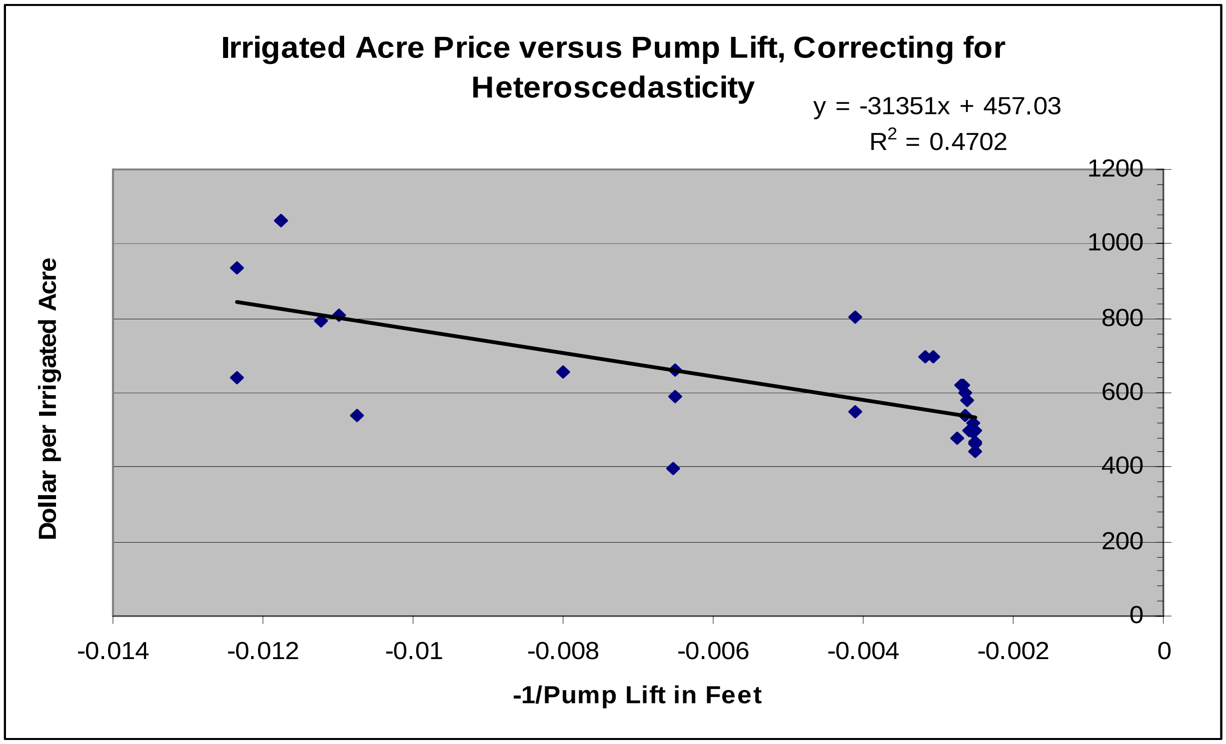


Figure 4: Plot of Actual Price Paid for Irrigated Acreage versus Negative 1 over the Pump Lift in Feet to correct for Heteroscedasticity.

Table 4: SAS Regression Results , Net Parcel Price against Well Capacity in Gallons per Minute and Negative One over Pump Lift in Feet.

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	522855	261428	21.32	<.0001
Error	25	306603	12256		
Corrected Total	27	829458			

Root MSE	110.74341	R-Square	0.6304
Dependent Mean	632.71429	Adj R-Sq	0.6008
Coeff Var	17.50291		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|	Variance Inflation
Intercept	1	166.21128	95.96520	1.73	0.0956	0
gpm	1	0.49205	0.14942	3.29	0.0030	1.06906
lift	1	-26533	5748.10	-4.62	0.0001	1.06906

An Econometric Investigation of Urban Water Demand in the U.S.

Basic Information

Title:	An Econometric Investigation of Urban Water Demand in the U.S.
Project Number:	2006TX253G
Start Date:	9/1/2006
End Date:	8/31/2008
Funding Source:	104G
Congressional District:	17
Research Category:	Social Sciences
Focus Category:	Management and Planning, Economics, Water Use
Descriptors:	None
Principal Investigators:	Ron Griffin

Publication

Progress Report
Oct. 2006 – Feb. 2007

USDI/USGS Award Grant # 06HQGR0188
An Econometric Investigation of Urban Water Demand in the U.S.

A potential sampling universe of 1300 cities with population greater than 30,000 has been identified. For each city, the ownership structure of the water utility and its name and website have been identified. The process of accumulating historical price data from electronic sources has been initiated. Exploratory contact has been made directed to a process for collecting monthly quantity data. Sources and parameters for income and climatic data have been established.
Literature review has been directed toward a dynamic theoretical model and the appropriate empirical methods necessary to depict both dynamic and structural properties of the data.

Ron Griffin
5/31/07

Information Transfer Program

Information Transfer

Basic Information

Title:	Information Transfer
Project Number:	2006TX232B
Start Date:	3/1/2006
End Date:	2/28/2007
Funding Source:	104B
Congressional District:	17
Research Category:	Not Applicable
Focus Category:	None, None, None
Descriptors:	None
Principal Investigators:	Bill L. Harris, Clint D. Wolfe

Publication

Texas Water Resources Institute
Information Transfer Activities
March 2006 – February 2007

In 2006, the Texas Water Resources Institute continued its outstanding communication efforts to communicate university-based water resources research and education outreach programs in Texas.

The Institute publishes weekly email media mentions, a monthly e-mail newsletter, a quarterly newsletter specific for one project and a magazine, published three times a year.

New Waves, the email newsletter, publishes timely information about water resources news, results of projects and programs, and new water-related research projects, publications and faculty at Texas universities. The newsletter has a subscription of 1200.

RGBI Outcomes, is 8-page newsletter specifically spotlighting research and education programs of the Rio Grande Basin Initiative, a federally funded project focused on increasing available water through efficient irrigation and water conservation. RGBI Outcomes has a subscription of over 500.

tx H_2O, a 30-page glossy magazine, is published three times a year and contains in-depth articles that spotlight major water resources issues in Texas, ranging from agricultural non-point source pollution to landscaping for water conservation. Over 2000 individuals and entities received the magazine via subscription and approximately 1000 more magazines are distributed.

Working to reach the general public and expand their audience, the Institute cooperates with Texas A&M University Agricultural Communications to produce news releases about projects as well as generates its own written releases. The Institute prepared numerous informational packets for Congressional contacts, and other meetings and prepared press packets for Governor Rick Perry's Trinity River Basin Initiative announcement. TWRI projects or researchers had at least 70 mentions in the media.

For each of the Institute's project, TWRI published one-page fact sheets that explained the purpose, background and objectives of each program.

In addition to the one-page fact sheets for its projects, the Institute developed specialty reports, such as white papers, educational fact sheets and brochures that highlight the need for certain programs in Texas, a history of an area, educational information or the advances made in water resources management in the private and public sector. These included 7 specialty reports, 2 brochures/fact sheets and the development and/or revision of 10 educational publications

In cooperation with research scientists and Extension education professionals, the Institute published 9 technical reports and 3 special reports, which provide in-depth detail of water resource issues for the state.

The Institute continues to enhance its Web presence by increasing its Web sites to 18 and continually updating the information contained within the Web sites. In addition, 4 new sites are under development and will become active this year.

Technical Publications:

TR-301 Economic, Hydrologic and Environmental Appraisal of Texas Inter-basin Water Transfers: Model Development and Initial Appraisal
Y. Cai, B. A. McCarl

TR-300 Watershed Protection Plan Development for the Pecos River
J. Villalobos, Z. Sheng, C. Hart

TR-299 Expected Economic Benefits of the El Morillo Drain
Ronald D. Lacewell, M. Edward Rister, Allen W. Sturdivant, Megan DuBois, Callie Rogers, Emily Seawright

TR-298 Water Balance, Salt Loading, and Salinity Control Options of Red Bluff Reservoir, Texas
S. Miyamoto, Fasong Yuan, and Shilpa Anand

TR-297 The Development of a Coordinated Database for Water Resources and Flow Model in the Paso Del Norte Watershed
Zhuping Sheng, Sue Tillery, J. Phillip King, Bobby Creel, Christopher Brown, Ari Michelsen, Raghavan Srinivasan, Alfredo Granados

TR-296 Federal Flood Assessment Conference Recommendations and Proceedings
Silvestre Reyes, Peter Brock, Ari Michelsen

TR-294 Update of Estimated Agricultural Benefits Attributable to Drainage and Flood Control in Willacy County, Texas
Ronald D. Lacewell, Roger Freeman, David Petit, Ed Rister, Allan Sturdivant, Luis Ribera, Michele Zinn

TR-292 Influence of Tributaries on Salinity of Amistad International Reservoir
S. Miyamoto, Fasong Yuan and Shilpa Anand

TR-291 Reconnaissance Survey of Salt Sources and Loading into the Pecos River
S. Miyamoto, Fasong Yuan, and Shilpa Anand

SR 2006-05 Hydrology of the Texas Blackland Prairie: Riesel Watershed Data and Published Hydrologic Relationships
U.S. Department of Agriculture-Agricultural Research Service

SR 2006-04 Validating the Estimated Cost of Saving Water Through Infrastructure Rehabilitation in the Texas Lower Rio Grande Valley
Allen W. Sturdivant, M. Edward Rister, Ronald D. Lacewell, Callie S. Rogers

SR 2006-02 Goal Seek Pamphlet for VIDRA© - HCID#1
C. Rogers, A. Sturdivant, M. Rister, R. Lacewell

Extension Publications:

The following new publications are available from the Texas Cooperative Extension bookstore at http://tcebookstore.org/

B-6182	Harvesting Rainwater for Wildlife James Cathey, Russell A. Persyn, Dana Porter, Monty Dozier, Michael Mecke and Billy Kniffen
B-6189	Best Management Practices for Conservation/Reduced Tillage Charles Abrameit, Charles Stichler and Mark L. McFarland
B-6192	Drinking Water Problems: Radionuclides Bruce J. Lesikar, Rebecca Melton , Michael Hare, Janie Hopkins and Monty Dozier
L-5475	On-Site Wastewater Treatment Systems: Responding to Power Outages and Floods Bruce J. Lesikar , Courtney O'Neill and David Smith
B-6125	Lawn Water Management James McAfee
B-6126	Keep Your Lawn Alive During Drought James McAfee
B-6120	Questions about Groundwater Conservation Districts in Texas Bruce J. Lesikar, Ronald Kaiser and Valeen Silvy
B-6191	Priority Groundwater Management Areas: Overview and Frequently Asked Questions Valeen Silvy, Bruce J. Lesikar and Russell A. Persyn
B-6194	Irrigation Monitoring with Soil Water Sensors Juan Enciso, Dana Porter and Xavier Peries
B-6195	Rainwater Harvesting: Soil Storage and Infiltration Justin Mechell and Bruce J. Lesikar
B-6196	Technologies for Reducing Nutrients in Dairy Effluent Saqib Mukhtar, Kevin Wagner and Lucas Gregory
L-5482	Rainwater Harvesting: Rain Gardens Justin Mechell and Bruce J. Lesikar
L-5483	On-Site Wastewater Treatment Systems: Ultraviolet Light Disinfection Bruce J. Lesikar

Web sites:

TWRI web sites	
Buck Creek Water Quality Project	http://twri.tamu.edu/buckcreek/
Dairy Compost Utilization	http://compost.tamu.edu/
Fort Hood Range Revegetation Project	http://forthoodreveg.tamu.edu/
Lake Granbury Water Quality	http://lakegranbury.tamu.edu/
North Central Texas Water Quality	http://nctx-water.tamu.edu/
Pecos River Basin Assessment Program	http://pecosbasin.tamu.edu/
Proper Organic Management	http://twri.tamu.edu/ipofm/
Rio Grande Basin Initiative	http://riogrande.tamu.edu/
Rio Grande Basin Initiative Conference	http://riogrande-conference.tamu.edu/
Texas Water Resources Institute	http://twri.tamu.edu/
Trinity River Basin Environmental Restoration	http://trinitybasin.tamu.edu
Other websites	
BioEnergy Alliance	http://bioenergy.tamu.edu/
SETAC Water Workshop	http://water-workshop.tamu.edu/
Texas Water Centers	http://txwatercenters.tamu.edu/
Save Texas Water	http://savetexaswater.tamu.edu/
Texas Congressional District GIS	http://congdistdata.tamu.edu/
C-Map (Catastrophe Mgmt & Assessment Prgm)	http://c-map.tamu.edu/
Texas Spatial Information System	http://tsis.tamu.edu/
In development	
Caddo Lake Institute Data Server	http://twri-dev.tamu.edu/clidata/
Copano Bay Water Quality Education	http://twri-dev.tamu.edu/copanobay/
Improving Water Quality of Grazing Lands	http://twri-dev.tamu.edu/lonestar/
Watershed Planning Short Course	http://twri-dev.tamu.edu/wppshortcourse/

Newsletters

tx H20, Volume 2, number 2. May 2006
tx H20, Volume 2, number 3. Fall 2006
tx H20, Volume 3, number 1. Spring 2007

New Waves, March 2006

New Waves, April 2006
New Waves, May 2006
New Waves, June 2006
New Waves, July 2006
New Waves, August 2006
New Waves, September 2006
New Waves, October, 2006
New Waves, December 2006
New Waves, February, 2007

Rio Grande Basin Initiatives Outcomes, Volume 5, number 2. May 2006
Rio Grande Basin Initiatives Outcomes, Volume 5, number 3. August 2006
Rio Grande Basin Initiatives Outcomes, Volume 5, number 4. November 2006
Rio Grande Basin Initiatives Outcomes, Volume 6, number 1. February 2007

Project Fact Sheets

Texas Water Resources Institute Fact Sheet
Arroyo Colorado
Buck Creek Water Quality
Environmental Infrastructures
Fort Hood Range Revegetation
Lake Granbury Water Quality Education
Mills Scholars Program
New Technologies
North Texas Water Quality
Ogallala Aquifer
Pecos River
Proper Organic Management
Rio Grande Basin Initiative
Seymour Aquifer
Trinity River Restoration Initiative
USGS Graduate Research Program

Other Publications/Brochures:

Golden Algae in Texas
Drought in Texas
Demonstration of an Electrocoagulation System
The Geotube® Dewatering System
Water Issues Facing the Pecos Basin of Texas
North Concho River Pilot Brush Control Project
Range Revegetation Pilot Project for Fort Hood, Texas
HAWQS brochure

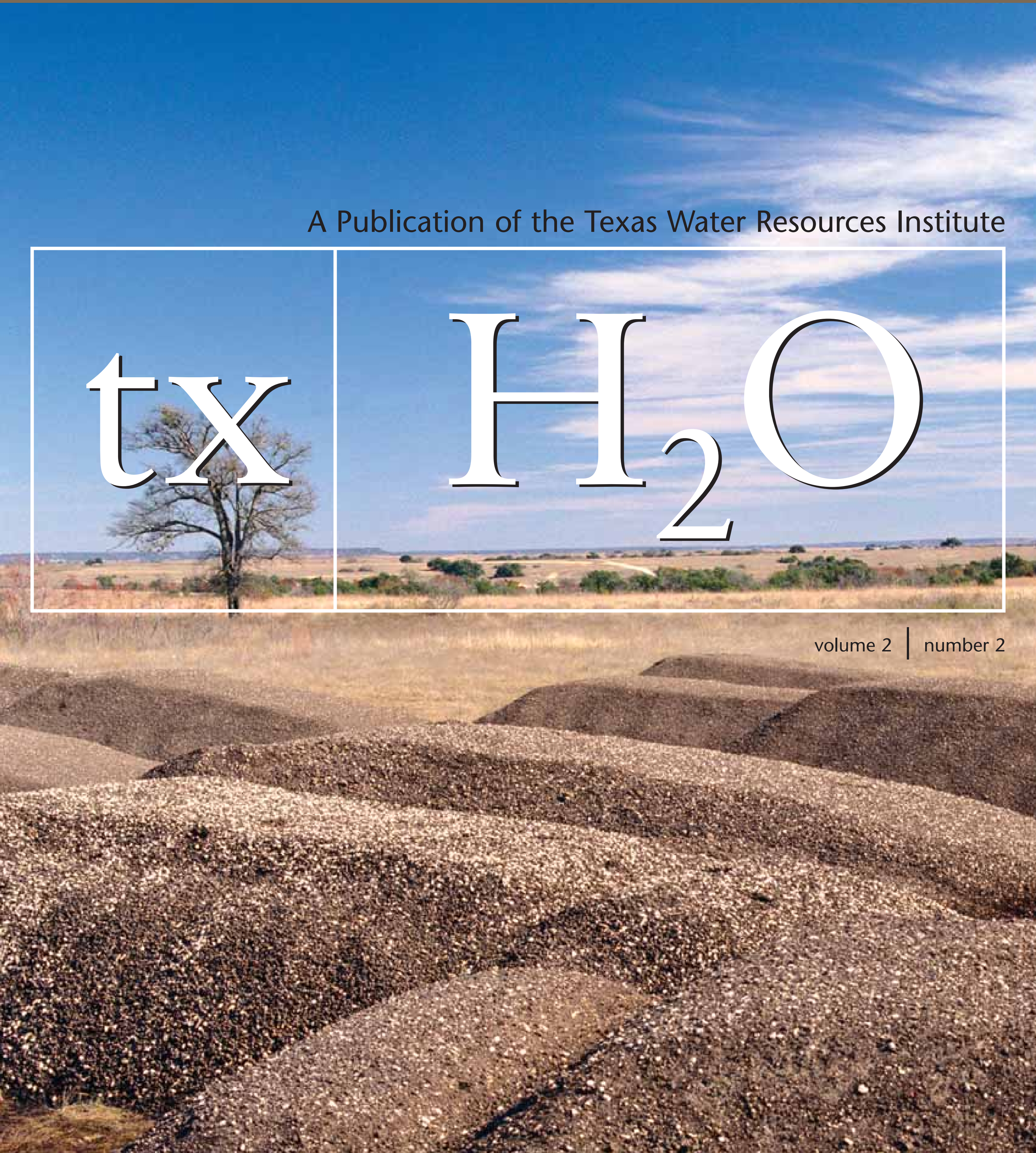
ZEROS fact sheets
Compost Sampling Guideline
Using Compost for Erosion Control and Revegetation
Using Organic Matter to Improve Sports Fields
Using Dairy Manure Compost in the Urban Environment
Using Compost to Establish New Landscapes
Economics of Using Composted Dairy Manure
Improving Compost Use through Application Methods
Using Dairy Manure Compost for Corn Production
Using Dairy Manure Compost for Forage Production
Using Dairy Manure Compost for Specialty Forages

Texas Water Resources Institute | Texas Agricultural Experiment Station | Texas Cooperative Extension

A Publication of the Texas Water Resources Institute

tx H_2O

volume 2 | number 2



In This Issue:

- PARTNERING WITH THE MILITARY • TEXAS GOLD RUSH • NATURAL PREDATOR
- A PIECE OF THE PUZZLE • EVERY DROP COUNTS • AND MORE

Working Together for Texas Water

An important component of restoring and maintaining water quality is the Total Maximum Daily Load (TMDL) Program, authorized by and created to fulfill the requirements of Section 303(d) of the federal Clean Water Act. A TMDL is the maximum amount of pollution a water body can receive and still meet water quality standards. The U.S. Environmental Protection Agency provides funds to the Texas Commission on Environmental Quality and Texas State Soil and Water Conservation Board to support the development and implementation of TMDLs.

To date, TCEQ has adopted 64 TMDLs for 35 water bodies and EPA has approved 60 of these TMDLs. Fifty TMDLs have implementation plans in place to reduce the impairment. Currently, TCEQ is working on 13 TMDL projects for water bodies in which bacterial levels are too great for safe contact recreation, such as swimming and wading.

As part of the process of identifying bacteria in water samples and its pollution source, scientists from Texas A&M University, the Agricultural Research Center at El Paso and Texas A&M University-Corpus Christi are developing and refining bacterial source tracking or BST. The scientists are developing genetic and phenotypic "fingerprint" libraries from known animal and human sources. These known fingerprints are then compared to bacteria from unknown sources in water samples. These scientists have worked to determine sources of bacterial contamination in streams in Central Texas, the San Antonio area and along the Texas Gulf Coast.

Using BST to develop TMDLs and implementation plans is part of a holistic approach to improving the quality of water in Texas. We all contribute to the problem; we must all contribute to the solution.

C. Allan Jones

tx H_2O

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Visit our Web site at
http://twri.tamu.edu
for more information.

On the cover:
Composted Dairy Manure at Fort Hood.
Photo by Jerrold Summerlin

Texas Agricultural Experiment Station
THE TEXAS A&M UNIVERSITY SYSTEM

Texas Cooperative EXTENSION
The Texas A&M University System

Texas Water Resources Institute
make every drop count

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Agriculture uses compost to restore Fort Hood's training lands

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Scientists seek to understand and control golden alga

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Foreign beetle shows promise for controlling saltcedar

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Rio Grande initiative expands efficient irrigation, water conservation

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The Leon River TMDL Process

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Story by Kathy Wythe

PARTNERING WITH THE MILITARY

Agriculture uses compost to restore Fort Hood's training lands

Texas Agricultural Experiment Station researchers have partnered with Fort Hood personnel to identify a natural "weapon" to restore the facility's tank training areas—land and soils seriously eroded, compacted and stripped of the most desirable vegetation by the repeated pounding of 70-ton tanks.

After three years of studies, researchers with the Texas Water Resources Institute (TWRI) in College Station and the Blackland Research and Extension Center (BREC) in Temple have determined that composted dairy manure can increase soil fertility and vegetation cover on some of the Fort's 200,000 acres of training areas and stabilize eroded soils without excessive nutrients entering the streams.

Dr. Bill Fox, TWRI senior research scientist, and Dr. Dennis Hoffman, BREC senior research scientist, the pilot project's co-leaders, and over 20 other scientists and land managers have established more than 500 acres of research and demonstration sites on the fort's primary tank maneuver training area.

"We needed to know that the compost applied on Fort Hood's land is not causing nutrient problems in the water and demonstrate that nutrients in compost can be turned into something positive—growing grass and reducing soil erosion," Fox said.

"We've seen nothing to indicate runoff of nutrients into streams," Hoffman said. Hoffman and his team of researchers monitor the water quality for the project.

The studies also show that research plots with certain rates of compost responded with better vegetation coverage than those without the compost, Fox said.

"After two years of comprehensive work on multiple sites, our research has demonstrated that sites receiving 15 or more cubic yards per acre of compost along with re-seeding treatments have produced significant vegetation increases," Fox said.

The compost not only adds nutrients and organic matter to the training land's soil but it also improves the soil's structure, increases its water-holding capacity and aids in erosion control. To date, the project has trucked in more than 15,000 tons of compost from the North Bosque River Watershed where too much phosphorus from dairy manure runoff is impairing that watershed.

Tanks within two armored divisions at Fort Hood have left some of the training land eroded, compacted and stripped of the most desirable vegetation. Restoration of these lands provides maintenance of quality training lands for military personnel and maintenance and improvement of the natural resources.

"The unique character of this project," said Fox, "is that two major environmental problems are being addressed at the same time. Excessive nutrients in one watershed are being used to fertilize nutrient-starved soil in another. Two 'bads' can make a 'good.'"

Dr. Scott Keating, a TWRI associate research scientist, successfully developed a unique, heavy-duty compost spreader for the project that can handle the rough terrain of the training lands. The stainless steel spreader on a 40-ton axle has an increased capacity and higher discharge rate than other spreaders, Keating said.

"With the gullies caused by erosion and the tracks of heavy military equipment, a standard spreader would not do the job," he said. Keating said there is interest from as far away as Canada about the spreader.

The group compared the percentage of change in ground cover, bare ground and litter (leaves and dead biomass on the ground) over time: 1) at the start of the project, 2) one year after compost was added, and 3) 18 months after compost treatment, which was also after one year of training on the site.

The amount of ground with no vegetation decreased from 50 percent to 32 percent one year after compost treatment and decreased even further to 24 percent 18 months after treatment. Fox attributed this decrease to the litter that remained on the ground after training maneuvers.

The research shows that it takes 12 to 18 months after compost and seed application to achieve significant changes in plant basal cover, Fox said. Preliminary analysis indicates that the treated sites are also more resilient after training exercises than before compost was added.

Along with studying the use of composted dairy manure on the training areas, researchers from the Experiment Station, Fort Hood's Integrated Training Area Management (ITAM), Fort Hood's Directorate of Public Works and U.S. Department of Agriculture-Natural Resources Conservation Service (NRCS) have studied the use of other conservation practices to heal the landscape for 12 years.

Hoffman and his team, working with Jerry Paruzinski of Fort Hood ITAM, and Rob Ziehr from NRCS have installed best management practices (BMPs) such as gully plugs, contour ripping, and sediment retention ponds. Results of water quality studies show that these BMPs play a significant role in reducing sediment loss from training areas into area streams and water bodies.

Their research shows that the ITAM/NRCS conservation practices have reduced stormwater runoff volume and intensity, reduced sediment loss from training areas by as much as 90 percent and improved the training areas' sustainability, Hoffman said.

The compost project, federally funded through the NRCS, is an example of the military's foresight and interest in the environment, saiD U.S. Rep. Chet Edwards, who has supported the program since 2003.

photo by Jerrold Summerlin

"This funding will help Fort Hood avoid environmental problems that could impose restrictions on training—training that is important to saving lives in theater," said Edwards. "Through this innovative program, Fort Hood is once again demonstrating its commitment to environmental stewardship, and by doing so, to the training that keeps our soldiers alive."

U. S. Rep. John Carter agreed. "The Fort Hood Revegetation Project is a necessary tool in enhancing the vegetative growth of the land while improving the training facilities at Fort Hood," Carter said. "This project is another example of the military working to protect the ecosystem surrounding its training areas."

Now the project is moving into its next phase—large-scale application and refining the specific recommendations of using the compost and grasses—and is bringing in two prominent researchers from Texas A&M to help with the project.

"Now that we know compost will not create a water concern, we are integrating this practice into our Critical Area Treatment (CAT) program to sustain training and our natural resources," said Paruzinski of Fort Hood ITAM.

"We will focus on the development of specific strategies for using the compost—how much and when we should use it and with what combination of other conservation practices currently used on the training areas," Fox said.

Dr. Fred Smeins, professor in the Rangeland Ecology and Management Department, will focus on developing better approaches to restoring vegetation on the training lands. Smeins will use a variety of plant materials along with the compost to see which species provide rapid cover for the soil in the training areas.

Dr. Tom Hallmark, professor in the Department of Soil and Crop Sciences, will study the compaction of the soil. "We'll be looking at what changes the plants are making in the soil," Hallmark said. "Some species may be better at relieving compaction than others."

Hoffman, working with others at BREC, NRCS and ITAM, will evaluate the effectiveness of vegetated buffer strips using compost to establish the vegetation along with contour ripping practices currently used.

Fox said the project will "ultimately end up with an integrated maintenance program that will allow Fort Hood to reduce erosion and maintain high quality training grounds."

Steve Burrow, chief of environmental programs, Fort Hood's Directorate of Public Works, agreed, saying the project is vital in providing long-term sustainable training capability for Fort Hood soldiers.

"We can now take what we have learned from this re-vegetation project and implement it into our land management strategy to maximize our resources, both natural resources and financial," Burrow said. "This allows Fort Hood to remain the Army's premier training installation."

"Our CAT program will integrate compost, seeding, ripping, land shaping, gully plugs, tank trail repairs, and rest to rehabilitate the damaged landscape and enhance training capabilities on Fort Hood," Paruzinski said. "Incorporating compost into CAT will increase our land sustainment and enabling training."

For more information on the project, visit: http://forthoodreveg.tamu.edu.

The compost spreader was custom designed and built by Dr. Scott Keating, a TWRI associate research scientist, to handle the rough terrain of Fort Hood's training lands.

Top photo: The heavy artillery traffic from Fort Hood's training leaves ruts and gullies on the land and heavily damages the soil and vegetation.

Bottom photo: A demonstration site treated with composted dairy manure to add organic matter and nutrients and then re-seeded with native grasses flourishes on a portion of Fort Hood's primary training areas.

Project wins environment award

The Fort Hood Range Revegetation Pilot Project, a joint project of the Texas Water Resources Institute and the Blackland Research and Extension Center, won the 2006 Texas Environmental Excellence Award for Agriculture. The award, sponsored by the Texas Commission on Environmental Quality and Gov. Rick Perry, was presented to the project staff at the agency's banquet in May.

The Texas Legislature created the awards in 1993 and TCEQ presents them to outstanding, innovative environmental programs in 10 diverse categories across the public and private sectors. The Governor's Blue Ribbon Committee, a group of leaders in public and private industry with expertise in environmental policy and practices, judge the applications.

Texas Agricultural Experiment Station Director and Vice Chancellor for Agriculture and Life Sciences Elsa Murano said, "I am so proud of the efforts of the Texas Water Resources Institute with in the Texas A&M Agriculture family for leading the way and being en example to all of us and our great state.

"I am proud of the creativity and drive it takes to develop and carry out a program such as this, which ultimately helps us preserve our precious natural resources for the future."

The Fort Hood project, federally funded through the U. S. Department of Agriculture-Natural Resources Conservation Service, was initiated in 2003 to assist Fort Hood in dealing with soil erosion and land degradation on the fort's training areas.

"As Texans, we understand and appreciate the importance of our state's natural resources," said Kathleen Hartnett White, TCEQ chairman. "These awards recognize the initiative and innovation of Texans who go above and beyond the call of duty to protect and enhance those resources."

U.S. Rep. Chet Edwards, who has supported the program with $2 million in federal funds since 2003, said of the award: "It is a privilege to be part of a program that is a model of collaboration and cooperation that is making a difference for our soldiers and our environment."

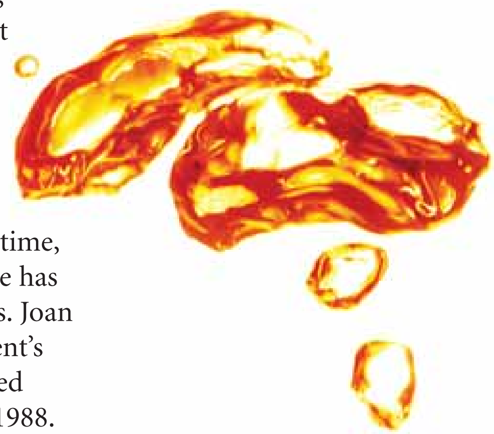
U.S. Rep. John Carter gave his congratulations for the award. "I applaud all of the partners in this project and am proud to support practices that will benefit not only Fort Hood's training capabilities, but also the environment," he said.

Story by Kathy Wythe

Texas Gold Rush

Scientists seek to understand and control golden alga

A free-floating microscopic alga is increasingly appearing in some Texas lakes and rivers, releasing its deadly toxins and wiping out millions of fish. Texas scientists have taken on the assignment of understanding the culprit and developing strategies for its control.



Golden alga, or *Prymnesium parvum,* was first identified in the Pecos River in 1985. Since that time, the alga with its signature golden-tea appearance has surfaced in most of the state's major river basins. Joan Glass, of the Texas Parks and Wildlife Department's (TPWD) Spills and Kills Team, said she witnessed 187 miles of dead fish along the Pecos River in 1988.

Although it can be present in waters without being harmful, the alga has caused fish kills in five of Texas' 25 major river systems. According to TPWD's statistics, the toxins from the organism have killed more than 25 million fish worth $10 million in the Canadian, Red, Brazos, Colorado and Rio Grande river basins.

In 2001, toxic blooms—explosive increases in the alga's population—killed more than 5 million fish at the Dundee State Fish Hatchery near Wichita Falls, with an entire year's production of striped bass lost. This fish kill and the others have caused major financial losses to Texas' fishing and recreational industries.

Golden alga is an enigma. Until recent research, little was known about the biology of the alga in natural inland waters, its toxins, the environmental requirements for its growth or the water quality conditions in the affected freshwaters before a toxic event occurs.

The alga is harmful when it out-competes other aquatic algae and blooms. It then begins to release toxins that affect gill-breathing animals, such as fish and clams. The toxins prevent exposed cells (cells without protective layers such as on the surface of gills and skin) from keeping out excess water and waterborne chemicals. In fish, this process leads to bleeding and lesions on the gills.

More than 13 entities are involved in golden alga research or monitoring in Texas. TPWD documents the status of golden alga in Texas waters on its Web site along with maintaining numerous informational Web pages about the alga and the current research.

Dr. David Sager, TPWD's Ecosystem/Habitat Assessment branch chief, said the department is conducting a statewide survey to determine the distribution of the alga. "The kills," he said, "are in central and western Texas, which is thought to be because of the higher salinity and pH of the water in these areas."

Sager said TPWD scientists have learned how to control golden alga in hatcheries and ponds using ammonium sulfate and copper compounds but "those controls don't work well in larger reservoirs."

Dr. Daniel Roelke of Texas A&M University, Dr. Bryan Brooks of Baylor University, Dr. James Grover of the University of Texas-Arlington and Richard Kiesling of the U.S. Geological Survey (USGS) are collaborating on projects to understand the environmental conditions that allow the organism to grow and cause fish kills. Once these conditions are understood, the researchers hope to develop a model to predict the environments that allow the alga to bloom and produce toxins and to determine cost-effective management options to prevent or disrupt the blooms.

Roelke, an associate professor in TAMU's Department of Wildlife and Fisheries Sciences, said the team used a three-pronged approach to study golden alga and its environment in a TPWD project completed recently. The research team conducted in-field experiments at Lake Possum Kingdom, performed laboratory experiments comparing lab and in-field samples and identified a biosensor to measure the alga's toxicity.

On the lake, the team floated 24 plastic enclosures or corrals filled with lake water, adding excessive nutrients of phosphorus, nitrogen and trace minerals; barley straw extract; enhanced populations of golden alga; and different combinations of the three additions.

The first finding, Roelke said, was that the barley straw extract, thought to be a natural algaecide based on research in other parts of the world, had no effect on limiting the alga's growth. "We hoped using the barley straw extract as a management tool would be the silver bullet we were looking for, but it didn't affect it at all," Roelke said.

"The second finding, which surprised everyone, was with the additional nutrients the exact opposite happened," Roelke said. When they spiked the enclosures with nutrients in excess of naturally occurring amounts in the lake, the alga grew but its toxicity was reduced, and, in many cases, was non-toxic.

Toxic golden alga, although not harmful to humans or most animals, has killed 25 million fish in Texas since 1985.
Photo courtesy of Texas Parks and Wildlife Department.

Working with the organisms in the laboratory, Grover, an associate professor in UTA's Department of Biology, found that the optimal growth of the alga occurred in higher temperatures and higher levels of salinity and light than is typical in Possum Kingdom and other Texas waters. The alga's toxicity, however, decreased under these optimal growing conditions but increased under the growing conditions found in Texas waters, Grover said.

"Winter conditions in Texas turned out to be conditions that, unfortunately, tend to promote toxicity," Grover said.

"It appears the organism is becoming more toxic under conditions that are not optimal for its growth, which implies the organism is getting stressed and releasing toxins," Brooks said.

Finally, in the project's third part, Brooks, director of the Ecotoxicology Research Laboratory at Baylor, performed bioassays with samples from the field and lab to identify toxic conditions caused by *P. parvum*. He discovered that the team could use fathead minnows as biosensors or the "canary in the coalmine" to alert researchers when the water conditions were toxic, Brooks said.

Texas Parks and Wildlife has funded the TAMU, Baylor, UTA, USGS team to continue its research at Lake Whitney where TPWD's scientists have been collecting samples for three years. Roelke said this project will look at "what other factors might cause toxic blooms and what factors might cause blooms to go away." The project will compare the amount of grazers, pathogens and salt content in Lake Whitney to Lake Waco where golden alga does not bloom to determine the roles these elements have in toxic bloom occurrences.

The research team will build a numerical model designed to measure many parameters and predict which environmental conditions allow the golden alga to grow and test potential management strategies, Roelke said.

The team is also collaborating on a federally funded research project at Lake Granbury, managed by the Texas Water Resources Institute. The lake has toxic golden algal blooms that are killing fish and elevated amounts of *E. coli* bacteria in some of the lake's coves. The team will investigate the distribution and dynamics of the alga in relation to *E. coli* as well as the linkages between water conditions, nutrients, dissolved organic matter and blooms.

Roelke and Dr. Steve Davis, assistant professor of wildlife and fisheries sciences at A&M, are producing a high-resolution spatial map of the lake to see if the blooms are occurring in the same places as *E. coli.*

Part of the golden alga research on Possum Kingdom Lake involved adding barley straw extract; excessive amounts of phosphorus, nitrogen and trace minerals; and enhanced populations of the alga to large volume enclosures floating in the lake.

"If we get strong correlative data of *P. parvum*, *E. coli* and dissolved organic matter, we can infer the cause," Roelke said.

In another project evaluating treatment options, the Brazos River Authority (BRA) began applying bales of wheat straw in the fall of 2005 to six coves where blooms occur in Lake Granbury and six coves in Possum Kingdom Lake in hopes of developing a cost-effective means to control or prevent the toxic blooms.

The BRA project, funded by the U.S. Environmental Protection Agency, is based on an English study of applying straw to areas where the alga have been in the past. The straw is submerged just below the surface of the water. The use of straw does not kill existing cells but prevents the growth of new algal cells.

Tiffany Morgan, project manager for the BRA study, said the river authority will continue monitoring the coves until August 2006, then start analyzing the data with a final report on the results by January 2007.

Sager said TPWD has funded projects investigating other aspects of the alga.

John La Claire of the University of Texas at Austin is developing a partial genome analysis of golden alga and is getting basic information needed for scientists to develop genetic probes that will be used to tell the amount of golden alga in water samples.

Dr. Chi-Ok Oh of the Department of Recreation, Park and Tourism Sciences and Dr. Robert Ditton of the Department of Wildlife and Fisheries Sciences of at Texas A&M University, studied the economic impacts of golden alga on recreational fishing at Possum Kingdom Lake. They estimated the total economic impact was a loss of $2.8 million and a 57 percent reduction in visitors from the 2001 fish kill.

Sager said TPWD is continuing its monitoring of water samples on Lake Whitney and has contracted with Dr. Ayal Anis of Texas A&M University-Galveston's Department of Oceanography to study water currents in Lake Whitney and how the currents spread the alga throughout the reservoir.

The ultimate mission for everyone is finding a management strategy to control the alga and stop the fish kills.

"It could take us years to find a good management strategy," Sager said. "But we are doing it as quickly as we can."

Texas A&M University graduate student Reagan Errera and undergraduate student Heather Thompson prepare to add elements to the large volume enclosures in Possum Kingdom Lake.

Story by Kathy Wythe

Natural Predator

Foreign beetle shows promise for controlling saltcedar

In the northern part of the Texas Panhandle and along the West Texas banks of the Colorado and Pecos rivers, Texas scientists are successfully introducing a foreign beetle to help control an invasive and exotic water-thirsty plant.

Saltcedar, or *Tamarix*, was introduced to the western United States in the 1800s from central Asia as an ornamental tree and planted along riverbanks for erosion control. Without a natural predator, the tree soon out-competed native plants and has now infested an estimated 500,000 acres of Texas streams and riverbanks.

Saltcedar is a big water user, withdrawing 3 to 4 feet of water per year depending on plant density, tree age and depth-to-water table. It also increases soil salinity and wildfire risk and crowds out native vegetation used by wildlife.

The Texas Riparian Invasive Plants Task Force has identified saltcedar among the "worst of the worst" invasive species in Texas.

Dr. Allan McGinty, professor and Extension range specialist at The Texas A&M University System Agricultural Research and Extension Center at San Angelo, initially organized the Upper Colorado River Saltcedar Control Task Force in February 2001 to manage the use of chemical herbicides and more recently the use of biological control.

Although researchers are using aerial sprays with herbicides as well as controlled burning to reduce saltcedar, its natural enemy, the saltcedar leaf beetle, or *Diorhabda elongata,* offers a low-cost, sustainable alternative. If established over time, a sufficient population of saltcedar beetles has the potential to shrink the saltcedar population, producing significant water savings, researchers said.

Dr. Jack DeLoach, an entomologist with the U.S. Department of Agriculture's Agricultural Research Service in Temple, has researched biological control of saltcedar for 20 years and has determined the saltcedar beetle feeds only on saltcedar and will not harm native plants or trees when introduced in the western United States.

The Saltcedar Biological Control Consortium, a group of federal and state agencies, private interests and universities, was formed by DeLoach in November 1998 to coordinate and promote the biological control program in the United States. He organized the Texas, New Mexico, Mexico Section of the consortium in March 2005 to coordinate research efforts in these areas. The Agricultural Research Service is the lead agency responsible for identifying and testing insects approved for biological control of saltcedar.

Consortium scientists are conducting laboratory and field research, which includes beetle taxonomy and behavior, host range, reproduction and overwintering success, climate-matching, release methods, saltcedar growth modeling and beetle dispersal. They are also measuring the impact of beetle feeding on plant survival and conducting remote sensing and vegetation and bird surveys.

The saltcedar beetle feeds on the invasive, water-thirsty saltcedar tree in the western United States. Researchers in Texas have identified a biotype from Greece that survives in west and northern Texas. Photos courtesy of USDA-Agricultural Research Service.

DeLoach, Dr. Jack Moran, ARS entomologist, and Dr. Allen Knutson, professor and Extension entomologist at the Texas Agricultural Research and Extension Center at Dallas, have successfully established field nursery sites for rearing saltcedar beetles from Greece in the Upper Colorado River watershed, near Big Spring, which has more than 22,000 acres of saltcedar.

After saltcedar beetles from China and Kazakhstan failed to survive in Texas, the research group imported a specific ecotype from Crete, Greece, which has overwintered successfully for three years. "It was a challenge to find a strain adapted to Texas," Knutson said.

In 2004, the Crete beetle population was established in the field at Big Spring in cooperation with Okla Thornton, wildlife biologist for the Colorado River Municipal Water District. The beetles defoliated three trees.

"In 2005, this population increased dramatically and defoliated about 200 trees and dispersed across about two acres," Knutson said, whose research is funded in part by a Texas Water Resources Institute's Soil and Water Research Grant. A total of 5,200 beetles were released at 18 new sites in 2005.

Dr. Joaquin Sanabria, assistant research scientist at Blackland Research and Extension Center in Temple, is modeling the dispersal of the saltcedar beetle and the defoliation it causes at Big Spring as part of a Texas State Soil and Water Conservation Board (TSSWCB) project.

"At this time we are using two types of models on the Big Spring data, diffusion (physically based) and statistical models," Sanabria said. The models will help determine how far and how fast the beetle moves and what factors affect the dispersal and the severity of the salt cedar defoliation by the beetle, he said.

Through the Big Spring project, Knutson and DeLoach said they have developed several recommendations for releasing and establishing beetles at new locations. The best way to establish nursery sites, Knutson said, is to cut the saltcedar down to 2 to 3 feet above the ground during the winter, so beetles can feed on fresh new shoots the following spring. In addition, beetles should be released at new sites as early in the spring as possible.

DeLoach said through the scientific studies they hope they can get a higher percentage of beetles established at future sites.

Jeremy Hudgeons, Knutson's graduate student in Texas A&M's Department of Entomology, has discovered that repeated defoliation by the beetles may cause the tree to use up its stored energy to grow new leaves, causing a "slow starvation" of the tree and eventually death.

Knutson said the project is now moving from the research stage to the implementation stage. During the spring and summer of 2006, the team will work with Extension agents to distribute the beetles to selected sites in six counties along the Upper Colorado River. "The goal is to establish a nursery site in each county that would serve as a source of beetles for distribution to ranchers and land owners within that county," he said. "Currently, beetles are in very short supply so we need to increase their numbers for re-distribution to new sites."

"If the beetles overwinter well, they could disperse naturally and defoliate over 100 to 200 acres at Big Spring this summer," DeLoach predicted.

Knutson said another objective is to integrate biological control with the herbicide spray programs for saltcedar control on the Pecos and Colorado rivers. Through the Pecos River Ecosystem Project, approximately 75 percent of saltcedar on the river in Texas has been treated with herbicides, according to Charles Hart, professor and Extension range

Researchers hope these saltcedar trees, defoliated by a saltcedar beetle, after repeated defoliation, will die. Saltcedar trees, introduced in the United States in the 1800s, take water away from native plants, deposit salt in the soil and increases the risk of wildfires.

specialist in Fort Stockton.

Knutson and DeLoach are working with Dr. Mark Muegge, associate professor and Extension entomologist at the Texas A&M Extension Center in Fort Stockton, to establish beetles along the Pecos River. "We have two sites on the Pecos River where we will evaluate the use of beetles for controlling re-growth from trees not entirely killed by herbicide and for suppressing saltcedar in areas where herbicide could not be used," Knutson said. "There is concern that these pockets of surviving trees will serve as sources of seeds that will be carried downriver and re-infest areas where saltcedar has been killed by herbicide."

Farther north at Lake Meredith on the Canadian River, researchers have successfully established saltcedar beetles imported from Posidi in northern Greece, Dr. Jerry Michels with The Texas A&M University System Agricultural Research and Extension Center at Amarillo, said.

Michels, professor of entomology, and Vanessa Carney, research associate, are working with the U. S. Department of Interior's Bureau of Reclamation, National Parks Service and the Canadian River Municipal Water Authority to establish the saltcedar beetle at Lake Meredith, which has approximately 6,000 acres of saltcedar.

In the spring of 2004, these researchers introduced about 2,000 beetle eggs into contained tents. The eggs produced about 150 adults in the spring. This initial population grew to over 1,500 by August 2004. They opened the tents in the fall to allow for natural establishment of the population.

"By the end of August 2005, we had probably thousands of beetles successfully established at significant distances from the initial release site," Michels said, including some at one kilometer from the original release site. The beetles seem to be following the saltcedar infestations to the northeast, along the course of the Canadian River, rather than concentrating in specific areas, he said.

Michels and his team are currently monitoring the beetles as they break dormancy and begin to feed again on saltcedar. "We are hoping that this summer will be a really good year and then we will move them around to different areas," Michels said, whose project was partially funded by a TWRI grant in 2004 and 2005.

"If the beetles increase at Lake Meredith as they have in other areas of the United States, we can expect significant defoliation to begin in one to three years," Michels said, adding that these estimates are based on good climate conditions for the beetles.

The Lake Meredith team is also monitoring 40 sentinel saltcedar trees, looking at their growth, seed production, soil type, percent ground cover, vegetative abundance and types of woody plants around these saltcedar. The scientists will use this data as a baseline in a comparative study to assess both the saltcedar's impact and extent in the area, along with the efficacy of the biocontrol agents in the future.

Michels said that saltcedar changes the soil structure, adding more salinity. When saltcedar is controlled, "we hope we get more favorable vegetation," he said.

DeLoach said he and Tyrus Fain of the Rio Grande Institute in Marathon and Patrick Moran of ARS in Weslaco are hoping to work with Mexico to control saltcedar along the Rio Grande, which has the highest concentration of saltcedar in Texas. DeLoach and Moran are currently doing open-field research at a release site near Kingsville on a related tree, athel (also an exotic *Tamarix*), grown in Mexico as an ornamental tree and a windbreak, to determine the amount of damage the saltcedar beetle may have on it.

The predicted water savings from controlling saltcedar could be enormous. Texas A&M University studies have shown that along the upper portion of the Pecos River, where there are an estimated 14,000 acres of saltcedar, an acre of dense saltcedar consumes an estimated 1 million gallons or about 3 to 4 feet of water per acre each year. With more than 22,000 acres of saltcedar in the Colorado River basin, the Colorado River Municipal Water District estimates that saltcedar consumes enough water in the district to meet the annual needs of the city of Odessa.

Complete eradication of the saltcedar is not the goal; reaching a balance is.

"We want the beetle and the plants to stay at low numbers," DeLoach said. Once populations of the beetles are established, they are self-sustaining and no additional releases, and hopefully no additional controls, will be necessary.

Getting the saltcedar back into the right balance is going to take time.

"We estimate that four to five years of repeated defoliation by beetles will be necessary to kill small saltcedar trees," Knutson said, "but, in the meantime, the saltcedar is not using as much water because it doesn't have the full canopy of leaves and other plants begin to grow in its place."

DeLoach agreed, saying that even without the death of the tree, the saltcedar uses only 5 percent to 10 percent of the water it previously used before beetle defoliation.

DeLoach predicted that saltcedar could be under control in Texas in five years "if everything goes well," referring to a site in Nevada where 50,000 to 60,000 acres are successfully in control five years after the first release. "All of this (defoliation after initial introduction) is at no cost and no damage to non-targeted plants," he said. "We think long-term, it's the way to go."

"No single person can do this research and implement biological control given the size of the saltcedar problem in Texas," Knutson said. "Fortunately we have a lot of people from many different agencies and organizations working together to accomplish this goal."

For more information on the TWRI-sponsored research, visit http://twri.tamu.edu/soil_water_grants/2005. A *Saltcedar Control* brochure is available at http://tcebookstore.org/tmppdfs/9714005-L5444.pdf.

An overview of the entire program is available as *Saltcedar Biological Control Consortium: Texas, New Mexico, Mexico Section, First (Organizational) Meeting: Minutes, Reviews of Research, Resource Guide* at http://bc4weeds.tamu.edu/weeds/rangeland/saltcedar.html#literature.

Saltcedar trees have been defoliated by its natural predator, saltcedar beetle from Crete, Greece, in fields near Big Spring.

Story by Danielle Supercinski

Every Drop Counts

Rio Grande initiative expands efficient irrigation, water conservation

Since its inception in 2001, the Rio Grande Basin Initiative (RGBI) has achieved significant water savings and accomplishments. A joint effort of Texas A&M Agriculture and New Mexico State University College of Agriculture and Home Economics, the initiative's nine research and education tasks address efficient irrigation and water conservation.

"The Rio Grande Basin Initiative has been very valuable because it has provided an opportunity to bring together all the things we know about water conservation into one package through research and development of new water practices," said B.L. Harris, RGBI project director and associate director of the Texas Water Resources Institute. "This research is coupled with an effective educational program to demonstrate and train people to implement the best and most appropriate practices to conserve water."

Roughly 160 Texas and New Mexico RGBI participants collaborating with local irrigation districts, agricultural producers, homeowners, 19 external agencies and other universities are dedicated to expanding efficient use of available water resources and creating new water supplies for the Rio Grande Basin.

Working in cooperation with irrigation districts, economists and engineers have developed evaluation tools to guide irrigation districts in water-use efficiency infrastructure and cost-of-saving-water analysis. The Rio Grande irrigation district economics tool (RGIDECON©), the rapid assessment tool (RAT) and geographic information systems (GIS) are three of the main tools developed during the RGBI's 5-year history.

To assist producers with irrigation scheduling, researchers have established on-farm monitoring of crop water use. They have taken extensive soil samples to determine nitrogen content with soil depth, rooting depth and other soil properties necessary for adapting the Crop Production and Management Model (CroPMan) to the area. CroPMan also allows producers to assess economic trade-offs of allocating limited water resources between various crops at varying crop growth stages.

Water is the primary factor limiting the production of many crops in the Lower Rio Grande Valley of Texas, and researchers have found using improved furrow irrigation techniques and scheduling for sugarcane production can save 10 percent to 15 percent of irrigation water or between 20,000 and 30,000 acre-feet.

RBGI researchers created the Precision Irrigators Network (PIN), which incorporates growers into the research process by demonstrating water saving, efficient irrigation techniques and installing soil moisture monitoring sensors. Researchers estimate that on a "typical" 100-acre field, water savings using PIN can amount to 6 to 8 inches of water per acre per year, or 163,000 to 217,000 gallons per year. Based on 620,000 acres of irrigated land in the Rio Grande region alone, PIN can save 311,000 to 413,000 acre-feet of water per year.

The use of flexible, plastic polypipe and water-metering devices to replace inefficient and leaky ditches and siphon tubes has steadily increased in the Lower Rio Grande Valley and in nearby Mexico. Three demonstrations conducted in Tamaulipas, Mexico showed that irrigation could be reduced by 30 percent by using polypipe.

Extension specialists have conducted in-home water conservation demonstrations in 45 households to determine the amount of water a typical family of four uses. Extension specialists provided them with in-home water audits and educational materials as well as lists of recommended behaviors and fixture changes. In some cases, they installed water-conserving fixtures. Preliminary results show that educational interventions can reduce water use by 25 percent.

RGBI funding also focuses on coordinating basinwide activities related to the Pecos River, a major tributary of the Rio Grande. The project is documenting how much water can be saved by large-scale saltcedar management programs. To date, scientists have treated more than 13,000 acres of saltcedar within the basin with herbicides. Current research indicates that potential water salvaged from saltcedar is at least 2 feet per acre per year. Assuming this minimum amount of salvage, more than 26,000 acre-feet of water has been salvaged from these saltcedar control programs.

Because increased use of soil testing as a standard best management practice will improve overall production economics and provide added protection for critical and limited water resources, Extension specialists conducted a four-county soil-testing program. Projected fertilizer savings based on soil tests were an estimated 1.7 million pounds of nitrogen and 2.3 million pounds of phosphorus. These reductions in fertilizer application represent a reduced threat for nutrient contamination of surface and groundwater resources. The total economic impact from the project was estimated at $1.0 million based on average per-pound costs for nitrogen and phosphorus.

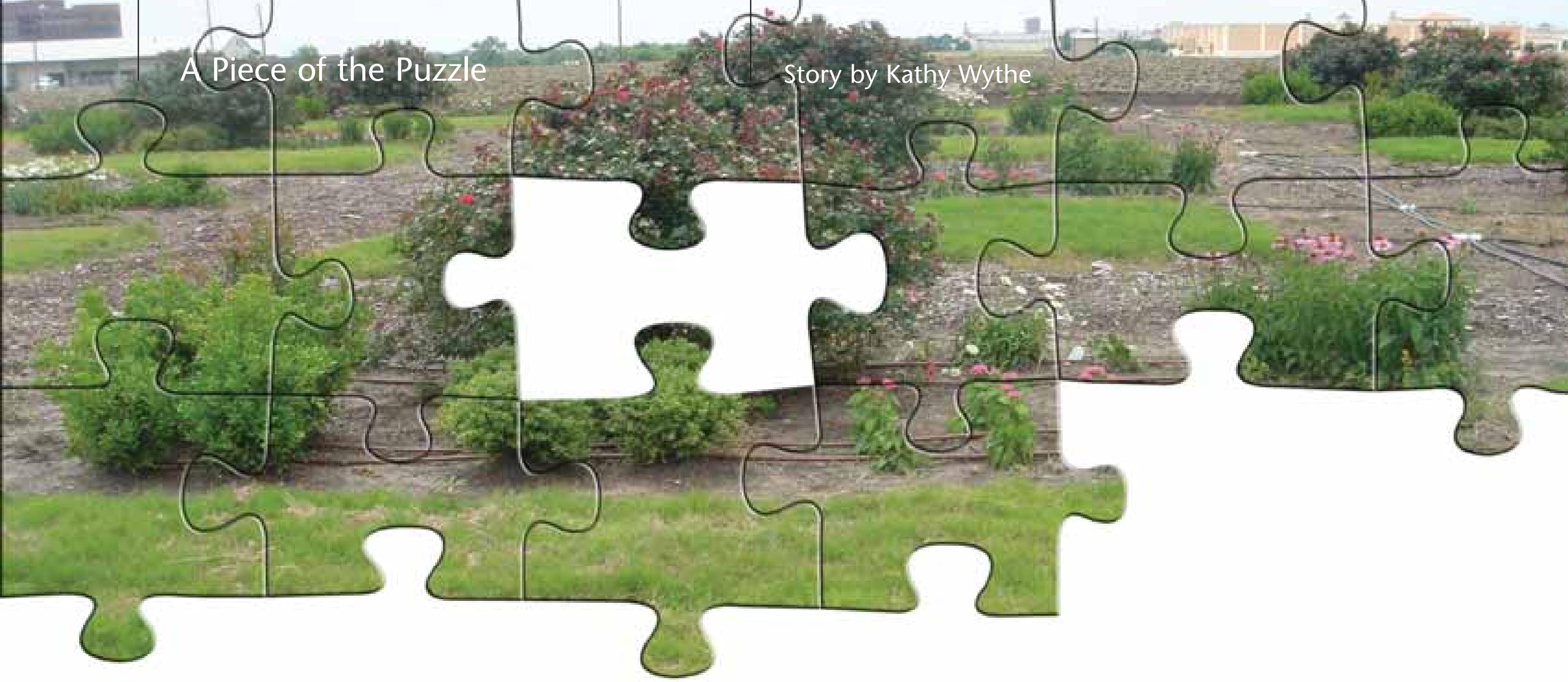
Researchers in El Paso used genetic typing to determine that the levels of certain bacteria in river water are much higher during the non-irrigation season than in the irrigation season. Researchers will use these data to assess the human and animal health risks associated with using winter return flows and will help develop strategies that can safely extend municipal and agricultural water supplies.

Since Texas presently reclaims about 5 percent of its wastewater with the potential to reclaim greater quantities, further research is being focused on salty groundwater, graywater and concentrate as alternative water sources for irrigation in rural and urban areas. The research strategy is to remove salts prior to irrigation to levels acceptable for salt-tolerant crops. RGBI researchers have evaluated more than 70 different landscape plant species for salt-tolerance. In El Paso, the urban landscape area irrigated with moderately salty reclaimed water has increased from 150 acres to 325 acres during the past seven years.

"One of the keys to a project of this type is widespread and collective collaboration," Harris said. "Water management districts, ag producers, municipal water users and others involved on both sides of the border working collaboratively is an absolute must."

The RGBI is federally funded, administered by the Texas Water Resources Institute, in collaboration with New Mexico State University, and funded through the U.S. Department of Agriculture Cooperative State Research, Education, and Extension Service.

For more detailed information regarding the RGBI and its progress and accomplishments, go to http://riogrande.tamu.edu.



Story by Kathy Wythe

A Piece of the Puzzle

Transporting dairy compost helps in water quality solutions

Transporting dairy manure from Central Texas dairy farms and turning it into marketable, quality compost is a "piece of the puzzle" in finding solutions to improve water quality in the North Bosque River and Leon River watersheds.

Approximately 148 dairies with more than 98,000 cows operate in these two watersheds. Studies have shown that excess manure applications to land near dairies contribute to impaired water quality in the basin. High phosphorus levels in water can cause excessive growth of algae and other aquatic plants, which then rob the water of oxygen, leading to fish kills.

For the past three and a half years, Texas Water Resources Institute (TWRI), Texas Agricultural Experiment Station and Texas Cooperative Extension staff have helped composters produce higher quality composted dairy manure and market it to public entities. These researchers also educated the public in various counties on the many uses for composted dairy manure and demonstrated applications within and outside the watershed.

These efforts significantly increased the quality, understanding, use and marketing of dairy manure compost, according to Cecilia Wagner, project manager for the TWRI/Experiment Station/Extension Dairy Compost Utilization project, which ended in April.

The marketing project is part of a larger plan developed by the Texas Commission on Environmental Quality (TCEQ) and the Texas State Soil and Water Conservation Board (TSSWCB) to produce composted dairy manure to encourage the transport of dairy manure out of the watersheds.

Since 2000, the state board has provided incentive payments to commercial haulers to transport approximately 960,000 tons of raw manure from dairies to compost facilities, according to this project's reports. About 450,000 cubic yards of compost from the watersheds were sold from that manure, with 71 percent exported out of the Bosque River watershed.

In a complementary program, TCEQ provided incentive payments to public entities to purchase dairy compost. In 2004, the incentive rebate payment was expanded to private agricultural producers and compost distributors through the Upper Leon Soil and Water Conservation District Compost Rebate Program. The rebate, offered through the Upper Leon Conservation District, led to the use and distribution of more than 3,000 cubic yards of composted dairy manure, Extension program specialist Wagner said.

Both programs were funded through a Clean Water Act Section 319(h) Grant from the U.S. Environmental Protection Agency and are scheduled to end August 2006 or when the incentive funds are depleted.

TCEQ provided funds to TWRI and Extension for the education and marketing component of the plan.

Extension worked with compost producers in the area to produce uniformly high quality compost. Because of the project, the majority of these dairy compost producers have joined the U.S. Composting Council's Seal of Testing Assurance Program.

"Dairy compost producers' knowledge of sound production practices, record keeping and testing has vastly increased," said Dr. Mark McFarland, Department of Soil and Crop Sciences professor and Extension soil fertility specialist. "The quality and consistency of composted material improved substantially over the life of the project."

Through the application demonstrations, fact sheets, news articles and workshops, compost customers learned about dairy compost. In addition, the project contracted with Ron Alexander and Associates to help conduct marketing activities.

Extension conducted more than 15 dairy compost use demonstrations as part of the project.

In one demonstration, the Santo Independent School District in Palo Pinto County, working with Scott Mauney, Extension agent, and Dr. Jim McAfee, Extension turfgrass specialist, used dairy compost as part of a sports management plan to successfully

Dr. Cynthia McKenney of the Texas Agricultural Research and Extension Center at Dallas discusses the use of dairy manure compost to establish newly constructed landscapes at the center's annual turf and ornamental field day.

restore the district's football field. The density and amount of grass across the field increased and grass texture was softer than in years before.

Extension conducted other demonstrations in Comanche, Erath, Stephens, Coryell, McLennan, Somervell and Tarrant counties.

Practice verification studies refined recommended use rates of compost on common turfgrass varieties, landscapes, forages, and row crops. Additionally, Extension specialists evaluated soil and water quality following various dairy compost erosion control applications to ensure environmental sustainability.

In some of the verification studies, researchers evaluated non-traditional uses for dairy compost.

Researchers at the Texas Agricultural Research and Extension Center at Dallas evaluated using dairy compost to establish landscapes at new construction sites. Post-construction landscaping is usually approached from only the plant-selection viewpoint; and little effort is devoted to the severely disturbed soil, said Dr. John Sloan, assistant professor in the Department of Soil and Crop Sciences.

Following three years of data collection by Sloan and ornamental horticulturalist Dr. Cynthia McKenney, the Dallas researchers concluded that adding dairy manure compost during establishment improves the long-term performance of ornamental and turf plants typically used in new urban landscapes.

Sloan said that the increased performance is primarily due to the greater levels of soil fertility and improved soil physical properties, such as increased water infiltration and reduced soil compaction. The group recently received additional funding from TCEQ to continue the study for an additional three years in order to assess the long-term benefits of dairy manure compost.

Scientists with TWRI and the Blackland Research and Extension Center in Temple are also studying the use of dairy compost to help restore damaged training lands at Fort Hood. *(See Fort Hood story in this issue on page 2.)*

"These programs are all pieces in the puzzle to restoring and protecting the Bosque River Watershed," Wagner said.

"We've seen the use of dairy manure compost increase in several markets," she said. "While we have not seen the market develop to the extent desired, we believe, as with most markets, it will continue to grow with time."

"Most importantly," McFarland said, "results from these projects have increased tremendously our understanding of the most effective and environmentally sound uses of dairy manure compost and will support future growth and development of the composting industry both in the region and statewide."

For more information on the project, visit http://compost.tamu.edu.

As part of a verification study within the Dairy Compost Project, Extension staff monitor runoff from vegetated plots during simulated rainfall. Two different treatments–erosion control using a 50/50 mix of compost, and woodchips and application of inorganic fertilizer–were applied to the plots and the quality and quantity of the runoff water was compared.

Saving an underground reservoir

Story by Kathy Wythe

Saving an underground reservoir

Scientists partner to document efficient use

A visitor to the Central and Southern High Plains of the United States can gaze upon field after field of crops and rangelands for cattle—the sources of a significant part of the region's agricultural economy. Though the area has few rivers and lakes, underneath it lies a supply of water that has provided groundwater for developing this economy.

This underground water, the Ogallala Aquifer, is a finite resource. The amount of water seeping back into the aquifer is much less than the water taken out, especially in the southern half of the aquifer, which spreads out from western Kansas to the High Plains of Texas.

"Water levels are declining 2 to 4 feet per year over the south half of the aquifer," said Nolan Clark, a research engineer with the U. S. Department of Agriculture's Agricultural Research Service (ARS).

"If all the water is removed, then the regional economy is gone," Clark said. "We have already seen isolated areas that have no irrigation water remaining and the economy has been crushed."

The region produces about 4 percent of the nation's corn, 25 percent of the hard red winter wheat, 23 percent of the grain sorghum, and 42 percent of the fed beef. Agricultural irrigation use accounts for 90 percent of the groundwater withdrawals in many areas of the Ogallala Aquifer region. A growing livestock industry accounts for another 3 percent, Clark said.

Because the economy and viability of the agricultural industries and rural communities are so dependent on the aquifer, scientists at the ARS, Texas A&M University, Kansas State University, Texas Tech University and West Texas A&M University joined forces in 2003 to develop water conservation technologies and policies to sustain the aquifer.

Sustaining Rural Economies Through New Water Management Technologies, the ARS-University Ogallala Aquifer Initiative funded by Congress, seeks "solutions to the complex water problems and challenges being faced in West Texas and Western Kansas," according to the project's description. Since 2003, Congress has appropriated approximately $8.5 million to multiple projects. More than 60 scientists and engineers from ARS and the universities are involved in the initiative.

Clark, one of the project's leaders, said the initiative's research projects are centered on seven research priorities. Accomplishments to date include:

ECONOMIC ASSESSMENTS AND IMPACTS (MICRO and MACRO)

- Calculated from regional economic models that the projected total present value of irrigation over 60 years is $19.3 billion or $990 per acre.
- Determined that if no water management strategies are implemented in 60 years, the saturated thickness of the Ogallala Aquifer will decrease by an average of 48 percent, with a range from 0 percent to 90 percent. Water use would drop from 18.32 million acre-feet to 4.26 million acre-feet.

IRRIGATION AND PRECIPITATION MANAGEMENT

- Demonstrated that tillage influences crop productivity and water use by as much as 25 percent.
- Determined that genetic variations in crops create more than 50 percent variation in transpiration efficiency, meaning that within the same crop species, some varieties can produce twice as much.
- Released early versions of planning models that helped determine the best crop and number of acres planted based on water availability and market grain prices.

photo by Shelby Axtell, Texas Tech University

IRRIGATION SYSTEMS AND TECHNOLOGIES

- Demonstrated that subsurface drip irrigation systems increased seed germination by 50 percent when used in a modified bed system and at deficit irrigation levels.
- Demonstrated through laboratory tests the practicality of developing a prototype variable rate irrigation nozzle for center pivot systems.

PRODUCTION SYSTEMS

- Demonstrated the feasibility of selecting plants with higher transpiration efficiencies that produce more biomass with less water.
- Showed that integrating limited stocker cattle grazing into crop rotations increases net profitability by $45 per acre.
- Identified forage sorghums that have similar digestibility and yield as corn silage, but require 40 percent less irrigation water.

HYDROLOGY / CLIMATOLOGY

- Compiled existing relevant hydrologic and climatological data into a GIS format and corrected errors.
- Developed Web interfaces to distribute hydrologic and climatological data.
- Used GIS data to show and understand water flow in crops and soils.

TECHNOLOGY TRANSFER EDUCATION AND TRAINING

- Developed a logo for recognition and use in information sources.
- Developed a Web site for information management and internal communication. (http://ogallala.tamu.edu)
- Provided two irrigation scheduling schemes for producers that are accessible on the Internet. (www.oznet.ksu.edu/mil & http://txhighplainset.tamu.edu)

CAFO AND PROCESSING INDUSTRY WATER ISSUES

- Determined that southwestern dairies require an average of 60 gallons of water per cow per day for a dry lot system and 95 gallons of water per cow day per day for freestall.
- Determined that beef cattle consume 9 to 10 gallons per day per animal with more consumed in the summer. An additional one-third gallon per head is consumed for steam flaking the corn and an additional 5 gallons is used in the winter for overflow watering.

"Most areas have sufficient water for the next 10 to 20 years," Clark said, "but to impact the long-term, we must begin changing now to provide a sustainable economy for the future."

photo by Shelby Axtell, Texas Tech University

Story by Courtney Swyden

Be Water Smart

Conservation program incorporates rain gardens

WaterSmart, a water conservation program, uses a unique approach to protect and conserve water quality and quantity in upper Texas Gulf Coast urban landscapes.

Part of the Texas Coastal Watershed Program (TCWP), WaterSmart is creating rain gardens as just one method of demonstrating how water conservation can function in an attractive landscape.

In December of 2005, the first demonstration WaterSmart rain garden was established at the Bay Area Courthouse Annex in Clear Lake City in partnership with Harris County Precinct 2. The rain garden, which filters stormwater coming from the annex's roof and sidewalks, has generated much interest from businesses and homeowners.

John Jacob, team leader of TCWP, said, "We are having a major impact with early adopters—those who are willing to make a switch to more sustainable landscaping practices now.

"We need many, many more of these early rain-garden adopters to be able to start to reach all the rest of the homeowners and groundskeepers who manage landscapes," he said.

Chris LaChance, WaterSmart Program coordinator, said rain gardens are a new concept to many people, although other parts of the country (Michigan, the northeast, Pacific Northwest) have been using them for several years. "When the light bulb goes off, they realize it's a win-win situation. They can create a beautiful addition to their landscape, help protect water quality, recharge groundwater and add habitat for wildlife," she said.

The WaterSmart program brings information about runoff pollution and water conservation to the attention of homeowners, garden clubs, environmental groups and city planners, and addresses coastal issues. Texas Cooperative Extension and Texas Sea Grant provide the leadership for the program. And a grant from Houston Endowment provides funding.

LaChance said there are other water conservation methods that can function in attractive landscaping such as edible landscapes, or even adding shrubs or vines.

According to the TCWP Web site, residential and commercial landscapes on the upper Gulf Coast of Texas consume at least 50 percent of municipal water supplies during the summer months. In addition, runoff from highly maintained landscapes pollutes sensitive bays and bayous.

Jacob said, "Residential and commercial landscapes are a major source of polluted runoff in our bays and bayous, and they are perhaps the 'lowest hanging fruit' that we can pick in addressing this area."

Rain gardens can be created by taking advantage of naturally low-lying areas that collect water. Rain gardens help divert the flow of excess water from roofs, driveways, parking lots, and lawns, while offering a low-maintenance way of gardening. This site is ready to be excavated and planted with water-loving plant species.

The program's Web site explains that rain gardens are made from a shallow depression in the landscape at least 10 feet from a building. The sod is removed and excavated to create a shallow, bowl-like area. Compost and sharp sand is added to the soil and planted with a mixture of native or non-invasive adapted trees, shrubs, grasses and flowers that can tolerate temporary wet conditions. A layer of mulch prevents weed growth and aids in filtration.

These low spots fill with water during periods of heavy rain, helping to reduce water runoff by capturing, soaking up and filtering excess water from roofs, driveways, parking lots and lawns.

She said that rain gardens can be simple or complex. No rain garden is too small or too large, and cost and size is really site specific. People need to understand deed restrictions and landscape ordinances to allow for any variance that might need to be obtained before installation. People must also understand that it is important to "call before you dig" to be sure that no utility lines are present, LaChance said.

Supplemental grants from entities such as Texas General Land Office's Coastal Management Program, Galveston Bay Estuary Program and others allow LaChance to install demonstration gardens; coordinate workshops; consult with communities, homeowners, and environmental groups; and offer presentations to a wide variety of audiences.

Minimal grass cover and maximum use of native and adapted plants produce a WaterSmart landscape that requires less water, little or no fertilizers and pesticides, and is easy to maintain. The WaterSmart

This rain garden has been designed to fit naturally with the landscape and was planted with water-loving plant species. These plant species create a landscape that will collect water and aid in diverting the flow of runoff water.

program's goal is to provide a tool that will help people landscape in a way that is low maintenance, beautiful and does not negatively impact the environment.

"The next phase of the WaterSmart program will add a new component to the existing program, landscaping for wildlife, called Habitat Highways," said LaChance.

Jacob said that the WaterSmart program will be needed for a long time because people will want to continue to water and fertilize lawns. "We will need to help them minimize the impacts," he said.

For more information, visit TCWP's WaterSmart Landscapes Web site at: http://www.watersmart.cc/.

Awards

Dr. Ed Smith, director, Texas Cooperative Extension (far left) and Dr. Elsa Murano, vice chancellor and dean for Agriculture and Life Sciences, and director, Texas Agricultural Experiment Station (far right) present a Partnership Award to Kenny Zajicek, fiscal officer; Aubrey Russell, chairman; and Joe Freeman, state district II field representative, all from Texas State Soil and Water Conservation Board, during the Texas A&M Agriculture Conference in January. The award recognizes agencies and organizations that collaborate with Extension to enhance the outreach and impact of Extension for the people of Texas. TWRI nominated the board for its work together.

Story by Kathy Wythe

Cooperating for Cleaner Water

The Leon River TMDL Process

The Texas Commission on Environmental Quality (TCEQ), working with a local stakeholder group and others in the Leon River Watershed, is developing a Total Maximum Daily Load, or TMDL, for bacteria, one of the first TMDLs for bacteria in the state.

In 2002, the TCEQ determined that the water quality for 44 miles of the Leon River between Proctor Lake and Lake Belton contained elevated bacteria concentrations that impair the water for contact recreation such as wading and swimming. This TMDL plan will budget how much bacteria pollution from point sources (like wastewater treatment facilities) and nonpoint sources (runoff from land) can occur in a single day and still maintain water quality standards.

Kerry Niemann, TCEQ project manager, said current estimates are that the impaired segment needs roughly 20 percent to 25 percent reduction to meet water quality standards for contact recreational use.

The federal Clean Water Act requires states to identify impaired segments of water on its 303(d) list (a list of water segments that do not meet water quality standards) and to develop a TMDL for each pollutant that impairs any segment, according to TCEQ documents. TCEQ has adopted 63 TMDLs with EPA approving 60 of those to date.

TCEQ contracted with James Miertschin & Associates to develop the Leon River TMDL. The company is using a water quality model to mimic the hydrologic conditions on the impaired segment of the river.

The Leon River Bacteria TMDL Advisory Group, which represents various interests in the watershed, has had five public/stakeholders meetings. More than 130 landowners attended a meeting in Comanche and more than 60 attended two meetings in Hamilton.

According to Bob Whitney, Comanche County Extension agent, "landowners are the key to developing and implementing this TMDL. In the last several meetings, we have seen tremendous participation by local citizens who want to understand and be a part of any watershed plans.

"They make their living here on the land and no one wants clean water more than they do. It is important for those of us in government to recognize that these landowners will be the ones who spend their own money to make this TMDL happen."

Researchers with the U.S. Department of Agriculture-Agricultural Research Service are collecting water quality data during run-off events.

Researchers with the U.S. Department of Agriculture-Agricultural Research Service are collecting water quality data during run-off events on an impacted creek and a non-impacted creek.

Niemann said the TMDL report should be finalized by August 2006. After the TMDL is reviewed internally and a public meeting held, then the TCEQ commissioners and EPA will examine it for approval. Once the TMDL is approved, TCEQ will work with the stakeholder advisory group to develop an implementation plan to reduce the bacteria. An implementation plan outlines steps necessary to reduce pollutant loads through regulatory and voluntary activities, according to TCEQ's Web site.

For the nonpoint source pollution, different agencies and private interests will develop projects to help producers voluntarily reduce the nonpoint pollution.

Extension agents from all four counties affected by the TMDL will be working with TCEQ to involve agriculture producers and other interested groups in developing allocation and implementation plans, Whitney said.

The Texas Water Resources Institute (TWRI), Texas Cooperative Extension and U.S. Department of Agriculture-Agricultural Research Service (ARS) are already implementing a 319(h) project on the Leon River.

The project, The Impact of Proper Organic Fertilizer Management in Production Agriculture, will assess the effectiveness of best management practices using organic fertilizer and then will educate farmers on the proper use of organic fertilizers, such as animal manures.

According to Clint Wolfe, TWRI's manager of the project, researchers and Extension specialists will implement organic fertilizer management practices on cultivated and pasture fields to demonstrate the importance of using the correct method, timing and application rate. Extension will demonstrate the water quality difference between Resley Creek, an impacted water body, to Mustang Creek, a non-impacted creek.

For more information about the TMDL program, visit TCEQ's Web site at: www.tceq.state.tx.us/implementation/water/tmdl/ or TWRI's news article about TMDLs at:
http://twri.tamu.edu/newsarticles.php?view=2004-05-07.

For the TWRI/Extension/ARS project, visit http://twri.tamu.edu/ipofm/.

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Commission honors Fort Hood project

Fort Hood Revegetation Project, a project of the Texas Water Resources Institute and Blackland Research and Extension Center, recently won the 2006 Texas Environmental Excellence Award for Agriculture. Larry R. Soward and Kathleen Hartnett White, (third from left) Texas Commission on Environmental Quality commissioners; present the award to Elsa Murano, director of Texas Agricultural Experiment Station and vice chancellor for Agriculture and Life Sciences, Texas A&M University; and Col. Victoria Bruzese, Fort Hood Garrison commander (see story on page 5).

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A Publication of the Texas Water Resources Institute

Fall 2006

In This Issue:

THE WAVE OF THE FUTURE

CHAMPIONS OF TEXAS WATER

GLOBAL PREDICTIONS

AND MUCH MORE...

Working Together for Texas Water

The Trinity River, which stretches 512 river miles from north of the Dallas–Fort Worth Metroplex to Galveston Bay, is the principal water supply for the Metroplex and the City of Houston. Many Texans, urban and rural, depend on the river and its natural resources for maintaining quality of life and economic prosperity. Increased development and changes in land use, however, threaten the water quality, wildlife habitats, recreational opportunities and flood control of the basin.

To help improve the river, its ecosystem and its water quality, Governor Rick Perry recently announced the Trinity River Basin Environmental Restoration Project. With this announcement, Gov. Perry asked The Texas A&M University System to serve as the lead for the initiative. The Institute for Renewable Natural Resources (IRNR) will facilitate environmental restoration projects in rural areas, with emphasis on improving wildlife habitats, fisheries and recreational opportunities. The Texas Water Resources Institute (TWRI) will serve as catalyst for projects in urban areas, with emphasis on water conservation, water quality and stormwater management.

Many local, state and federal organizations are already involved in restoring the Trinity River. This initiative will bring together the talents and knowledge of these organizations and others to improve rural and urban streams, reservoirs and watersheds; to enhance wildlife habitat; and to expand ecotourism opportunities in the Trinity basin.

We have to remember that a river and its watershed include three important components: land, water and people. This initiative will help us better manage both our land and water resources for the benefit of people living in and around the basin.

TWRI is looking forward to working with IRNR and federal, state and local organizations to restore the Trinity River.

C. Allan Jones

tx H_2O

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Visit our Web site at
http://twri.tamu.edu
for more information.

On the cover:
Arroyo Colorado in south Texas.
Photo by Brad Cowan, County Extension Agent, Hidalgo County

Texas Agricultural Experiment Station
THE TEXAS A&M UNIVERSITY SYSTEM

Texas Cooperative EXTENSION
The Texas A&M University System

Texas Water Resources Institute
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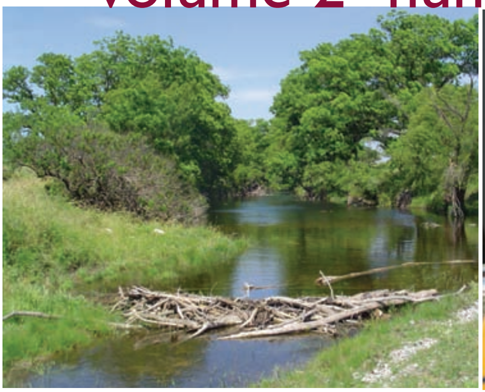

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Story by Courtney Swyden

THE WAVE OF THE FUTURE

Plans use local involvement to enhance water quality

Comprehensive watershed protection plans, outlining ways to preserve or restore watersheds, are becoming a popular approach for protecting Texas surface waters.

The Texas Water Resources Institute (TWRI), Texas Agricultural Experiment Station and Texas Cooperative Extension are taking an active role in providing assessment, educational outreach, management and training to assist in the development of watershed protection plans across the state.

A watershed is a particular land area from which water drains into a common body of water. A watershed protection plan outlines ways to preserve a watershed or restore an impaired one. These plans are becoming more prevalent as populations grow and water quality concerns from point and nonpoint pollution sources increase.

According to the U.S. Environmental Protection Agency (EPA), using a watershed approach to restore impaired water bodies is beneficial because it addresses the problems in a holistic manner and stakeholders in the watershed are actively involved in selecting the management strategies implemented to solve the problems.

The EPA has established nine key elements that must be addressed in order to have a successful plan (see page 5).

"A successful watershed protection plan will use scientifically-based methods to identify sources of water quality impairments and develop estimates of the load reductions required to meet water quality standards," said TWRI Project Manager Clint Wolfe. A good plan should evaluate the costs and benefits of addressing these sources, develop effective management measures, identify potential funding sources to correct problems, and outline ways to track progress and water quality improvements once the plan is implemented, he said.

Linda Brookins of the Texas Commission on Environmental Quality (TCEQ) said watershed protection plans embody the "watershed approach" to restoring and protecting water quality. "They assess all the factors affecting a body of water, which are bounded by its watershed and develop a strategy for reducing the loading of pollutants to the degree required to meet water quality goals, including state water quality standards," she said.

The Texas State Soil and Water Conservation Board (TSSWCB) and TCEQ are heavily involved in watershed protection plans in Texas. TSSWCB focuses on agricultural and silvicultural sources of nonpoint source pollution, and TCEQ focuses on all other sources, but both agencies are involved in the plans.

"Our two agencies work closely with local stakeholders to develop watershed protection plans and later assist in implementation of these plans," Brookins, special assistant in the Office of Compliance and Enforcement, said.

Aaron Wendt, the TSSWCB's state watershed coordinator, said, "Watershed protection plans are really an avenue for local stakeholders to get involved and to get together to make decisions about their watershed."

With its capabilities of water quality modeling, economic analysis, education and outreach, monitoring and data collection, and plan development and training, Texas A&M Agriculture—through TWRI, the Experiment Station and Extension—is providing leadership in watershed management and developing protection plans, Wolfe said. These capabilities allow the groups to assist in all aspects of watershed protection planning from individual elements to total plan development.

TWRI is currently involved in watershed management projects in the Arroyo Colorado, five reservoirs in North Central Texas, Lake Granbury, Buck Creek and the Pecos River. It is working with agencies and local stakeholders to assess current issues in these watersheds and implement watershed protection plans. Most of these projects are in collaborative efforts with the Experiment Station, Extension,

Lake Granbury, a critical water supply in North Central Texas, has recently experienced golden algae blooms and bacterial contamination. The Brazos River Authority is working with the Texas Commission on Environmental Quality, local entities and federal and state agencies to implement an integrated watershed protection plan.

TSSWCB, TCEQ, soil and water conservation districts, and local river authorities.

Wolfe, TWRI manager for the North Central Texas Water Quality Project, said, “A successful watershed protection plan for the project will be one that works to reduce sediment and nutrient loadings in the five water supply reservoirs managed by the Tarrant Regional Water District while accommodating a growing population and maintaining water quality.”

TWRI, working with Texas A&M University Spatial Sciences Laboratory and engineering consulting firms, is using EPA-supported water quality models to estimate sediment and nutrient loading in the five reservoirs. The water quality models also predict the impacts of agricultural management and land uses on water quality. With federal funds from the USDA–Natural Resources Conservation Service (USDA–NRCS), TWRI and Extension are developing a water quality education program to help landowners, homeowners, businesses and municipalities reduce nonpoint source pollution.

After the Brazos River Authority detected high levels of bacteria in some areas of Lake Granbury, a critical water supply for 250,000 North Central Texas residents, the river authority solicited funds from TCEQ and EPA to work with local groups to develop a watershed protection plan for the lake. To assist in the effort, TWRI and Extension are developing a water quality education program to help local stakeholders and businesses reduce bacterial contamination from nonpoint sources of pollution. This effort is supported by federal funds from USDA-NRCS.

Water samples from Buck Creek in the Texas Panhandle, collected and analyzed by the Experiment Station through the Bacterial Monitoring for the Buck Creek Watershed Project, have confirmed elevated *Escherichia coli* bacteria levels. The next step is a watershed protection plan in cooperation with the TSSWCB, local soil and water conservation districts and other stakeholders, according to Kevin Wagner, TWRI manager for the project.

TWRI, the Experiment Station and Extension have also teamed with the TSSWCB and local conservation districts to assess the Pecos River Basin. The Pecos River, a tributary of the Rio Grande, and Lake Amistad have experienced increased salinity and dwindled flows because of irrigation demands, droughts, dams, invasive species and oil and gas production. The team is researching and monitoring water quality and quantity, educating rural and urban stakeholders and developing a watershed protection plan describing current and future management measures to protect the river’s water quality.

Five of the major reservoirs in the Trinity River Basin managed by Tarrant Regional Water District (TRWD) have problems of sediment and nutrient loading. TWRI and Texas A&M Agriculture are collaborating with TRWD to study water quality protection and improvement.

What is a Watershed Protection Plan?

A watershed protection plan is a voluntary effort developed by local stakeholders that is formed from science-based information to protect unimpaired surface waters and to restore impaired surface waters. The following elements, established by the U.S. Environmental Protection Agency, are included in a Watershed Protection Plan:

- Identification of causes that need to be controlled to achieve load reductions
- Estimate of load reductions expected for management measures
- Description of management measures needed to achieve load reductions
- Estimate of technical and financial assistance needed to implement the plan
- Information/education component to enhance public understanding
- Implementation schedule for management measures
- Description of measurable milestones to determine implementation of management measures
- Set of criteria to determine whether load reductions are being achieved
- Water quality monitoring component to evaluate the plan effectiveness

Using funds from a TCEQ grant, TWRI is developing a course to train watershed coordinators and others interested in developing watershed protection plans. The Texas Watershed Planning Short Course is a collaborative effort between the EPA, TCEQ, TSSWCB, Extension and Texas River Systems Institute at Texas State University. The course will support the development of watershed protection plans and promote sustainable, proactive approaches to managing water quality throughout Texas.

"A well-coordinated watershed training approach is needed to provide the framework for focusing public- and private-sector efforts to address the highest-priority water quality impairments," Wolfe said.

The watershed planning course, a week-long event, will provide information on stakeholder coordination and in-depth analysis of EPA's nine plan elements and guidelines. The course will also include information about data collection and analysis; the tools available for plan development, education and outreach related to water quality; and the use of case study examples.

"Case studies will allow the participants to see how others are developing their plans as well as provide ongoing watershed planning efforts with valuable input from participants and national experts on the methods being used," Wagner said.

Other efforts in watershed protection planning within The Texas A&M University System include:

- Little Wichita River—Texas Institute for Applied Environmental Research
- Plum Creek—Texas Cooperative Extension
- Arroyo Colorado—Texas Sea Grant
- Dickinson Bayou—Texas Sea Grant
- Armand Bayou—Texas Sea Grant and Trust for Public Land

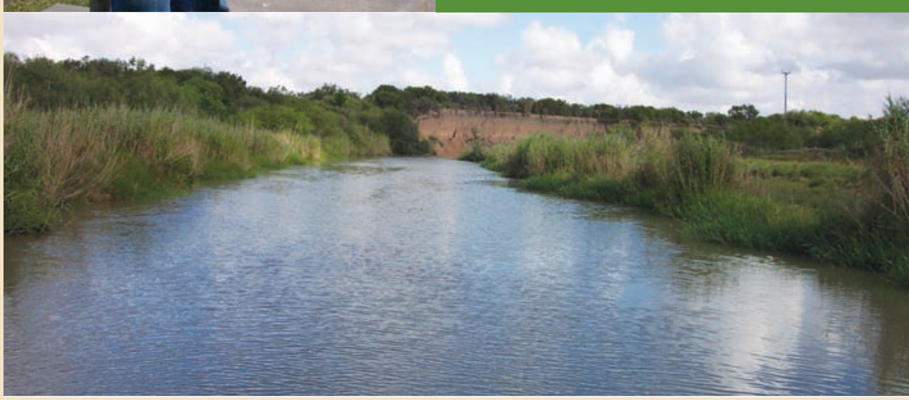
Collaborative partnerships, agency cooperation and technical support are all important in assessing water quality conditions to develop a successful watershed protection plan, Wolfe said. Stakeholder participation is key, so that in the end, they have a plan that can be implemented and has local support.

For more information on current projects, visit the Texas Water Resources Institute Web site at http://twri.tamu.edu.

Story by Kathy Wythe

Recovering from the Past

Group committed to restoring the Arroyo Colorado



Paul Bergh's love of the Arroyo Colorado in the Lower Rio Grande Valley goes back more than 40 years. His first experience with the Arroyo was in 1961 when the then 15-year-old was a guest of his girlfriend whose family had a place on the channel.

"Drinking water was hauled in by truck and stored in a cistern and the toilet flushed with water scooped out of the Arroyo," Bergh said. "It was pretty rustic to say the least, but the fishing was fantastic."

That same trip Bergh remembers the water being "much cleaner and clearer, still green but a very pretty and clear green."

Time went on. Bergh married his girlfriend. They inherited the family place and spent much of their free time with their kids, fishing and swimming the Arroyo Colorado.

As more time passed, shrimp farms moved to the area, additional municipal water plants were built to serve the growing population, and dredging for barges and flood control continued. The Arroyo Colorado, which begins in Mission and empties into the Lower Laguna Madre, became less clean and less clear.

"Fishing went to hell in a handbag and the water stunk," Bergh said.

Today, Bergh and a diverse group of individuals from agriculture, wastewater management, urban planning, environmental protection, economic development, academia and other disciplines are united in a common purpose—to restore this ancient channel of the Rio Grande. The Arroyo Colorado Watershed Partnership is developing a voluntary watershed protection plan that outlines ways to clean up the 90-mile polluted stream.

The Arroyo Colorado is the primary source of fresh water to the Lower Laguna Madre, a lagoon off the Gulf of Mexico and home to many fish and shrimp species. Commercial barges travel up and down the stream from the Port of Harlingen to the Laguna Madre and the Gulf Intracoastal Waterway. The stream, which receives natural flow beginning about halfway down the channel, collects treated wastewater from 18 municipal water plants along with excess floodwaters and stormwater runoff from urban and agricultural areas, and excess irrigation water from approximately 300,000 acres of cotton, citrus, vegetables, grain sorghum, corn and sugarcane. With its abundance of birds, plants and fish, the area attracts tourists and naturalists to its birding centers and Laguna Atascosa National Wildlife Refuge along with sports enthusiasts to fish the waters.

Unfortunately, because of the dredging and runoff, the Arroyo Colorado has one of the highest levels of nutrients, such as phosphorus and nitrogen, of all streams in Texas, according to the Texas Commission on Environmental Quality (TCEQ).

Since 1998, Texas has included the lower tidal part of the Arroyo Colorado on the Clean Water Act list of impaired water bodies for low levels of dissolved oxygen. From 1999 to 2004, the stream had 19 documented fish kills, claiming 26 million fish, according to the Texas Parks and Wildlife Department. The upper part of the stream is on the impaired list for bacteria.

In 2002, TCEQ completed the first phase of a total maximum daily load (TMDL) study that showed that extensive physical modifications of the Arroyo Colorado along with excessive nutrients from urban, agricultural and wastewater sources caused the low levels of dissolved oxygen. The TMDL results indicated that achieving healthy dissolved oxygen levels would require a 90 percent reduction of nutrients and biochemical oxygen demand. Faced with this large and virtually unachievable load reduction, TCEQ turned to local stakeholders to develop a watershed protection plan to reduce pollutants, said Roger Miranda, TCEQ strategic assessment division coordinator.

The partnership, originally organized by TCEQ and the Texas State Soil and Water Conservation Board (TSSWCB), is led by a 25-member steering committee. The committee oversees the efforts of seven work groups: wastewater infrastructure, agriculture, habitat restoration, land use and development, education and outreach, TMDL and monitoring. The Arroyo Colorado Watershed Protection Plan should be published by the end of 2006 and will be one of the first completed watershed protection plans for Texas.

(clockwise from top left)

Paul Bergh, a member of the Arroyo Colorado Watershed Partnership steering committee, grew up fishing and swimming in the Arroyo Colorado. He became involved in protecting and cleaning up the Arroyo in the early 1990s. Photo by Rod Santa Ana.

Because the Arroyo Colorado is dredged, commercial barges can travel up and down the Arroyo Colorado from the Port of Harlingen to the Laguna Madre and the Gulf Intracoastal Waterway. Photo by Brad Cowan.

The Arroyo Colorado collects irrigation water from 300,000 acres of cotton, citrus, vegetables, gain sorghum, corn and sugarcane as well as floodwaters and storm water runoff from urban and agricultural areas. Photo by Laura De La Garza.

The Arroyo Colorado Watershed Partnership's mission is to reduce the addition of pollutants to the Arroyo Colorado to meet state water quality standards and to improve natural terrestrial, riparian and aquatic habitats associated with the watershed.
Photo by Brad Cowan.

Dr. Jude Benavides, steering committee chairman, said this is one of the first times the state has tried to use a voluntary effort to restore a watershed that failed to meet TMDL requirements.

"We need to succeed," said Benavides, assistant professor of hydrology and water resources at the University of Texas at Brownsville.

"I think it is most important that each member can acknowledge the importance of succeeding so we can serve as a template for other watersheds and other local stakeholders," Benavides said

Laura De La Garza, the partnership's watershed coordinator, said the plan's goal "is to reduce the nutrient levels to the maximum extent feasible and, for this first phase of the planning process, we are aiming for a 20 percent reduction after the plan's recommendations are implemented."

One of the plan's top recommendations, De La Garza said, is to construct wetlands for treatment of point source and nonpoint source pollution. Wetlands can serve as a habitat for fish and other aquatic animals, stabilize streambeds and banks, and filter and process wastewater contaminants in the water, she said.

Bergh agreed that wetlands are a priority. "They will not only provide for cleaning of the water but will create habitat for wildlife that local municipal and special interest groups can take charge of, creating awareness and education and a sense of pride for the populace," he said.

Thirteen cities and public utilities have agreed to undertake projects or change their permits to reduce wastewater runoff into the stream, De La Garza said. The plan supports upgrades for a few cities, additional reuse and construction of treatment ponds and wetlands.

Miranda said the wastewater infrastructure work group has recommended voluntary permit reductions and enhanced wastewater treatment to further reduce nutrients and suspended solids in the effluent.

"Most of our municipalities have improved or plan to improve their wastewater collection and treatment systems in some way," De La Garza said. "Our cities should be commended for the numerous colonia hook-ups and for the partial reuse of their wastewater effluent."

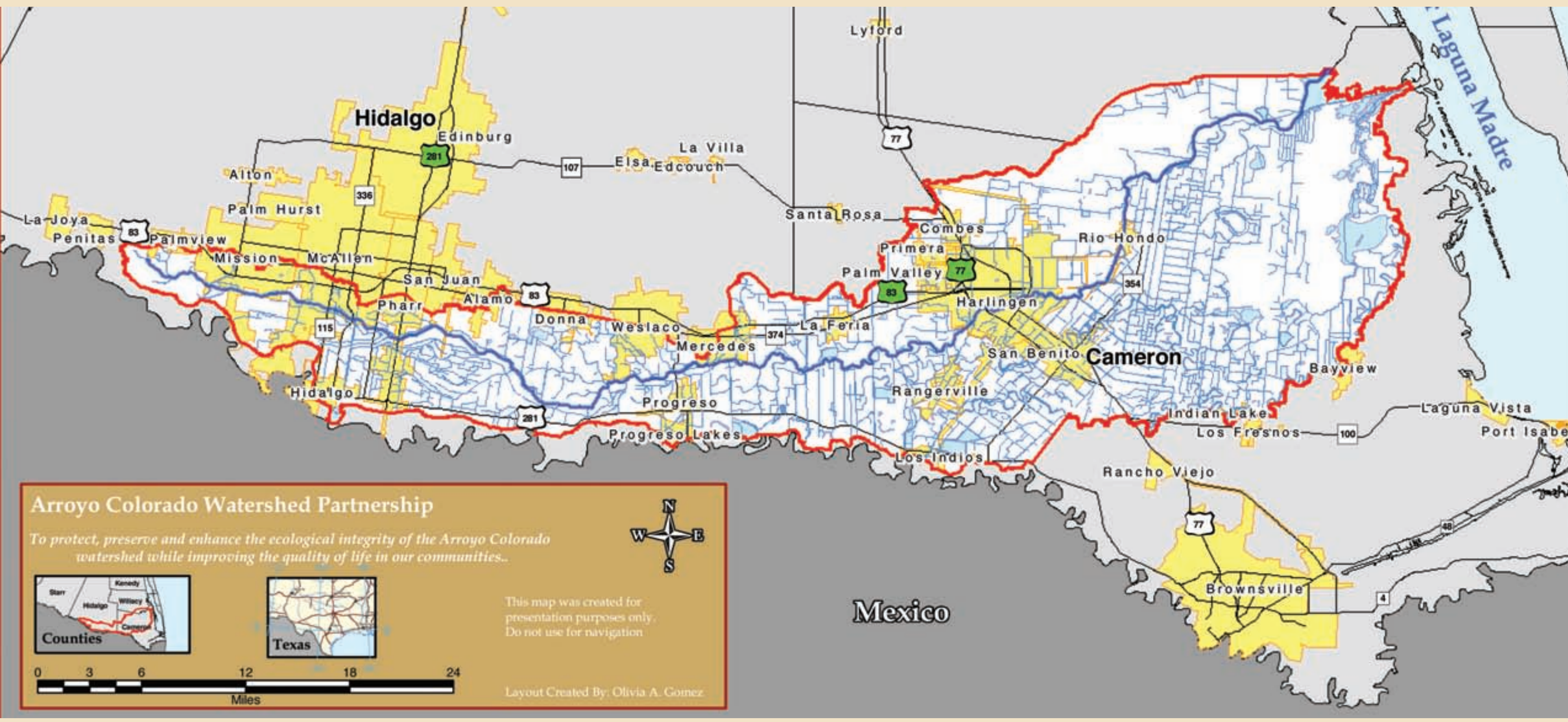
Because most of the land surrounding the Arroyo Colorado is farmland, management of nonpoint pollution from agricultural runoff that includes fertilizer and pesticides is included in the plan.

Kevin Wagner of the Texas Water Resources Institute (TWRI) said the plan's agricultural section recommends education on proper nutrient and irrigation management practices and how to implement best management practices that work on irrigated cropland. Then, monitoring actual impacts will be crucial to gauge the effectiveness of educational programs and the use of best management practices, he said.

TWRI and Texas Cooperative Extension staff, through a Clean Water Act 319(h) project funded by TSSWCB, are already addressing some of the agricultural issues addressed in the watershed protection plan. Extension agents in Cameron, Willacy and Hidalgo counties are educating farmers on managing their land to reduce the potential for nonpoint source pollution.

Wagner, TWRI's manager of the project, said Extension has sponsored free soil-testing campaigns to encourage soil testing and to endorse proper fertilizer use. Other programs provide training on crop production, integrated pest management and irrigation management. To help the producers implement these best management practices, the project promotes cost-share programs such as the USDA–Natural Resources Conservation Service's EQIP program, which provides farmers funds to apply specific conservation practices on their land, Wagner said.

"Our goal is for 50 percent or more of the farmers to implement best management practices by 2015 as a result of the educational efforts and cost-share programs," he said.



Wagner said the institute is seeking additional 319(h) funding to do the monitoring and assessment of the education and best management practices as recommended in the watershed protection plan.

The habitat restoration group puts a priority on conserving and restoring existing riparian and wetlands habitats, constructing additional wetlands, and reducing channel and stream bank erosion to reduce nonpoint source pollution.

De La Garza said the plan also calls for increasing awareness of water quality issues and their impacts through public education, school-based curriculum and outreach projects.

Benavides believes the education and outreach component, particularly in the Rio Grande Valley, is an important part of this protection plan, because as more people learn about the Arroyo Colorado and its importance, they will learn to take care of it.

When the plan is finished, the group will sponsor a "pachanga," or party, to present the plan and raise awareness of the Arroyo Colorado water quality issues within the valley.

As the watershed protection plan is implemented, TCEQ is working on Phase II of the TMDL study to determine more specifically how much of the low dissolved oxygen is caused from excessive nutrients and how much is from the stream's physical condition, Miranda said. He said the TMDL study will not be completed for a few more years pending evaluation of the implementation of the protection plan.

Once the plan is published, the partnership will continue. A watershed protection plan is an "evolving plan," De La Garza said. "We know we will need to adjust it as plan elements are implemented with a formal revision every five years."

Benavides expects the steering committee to continue to monitor activities in the watershed to ensure the partnership is reaching its objectives.

"I hope that we can come up with a good enough plan that is not only strong enough to get into compliance, but also flexible enough in the future to keep everyone behind it," Benavides said. "I hope the arroyo can serve as a model to other watersheds that fail to meet compliance in whatever regulation."

For Bergh, the success of the protection plan is more personal.

"My involvement is about protecting land and water that belongs to us all," Bergh said. "My benefit will come from enjoying the fish and wildlife and knowing that others behind me might get an even greater enjoyment of it if they take care of it."

Story by Kathy Wythe

CHAMPIONS OF TEXAS WATER

At quick glance, the two Texas women might seem opposite. One is tall, brown-haired and East-coast educated; the other petite, blonde and educated on the West coast. A closer look reveals two women who are both ranchers and state officials with a similar passion for Texas and preserving its waters.

Kathleen Hartnett White is chair of the Texas Commission on Environmental Quality (TCEQ), and Susan Combs is Texas Department of Agriculture Commissioner. In private business and in public service, both have made an impact in the arena of Texas water.

Combs oversees an agency dedicated to the state's second-largest industry—agriculture, which generates $73 billion a year and provides a job for one out of every seven working Texans. As agriculture commissioner, Combs has championed Texas groundwater rights issues and battled Mexican officials over water that country owed the United States.

White, as TCEQ's chairwoman, is involved in maintaining and improving the quality of Texas water as well as regulating surface water rights.

Both women come from a long line of West Texas ranchers from whom they developed their love of the land and respect for water. White and her husband own a 115-year-old ranch that spans Jeff Davis and Presidio counties. Ninety miles down the road, in Brewster County, Combs and her family have a working ranch established by her great-grandfather more than 120 years ago.

When asked what personal characteristics make the women effective in their positions, people who work with them say they are "highly intelligent," "articulate," "personable" and "understanding of issues."

Glenn Jarvis, a South Texas lawyer for 40 years, has worked with Combs and White on several water issues. "They both have real high quality of moral courage; they stand for and support what they believe in as opposed to what people might want them to stand for," he said. "We've been fortunate to have each of them in their respective positions."

Jarvis has worked with White through his involvement in converting water rights from irrigation to municipal purposes. "She has a good grasp of water rights and water resources. She has the ability to analyze and get to the real issues," he said, adding that she applies "legal principles in a very logical, straightforward way."

Representing the Rio Grande Valley's water users, Jarvis teamed with Combs and White, among others, in the recent fight to get Mexico to repay its water debt from the Rio Grande. Under a 1944 treaty, Mexico agreed to release water into the Rio Grande from six Mexican tributaries. In return, the United States releases water to Mexico from the Colorado River. Mexico fell behind on its obligations in the 1990s and the Mexican deficit, which peaked at more than 1.5 million acre-feet from 1992 to 2002, was repaid September 2005, but not until after a political struggle.

Combs was "very aggressive in protecting agriculture's interests" during the struggle, Jarvis said.

Ray Prewett, president of Texas Citrus Mutual and executive vice president of Texas Vegetable Association, two trade associations, also worked on the water debt issue with Combs and White. "Both were strong advocates for Texas," he said.

He described Combs as "unrelenting" in getting the debt repaid. "She was very outspoken and persistent to take on that issue and work with key officials in Washington and Austin," he said. "She has a bully pulpit and status as agricultural commissioner to become involved in water issues. Had it not been for her strong, persistent voice, I am not sure the water debt would have ever been paid back."

Susan Combs,
Commissioner,
Texas Department
of Agriculture

- Born in San Antonio
- Graduated from Vassar College, New York
- Received a law degree from The University of Texas Law School
- Served as Texas state representative from 1993-1996
- Elected as Texas Agriculture Commissioner in 1998
- Married with three sons
- Operates Combs Cattle Co., a family ranching business in Brewster County

Kathleen Hartnett White,
Chair,
Texas Commission
on Environmental
Quality

- Born in Salina, Kansas
- Graduated from Stanford University, California
- Studied law at Texas Tech University, Lubbock
- Appointed to the Texas Water Development Board in 1999
- Appointed to Texas Commission on Environmental Quality in 2001
- Named chair of the commission by Gov. Rick Perry in 2003
- Co-owner of White Herefords and a 115-year-old ranch in Jeff Davis and Presidio counties

Having ranching in their backgrounds has helped both women understand the issues facing agriculture, said Ned Meister, the Texas Farm Bureau's director of commodity and regulatory activities.

Of Combs, he said: "Owning a ranch in West Texas, having had management responsibilities on that ranch, gives her a fundamental understanding of agriculture. She is a very quick study on issues she may not be familiar with. She has good political connections, which is important in a political job like hers. That gives her the ability to help move her agenda forward."

White's ranching background, Meister said, has also given her an understanding of the challenges people in agriculture face. "When she has to make a decision that affects agriculture, she makes it with the knowledge of the impact on agriculture," he said. "She can put herself in the place of someone who is going to be regulated and she understands that."

Meister said being chair of the Commission is not an easy position because of all the environmental requirements and regulations. "It takes somebody with a lot of stamina, willpower and dedication to do that."

Meister has also worked with White on identifying the sources of bacterial pollution in Central Texas lakes and rivers. Until recently, many people felt dairies were the major source of bacterial pollution. Through bacterial source tracking, Meister said, wildlife is also recognized as a major source.

"She's very supportive in finding a way to account for the sources equitably. She's very understanding that the process needs some tweaking so it does take into account what we call background sources, which would include wildlife," Meister said.

Combs and White agreed the most pressing Texas water needs are all tied to the growing demand on the state's water supply, whether it is surface or groundwater.

In the draft *Water for Texas–2007*, the state's water plan, the Texas Water Development Board predicted that by 2060, Texas' population would double to 46 million, with a 27 percent increase in water demand. At the same time, total water supplies are projected to decrease by about 18 percent.

"Water is hugely important." Combs said. "It determines all economic activity. You can't put a dollar value on how important it is. It is critical to the state that we have adequate water."

White said, "The state's ability to meet future water demand is the overarching problem because from that steadily, rapidly increasing demand on our groundwater and surface water comes a host of other issues. Water quality, environmental flows and water rights all rear their heads as very important issues as the state tries to meet the increasing demand on our water supply."

For Combs, the increased demand plays out in one area she calls "the urban-rural interface conflict."

"There is a tension between the growing urban need for water and rural landowner rights," Combs said. An example, she said, is in East Texas where cities such as Dallas are trying to build reservoirs to meet their increased water needs, but are meeting opposition from the local residents. "This tension is going to get worse until a rational market system is found, a rational system that does not leave the rural guy without water," Combs said.

She said there also needs to be an equitable way to manage the state's groundwater rights, which unlike surface water rights, have only recently been regulated. For years, Texas landowners followed the 1904 rule-of-capture law that says landowners can pump as much water as they can use as long as it is not wasteful or malicious. In 2001, groundwater districts were given some authority to regulate groundwater use.

Today, approximately 85 percent of Texas land is in groundwater districts that manage and protect groundwater, but, Combs said, the districts vary in their ability to gather and analyze data and make decisions about competing interests for the groundwater.

Some groundwater owners, such as cities, pump large amounts of water while ranchers, farmers or small towns may pump a smaller amount. Combs compared it to straws, with some sipping from big straws; others from small straws.

"I do think that the legislature needs to come up with a way to look at balancing competing interests for groundwater," Combs said. "We should maintain and enhance the ability of these local districts to do their job and to ensure local landowners are protected and fairly treated," she said.

Advocates of preserving property rights, Combs and White said the legislature should move in the direction of a system similar to the correlative rights of the oil and gas industry, which allows landowners the opportunity to produce their fair share of the recoverable oil and gas beneath their land as long as it does not adversely impact their neighbors.

Another issue that needs legislative clarification, both said, is the reuse of water by cities after they have used it for drinking water. Until recently, cities would use the water, clean it up and then discharge it back into the river for downstream users. Some cities want to reuse the water to irrigate golf courses or for industrial use, leaving the rivers and water users downstream without that water.

"It is unclear under the Texas Water Code the manner in which the state can or can not authorize that so the issue of reuse needs clarification in law," White said.

"You start seeing interesting policy questions about purchase of water by cities and what it means downstream," Combs said. "It has far-reaching policy implications."

Because the need for water is growing, White said a concerted statewide effort on water conservation is needed. "It is very important that this state realizes the current and ever-increasing scarcity and, therefore, the greater value of our water supply and develops ways to use water more efficiently, to use less water for the same thing."

"Proper land-stewardship management techniques, including brush management and responsible grazing, increase surface and groundwater supplies," Combs said. "They are keys to meeting the state's future needs and are extremely cost-effective strategies."

Although White said she believes the legislature needs to clarify the law about groundwater rights, environmental flows and water reuse, she is a firm believer in the market system. "I think the market is the solution. I think the state forcing rural people to give underpriced water to urban areas is not right."

Solving these water issues needs to be sooner rather than later, they agreed.

"I think the quality of life, the Texas economy and the Texas environment depend on how we handle this water problem in the next few years, the next 20-30 years," White said. "There won't be any time after that.

"I think it's possible for Texas to meet that double population and be able to meet the water supply of the still-growing economy as well as protect the aquatic systems and the flows in our surface water because I think there is a growing awareness that water efficiency and water conservation is paramount to the future of this state."

Combs agreed the future of Texas depends on how the state approaches water policies today.

"Thoughtful water policy is a Texas issue that is going to take the dedication and commitment of all Texans to develop fair and equitable solutions to our future water needs."

Story by Kathy Wythe

Freeing up Water

Brush control efforts yield water

For 10 years during the 1990s drought, H. R. Wardlaw, a West Texas rancher, watched and waited.

He watched as the Middle Concho River and Rocky Creek running through his ranch near San Angelo became dry. He watched as the Florida bass from East Texas he stocked in the river and 75- to 100-year-old pecan trees lining the banks of the river died. And, he waited for the water to return.

In 2003, he stopped waiting and began participating in the North Concho River Pilot Brush Control Project and the Twin Buttes Brush Control Project. The projects are part of the Texas Brush Control Program, administered by the Texas State Soil and Water Conservation Board and designed to increase water yield by removing or controlling water-consuming plants such as mesquite, cedar and saltcedar.

In 2004, just as he finished excavating cedar, aerially spraying mesquite and hand spraying the remaining mesquite and cedar on his land on the Twin Buttes watershed, it started raining.

"The Middle Concho River and Rocky Creek started flowing again," Wardlaw recalled. "It was almost instantaneous recharge. It overcame 10 years of extreme drought in just that one year, which amazed everybody."

Wardlaw said even though the last year has been short on rainfall, the Middle Concho and Rocky Creek are still running.

"Even without the normal rain in the fall and winter, the Middle Concho River continued to flow great, and Rocky Creek continued to flow straight through the winter with no rain whatsoever," he said. "It absolutely wouldn't have continued over a dry winter and dry spring without brush control work, I am absolutely convinced."

Historically, the North Concho River and many of its tributaries flowed year round. But, since the early 1960s, the North Concho had been virtually dry and water flow into O. C. Fisher Reservoir was reduced to less than 20 percent of its normal amount, according to a study conducted by the Upper Colorado River Authority (UCRA).

The Texas Legislature authorized the State Board's brush control program in 1985, and funded the first project, North Concho River Pilot Brush Control Project, in 1999.

The State Board chose the North Concho River as the first watershed for the program because a feasibility study published by the UCRA showed that brush control could increase water flows from the river to O. C. Fisher Reservoir, a water supply source for San Angelo.

The voluntary program includes cost-share assistance for the "selective control, removal or reduction of noxious brush such as mesquite, saltcedar or other brush species that consume water to a degree that is detrimental to water conservation," according to the State Board's Web site. The program currently has three completed and 10 ongoing projects.

Working with the local soil and water conservation district's staff, landowners develop individual resource management plans that address brush control and other natural resources issues such as soil erosion, water quality and wildlife habitat. They then receive financial assistance (up to 70 percent of the costs) to clear their land of the water-consuming brush by physically removing it with bulldozers or excavators, by aerially spraying the land with herbicides or, in some cases, controlled burning. To date, landowners have treated 554,000 acres mechanically and 65,000 acres by aerial spray through the Texas Brush Control Program.

The principle is that by removing the brush, more water is left to seep into the groundwater or flow into the streams, rivers and lakes. The land also reverts to grassland.

Top photo: The Upper Colorado River Authority observed the return of perennial flow to 40 miles of Sterling Creek (top), the East Fork of Grape Creek and the North Concho River in 2005, flows that did not exist in 2000 before brush control.

Left bottom: H. R. Wardlaw, a rancher near San Angelo, has seen the streams on his land restored after he participated in the Texas Brush Control Program.

Right bottom: Chuck Brown, staff hydrologist for the Upper Colorado River Authority, measures flow in Sterling Creek after brush control.

Jimmy Powell, a West Texas rancher for 60 years, has photos of his land in the early 1900s. "There was no brush except live oak," said Powell, who began participating in the State Board's brush control program in 2002. Through the years, mesquite and cedar took over the land.

Powell, who owns land in Tom Green, Sutton, Schleicher and Menard counties, has treated 22,000 acres of his land in the Pecan Creek and South Concho River watersheds, by mechanically removing the cedar and aerially spraying the mesquite.

"I had not seen Pecan Creek run in 25 to 30 years," he said. "After removing the brush, the springs almost immediately began flowing. Pecan Creek is still flowing."

The North Concho pilot project finished with more than 300,000 acres treated and 314 landowners participating, according to Johnny Oswald, manager of the brush control program.

"We believe brush control works," Oswald said.

He cited a 2006 report by UCRA that said approximately 40 miles of the North Concho River and two tributaries, Sterling Creek and the East Fork of Grape Creek, that had brush removed had perennial flow in 2005. The report also indicated that treatment of 18,270 acres on the East Fork of Grape Creek yielded almost 1,900 acre-feet of water while the adjacent, similar-sized West Fork of the creek with no brush control remained dry.

Regional groundwater levels have risen by 3 feet, on average, since the State Board and landowners initiated brush control in the North Concho watershed, the report said.

Oswald said since the North Concho River project was a pilot project, the State Board made adaptations to the program as it went along.

One of the biggest changes, Oswald said, is targeting smaller sub-basins based on feasibility studies showing a strong potential for high water yield, cost effectiveness and landowner participation.

"Not every watershed and, within the watershed, not every area will be a good candidate for brush control," Oswald said. "Since landowners pay for their own economic benefit, we have to implement it (the program) in a way that landowners will participate. If we don't have landowner participation, we don't have a program."

Brush control for water savings is being implemented in other areas of Texas.

As part of the Pecos River Ecosystem Project, herbicide spraying to control saltcedar, an invasive water-thirsty plant, along the Pecos River began in 1999. For the project's first seven years, total water salvage estimates are between 17.7 to 26.5 billion gallons, according to Dr. Charles Hart, Extension range specialist.

Researchers have identified brush control, primarily Ashe juniper removal, as a method to increase Edwards Aquifer recharge. In January 2006, the Edwards Aquifer Authority and USDA-Natural Resources Conservation Service signed an agreement to offer cost-share to landowners in the Edwards Aquifer region to do brush control.

Johnny Oswald, the Texas State Soil and Water Conservation Board's Brush Control Program coordinator, and Tuffy Wood, program specialist, have worked with West Texas rancher James Powell (center) in clearing brush from his land as part of the Texas Brush Control Program.

While ranchers Wardlaw and Powell provide personal evidence of water savings gained by using brush control, Texas A&M University researchers have studied what watershed elements are necessary to get water savings through brush control for several years.

Dr. Richard Conner, an Agricultural Economics Department professor, has studied brush control from an economics and landowner participation standpoint. From his research, he said that usually 60 to 80 percent of landowners with 50 or more acres are willing to participate in the cost-share program. Using research conducted by NRCS for the feasibility studies of the Hondo, Medina, Sabinal and Perdernales Rivers and Seco Creek watersheds, which concluded additional water could be produced with brush control, Connor also analyzed the cost of the brush control to determine the costs to the state of $16.41 to $42 per acre-foot of additional water.

Connor said brush control can be an economical way to yield water. "If the brush control will yield additional water, and if the brush control is not too costly, and the additional water can be captured and held for use, then $16.41 to $42 is a competitive cost for additional water compared to other alternatives such as new lakes or de-salting of sea water," he said.

According to a 2005 Texas Agricultural Experiment Station research report, the relationship between brush removal and increased water yields becomes stronger as annual rainfall increases and when brush is removed from land adjacent to streams rather than in areas away from the streams.

The report's authors said the linkage between brush removal and increased water yield in upland areas (land away from the surface water) is stronger in areas where water can move rapidly through the soil or in areas where springs currently exist or historically have existed. They also concluded that the highest probabilities of water yield increases are likely for riparian areas where herbaceous plants would replace woody plants such as saltcedar and in areas where groundwater recharge is naturally rapid and high.

In areas with little subsurface water movement and where shrubs are not accessing groundwater, brush control is less likely to increase recharge or stream flow, except where direct runoff is increased.

The authors said that well-designed monitoring studies are needed in conjunction with the brush control program, and that brush control should be broadened to include "best management practices for watershed health and sustainability" rather than a simple focus on water yield.

Texas Agricultural Experiment Station researchers Brad Wilcox, William Dugas, Keith Owens, Darrell Ueckert, and Extension specialist Charles Hart were authors of this report.

The 2005 Experiment report may be read at: http://twri.tamu.edu/reports/2005/TAESResearchReport_Shrub.pdf.

A summary of the report is available at: http://twri.tamu.edu/reports/2005/TAESResearchReport_ShrubWater.pdf.

For a report on past brush control projects, read the "Texas Water Resources" article, December 2001, at: http://twri.tamu.edu/newsletters/TexasWaterResources/twr-v26n3.pdf.

The Texas State Soil and Water Conservation Board incorporated lessons learned from a pilot brush control project in the North Concho River Basin into subsequent projects.

Story by Danielle Supercinski

A DASH OF SALT

Researcher assesses salinity impacts on grasses, trees and shrubs

{ A Texas A&M researcher is assessing the impact of using moderately saline water for irrigating urban landscapes in West Texas and southern New Mexico. }

Fig. 1 – Foliar damage in Mulberry (*Morus alba)*, pictured at left, and Arizona Cypress (*Cupressus arizonica*).

"The primary purpose of using moderately saline water for irrigation, including reclaimed water, is to conserve potable [drinkable] water," said Dr. Seiichi Miyamoto, a professor and researcher with the Texas Agricultural Experiment Station at The Texas A&M University System Agricultural Research and Extension Center at El Paso. Miyamoto said he is evaluating salinity in water used for landscapes because he is seeing more landscapes damaged from too much salt in the water (containing dissolved salts near or in excess of 1,000 parts per million) used for irrigation. "We just do not have good guidelines to assess potential salinity hazards to landscape plants and soils," he said.

Most reclaimed water in California, Arizona and New Mexico has salinity well below 1,000 ppm, but salinities of reclaimed waters in West Texas and some areas of southern New Mexico and central Arizona usually exceed 1,000 ppm, sometimes reaching 1,500 ppm or higher, Miyamoto said. Other areas, such as Midland-Odessa, may have even higher salinity levels.

The most common salt-induced problem appears as foliar damage when broadleaf trees or shrubs are sprinkler-irrigated, he said. Plant damage caused by sprinkler application of reclaimed water has been extensive and acute (fig. 1).

"We did not know plants are so sensitive to this form of salt damage," Miyamoto said. "Many plants grow fine along the coast where seawater spray containing 35,000 ppm of salt hits foliage during high winds. "We conducted an experiment where different types of landscape plants were sprinkled for 30 minutes every other day, a practice common at golf courses and city parks. We found that broadleaf deciduous trees are sensitive to this form of salt damage, while pines and junipers, which grow near the coast, are tolerant."

Miyamoto said he believes that high-frequency irrigation used for maintaining landscapes is compounding this problem. Researchers also found salt crusts on leaf surfaces.

"It was a bit of a surprise when we saw salt crusts directly on the leaves, but it is not really surprising if you consider how the windshield of your car would look if it were sprinkled every other day for 180 days a year, with little or no rain," he said. "You would not be able to see through it. We now have a guideline for assessing this type of salt damage for different species of plants."

With this type of problem, Miyamoto said, "the key thing to remember is not to hit the plant leaves with sprinkler streams."

In mature trees, this can be accomplished by converting sprinklers to low-trajectory or under-canopy types of sprinklers (fig. 2); however, this option may not work for shrubs and ground covers. The use of non-sprinkling irrigation systems, such as bubblers and drips may be needed. Infrequent deep irrigation does help, but not enough to correct the problem, he said.

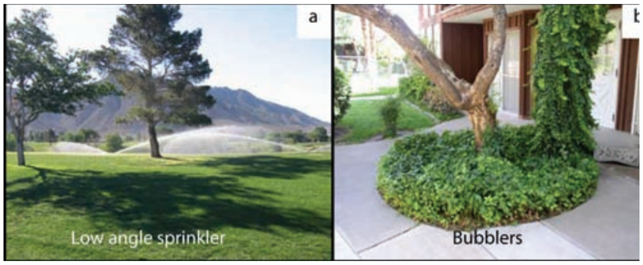


Fig. 2 – Conversion to low trajectory sprinkler (a) and to bubblers (b) for reducing foliar damage.

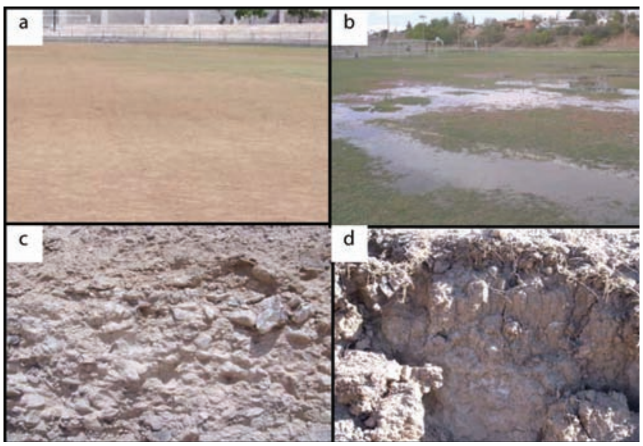


Fig. 3 – Examples of athletic fields affected by poor soils and salt accumulation. Clockwise: (a) upland soil, caliche, (b) bottomland soil, (d) a closeup of (b), and (c) a closeup of (a).

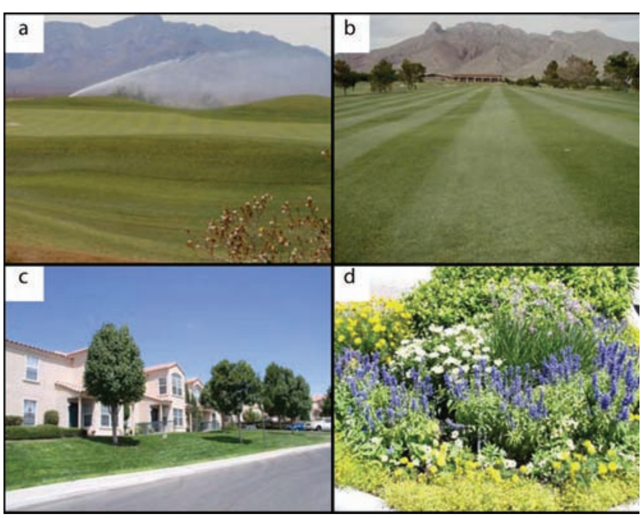


Fig. 4 – Successful use of reclaimed water for landscape irrigation: (a) golf course without trees, (b) upland soils with slope, (c) upscale apartments, and (d) flower beds with drip.

The second most frequent problem is soil salinization, or too much salt accumulation in the soil. This usually occurs in clayey (silty clay loam, clay loam and clay) bottomland and some upland soils that are poorly drained. Poor soil and irrigation management can also lead to soil salinization, even when inherent soil properties are suitable, he said.

Miyamoto said there is a definite need to develop guidelines for assessing soil suitability for irrigation with moderately saline water. To develop these guidelines, scientists are using athletic fields for their research. Poor turf growth caused by insufficient top soil, poor drainage and salt accumulation are just a few of the soil problems found in old and new athletic fields (fig.3).

Miyamoto's research group at El Paso has developed a simple method of assessing soil salinization potential for recently formed, relatively uniform alluvial soils in the valley, referred to as Entisols. The research results show that soil salinity under the prevailing irrigation practices is influenced greatly by soil permeability. In Entisols, soil permeability is controlled to a large extent by soil texture and soil compaction. Therefore, soil salinization potential can be estimated from soil textural classes, field-use categories, and, of course, irrigation water salinity, Miyamoto said. According to these guidelines developed by Miyamoto and Chacon, soil salinization is likely in athletic fields (with extensive foot traffic) when the field consists of clayey soils and is irrigated with moderately saline water.

Miyamoto and his associates also developed publications in cooperation with El Paso Water Utilities on plant response to soil salinity. *Landscape plant lists for salt tolerance assessment* and *Photo Guide: Landscape plant response to salinity* covers more than 100 species of plants used for landscapes in the Southwest. Copies of these publications are available by contacting the Research and Extension Center at El Paso at (915) 859-9111.

Research is still not completed for upland areas where soils rich in calcium carbonate prevail. There are several cases where drainage problems appeared in stony sediments that make up foothills. These areas are prime locations for urban growth, and athletic fields are constructed by placing topsoil over the stony sediment. According to Miyamoto, these stony sediments tend to seal and impair drainage. The cause is currently being investigated.

"These findings are somewhat of a concern to us," Miyamoto said. "For one thing, public parks and school sports fields are built with engineering specifications covering soil stability and strength, but not for suitability for maintaining turf with water of moderate to elevated salinity.

"Knowing salt accumulation in certain types of soils, it seems that we may have to modify existing soil preparation guidelines in one of these clays," he said.

At the same time, we should keep things in perspective, he said. When soil conditions are suitable and leaf damage is controlled, moderately saline water is excellent for turf irrigation, he said. There are many examples of successful uses on urban landscapes and golf courses (fig. 4). When the soil condition is not good, researchers said they need to find ways to amend it. This is also part of their ongoing research.

Miyamoto said the Rio Grande Basin Initiative, along with a matching fund from municipalities, have been instrumental for funding this type of applied research program. Without them, he said, "we would not have come this far."

For additional information and a list of resources, please visit http://twri.tamu.edu/news/2006-09-25-01/ or contact the Research and Extension Center at El Paso at (915) 859-9111.

TWRI awards Mills Scholarships to graduate students

The Texas Water Resources Institute recently awarded Mills Scholarships to 13 Texas A&M University graduate students to pursue water-related research for the 2006-07 academic year.

TWRI's Mills Scholars Program, an endowed fund that supports research in water conservation and management, provided the $1,500 scholarships to the students to use for education-related expenses. The scholarship program supports graduate students in diverse water research programs at Texas A&M University.

Students receiving the scholarships and their departments include: Kendra Johnson, Department of Biological and Agricultural Engineering; Vanessa Kelly, Jeremy Rice, Nick Russo III and Kati Stoddard, Water Management and Hydrologic Sciences; Trevor Knight, Department of Wildlife and Fisheries Sciences; Meredith Langille, Oke Nwaneshiudu and Sucheta Parkhi, Department of Civil Engineering; Anna Marie Nordfelt, Department of Geography; Lisa Prcin, Department of Rangeland Ecology and Management; Ronnie Schnell, Department of Soil and Crop Sciences; and Zach Vernon, Department of Forest Science.

Mills Cox, a former chairman of the Texas Water Development Board, endowed this scholarship program.

For more information on the Mill's Scholarship program or to learn more about the projects, contact the Texas Water Resources Institute at (979) 845-1851 or twri@tamu.edu.

Story by Courtney Swyden

Global Predictions

Lab uses advanced technologies to forecast change

Every morning forest rangers and specialists from the Texas Forest Service meet to make decisions about protecting the state's natural resources from fire. Essential to making these decisions are Keetch–Byram Drought Index (KBDI) maps produced daily by the Spatial Sciences Laboratory in College Station.

Spatial Sciences Laboratory Director Dr. Raghavan Srinivasan said county commissioners across the state also use the KBDI maps to determine whether to issue countywide outdoor burn bans in their county.

"The drought index is based on a daily water balance, where a drought factor is calculated with precipitation and soil moisture," Srinivasan said.

KBDI represents dryness and wetness in Texas counties on a scale of 0 (no moisture depletion) to 800 (absolutely dry conditions) and are used to estimate forest fire potential. A county with an index above 500 will institute a burn ban.

The index uses weather station estimates of temperature and Doppler radar-based precipitation estimates to produce geographic information systems (GIS) maps.

The KBDI maps are one of more than 15 map products created every day by the lab and used by the forest service, county commissioners and others.

Using computer technology and satellites, the lab currently focuses on three core spatial technologies—GIS, global positioning systems (GPS) and remote sensing technology. The lab uses these technologies to create interactive, multi-layered maps to help environmental and natural resources managers in environmental decision making, planning and problem solving as well as providing information about demographics, socioeconomic factors and public health information.

GIS technology is a computerized system that can capture, store, process and analyze spatial data. The lab uses GIS to produce the Texas Spatial Information System Web site. The Web site provides an interactive map of the state and gives information about transportation, water resources, boundaries, land and biological resources, agricultural data, demography, environmental quality and more.

The lab is currently working with the U.S. Army Corps of Engineers in developing GIS maps for its reservoirs so the Corps can better manage and conserve natural resources while providing quality outdoor recreation.

For example, GIS technology can determine boundaries of a reservoir as well as all of the features within those boundaries such as general land leasing or facilities as well as hunting and park boundaries.

Kim Hart, research assistant, and Greg Michalak, graduate student, evaluate Keetch-Byram Drought Index maps to determine drought conditions across the state.

"Boundaries need to be established so hunters, campers or park visitors can know their limits and prevent hazards," said Srinivasan.

The lab also uses GPS, a satellite navigation system useful for surveying property boundaries and fields. GPS uses satellites to locate and track any feature on Earth at any given time.

The lab is using GPS in identifying the Corps reservoirs' physical features, such as boating dock locations and park and recreation locations. The Corps puts that information on its Web site so the public has
easier access to parks or recreational areas.

Remote sensing technology uses satellites to collect data about the earth's surface to analyze changes and variations in land use and crop patterns and vegetation variations over time or as damage assessment after a natural disaster.

"Remote sensing is used to measure urban growth and what it affects," Srinivasan said. "We look at growth in terms of how it affects water quality, its impact on natural resources and how many wetlands are lost."

The lab recently worked with the Houston-Galveston Area Council to determine how many wetlands have been lost to urbanization or other land uses. Changes are easily detected using satellite images as well as high-resolution aerial photographs.

The lab has also used water quality models to study water quality protection and improvement. Water quality models are computer programs used to mimic the biological, physical, chemical and economic aspects of current land management and estimate the water quality impacts of implementing best management practices. This information helps assess water quality problems in a watershed.

Water quality models like SWAT (Soil and Water Assessment Tool), a landscaped-based (watershed) model, can predict impacts of agriculture management practices on landscapes.

The river-based water quality model, QUAL-2E, can illustrate how a river will react to certain chemicals and its processes.

WASP (Water Quality Analysis Simulation Program) is a lake-based water quality model that divides a lake into a 3-dimensional system to simulate the various chemical and biological exchanges both horizontally and vertically.

Because water quality models are vital to the Environmental Protection Agency (EPA), it provided USDA–Agricultural Research Service (USDA–ARS) with $1 million to develop the HAWQS Project (Hydrological Water Quality Modeling System). The lab is working closely with EPA and USDA–ARS to implement the project.

"The overall objective of this project is to provide a water quality modeling system that is capable of supporting a wide variety of national-scale economic benefit assessments in the EPA's Office of Water due to water quality impairments," Srinivasan said.

The modeling system will be a software product that can be installed, modified and run on EPA servers and can be made publicly available for downloading to other computers, he said.

Research is not the only aspect of the lab; education is also available for undergraduate students who want advanced knowledge of spatial analysis. A bachelor's of science degree in spatial sciences is offered under Texas A&M University's College of Agriculture and Life Sciences and College of Geosciences. Course work allows the students to use the potential of spatial sciences in problem solving.

Texas A&M also offers a graduate certificate program for GIS and remote sensing technologies. The program gives students in-depth, practical knowledge and opens the door for better job opportunities.

"The certificate program has been really successful," Srinivasan said. "We've had about 15 to 20 students every year since we started this in 2004."

LEFT: Graduate students in the Department of Forest Science use GPS technology in their studies.

RIGHT: Jennifer Jacobs, senior research associate, Kim Hart, research assistant, and Zach Vernon, graduate student, observe a GIS map generated by the lab for information on agricultural data in a certain area.

The lab collaborates with many state and federal agencies, including:

- Texas Forest Service
- Texas Water Development Board
- Texas Commission on Environmental Quality
- Texas State Soil and Water Conservation Board
- USDA–Agricultural Research Service
- USDA–Natural Resources Conservation Service
- U.S. Army Corp of Engineers
- National Weather Service

For more information about the lab, visit their Web site at http://css.tamu.edu.

Graduate students awarded water research grants

Texas Water Resources Institute (TWRI) recently funded 10 water-related research projects for graduate students from Texas A&M University, Texas Tech University, the University of Texas at Austin and West Texas A&M University.

The students were awarded up to $5,000 to begin, expand or extend water-related research projects. TWRI received more than 30 applications in response to the request for proposals for the 2006–2007 grants.

The institute funds the graduate student projects through money provided by the U.S. Geological Survey as part of the National Institutes for Water Research annual research program. TWRI will publish articles and reports about the progress of each project.

Graduate students, their projects and their advisors are:

David Barre, Texas A&M, Georgianne Moore, advisor. "Determining effects of brush clearing on deep drainage using soil chloride; a feasibility study for South Texas rangelands"

Yongxia Cai, Texas A&M, Bruce McCarl, advisor. "Impacts of Texas inter-basin water transfers on the water dependent economy and the environment"

Bassil El-Masri, Texas Tech, Faiz Rahman, advisor. "Estimation of water quality parameters for Lake Kemp Texas, derived from remotely sensed data"

Dongsuk Han, Texas A&M, Bill Batchelor, advisor. "Arsenic removal by novel nanoporous adsorbents"

Mohammad Islam, Texas A&M, James Bonner, advisor. "Development of a coastal margin observation and assessment system to monitor the water quality in the Corpus Christi Bay"

Andrew Karonen, UT at Austin, Steven Moore, advisor. "A socio-technical case study of sustainable stormwater management in Austin, Texas"

Megan Meier, Texas A&M, Anne Chin, advisor. "Post-restoration evaluation of urban streams in Central Texas"

Arwa Rabie, Texas A&M, Mahmoud El-Halwagi, advisor. "Property-based management and optimization of water usage and discharge in industrial facilities"

Debabrata Sahoo, Texas A&M, Patricia Haan, advisor. "Modeling the effect of urbanization and optimizing land use for estuarine environmental flows"

Robert Taylor, West Texas A&M, Lal Almas, advisor. "A pricing model to assess the effects of groundwater availability on land valuation"

For more information and updates about each project, visit http://twri.tamu.edu/usgs.php.

Story by Kathy Wythe

Ripple Effects

Water conservation policies, practices impact Ogallala region's economy

With water levels in the southern part of the Ogallala Aquifer—the major source of groundwater for the Southern Great Plains—declining, researchers across the Texas High Plains and Kansas are developing agricultural practices and technologies that use water more efficiently.

At the same time, a group of agricultural economists is determining the impacts water conservation policies and practices might have on producers' incomes and water savings, as well as the ripple effects on the regional economy.

Drs. Steve Amosson of Texas Cooperative Extension in Amarillo, Lal K. Almas of West Texas A&M University, Jeff Peterson of Kansas State University, and Jeff Johnson of Texas Tech University are principal investigators of the project. Part of the Ogallala Aquifer Initiative, a federally funded project through the USDA–Agricultural Research Service, the economics project began in 2003 and is scheduled to continue at least until 2008.

The economists have divided the southern Ogallala Aquifer region into three smaller regions based on similarities in cropping patterns and water availability. Texas Tech researchers are developing economic models in the southern part; West Texas A&M, the central part; and Kansas State, the northern part. These researchers have developed economic optimization models that project for a 60-year period water use, farm net income and aquifer-saturated thickness for each county in the study.

Almas, assistant professor of agricultural business and economics, said the optimization model determines the number of irrigated acres for each crop that maximizes the value of irrigation for each county, subject to water availability. The model also keeps track of changes in inputs, such as fertilizers and natural gas used to produce crops.

The economists are then able to project the use of water for a 60-year horizon based on the current irrigation technologies and water conservation management strategies, the current mix of crops for each county and the current amount of water pumped, Almas said.

"We have estimated in our region of 23 counties in the northern Texas Panhandle that, on average, 60 percent of the crop acres are under irrigation and 40 percent is dryland," he said. Projections from the optimization model indicate that after 60 years, only 12 percent of the crop acres will be irrigated because of lack of water.

In another portion of the economics project, Amosson and Extension Associate Bridget Guerrero take the results a step further. Using a socio-economic planning model, they first incorporate economic data for the counties in each sub-region and in particular crop production costs. Finally, they input the initial effects on farmers' incomes gained from the optimization models into the socio-economic modeling program. The results give an idea of what specific policies or technological advances will do to the

Photos Courtesy of Shelby Axtell, Texas Tech University overall economy and society in the region, including household incomes and employment levels.

The socio-economic planning model, called IMPLAN (Impact analysis for PLANning), is one of the most widely used socio-economic planning models in the country. To measure impacts, the model produces multipliers that estimate the total economic impact of a "shock" to an economy. These impacts are referred to as direct, indirect and induced effects. The model contains comprehensive and detailed data coverage of the entire United States by county.

What the economists have found is that certain strategies that save the most water may have negative impacts on producers' income.

Now, Amosson said, they are taking it a step further to see how what is happening with producers will affect the entire economy.

They are using the economic models to determine the effect of water conservation policies, such as USDA–Natural Resources Conservation Service's Conservation Reserve Program, which compensates farmers for converting farmlands to grasslands, may have on long-term water availability from the Ogallala Aquifer and the cost of water saved.

Amosson said policies or program changes, such as reducing irrigated acreage, can reverberate through the rural community. An example is "if you reduce the amount of irrigated acreage, you may not need to buy as much fertilizer," Amosson said. "If you don't buy as much fertilizer, you may not need as many fertilizer dealers. And, if you don't need fertilizer dealers, they move away, and if their kids are not going to school, you may lose a schoolteacher.

"Certain policies will have positive effects; some will have negative effects within the regional economy. Some will not have an effect at all."

Guerrero said they are currently surveying decision makers to determine the most important water conservation policies to analyze. From the survey, they will pick the top policies to run optimization and socio-economic modeling scenarios.

Amosson said the information gathered will provide scientific facts to decision makers and farmers so they understand the consequences of implementing policies or practices, and they can make informed decisions.

He said the modeling research will be able to tell them "if you implement this at this level, here are the impacts on the producer's income; here are what we are projecting are the impacts on the regional economy; here are the estimated water savings; here are the implementation costs. Then it is up to them."

Another objective of the economic research project is establishing a benchmark of currently used water-use practices and technologies, Guerrero said. This benchmark will enable the group to estimate more accurately current producer practices and irrigation technologies and get a more accurate picture of how changes in water management practices and technologies will affect the economy.

The ultimate goal of the economic project is "to minimize the drawing down of the aquifer and minimize the negative effects on the economy," Amosson said.

"We are trying to extend the useful life of the Ogallala Aquifer and make sure that water is available for future generations without compromising sustainability of rural communities," Almas said.

Charting the Course

"Charting the Course," a Texas water planning and policy development conference, is set for Nov. 15–17 at the State Capitol Extension in Austin.

Sponsored by the River Systems Institute, the conference will feature symposia by the state's leading scientists and representatives from water-resource management agencies focusing on how far the state has come in terms of water-resource management and planning. The conference will also highlight the development of the 2007 Texas Water Plan, the implications and obstacles to its implementation and how policy activities of the next legislative session can provide a framework for overcoming these obstacles. Other issues, including water conservation, reuse, environmental flows and groundwater management, will be discussed.

More information is available at www.rivers.txstate.edu or contact Annette Paulin at (512) 558-4523 or chart.the.course@grandecom.net.

New Faculty

Biological and Agricultural Engineering

Dr. Vijay P. Singh was selected in July 2006 as the inaugural holder of the Caroline and William N. Lehrer Distinguished Chair in Water Engineering in the Department of Biological and Agricultural Engineering.

Singh was a professor in civil and environmental engineering at Louisiana State University and held the Arthur K. Barton Endowed Professorship.

He received his doctorate in civil engineering with an emphasis on hydrology and water resources from Colorado State University and a doctorate of science in engineering with an emphasis on environmental and water resources from the University of the Witwatersrand, Johannesburg, South Africa.

Singh will provide continuing research, teaching and Extension programs in water engineering covering topics such as urban water resource management, water quality remediation, reuse of municipal wastewater and more.

Soil and Crop Sciences

Dr. Terry Gentry, assistant professor of soil and microbiology, joined the Department of Soil and Crop Sciences in January 2006.

Gentry received his doctorate in microbiology and immunology from the University of Arizona in 2003.

His expertise is in the area of the development and use of molecular technologies to enhance the detection and remediation of environmental contamination. This includes the detection and identification of microbial pathogens from animal, human and natural sources, and the characterization of microbial populations and communities contributing to applied remediation processes such as the bioremediation of organic and metal contaminants.

Soil and Crop Sciences

Dr. Kurt Steinke, assistant professor of turfgrass ecology, joined the Department of Soil and Crop Sciences in April 2006.

He received his doctorate from the University of Wisconsin–Madison in 2006.

Steinke's research will focus on the biology, management and ecology of plant communities within the urban/suburban environment, and what effects these systems have on the soil and surrounding areas within the shifting urban landscape. This includes urban water and nutrient management, sustainability, cultural management, soil amendments and best management practices promoting the judicious use of water and nutrients within turfgrass, native and agricultural ecosystems in order to sustain and improve soil quality.

TWRI Welcomes New Faces

Lucas Gregory joined Texas Water Resources Institute in June 2006. As a project manager, he provides leadership for several projects and is a team member for directing 319(h) projects funded by the Environmental Protection Agency through the Texas State Soil and Water Conservation Board and Texas Commission on Environmental Quality.

He earned his bachelor of science degree in agricultural systems management and a masters of science degree in water management and hydrologic sciences, both from Texas A&M University.

Cecilia Wagner joined Texas Water Resources Institute in June 2006. As a project manager, Wagner is responsible for programs pertaining to agricultural water conservation. She coordinates a collaborative Irrigation Training Program funded by the Texas Water Development Board. In addition, Wagner provides administrative guidance for the Precision Irrigation Network, a task of the Rio Grande Basin Initiative.

She earned her bachelor of science degree in plant and environmental soil science and her masters of science degree in agronomy, both from Texas A&M University.

Kathy Woodard joined Texas Water Resources Institute as office associate in August 2006. She performs general office procedures, advanced clerical assignments and special projects for the institute.

Woodard recently relocated to this area from Lubbock where she worked as a computer support specialist at Texas Tech University.

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Governor announces initiative for Trinity River Basin

Gov. Rick Perry announced the Trinity River Basin Environmental Restoration project Sept. 5 in news conferences in Houston and Arlington. Rod Pittman, Texas Water Development Board chairman as well as other local, state and federal officials were on hand for the announcement. The initiative will focus on projects to improve water quality, hydrology, wetland restoration, hardwood reforestation, wildlife habitat and voluntary landowner stewardship.

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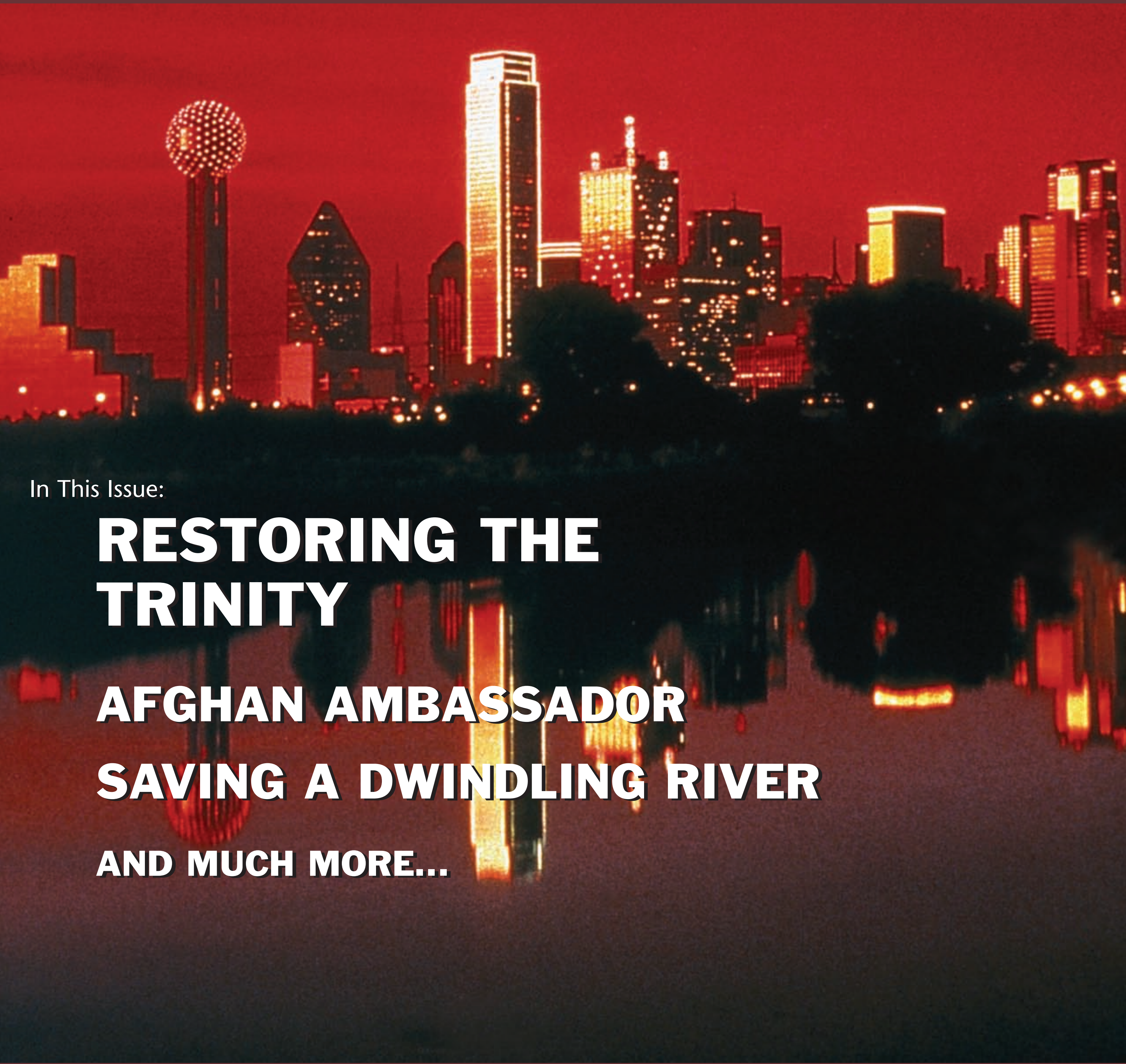

In This Issue:

RESTORING THE TRINITY

AFGHAN AMBASSADOR

SAVING A DWINDLING RIVER

AND MUCH MORE...

Working Together for Texas Water

The end of 2006 proved to be an award-winning year for Texas Water Resources Institute. The Institute nominated several individuals and TWRI projects during the year, and the results have been great.

The following awards were presented to the selected individuals and projects in January 2007:

- *2006 Vice Chancellor's Awards in Excellence: Award in Research* to the Rio Grande Basin Initiative Research Team consisting of Drs. Edward Rister, Giovanni Piccinni, Bob Wiedenfeld, Juan Enciso, Zhuping Sheng and Ari Michelsen
- *2006 Vice Chancellor's Awards in Excellence: Award in Professional Special Services* to Patricia "Patt" Junek of Contracts & Grants for her help and guidance through the TWRI grant submission and approval process
- *2006 Vice Chancellor's Awards in Excellence: Award in Extension Education and Service* to Robert "Bob" Whitney, Comanche County agriculture and natural resources Extension agent, for his assistance with numerous TWRI programs over the years
- *2006 Vice Chancellor's Awards in Excellence: Award for Administration* to Dr. C. Allan Jones for his leadership as TWRI director
- *2006 Epsilon Sigma Phi Retiree Service Award* to Dr. Bill Harris, TWRI associate director
- *U.S. Department of Agriculture–Cooperative State Research, Education and Extension Service National Water Program 2007 Awards in the Outstanding Integrated Activities for Water Resources* to the Rio Grande Basin Initiative project

We thank these individuals for their continuous efforts toward water quality and conservation and for the help and services they provide. Congratulations!

Charles Allan Jones

C. Allan Jones

tx H_2O

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Assistant Editor
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Visit our Web site at
http://twri.tamu.edu
for more information.

On the cover:
Trinity River reflects the Dallas skyline.
Photo by Dallas Convention and Visitors Bureau

Texas Agricultural Experiment Station
THE TEXAS A&M UNIVERSITY SYSTEM

Texas Cooperative EXTENSION
The Texas A&M University System

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tx H_2O is published three times a year by the Texas Water Resources Institute, which is a unit of the Texas Agricultural Experiment Station and Texas Cooperative Extension. TWRI is funded in part by the U.S. Geological Survey and authorized by the Water Resources Research Act.

Story by Kathy Wythe

RESTORING THE TRINITY

Governor's initiative accelerates efforts to improve river

Editor's Note: The Trinity River Basin has been the center of water resources projects for years. With Gov. Rick Perry's announcement of the Trinity River Environmental Restoration Initiative, attention has increased concerning this river that stretches from North Texas to Galveston Bay. The following stories feature a few of the projects that deal with water conservation and water quality of the river.

A comprehensive effort to improve the Trinity River Basin watershed, its ecosystem and water quality is underway with federal, state and local agencies working together with The Texas A&M University System. In September 2006, Gov. Rick Perry announced the Trinity River Basin Environmental Restoration Initiative.

The Trinity River, the 512-mile-long river that stretches from north of the Dallas/Fort Worth Metroplex to Galveston Bay, and its natural resources are important assets to Texas. Providing drinking water for more than 8.9 million residents, the river and its 1,983 miles of major tributaries drain an area of more than 11.5 million acres.

The city of Fort Worth, Tarrant Regional Water District, Streams and Valleys and the Corps of Engineers all work together in providing access to the river to the citizens of Fort Worth. Fort Worth's Main Street crosses the Trinity River just past the convergence of the West and Clear Forks of the river. *Photo by Clay Church, Corps of Engineers*

Rapid development and changes in land use, however, strain its reservoirs' capacities and threaten its water quality, according to those involved in restoring the river.

Although many projects are already in place to protect the river, it received additional attention when Gov. Rick Perry announced the Trinity River initiative at news conferences in Arlington and Houston.

"The cities of Fort Worth and Dallas both have major, ongoing Trinity River projects, and I compliment city and county leaders for their vision for restoring the vitality of this great river," Perry said at a press conference in Arlington. "Our objective is to work closely with the cities, private landowners and federal and state agencies to build on the success that the Metroplex has enjoyed.

"If Texans all along the Trinity River band together to fully protect its water quality and restore the river to its more pristine past, it will have a dramatic impact on birds and wildlife, ecotourism and water quality," Perry said.

The A&M System's Institute of Renewable Natural Resources (IRNR) is working with the Trinity River Authority (TRA), the Trinity Basin Conservation Foundation and other agencies and non-profit organizations to help landowners and other stakeholders make their own decisions on how the watershed is managed and restored, said Dr. Neal Wilkins, IRNR director. "The stakeholders have the most at stake in restoring the river," he said.

IRNR and TRA are developing a user-friendly Trinity River Internet Mapping System (TRIMS) that will give users access to mapping data, remote-sensing data and low-elevation aerial photographs and other information that will help in planning the restoration. Funded by a Clean Rivers Program grant from Texas Commission on Environmental Quality (TCEQ), TRIMS will generate information for future projects that will address water quality, hydrology, floodplain management, wetland restoration, bottomland hardwood establishment and wildlife habitat management, Wilkins said.

TRA General Manager Danny Vance said, "The databases that are being pulled together show a lot about how the river is doing. We are glad to be working with other Trinity interests on this."

IRNR also has funding from the Texas State Soil and Water Conservation Board (TSSWCB). Through partnerships with local soil and water conservation districts, TSSWCB provides technical resources to assist rural, agricultural producers in making land-use management decisions that protect water quality and enhance water conservation.

"The governor's Trinity River Basin Environmental Restoration Initiative will strengthen the Board's work with farmers and ranchers to address rural-urban interface issues," said Aubrey Russell, TSSWCB chairman. "The programs and tools developed through this initiative will improve the ability of landowners to make informed local decisions on watershed management."

The project's Web site is **http://trinityriverbasin.tamu.edu/**.

"TRIMS is the first step then we will begin the planning process," Wilkins said. "Long-term, we want to provide a means for local stakeholders to make sustainable and measurable contributions to the restoration of the Trinity River."

Tarrant Regional Water District (TRWD) and the Agricultural Research and Extension Center at Dallas are combining efforts to develop a comprehensive urban water conservation education program in both the Dallas/Fort Worth Metroplex and Houston areas.

Urban water conservation is essential to meet the rising demands of these rapidly growing areas. In addition to the growth, the region's worst drought in 50 years resulted in many cities in the Metroplex implementing outdoor water restriction programs in 2006, and reservoirs such as Lakes Lavon and Chapman were substantially below normal levels.

"This urban water conservation educational program will be a large-scale undertaking to the public," said Dr. Frank Gilstrap, resident director of the Dallas center.

With funding by the Texas Water Development Board (TWDB) and TCEQ, the urban education program will teach the public through workshops about urban land stewardship, with

Gov. Rick Perry announces the Trinity River Basin Environmental Initiative in Houston in September 2006.

emphasis on water-efficient landscaping techniques, water-conserving plants and landscapes that help prevent nonpoint source pollution.

"We will be using existing water education programs such as WaterWise, Water IQ, Earth Kind and Texas SmartScape®," said Clint Wolfe, manager of the project. "In addition, the Dallas center will be working with Texas Cooperative Extension specialists to develop topical information on water conservation for local cities and organizations.

"TRWD will be developing demonstration gardens within the community so people can see that water conservation landscapes can be attractive and economical," Wolfe said.

Workshops will teach landscapers, engineers, grounds managers, nursery owners, developers and builders how to design and install landscapes that not only conserve water but also prevent nonpoint source pollution. The program will also provide mini-grants for cities, counties and agencies to conduct water education programs in the Metroplex and Houston areas, Wolfe said.

This educational effort will involve a number of local organizations and cooperators, including the North Central Texas Council of Governments, University of Texas at Arlington, TSSWCB, Master Gardeners, Botanical Research Institute of Texas and others. The Web site for the project is **http://trinitybasin.tamu.edu**.

In another project funded by the TWDB, SSL will study how urbanization and other land-use changes in the Upper Trinity watershed have affected sediment and nutrient loading into the reservoirs.

Dr. Raghavan Srinivasan, SSL director, said his lab will use the SWAT model to predict the effects of urbanization over the past three decades as well as practices designed to reduce stormwater runoff and soil and stream-bank erosion.

The Trinity River drains one of the largest and most rapidly urbanizing areas in the United States. From its headwaters north and west of the Dallas/Fort Worth Metroplex to its outlet into Galveston Bay, the Trinity River and its tributaries drain an area of over 11.5 million acres. *Photo by Danielle Supercinski, TWRI*

"Modeling will provide information to help managers identify specific projects needed to protect the watershed and maintain reservoir capacity and improvement of water quality," Srinivasan said. "Once completed, this modeling could serve as a prototype for the remainder of the basin and the rest of the state."

Dr. Allan Jones, Texas Water Resources Institute director, said the governor's initiative has pulled together a diverse group of organizations for a common purpose and served as the catalyst for these projects.

The funding agencies also see this initiative as positive for the state and its citizens.

"These projects, as part of the governor's Trinity River Basin Environmental Restoration Initiative, will provide citizens and professionals alike with powerful tools and programs for understanding water quality issues, making informed planning decisions and promoting effective restoration projects," TCEQ Chairman Kathleen Hartnett White said.

"The TWDB is pleased to participate along with other state and federal agencies in this effort to better understand the many complexities of the Trinity River Basin," said Kevin Ward, TWDB executive administrator. "A very important component of this effort will be to contribute to the advancement of municipal water conservation through education."

Ward said the $200,000 in grant funds was given to the TRWD and fellow A&M System collaborators to study how land-use changes may impact sediment and nutrient loading of reservoirs in the basin and the development of an urban water conservation education program. "These are fundamental components of our long-range goal of the best use of the natural resources in the Trinity River Basin."

Some of the other ongoing projects along the Trinity River include:

Trinity River Vision–Fort Worth

The Trinity River Vision Master Plan addresses the environment, ecosystems, flood protection, recreational opportunities, access to the waterfront, preservation of green space and urban revitalization on eight segments of the river and its tributaries within the Fort Worth area. (**http://www.trinityrivervision.org/**)

Trinity River Corridor Project–Dallas

The city of Dallas is collaborating with state and federal agencies to construct the Trinity River Corridor Project involving flood control and transportation improvements, downtown lakes, park facilities and the environmental preservation of the Great Trinity Forest through the acquisition of 3,500 acres of land along the Trinity. (**http://www.trinityrivercorridor.org/**)

North Central Texas Water Quality

TWRI, Texas Agricultural Experiment Station and Texas Cooperative Extension are collaborating with TRWD to study water quality protection and sediment- and nutrient-loading improvements in five reservoirs along the Trinity River. (**http://nctx-water.tamu.edu/**)

Richland–Chambers Water Quality

Texas Agricultural Experiment Station and USDA's Agricultural Research Service scientists are verifying the effectiveness of best management practices installed on Mills Creek within the Richland–Chambers Reservoir watershed to reduce nutrient enrichment and algal growth from excess nitrate and nitrite and high pH.

Richland–Chambers Wetlands

TRWD is diverting water from the Trinity River, treating it in constructed wetland water-treatment units and storing the water in reservoirs. Additional stages of the project will consist of constructing approximately 1,229 acres of treatment wetlands.

Texas Coastal Watershed Program

The Texas Coastal Watershed Program, a part of Texas Sea Grant and Texas Cooperative Extension, provides education and outreach to local governments and citizens on the impacts of land use on watershed health and water quality. Project areas focus on water quality and land use, soil and site evaluation for on-site sewage systems, urban stormwater treatment, and wetland creation and restoration. (**http://www.urban-nature.org/**)

Story by Kathy Wythe

CORPS IMPROVEMENT

Engineers key players in basin restoration

One of the key federal players in the restoration of the Trinity River Basin is the U.S. Army Corps of Engineers, whose primary civil mission is developing and managing the nation's water resources, including projects to reduce flood damage; improve navigation channels and harbors; protect wetlands; and preserve, safeguard and enhance the environment.

The Corps has been involved in the Trinity River Basin for more than 50 years, but the impetus for the current projects in the Upper Trinity River Basin was mainly from findings in a Corps environmental impact statement (EIS) report in the 1980s, according to Gene Rice, Corps project manager of the Dallas Floodway and Dallas Floodway Extension projects, two of the Trinity River Basin projects.

Two major conclusions of the report were: (1) a widespread lack of Standard Project Flood protection existed, and (2) Corps and local community permitting strategies significantly increased this lack of flood protection. At the time the EIS was issued, each city in the river basin was using its own set of criteria for permitting floodplain development.

Based on these conclusions, federal legislation was enacted to initiate studies. A reconnaissance report, published in March 1990, investigated the possible federal interest in flood control efforts/projects within the Upper Trinity River Basin. The serious potential flood threat was further verified in this report, Rice said.

The Corps, in partnership with the North Central Texas Council of Governments and its member governments along with the Texas Water Development Board, initiated a follow-up feasibility study in 1990. Study efforts were directed toward addressing improvements in flood protection, ecosystem restoration, water quality, recreation and other purposes in the Upper Trinity River Basin, with specific attention to the Dallas/Fort Worth Metroplex. Phase I of this feasibility study, which established base conditions, was completed in February 1995. Phase II of the feasibility study is ongoing.

The Corps of Engineers recently opened a new channel for the Trinity River in south Dallas. The realigned channel will help with overall flood-damage reduction within the Dallas Floodway and ensure the structural integrity of the I-45 Bridge. *Photo by Al Petrasek, Carter & Burgess*

As a result of these studies, the Corps has numerous projects within the Upper Trinity River Basin, including:

Central City Project, Fort Worth

The Corps' Central City project, part of the larger Trinity River Vision, a master-plan community project that includes 88 miles of hike and bike trails, roads and bridges, is constructing a bypass channel and associated structures to control flood flows along the Clear Fork and West Fork of the Trinity River. The project will replace an aging levee system designed for the city's population in 1960s. Ecosystem restoration and recreation facilities are also included at locations along the project footprint.

Trinity River Project, Dallas

The project consists of raising the existing east and west levees, removing the abandoned AT&SF railroad bridge, restoring historic wetlands, bottomland hardwoods, river meanders and constructing linear recreation facilities. The Trinity River Corridor Project, a much larger overall project by the City of Dallas, includes various transportation facilities and open water for recreation.

Dallas Floodway Extension

The Dallas Floodway Extension project consists of a chain of wetlands, two levees, 123 acres of wetlands for ecosystem restoration, realignment of the Trinity River at Interstate Highway 45, 31 miles of recreational trails and protection of 1,179 acres in their natural state to mitigate environmental impacts of the project. The Corps' Fort Worth District and the City of Dallas are using an innovative approach to return floodplain value to the Trinity River, while improving flood damage reduction.

Big Fossil Creek Watershed

The Big Fossil Watershed Study will address flood damage reduction, while identifying associated water quality, ecosystem restoration and recreational opportunities within the basin. The watershed, located in northern Tarrant County, encompasses 73 square miles and drains into the West Fork of the Trinity River.

The Corps is constructing a chain of wetland cells along the west bank of the Trinity River including Cell G (far top right) that will provide overbank capacity during flood events and restoration of wetlands and native grasslands during normal time. *Photo by Al Petrasek, Carter & Burgess*

Corps Project Manager Gene Rice describes the Riverside Oxbow Project with Brigadier General Robert Crear and Colonel John Minahan near the Beach Street Bridge at I-30 in Fort Worth. *Photo by Melanie Ellis, Corps of Engineers*

The Corps is a partner in the Central City or Trinity Uptown project, part of the larger Trinity River Vision, a master plan project. *Photo by Clay Church, Corps of Engineers*

Story by Kathy Wythe

SURVIVAL OF THE FITTEST

SmartScape® landscapes fare better during drought

The Native Plant Society of Texas and Texas Master Gardener volunteers maintain a SmartScape landscape demonstration at the Southwest Regional Library on Hulen Street in Fort Worth.

The SmartScape demonstration at the Hulen Street Library is one of numerous gardens throughout the Dallas/Fort Worth Metroplex.

During last year's drought, North Central Texas homeowners using Texas SmartScape® landscapes fared much better than homeowners with traditional landscapes when cities in the Dallas/Fort Worth Metroplex imposed water restrictions.

"Traditional landscapes suffer a great deal more than Texas SmartScape landscapes," said Dotty Woodson, Tarrant County Extension horticulture agent. Texas SmartScape is an educational program intended to help homeowners design and maintain attractive landscapes using native or adapted plants that require less water.

Woodson said by using the program's principles "people can have beautiful, sustainable landscapes even while water restrictions are in place."

Texas SmartScape has joined Tarrant Regional Water District (TRWD), The Texas A&M University System's Agricultural Research and Extension Center at Dallas and other partners in an urban water education initiative, part of Gov. Rick Perry's Trinity River Basin Environmental Restoration Initiative (see accompanying story).

Texas SmartScape complements the Water IQ program used by the North Texas Municipal Water District and e-Life, the environmental education program sponsored by North Central Texas Council of Governments, U.S. Environmental Protection Agency, Texas State Soil and Water Conservation Board and KTVT-TV CBS 11.

Texas SmartScape staff trains Master Gardeners to present educational seminars to individuals, civic organizations, homeowner associations and others. With the drought and corresponding water restrictions, interest in the program increased over the past year, Woodson said.

Many cities proclaim March as Texas SmartScape month to heighten awareness about the program. This year's theme, "Keep Your Green" highlighted the cost benefits of using native and adapted plants that use less water and less fertilizers to thrive in our local climate. Throughout the region, events presented the "how's" and "why's" of SmartScaping.

The SmartScape Web site (**http://www.txmartscape.com/about.asp**) is an interactive how-to guide that walks viewers through the SmartScape concept. Using the Web site, viewers can search for more than 200 plants, shrubs and trees that thrive in North Central Texas and learn how to care for them in a manner that saves time and money.

The ultimate goal of the program, Woodson said, is to conserve local water supplies and improve stormwater runoff quality by reducing the amount of water needed to maintain landscapes while decreasing the amounts of pesticide, fertilizer and herbicide used in landscaping plants.

Woodson said the program addresses how individuals can make a difference. "Individuals can't do anything about the millions of dollars needed for more water resources," she said, "but Texas SmartScape provides something every individual with a landscape can do."

Texas SmartScape was initially created in 2001 through the leadership of the North Central Texas Council of Governments. Other agencies involved in the project are the Tarrant County Health Department, Texas Cooperative Extension, TRWD, Texas Parks and Wildlife Department and Weston Gardens. The program Web site was developed in 2003 through sponsorship from Dallas Water Utilities, City of Irving, North Texas Municipal Water District, TRWD and the Upper Trinity Regional Water District.

Story by Kathy Wythe

Environmental education goes multimedia

A new environmental education program, "e-Life," that combines an interactive Web site and television news spots, premiered last fall as the latest tool to help North Texans learn more about their environmental quality of life.

"Whether by mouse or remote control, North Texans can click their way to a whole new world of environmental information," said Richard E. Greene, U.S. Environmental Protection Agency's (EPA) Region 6 administrator, at the kick-off event.

"The e-Life project is intended to increase awareness about local environmental issues and individual, voluntary measures that the public can take to protect our North Central Texas watershed resources," said Project Coordinator Leslie Rauscher of the North Central Texas Council of Governments (NCTCOG).

e-Life is co-sponsored by EPA, Texas State Soil and Water Conservation Board (TSSWCB), NCTCOG and KTVT-TV CBS 11.

The environmental program focuses on the nine watersheds in the Upper Trinity River Basin with its network of lakes, creeks and rivers that supply North Texas with fresh water.

Through on-air news stories and public service announcements, KTVT-TV and its team of meteorologists and reporters broadcast useful information to viewers on how they can help conserve water and prevent or minimize nonpoint source (NPS) pollution. Through an Environmental Education Events calendar, citizens also learn how they can get involved in local watershed protection and NPS pollution prevention efforts in their communities.

"We are so excited about this opportunity to help our viewers better understand where their water comes from and the risks of taking it for granted," said KTVT-TV Chief Meteorologist Kristine Kahanek. "I hope this awareness leads to a community ready to do whatever it takes to protect our watersheds."

The comprehensive Web site, **http://ktvt.iewatershed.com**, is an educational tool to help individuals learn how they can help prevent water pollution at home and in the community, Rauscher said.

Interactive watershed tools provide information about drinking-water quality, wetlands, floods and droughts, agriculture, land use, forestry, soil erosion, urbanization and other watershed topics. Animated movies compiled from satellite and radar technology replicate moving "flyovers" of specific watersheds.

"Through sponsorship of e-Life, TSSWCB hopes to bridge the rural-urban interface to educate and involve the public in improving and maintaining the quality of water resources for current and future generations of Texans," said Aubrey Russell, TSSWCB chairman.

Rauscher said the project uses stakeholders to provide expertise in a variety of topic areas, including NPS prevention and abatement, stormwater management, water conservation, solid-waste management, air quality, flooding, soil erosion and applied environmental science. Eligible participants include local governments, federal and state agencies, soil and water conservation districts, water districts, universities, environmental associations and environmental non-profit groups that operate in the Upper Trinity River project watersheds. Interested stakeholders can contact Rauscher at **LRauscher@nctcog.org**.

To be successful, Rauscher said the project needs local information about the Upper Trinity River watersheds such as:

- Upcoming local, educational events the public can attend
- Ideas for environmental news stories
- Links to local Web sites that contain useful information about the project watersheds
- Digital copies of helpful brochures and other educational materials that can be posted to the Web site
- Photos of the project watersheds for the photo gallery

The project is modeled after a successful collaborative effort anchored by EPA and supported by StormCenter Communications for the Chesapeake Bay Watershed. These innovative projects are now active in nine metropolitan areas across the nation.

(This story was compiled from EPA and CBS 11 news releases and the project's Web site.)

Story by Courtney Swyden

GROWING SMARTER

Water IQ campaign raises awareness of water sources, conservation

The North Texas Municipal Water District (NTMWD) has launched a "Water IQ: Know Your Water" education campaign to help residents conserve water, providing North Texans with a goal they can embrace—reduce water use by 5 percent and save money on monthly water bills.

Lubbock and Austin are also implementing the campaign in their regions. Lubbock Water Utilities along with the High Plains Underground Water Conservation District No. 1 and the city of Austin along with Lower Colorado River Authority are challenging residents to use 10 percent less water. Both cities are prepared to show residents how to save water and are working towards raising residents' water IQ.

To kick off its campaign, NTMWD chose a Plano couple—Mike and Candace Fountoulakis—to employ water-saving tips and reduce water-use by the target goal of 5 percent. NTMWD will work with the Fountoulakis', who were featured in an educational video during outreach events, as they take the challenge and pledge to do their part to save water.

The Fountoulakis' recorded water consumption from June through September 2006 showed a 6.3 percent reduction in water use compared to the same months in 2005, said Ted Burton, vice president of EnviroMedia, the public relations and advertising agency that developed the campaign.

"This is really great news," Burton said, adding that he is pleased with their results since the Fountoulakis' savings were about the same as the program's goal.

The campaign was developed from research funded by the Texas Water Development Board. NTMWD—the first in Texas to launch the campaign—is working with EnviroMedia to participate in aggressive consumer outreach to educate businesses and individuals on the source of their water and how to conserve it.

"The public education campaign was launched the same day that Drought–Stage 3 was initiated for the area," said Denise Hickey, NTMWD public relations coordinator, of the June 1, 2006 kick-off date.

The restrictions affected more than 1.6 million people in Collin, Dallas, Denton, Hunt, Kaufman and Rockwall counties. With the Drought–Stage 3 restrictions, residents are restricted to watering landscapes once every seven days. Outdoor watering with sprinklers is prohibited from 10 a.m. to 6 p.m. and residents cannot wash vehicles with a hose or drain and refill swimming pools, except to replace normal water loss.

A press conference in the Fountoulakis' front yard on June 1, the first day of mandatory water restrictions throughout the region, illustrated the water-saving contributions the district is asking of all North Texans. Stations were set up demonstrating sensible, easy tips for outdoor water use that residents can implement around the home such as raising the height of lawn mower blades and using soaker hoses, as well as swimming pool tips and explanations on how to read water bills.

EnviroMedia originally conducted statewide research in 2004 on behalf of the governor's Water Conservation Implementation Task Force.

"Based on that research, we found that only 28 percent of Texans knew the natural source of their water," Burton said.

Once they knew where their water came from, 87 percent polled said that they would be much more likely to conserve and save water, he said.

Servicing 1.6 million people in 60 cities, towns, special utility districts and water-supply corporations, NTMWD is educating locals on their primary water source, Lake Lavon, which reached dangerously low levels in 2006. Lake Lavon was constructed in 1948, shortly before the 1950s drought, when there was a high concern for dwindling water supplies in the area. Today, North Texans are facing the same drought conditions. The National Weather Service reported that 2005 was the driest year on record in North Texas since the '50s.

The Water IQ campaign provides simple and cost-effective tips to conserve water, and it is focus-group tested. For more information and to identify your water source, visit **http://www.wateriq.org/**.

The campaign offers easy water-saving tips to help consumers use less water at home or at the office:

- Use 5 percent less water. Read your latest utility bill and note how many gallons you consumed. Simply multiply the number of gallons by .05—that's your 5 percent goal (i.e.: 8,000 gallons X .05 = 400 gallons).
- Water your lawn 1 inch every seven days.
- Water your lawn in the early morning or at night. Mid-day watering results in fast evaporation and scorches your lawn and plants.
- Operate your in-ground sprinkler system manually—don't use the timer.
- If you own a pool, pay close attention to the water level.
- Use plenty of mulch in flower beds; experts recommend 4 to 6 inches to prevent evaporation and keep soil moist.
- Choose "water wise" or native Texas plants such as lantana, salvia and Mexican sage.
- Raise your lawn mower blade and cut grass to a height of 3 inches—this shades the soil, which reduces evaporation and allows roots to grow deeper.
- Check for leaks in taps, pipes and hoses.
- Use soaker hoses instead of sprinklers to water trees, shrubs and beds more efficiently.

Story by Kathy Wythe

Afghan Ambassador

Professor advises war-torn country on water resources

In December 2005, Dr. Guy Fipps, a Texas A&M University biological and agricultural engineering professor, traveled to Afghanistan to become an ambassador of water for the U.S. Department of State....

As senior advisor for water at the U.S. Embassy in Kabul, Afghanistan, Fipps' mission was to conduct strategic analysis and water planning for the war-torn country and advise the ambassador on related policies and programs. He also provided technical assistance to the U.S. Agency for International Development (USAID), the military and non-governmental organizations involved in reconstruction efforts in Afghanistan. Stationed in Kabul, Afghanistan's capital, he traveled throughout 14 provinces in the country, examining water infrastructures, evaluating issues and, finally, recommending solutions.

Fipps worked closely with the Afghan Deputy Minister for Water and the First Vice President in developing a strategy and organizational framework to address the highly contentious issues related to water-use, allocations and development.

Water is recognized as a key, and usually as the key to Afghanistan's future, he said. According to Afghanistan's Ministry of Energy and Water, 85 percent of the population is involved in irrigation-dependent agriculture and 98 percent of all water diverted from the rivers is used by agriculture, with 60 percent or more of that water lost to seepage and poor on-farm efficiency. In addition, the irrigation canal systems also provide drinking water to the vast majority of the population.

After 20 years of war, Soviet occupation and then Taliban rule, what little water infrastructure for irrigation and domestic drinking water the country had was destroyed or had deteriorated, Fipps said. Only 30 percent of the irrigation infrastructure was functioning when Fipps was in the country, and modern domestic water supply and waste treatment systems do not exist.

"Water has the same urgency as security, energy and roads, and it is even more critical to the long-term stability and economic development of the country," he said. "Unless effective programs are implemented, water shortages, internal water conflicts and international water disputes will increase and become more serious, with destabilizing consequences."

Since the majority of the population is involved in agriculture, Fipps said improving irrigated agricultural production and livelihoods is critical for maintaining social order in the country. With so many refugees who fled the country during the Soviet occupation and Taliban rule returning to the country, he said there is a need to develop new irrigated farmland for these displaced people, some of whom are involved in the insurgency against the government.

"The thinking is by getting them back into Afghan society through farming, they will no longer need to seek payment from the insurgency," he said.

He recommended increasing water infrastructure projects that would expand irrigated land and provide rural drinking water.

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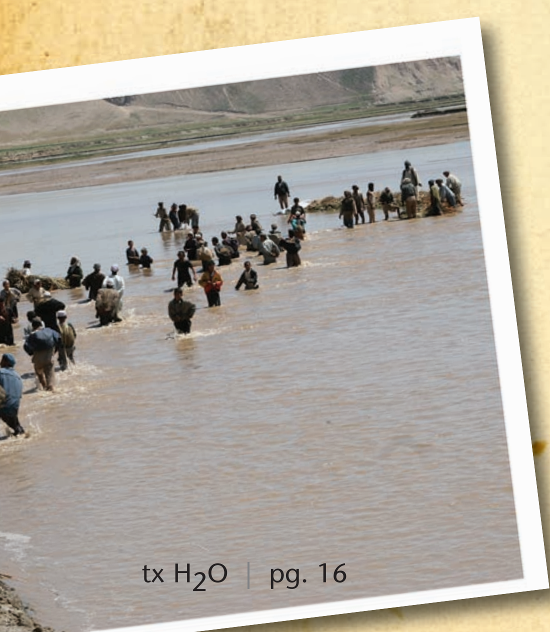
RESTORING THE TRINITY

Federal, state and local organizations are working together to restore the Trinity River Basin. Gov. Rick Perry's announcement of the Trinity River Basin Environmental Restoration Initiative in September 2006 provided a catalyst for additional projects to improve the Trinity River Basin watershed, its ecosystem and water quality *(see story on page 2).*



"Rehabilitation of irrigation systems and increasing the water supply to farmers is important," he said. "There's an urgent need for rural residents to see some benefits from the new government."

The rural economy and standard of living would improve vastly if the traditional two-crops-per-year system could be reestablished, and would reduce the need for farmers to grow poppies, Fipps said.

Another major problem Fipps said he saw was the lack of standards for the water infrastructure projects being implemented by organizations and the military. He documented through photographs examples of poor workmanship or inadequate design or use of insufficient materials. Before leaving, he presented a plan for developing standards for design, materials and performance of water structures.

Because he identified transboundary water issues between Afghanistan and its neighbors as a major issue for long-term stability of the country and the region, Fipps helped implement a memorandum of understanding between Afghanistan and neighboring Tajikistan to cooperate on joint development of water resources, such as a large hydro facility on the Amu Daya River.

Other threats Fipps identified were rapid and uncontrolled exploration of groundwater, conflicts between upstream and downstream water-users, the lack of water laws and regulations and recurring droughts.

Besides working on the water planning, Fipps said his best memories are of spending time with the military. When he first arrived, he visited provincial reconstruction teams or PRTs, which are military units that provide security for the reconstruction projects.

"I was able to help them out on what they are trying to accomplish in the PRTs," he said. "We all should be proud of our young men and women serving in Afghanistan. They're very dedicated and committed to the mission in spite of the tough and dangerous conditions they have to deal with."

Because of his diplomatic status, he was escorted by the military when traveling beyond Kabul.

"It's a rather unique experience to be taken out to look at an irrigation project escorted by three to four Humvees and guarded by 10 or more armed soldiers," he said.

While his official work as water advisor is over, Fipps remains involved in Afghan water concerns. He continues to advise the Afghan government on water issues, and USAID has asked him to return for a short-term assignment to help establish a national water agency for the country, an idea that he promoted while in Afghanistan.

In the Spring 2007, he will return to Afghanistan for a few weeks to help USAID in planning its water sector development program and to assist the Afghan government in developing its international transboundary water policy.

He will follow up on his project of designing the water supply and irrigation systems for irrigation teaching farms at three Afghan universities and introduce polypipe, a thin-walled, flexible pipe material used in irrigation to save water. He said Afghans suffer from a lack of expertise and experience with modern irrigation technologies and management practices needed to increase crop yield and farm income, while conserving water.

"Introducing polypipe could have a major impact on irrigation in Afghanistan," he said.

This training is important, he said, because the country lost a whole generation of college-trained Afghans during the Soviet war and Taliban rule.

Top photo, page 15
Afghan farmers and their sons work to repair a dike that was destroyed in a rainstorm.

Middle photo, page 15
A group of Afghan men weave ropes from thick straw brought in from 50 km away. The farmers use these ropes to transport dirt clods on their backs to the dike and bind together bales of reeds.

Bottom photo, page 15
An Afghan farmer weaves ropes from thick straw that looks like dried water reeds.

Top photo, page 16
Afghan men wade out into the river to fill the dike with straw and dirt clods, leaving gaps in the dike to reduce pressure and erosion from the river.

Middle photo, page 16
Twenty men float the large bales of dried reeds into the river to plug the gaps left in the dike. Once the bales are in the dikes, dirt clods are then layered onto the bales.

Bottom photo, page 16
As time goes on, more layers of clods and straw are built up and the dike expands further into the river.

Top photo, page 17
Restoring the diversion dike is demanding but necessary work for the Afghan farmers.

"Outside of Kabul, the country is essentially still in the 13th century...."

An excerpt from Guy Fipps' journal

Dr. Guy Fipps, a Texas A&M University professor in the Department of Biological and Agricultural Engineering, spent nine months in Afghanistan as senior advisor for Water of the Afghan Reconstruction Group. "There are lots of disadvantages to these structures," he said, recounting Afghan farmers and their families rebuilding an irrigation water diversion dike. "They wash out two or three times a year and they don't provide good control of water. It's a big strain on their subsistence economy to take the time to rebuild the dikes. But they work."

The following is an excerpt from his journal:

Kunduz is the capital of Kunduz Province in Northern Afghanistan, a regional center surrounded by vast expanses of agricultural land. Every trip out is eye-opening, but in Kunduz, I saw something really extraordinary: the construction of an irrigation diversion dike using methods and materials that have not changed for centuries, maybe for thousands of years....

For thousands of years people have lived along the rivers of what is now Afghanistan and diverted water into hand-dug canals to irrigate their crops. Taking advantage of the mountains and slopes, a single canal can run many miles and provide water to many villages, tens of thousands of people and large irrigated areas.

Afghans construct earthen dikes extending out into the river to divert water. Unfortunately, these dikes frequently wash out when the rivers rise in the spring and early summer as the melting of the mountain snow accelerates. It is the snow that falls in winter that gives water and life to this arid land.

Such was the case of the KZ canal. A weekend rainstorm just three days ago caused the river to rise high enough to completely wash out the existing diversion dike. Now, very little water is flowing into their canal, and approximately 20,000 families cannot irrigate their crops. It's early in the growing season; plants are short and cannot go more than a week without water. As of today, the local farmers have only five days to get the dike rebuilt before facing the danger of crop failure....

...we're amazed at the size of the operation, approximately 400 men and adolescents hard at work.

And what an operation it is. The men are divided into several different work crews. One crew digs up large dirt clods, each weighing around 50 pounds…. The Afghans hope that the grass will take root and help hold the dikes together.

A group of men are busy weaving ropes from a thick straw that looks like dried water reeds…. Some of these ropes are used by the men to cradle the dirt clods on their backs. A group of men lift the dirt clods and help secure them on the backs of the workers who then carry them to the river and wade out into the moving water to drop them onto the expanding dike. Layers of clods and straw are built up, and the dike is extended farther into the river.

The work is very hard and demanding; it must be extremely difficult, first carrying a large load of dirt on your back, then wading though the water with the thick underfooting of river bottom silt.

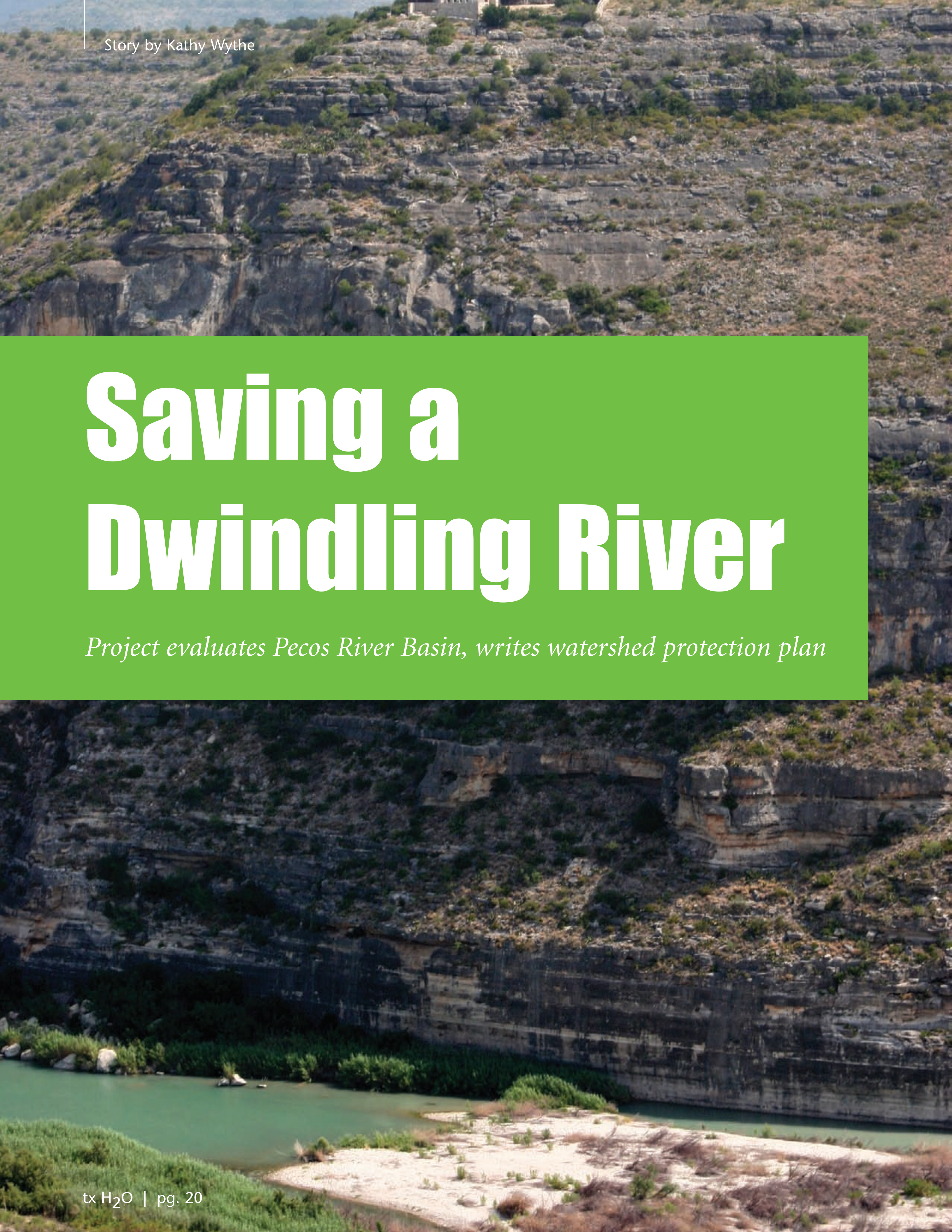
We watch as the dike quickly forms and extends farther into the river. Such a massive and organized operation is amazing and fascinating to watch. Each farmer along the canal contributes labor or money proportionally to the size of his land.

I watch as the straw men make huge rectangular bales of dried reeds held together by the thick ropes of woven straw. Finally, their purpose becomes clear. As the dike is constructed, gaps are left in the dike in order to reduce the pressure and erosion caused by the moving water in the river. It takes 20 men to roll the huge bales into the river and to float them out to the dike to plug these gaps. Dirt clods are then layered on the straw bales to complete the dike….

The dike will wash out a few times a year, taking money and labor away from cultivation and harvesting of crops, further hurting the subsistence agriculture of the region.

Three weeks later, I visit the site. The dike is still standing even though the river has already risen a foot since my last visit. The dike is working perfectly and diverts large amounts of water into the KZ canal.

Dr. Guy Fipps of Texas A&M's Department of Biological and Agricultural Engineering was escorted by the U.S. military as he traveled throughout Afghanistan to inspect water resources projects.



Story by Kathy Wythe

Saving a Dwindling River

Project evaluates Pecos River Basin, writes watershed protection plan

A group of researchers, educators and stakeholders are deciphering the Pecos River Basin and its ecosystem as the first step in solving the watershed's water quality and quantity problems. This multiagency group is evaluating the river and developing a watershed protection plan as part of the Pecos River Assessment Program.

The Pecos River, which winds more than 800 miles through semiarid and arid landscapes of eastern New Mexico and West Texas, is crucial to many communities, mainly for irrigation, recreational and environmental use and recharging underlying aquifers. The river is the largest U.S. tributary flowing into the Rio Grande, accounting for 11 percent of stream inflow into the Amistad Reservoir.

The Pecos was once a grand river, providing early settlers with abundant water to irrigate crops and furnishing their families with drinking water. Today, however, the river's flow has dwindled—to a trickle in some areas—due to natural and man-induced causes. Irrigation demands and the use of inefficient systems, reoccurring droughts and the spread of non-native, water-thirsty saltcedars have depleted the water supply. The river's salinity is so high that the water is sometimes harmful for irrigation, livestock and drinking. This salinity stems from natural saline deposits—remnants of the shallow Permian Sea that once covered the area—in soils and rocks. The reduced quality and quantity has also harmed the river basin's biodiversity. These problems have persisted for many years and have only been intensified by human influences.

The three-year project that began in 2004 is a collaborative effort of Texas Cooperative Extension, Texas Agricultural Experiment Station, Texas Water Resources Institute and the U.S. International Boundary Water Commission's (IBWC) Clean Rivers Program. The Texas State Soil and Water Conservation Board (TSSWCB) funded the project through the Clean Water Act, Section 319 from the U.S. Environmental Protection Agency.

"The river's importance—historically, biologically, hydrologically and economically—to the future of the entire Pecos River Basin and the Rio Grande is huge," said Will Hatler, project coordinator. "If the integrity of the Pecos is to be improved and maintained, it is crucial that its water quality and quantity be increased."

According to Dr. Charles Hart, project director, the project's first objective is establishing a research baseline for the watershed by identifying and evaluating the river basin's physical features, from both a historical view as well as current conditions.

"We needed to determine what we could do to alleviate some of the problems," said Hart, an Extension range specialist and professor in Texas A&M's Department of Rangeland Ecology and Management.

Aerial photographs, delineations and characterizations of riparian zones and the river system are currently being incorporated into multilayered, interactive maps, Hart said. These maps will cover the entire basin and link with a database allowing users to access information about specific points, such as water quality testing sites.

High salinity was already known as the river's biggest water quality concern—it is one of the saltiest rivers in North America—and has affected its biodiversity as well as making it nonpalatable for livestock or irrigation use.

According to Dr. Seiichi Miyamoto, professor at The Texas A&M University System Agricultural Research and Extension Center at El Paso, the flow of the Pecos accounts for a significant amount of salts entering Amistad International Reservoir, a water supply source for much of the lower Rio Grande Valley. The reservoir provides water for municipal as well as agricultural uses. Its salinity reached 1,000 mg per liter (the upper limit of secondary drinking water standard) in 1988, Miyamoto said, and, unless salinity is controlled, there is a concern that such incidents may occur with greater frequency.

Miyamoto, Fasong Yuan and Shilpa Anand of the El Paso center analyzed the streamflow and salinity data from 11 gauging stations and found much of the Pecos Basin's salinity stems from dissolution of salts from natural sources that are remnants of the

shallow Permian Sea that once covered the area. They also found that the main salt loading is occurring upstream of Red Bluff Reservoir, north of the Texas/New Mexico border. More detailed information on this research is available by downloading TWRI Technical Report 291, "Reconnaissance Survey of Salt Sources and Loading into the Pecos River," at **http://twri.tamu.edu/reports.php**.

The research team has also compared flow and salinity data from the Pecos River to salinity levels in Amistad International Reservoir. Their report, "Influence of Tributaries on the Salinity of Amistad International Reservoir," was completed in April 2006 and is available to download as TWRI Technical Report 292 at **http://twri.tamu.edu/reports.php**.

Another portion of the project assesses the fate of salvaged water from controlling saltcedar, a non-native water-thirsty plant. Hart, Hatler, Alyson McDonald a range management specialist for Extension in Fort Stockton, and Dr. Zhuping Sheng, assistant professor at the El Paso center are evaluating how much water can be salvaged by eliminating saltcedars, and how water flows between the river and the shallow aquifer.

"Our preliminary results show that an acre of saltcedar uses two to four acre-feet of water a year," Hart said. "And we are able to salvage about 65 percent of that" by controlling the plant with aerial spraying of herbicides and other methods of control.

Controlling saltcedar was the focus of another project, the Pecos River Ecosystem Project.

Hart, McDonald and Sheng are also assessing the amount of water saved with saltcedar control that may contribute to downstream flow and/or groundwater recharge. Monitoring data demonstrate a good interaction between the river water and shallow groundwater. Hydrologic conditions control whether the saltcedar control can generate a greater stream flow or a greater recharge into the shallow aquifer. The information collected will help predict the effect of saltcedar control on water quantity as well as quality under different management scenarios.

"We are expecting that by treating saltcedar, base flows in the river will increase," Hatler said.

Both Hatler and Hart said having local landowners and other stakeholders involved in the project was important. The team conducted a survey and held stakeholder meetings to receive their input. The survey found that most stakeholders believe the invasive, water-thirsty saltcedar and debris left from killing it are the biggest concerns for the river.

"We have taken all the information gained from the survey and meetings and incorporated it into the watershed protection plan," Hatler said.

The plan is now a working document and is being reviewed and refined, said Lucas Gregory, who manages the project for TWRI. Once the project's team finishes the draft, local stakeholders will give their input on the plan. The watershed protection plan assesses current management measures as well as determines what future management measures need to be implemented in the river basin to protect the river's water quality, Gregory said.

Gregory, who oversees the development of the project's research and educational programs and is responsible for project reporting, said some members of the project's team have developed a historical paper, "The Influence of Human Activities on the Waters of the Pecos Basin of Texas: A Brief Overview" as well as a historical fact sheet, "Historic Water Issues Facing the Pecos Basin of Texas." These publications give stakeholders an overview of the river, its history and issues and are available on the project's Web site.

Other state and federal agencies are conducting research on the Pecos.

IBWC, Texas Commission on Environmental Quality's Clean Rivers Program, Texas Parks and Wildlife Department and the U. S. Geological Survey are conducting ongoing programs to monitor the river's water quality and biology. Monitoring the aquatic species that are present in the Pecos River will provide insights to assess the effects of point and nonpoint sources of pollution such as nutrient enrichment and sedimentation. This information can also be used to develop plans to protect threatened and endangered species in the region and to increase the diversity of aquatic species in the Pecos River.

The Texas Nature Conservancy is working with private landowners to acquire, protect and manage critical habitat in the lower reach of the river near its confluence with Independence Creek.

Hatler said it will take a long-term commitment from everyone involved, especially stakeholders, to restore the Pecos. "We want to see success in long-term management," he said.

For more information on the project, contact Will Hatler at **wlhatler@ag.tamu.edu** or go to the Web site at **http://pecosbasin.tamu.edu**.

Story by Danielle Supercinski

Practicing Precision

Researchers demonstrate irrigation techniques on producers' farms

Wintergarden and High Plains researchers and county agents worked with 30 growers from various counties to conduct on-farm research demonstrations evaluating the extent to which limited irrigation practices may provide water savings and associated benefits.

These growers, Texas Agricultural Experiment Station researchers and Texas Cooperative Extension specialists and county agents have been working together since 2005 as part of the Precision Irrigators Network (PIN). The first stage of the PIN project was completed in September 2006, yielding preliminary water savings and establishing on-farm collaborations.

"Results from the first year of the study show tremendous possibility for water savings," said Dr. Giovanni Piccinni, PIN project leader and assistant professor of crop physiology with the Experiment Station at Uvalde. "While some growers are doing a very good job using limited irrigation strategies, others are overwatering their crops. These are the growers we want to target next year to improve their water-use efficiency."

PIN is educating agricultural producers about water conservation and irrigation management of various crops, including corn, cotton, grain sorghum, wheat and such winter vegetables as onions, spinach and other economically significant crops. The project's main tasks include: (1) evaluating limited irrigation on agronomic and vegetable crops, (2) evaluating the use of subsurface drip irrigation for forage production, (3) validating the High Plains Potential Evapotranspiration Network, and (4) developing and delivering educational programs.

A LEPA (Low Energy Precision Application) irrigation system is used on the PIN cotton field at The Texas A&M University System Agricultural Research and Extension Center at Uvalde along with lysimeters to evaluate crop water use and develop deficit-irrigation management strategies.

This project was built upon ongoing success achieved through the North Plains Potential Evapotranspiration Network (NPET), which provides updated data agricultural producers can use to precisely apply the amount of water that meets crop needs, thus resulting in water conservation. In the past, translating new research discoveries into farming practices were often stalled because of the perception that research results do not conform to on-farm reality, Piccinni said. Therefore, PIN demonstration trials are carried out on producers' fields in the Wintergarden and High Plains regions, rather than on research centers, so producers can be involved in the research as well.

"We involve the producers in the research project by developing strategies specific for his/her farming system," Piccinni said. "By being involved firsthand in the research process, the producers are more likely to 'buy' into it and continue to apply newly developed strategies on his/her field, giving immediate adoption of research-proven practices.

"Furthermore, we envision that neighboring growers will be more likely to implement new management practices demonstrated on nearby farms rather than those shown only on small Experiment Station plots."

PIN strives to achieve these water savings through producer education, which results in the adoption of advanced technologies and conservation practices. Preliminary studies suggest that, based on 90,000 acres of irrigated land, widespread use of deficit irrigation practices have the potential to save up to 60,000 acre-feet or 19,530 million gallons of water annually in the Wintergarden region, and as much as 413,000 acre-feet of water each year in the Lower Rio Grande Valley (TWDB report 347, August 2001). In the High Plains region, the sum of the 12 producer fields totaled water savings (water pumped) of 16,715 acre-inches for the 1,900 acres of production monitored. The average water savings per corn producer was 8.7 inches per acre annually.

Studies conducted through this PIN project serve as a baseline for potential water savings and serve as a focus for Extension educational programs. A second project, which continues using PIN project data, began in September 2006, and researchers and county agents will continue working on-farm with agricultural producers to evaluate crop water needs and uses to further test irrigation methods to find the most water-efficient methods and amounts.

"We would like total participation of the Wintergarden and High Plains producers," Piccinni said. "By joining the Precision Irrigators Network, producers can achieve water savings resulting in increased profits. As always, when we talk about limited irrigation, the bottom line is we want to 'make every drop count.'"

PIN, as well as the continuation project, was funded by the Texas Water Development Board. Additional support was provided by the Rio Grande Basin Initiative through the Texas Water Resources Institute, Texas Agricultural Experiment Station, Texas Cooperative Extension, San Antonio Water Systems and Edwards Aquifer Authority.

Lysimeters are used in the cotton field to determine crop coefficients to use in combination with deficit-irrigation methods.

Story by Kathy Wythe

Gaining a World View

A&M students exposed to European environmental issues

The Summer 2006 group of the Environmental Soil and Water Study Abroad program in Belgium, a program of Texas A&M University's Department of Biological and Agricultural Engineering traveled to the Delta Works project in the Netherlands.

When Brandon Hartley traveled to Belgium last summer, he gained a first-hand appreciation for international soil and water issues.

Hartley, a Texas A&M University biological and agricultural engineering major from Santa Fe, Texas, is one of 24 students who have traveled with the department's Environmental Soil and Water Study Abroad Program to Belgium over the last two summers to obtain a different view of environmental soil and water issues.

"The program gave me a chance to experience something totally different from what I was used to," Hartley said. "It gave me a global perspective on what I will be pursuing after graduation and some of the problems I may need to face in a global market."

Dr. Clyde Munster, a professor in the Department of Biological and Agricultural Engineering, organized the program. "Our students need to get international experience," he said. "The job market is not just state- or United States-wide anymore."

The five-week program, scheduled to correspond with A&M's second summer session, is hosted by the Katholieke Universiteit of Leuven, Belgium. The Belgium Study Abroad program costs $3,000, which includes lodging, meals and field trips. Students are responsible for their A&M tuition, airline ticket and spending money.

Each summer the program offers two nonengineering courses and one engineering class for six hours of course credit toward graduation. Engineering students can take one of the nonengineering courses as a technical elective. The study abroad program, which satisfies the international and cultural diversity requirement, is open to all students in The Texas A&M University System.

In summer 2007, Munster and Dr. Ann Kenimer, a biological and agricultural engineering professor, will teach a basic environmental hydrology class (one engineering section and one nonengineering section) and an overview class on the technology

The Oosterscheldekering, the largest of the 13 series of dams of the Delta Works project, is a series of gates that can be opened and closed to protect the land from storm surges of the ocean.

for environmental and natural resource protection (nonengineering course).

Munster said classes are intense with all-day, in-class teaching on Tuesdays and Wednesdays, and field trips to different water and wastewater projects unique to Europe on Thursdays. Since Belgium is small and centrally located, the group has traveled to the Ardennes region of Belgium as well as the Netherlands and Germany on field trips.

"The field trips allow the students to compare and contrast European ways to solve environmental problems," he said.

One of the students' favorite trips is to the Delta Works project in the Netherlands. The Dutch developed this project after a huge North Sea flood in 1953 broke dikes and seawalls, killing nearly 2,000 people and forcing evacuation of 70,000 more. The flood-defense system consists of 13 projects, one of which is called *Oosterscheldekering*, which is a series of 50 to 60 gates that can be opened and closed to keep the sea at bay while preserving the saltwater river delta for wildlife and for the fishing industry.

"They came up with a solution that is environmentally sound but still protects," Munster said. "It's very cutting-edge technology."

Hartley, whose home is near Galveston on Texas' coast, said he was particularly interested in this project because of the damage of Hurricane Katrina in 2005. "Observing this project has reassured me that once people put their minds to something, they can accomplish just about anything," he said.

Hartley said since the A&M classes are open to other international students—students from Vietnam, Iran and Kenya were in the 2006 classes—he learned about environmental problems in those countries as well.

Both Hartley and Craig Birkenfeld, a biological and agricultural engineering student from Nazareth, Texas, said they were intrigued with Belgium's sophisticated recycling program.

In Belgium, Hartley said, every piece of land is put to good use. "What is not used for towns or cities is used for agriculture," he said. "Everything is recycled because they do not have any land for landfills."

"I was amazed at how much effort is put forth to avoid wasting materials," Birkenfeld said. "I think I may be able to apply these practices to my career field some day."

Elvin Sterns, who participated in the program in 2005, said that in every interview he has had since participating, he has been asked about his experience and what he gained from the program. Sterns, who graduated in May 2006 and is currently interning at the National Association of State Departments of Agriculture, said he became interested in international water issues because of the program.

"Many other countries are not as modern as the United States when it comes to water management," he said, "and that is something where we could use our knowledge to help others."

Munster agreed that the program gives students a diverse outlook.

"The students gain a different perspective on the world and other people's culture. They see things a little bit differently." Munster said. "But they also see that we're all basically the same."

TWRI Briefs

The *Efficient Irrigation for Water Conservation in the Rio Grande Basin* project received the Cooperative State Research, Education and Extension Service's National Water Program 2007 Award for its Outstanding Integrated Activities for Water Resources. Dr. Michael O'Neill, national program leader for water resources at CSREES, presents Dr. Bill Harris of TWRI and Craig Runyun of New Mexico State University the award. RGBI was one of the 37 projects nominated.

Dr. Elsa Murano presents Dr. C. Allan Jones, director of TWRI, with the Vice Chancellor's Awards in Excellence: Award for Administration for his expertise and commitment to TWRI. Respected throughout the state and nation, Jones grew TWRI's three projects and $300,000 budget in 2001 to today's 70 projects with more than $13.5 million in funding.

The Rio Grande Basin Initiative Research team won the 2006 Vice Chancellor's Awards in Excellence: Award in Research. Drs. Elsa Murano, (far left) vice chancellor and dean for Agriculture and Life Sciences, and director, Texas Agricultural Experiment Station, and Bill Dugas, (far right) associate director for operations, Texas Agricultural Experiment Station, present Drs. Bob Wiedenfeld, Edward Rister, Juan Enciso, Zhuping Sheng, Ari Michelsen and Giovanni Piccinni the award for the entire research team.

Sandra K. Fry, Epsilon Sigma Phi chapter president, and Dr. Ed Smith, Texas Cooperative Extension director, present Dr. Bill Harris, associate director of TWRI, with the Epsilon Sigma Phi Retiree Service Award, an honor that recognizes a retired Extension professional who continues to contribute to Extension programs and volunteers in community activities. Since Harris retired from Extension in 2001 and joined TWRI, he has been active in acquiring nearly $14 million and eight major projects for Extension in Texas.

New Faculty

Dr. Humberto Perotto-Baldivieso

Agricultural Research and Extension Center at Uvalde

Dr. Humberto Perotto-Baldivieso joined the Uvalde center in August 2006.

Perotto received his doctorate in rangeland ecology and management from Texas A&M University in 2006.

Perotto is the first landscape ecologist to be on staff at the Uvalde center where he will perform spatial structural analysis of crop lands for precision agricultural applications and vegetation as well as animal landscape interactions in South Central Texas rangelands in order to improve water resources management and improve farming and ranching efficiency.

Dr. Armen Kemanian

Blackland Research and Extension Center at Temple

Dr. Armen Kemanian recently joined the Temple center as an assistant professor.

Kemanian received his doctorate in biological systems engineering from Washington State University in 2003.

Kemanian's research focuses on the development and application of biophysical models to agroecosystems with an interest in watershed level, plant, crop, soil and whole-farm systems. His research includes measuring and modeling ammonium flux from irrigated, high-input crops.

Dr. Yongheng Huang

Department of Biological and Agricultural Engineering

Dr. Yongheng Huang joined the Department of Biological and Agricultural Engineering as an assistant professor.

Huang received his doctorate in civil engineering from the University of Nebraska–Lincoln in 2002.

Huang's research interests include water treatment technologies, environmental chemistry, environmental-remediation technologies and water quality modeling with concentrations in anaerobic biological wastewater treatment and membrane technology for desalination.

Rio Grande Basin Initiative

OUTCOMES

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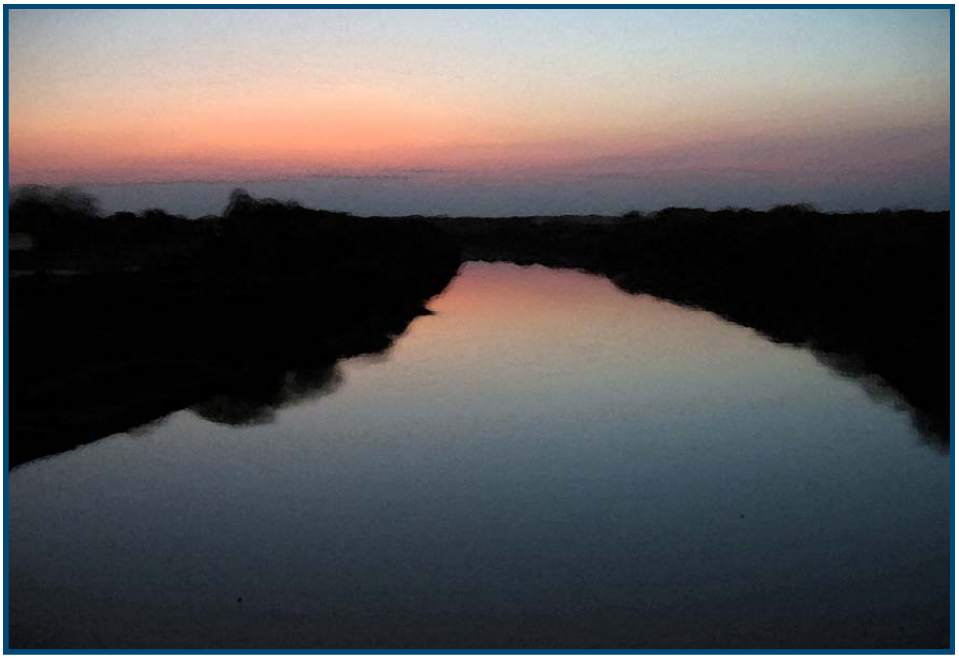

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Home Economics

For these and other stories, please visit:
http://riogrande.tamu.edu

RGBI Researchers Spend Time in Prison

Graywater versus well water study in El Paso

by
Danielle Supercinski

Naomi Assadian and other researchers have been going to Rogelio Sanchez State Prison in El Paso, Texas, not serving time, but spending time exploring the potential for safe and beneficial uses of graywater for irrigation.

"We have been interested in wastewater reclamation to conserve fresh water supplies and realized little work had been done with graywater in far West Texas," said Naomi Assadian, associate research scientist at the El Paso Agricultural Research and Extension Center. "We also wanted to do something at the state prison because a prison crew helps us at the Research Center. One crew is assigned to work at our Research Center three-quarters time and they assist and get trained in maintenance projects. A different crew maintains our research plots located at the prison."

Assadian decided to use the prison grounds to construct a field test and study how graywater irrigation affects crop yields versus using salty groundwater. The prison provided a non-traditional site on a desert mesa of shallow, loamy sand underlain by caliche, receiving less than 10 inches of rain during the growing season. Graywater, diluted wastewater coming from showers, kitchens and laundry, comprises 68 percent of total domestic wastewater. At the prison, 11 loads of laundry are washed per day going through two wash cycles, two rinse cycles and one sour bath/bleach cycle, using 3,500 gallons of water daily.

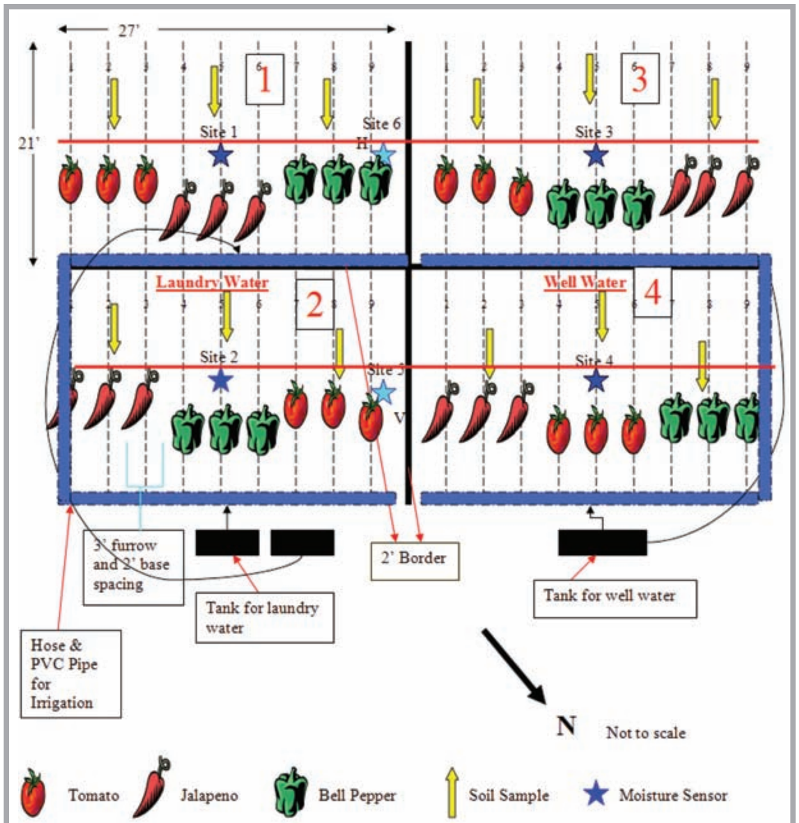

Figure 1: *The plot design to evaluate the potential of prison laundry water as an irrigation supply at Rogelio Sanchez Prison, El Paso, Texas.*

"Using laundry water was an excellent choice because in most households and in the prison, laundry consumes vast amounts of water," Assadian said.

The prison's only source of landscape irrigation up to this point was salty groundwater. The researchers decided that reusing the laundry wastewater provided an alternative to using potable water or the salty groundwater.

Prior to planting, two moisture sensors were placed 5 and 8 inches below the soil surface and connected to above-ground data loggers. Vegetable seedlings were purchased from a local nursery and transplanted to the plots on May 3, 2005. Tomatoes, long green chilies and bell peppers were the vegetables chosen for this study because they are very susceptible to salinity.

"If we could grow high maintenance veggies with poor water, we knew we could grow almost any crop," Assadian said. "We also wanted to verify that pathogen contamination may be little to none under a hot and dry desert environment in spite of potential waterborne pathogens."

Bell pepper mortality was highest, suggesting more sensitivity to environmental change and salinity than tomatoes or long green chilies.


Photos courtesy of Naomi Assadian

Tomatoes, green chilies and bell peppers are grown in this demonstration plot at the prison. Four sets of each plant receive graywater and another four sets of each plant receives salty groundwater.

"Hot temperatures in May followed by a cool, moist winter and spring flushed leaf hopper populations from the fringe of the desert onto the plots," Assadian said. "Leaf hoppers were vectors that transmitted curly leaf virus to the vegetable plants. About 30 percent of all plants were infected with the virus by June 10, 2005."

Evidence of infection increased and affected overall plot production, she said. Insecticide application alone did not control the transmission of disease. However, in spite of the infection, all vegetables grew well in all plots.

The most challenging issue was establishing a water delivery system to the demonstration plots, Assadian said.

"Security prevented construction of a continuous pipe system from the laundry trap inside the prison to the field test site outside of the prison," she said. "As a consequence, water was pumped and transferred from a mobile reservoir to a stationary one. The 250-gallon capacity of the stationary water tanks and the tedious pumping process dictated irrigation volumes for each application."

Shallow, salty groundwater was pumped from a well, hauled and placed in a 900-gallon stationary tank. Water delivery from the tanks to the blocks was via a 2-inch diameter PVC pipe using gravitational flow. The PVC delivery pipe was connected to a perforated PVC pipe laid perpendicular to the nine rows in each plot, so that water was distributed uniformly to each furrow (see Figure 1).

The plots were irrigated every two to three days, and soil moisture was measured by the moisture sensors. Salinity, soil moisture, *E. coli* and vegetable data were collected regularly. *E. coli* was not found in laundry water collected directly from the subsurface laundry water trap. Both the laundry water and well water were tested for salinity, and the laundry water was less saline than the well water. Soil moisture data was collected for each plot at time intervals from 1 minute to 15 minutes and this data was downloaded every other week.

Researchers originally thought that salty well water may be a superior irrigation source to laundry water. Instead, laundry water irrigation significantly increased vegetable production relative to well water irrigation.

Preliminary results suggest that the reuse of laundry water for irrigation may be beneficial and safe even for salt sensitive crops like vegetables, she said. Vegetable data results suggest laundry water had no detrimental affect on early transplant stress and plant growth. Irrigation with laundry water actually increased fruit yields, fruit size and the number of fruits harvested from selected plants relative to those receiving well water irrigation, Assadian said. Average yields from the three plants irrigated with laundry water were almost four times greater than those from well water plots. Tomatoes produced the highest yields, followed by bell peppers and long green chilies.

"Our field observations indicate that long green chilies and bell peppers were more salt sensitive than tomatoes," Assadian said. "Salts decreased long green chili pods to the size of jalapeno peppers."

*See **Prison** on page 5*

Precision Irrigators Network

Helping growers conserve water and schedule irrigations

by
Danielle Supercinski

Growers are becoming more involved with on-farm irrigation research to conserve water through the Precision Irrigators Network (PIN) project, funded by the Texas Water Development Board, which came from a natural progression of the Rio Grande Basin Initiative (RGBI).

"RGBI provided the lab to develop the knowledge we have of crop-water use," said Dr. Giovanni Piccinni, assistant professor of crop physiology with the Texas Agricultural Experiment Station. "Lysimeters at the Uvalde Agricultural Research and Extension Center allow us to provide growers in the region with precise data of crop-water use. The Uvalde Center currently has five lysimeters installed, with two more to come sponsored by the Wintergarden Groundwater Conservation District."

In addition, RGBI provides precise research data that must be done on the research station farm so if losses occur they can be corrected. PIN then takes this research to the growers to calibrate it further for the Edwards region. Researchers want growers to implement an irrigation schedule based on precise meteorological data from nearby weather stations, providing estimates of evapotranspiration (ET) and crop coefficients developed using lysimeters.

"We know how to manage full irrigation, unfortunately full irrigation is often not an option."

"PIN provides a support system for irrigation management," Piccinni said. "Irrigation needs to be calibrated to different soils, cropping systems and the environment. We're trying to do this with the collaboration of the growers so they can see how it works on each farm."

When a grower begins participating in PIN, researchers visit with the growers, go on-farm and look at the field, and try to collect data off the field – crop rotation, irrigation schedules, type of irrigation, planting date, plant growth, soil type, etc. Watermark sensors are installed to monitor soil moisture. This data is inputted into a computer model and researchers explain the information they have found to the growers.

"These irrigation scheduling data are then compared with the grower's experience and knowledge of the field," Piccinni said. "Then we compare his irrigation schedule with what the potential ET calculator is telling us, what the soil moisture sensor is telling us and what the grower experience is telling us. This way, everyone is participating in the research process."

"We want to give as much water as the crop needs and not a drop more because we want to make every drop count!"

Once the growers buy into this process and the new irrigation strategies, it is more likely their neighbor can see what's going on and buy into it as well. Piccinni is trying to get away from grower's skepticism of these irrigation practices working at the research center plots, but not in the field.

"PIN has allowed us to get away from small replicated research plots and do large scale research with different treatments imposed by the landscape variability that exists throughout the Edwards region," he said.

The ultimate PIN goal is for growers to gain more knowledge on how to schedule irrigations and how to manage limited irrigation.

"We know how to manage full irrigation, unfortunately, given water restrictions in this region, full irrigation is often not an option," Piccinni said.

The PIN project currently consists of 15 growers throughout Atascosa, Bexar, Frio, Medina, Uvalde and Zavala counties. Researchers work with the PIN growers to help schedule limited irrigation by using decision support systems such as the potential ET networks and CroPMan computer models.

Growers, county Extension agents and researchers all collaborate and work together on this project to implement efficient irrigation management. Extension agents identify growers to participate in PIN, and

Photo courtesy of Kenneth White

Photo courtesy of Giovanni Piccinni

(Left) Growers learn about the PIN during the National Spinach Conference Field Day tour. (Right) Eddie Byrom, Giovanni Piccinni and Brad Ensterling in a center pivot-irrigated corn field installing watermark sensors to monitor soil moisture.

they hold meetings to explain how PIN works to the growers.

Kenneth White, ag and natural resources county Extension agent in Uvalde County, is one of these county agents who began implementing PIN in the fall of 2004 by taking ET information out to a few grower's fields.

"The first cooperator I used the data logger and sensors with kept track of fuel costs and irrigations," White said. "He reported they were able to save more than 4 inches of irrigations, or 50 acre-feet of water, and fuel costs of $20 per acre. They used this information on their bermudagrass pastures and winter pastures."

He currently works with 11 growers on corn, cotton, bermadagrass and cool season forages. Watermark sensors and data loggers are established in all fields, and result demonstrations on drip irrigated onions, spinach, cantaloupes and warm season grasses are established.

"As a result of implementing the PIN and weather stations, growers and consultants will be able to use local ET Web sites, newspapers and radios to assist with their irrigation scheduling," White said.

Bill Howell, producer at the Chaparrosa Ranch west of La Pryor, said: "Utilizing the information from the weather station takes 85 to 90 percent of the guess work out of how much water to apply in their forage operation. I can use that information along with information from the watermark sensors to determine when I need to irrigate our forages."

Austin Clary, a cotton producer in Sabinal, called White asking if he was still planning on establishing result demonstrations on using soil moisture sensors and data loggers. Clary said this was the best and most informative information he has ever used to assist him with his irrigation scheduling.

"We want to give as much water as the crop needs and not a drop more because we want to make every drop count," Piccinni said.

Prison

continued from page 3

"We are now entering year two of a three year project, and we are hoping to gather more data on potential salt accumulation in the soil, the persistence of *E. coli* in soil and on mature fruits, and the yield performance of relatively salt sensitive crops," Assadian said. "RGBI contributes to this project in a tremendous way. I use RGBI support for labor, chemical analysis and supplies. Without RGBI funds, this project would be reduced to a show and tell project without any data."

Additional funds for this project are received from the U.S. Bureau of Reclamation (BOR). Collaborators are Woody Irving with BOR and Sergeant Gibson, Officer Barnes and offenders at Rogelio Sanchez State Prison. Critical support is also provided by co-PI Dr. Zhuping Sheng, Dr. Wesley Brown, Joshua Villalobos and Elizabeth Gonzalez from the Texas A&M El Paso Research Center.

"Water reclamation is not an easy task and often is more challenging than using good water supplies," Assadian said. "However, this project demonstrates that a multiple-agency, multiple-team effort can successfully work toward a common, but challenging goal to beneficially use every drop of precious water."

Communicating Outcomes

Annual collaborating and sharing of information

by
Danielle Supercinski

(L to R) Allan Jones, TWRI director; Ari Michelsen, TAMU; Kevin Urbanczyk, TSUS; Vic Morgan, Sul Ross President; Bill Harris, TWRI; and Daene McKinney, UT-Austin.

As participants arrived in beautiful Ruidoso, New Mexico, cool, breezy weather greeted them for the fifth annual Rio Grande Basin Initiatives (RGBI) Conference held March 28-30, 2006.

The week began with welcome talks from project and university administrators and an overview of New Mexico region water issues. The first day moved quickly into individual task group and county program presentations, which continued throughout most of the conference. The week ended with additional project reports from the U.S. Geological Survey, New Mexico Water Resources Research Institute and an overview of the River Systems Institute, Transboundary Studies Center and Edwards Aquifer Center at Texas State University. The conference closed with wrap-up discussions regarding future collaborations.

RGBI project participants from New Mexico State University (NMSU) and the Texas A&M University System (TAMUS) attended along with participants from two other Rio Grande projects from the Texas State University System (TSUS) and the University of Texas (UT). This three-day event brought together project administrators, state and federal agency partners, irrigation district managers, Extension agents and specialists, and Experiment Station researchers.

"We have a lot of friends in this room and we enjoy the opportunity to get together, meet and discuss our research and educational efforts and results," said Dr. Bill Harris, RGBI project director and associate director of Texas Water Resources Institute. "It is a great pleasure to collaborate with NMSU in our RGBI project and we enjoy our newer interactions and collaboration with Kevin Urbanczyk from TSUS and Daene McKinney from UT."

Having this joint conference between the three initiatives allows project participants from the different universities to visit with each other and discuss opportunities for collaboration on their projects in the future, Harris said. The format for this year's conference was set-up different than previously to allow each of the three projects time to talk and present each individual's project efforts and results.

"Most of the time project participants within the same project aren't aware of each other's efforts," Harris said. "This format gave everyone a chance to see what everyone else is doing within their own initiative."

The RGBI project is in its fifth year and success continually builds toward conserving water in the Rio Grande Basin.

"You might think that the enthusiasm and excitement might be diminishing, but I don't see that," said Craig Runyan, water quality and RGBI program coordinator at NMSU. "It's a synergy that builds upon itself. As long as we're showing enthusiasm and getting results then we help to ensure we continue with these activities."

However, it is apparent that collaboration is the key.

"It is important for TAMUS, NMSU, UT and TSUS to know what each other is doing," said Kevin Urbanczyk, project director for the Sustainable Agricultural Water Conservation Project and Earth and Physical Sciences Department chair at Sul Ross State University. "This is a perfect example of collaboration. I plan on attending all of these meetings in the years to come."

To view the 2006 and past conference materials, presentations, photos and all initiatives' Web sites go to http://riogrande-conference.tamu.edu.

County Program Highlights

Uvalde County

Kenneth White
Uvalde County
Agriculture and Natural Resources Extension Agent

Programs: Extensive programs and result demonstrations in field crops, vegetables and forages. Other programs involve livestock and wildlife. Work with the Precision Irrigators Network producers monitoring soil moisture and collecting information from data loggers.

Crops: Corn, cotton, grain sorghum and wheat

2005 Accomplishments: As a result of irrigation work, the Precision Irrigators Network (PIN) was developed and implemented in 2005 and has expanded to six additional counties. Producers have been able to reduce pumping costs and conserve water by utilizing soil moisture sensors, data loggers and weather station data to schedule irrigations. County crop tours have been conducted with more than 100 participants to view the latest information on water conservation and irrigation management.

Kenneth White said: "One of the most enjoyable things in my 32 year career as an Extension Agent has been the opportunity to work with producers in implementing new or different ways of doing things."

Faces of RGBI

Web site guru provides technical support

by
Bill Harris

When anyone at TWRI needs a project Web site developed, changed or edited, they head straight to Jaclyn Tech's office. She joined TWRI in 2003, and she now manages more than 20 project Web sites, including the RGBI Web site, and works for both TWRI and the Spatial Sciences Lab.

Jaclyn is always more than happy to add new stories to the homepage, add a couple more pictures, make a few changes here and there, and whatever else is asked. She has done a wonderful job maintaining the RGBI Web site, as well as developing the joint Rio Grande Basin Initiatives Conference Web site in such an efficient and speedy fashion.

As a member of the TWRI-RGBI team, Jaclyn attended the conference in Ruidoso, NM and provided excellent support with setting up Power Point presentations so they would flow seamlessly. From re-linking all the presentations to the presenters' names to making updates to presentations and copying new presentations from jump drives to the computer at the last minute, Jaclyn kept it all under control and flowing smoothly. She is also creator/webmaster of the joint three initiatives' conference wrap-up CD and Web site.

We really appreciate Jaclyn's technical support that she provides the RGBI as well as all the other projects she works on. Thank you, Jaclyn! Your cheerful face brightens our days.

Increasing Irrigation Efficiency in the Rio Grande Basin through Research and Education

Through Extension and research efforts, the Texas Agricultural Experiment Station and Texas Cooperative Extension and counterparts at New Mexico State University are implementing strategies for meeting present and future water demands in the Rio Grande Basin. These strategies expand the efficient use of available water and create new water supplies. This federally funded initiative is administered by the Texas Water Resources Institute and the New Mexico State University Water Task Force with funds from the Cooperative State Research, Education and Extension Service.

Rio Grande Basin Initiative Outcomes
May 2006, Vol 5. No. 2

Bill Harris, Project Director,
Associate Director,
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Craig Runyan, Project Director,
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New Mexico State University Plant Sciences

Danielle Supercinski, Editor

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Rio Grande Basin Initiative

OUTCOMES

August 2006, Vol 5. No. 3

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For these and other stories, please visit:
http://riogrande.tamu.edu

Controlling Water-Thirsty Saltcedar

Biological methods using imported leaf beetles are a hot topic

by
Danielle Supercinski

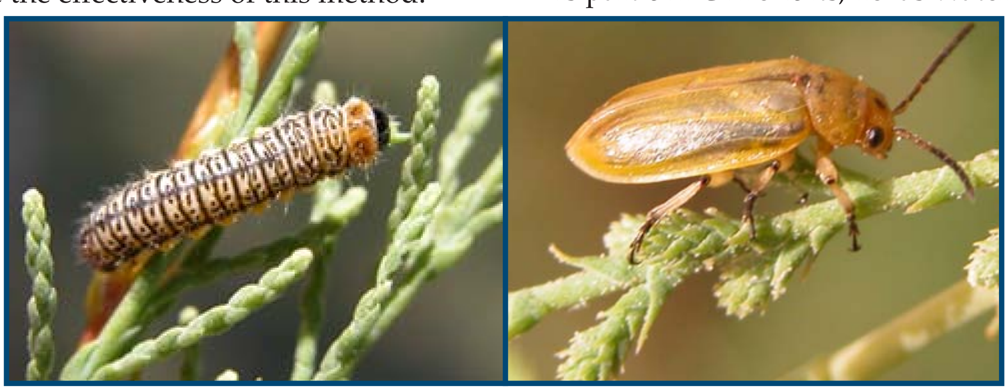
Along the Rio Grande and Pecos River in Texas, saltcedar control methods vary from chemical to mechanical control. Biological control using leaf beetles, *Diorhabda elongata*, is a hot topic throughout these regions and other areas throughout Texas and the United States.

Dr. Mark Muegge, associate professor and Texas Cooperative Extension entomologist at Fort Stockton, has begun preliminary studies using leaf beetles imported from Central Asia and the Mediterranean area as a biological control for saltcedar at specific locations along the Pecos River ecosystem in Texas.

"Both adults and the immature stage, or larva, feed on the leaves and tender bark of saltcedar trees, and if beetle populations are high enough, they can completely defoliate a tree," Muegge said. "Although the saltcedar tree will refoliate, this requires the tree to use the stored energy it has in its roots. Repeated defoliation by the beetles eventually causes stunting, death of limbs and finally tree death."

Death of a saltcedar tree requires two or more years of defoliation by the beetles depending on the size and health of the tree, he said. There is very little risk of these beetles feeding on native plants because it has also been found that the beetle has no alternate source of food than saltcedar, except for another closely related species used as a shade tree in Mexico.

The preliminary studies Muegge is conducting will demonstrate the effectiveness of this method. Biological control is a less expensive and more natural method to rid streams and lakes of this water-thirsty invader than current chemical and mechanical control methods. Using the leaf beetles provides a new method that may be used alone or in combination with chemical and/or mechanical treatments.



A sustainable approach to suppress saltcedar infestations is using natural enemies - the Crete diorhabda leaf beetle. They start out as larva (left) and mature into an adult (right). Photos courtesy of Mark Muegge.

"Biological control of saltcedar is not a replacement for other control methods such as chemical and mechanical control, but an additional tool that will aid in our efforts to control saltcedar," Muegge said.

Muegge's study is a pilot project as part of the Rio Grande Basin Initiative (RGBI). Other scientists throughout the state are working on similar biological control studies as well.

Dr. Jerry Michels, entomologist at the Agricultural Research and Extension Center at Amarillo, is working on biological control of saltcedar farther north at Lake Meredith on the Canadian River. Dr. Allen Knutson, Extension and research entomologist at Dallas, and Dr. Jack DeLoach, entomologist with the USDA-Agricultural Research Service at Temple, have successfully established field nursery sites for rearing saltcedar beetles in the Upper Colorado River watershed, near Big Spring.

A more detailed description of these projects can be found in Texas Water Resources Institute's Summer 2006 "tx H_2O" newsletter Vol. 2, No. 2, available at http://twri.tamu.edu/newsletters.php. For more general information on biological control of saltcedar, visit http://tcebookstore.org/pubinfo.cfm?pubid=1854 to view the Texas Cooperative Extension brochure.

As part of RGBI efforts, Texas Water Resources Institute and other partners throughout both New Mexico and Texas are seeking additional federal support to expand this program.

Cutting Turf Irrigation

Workshops help homeowners keep lawns green with little water

by
Kevin Robinson-Avila

Homeowners learned how to maintain plush green lawns despite drought at two free workshops held in Santa Fe and Albuquerque. Specialists with New Mexico State University's Cooperative Extension Service taught participants how to install subsurface drip systems, choose low-water-use grasses, and cut irrigation time to a minimum by watering only when grass needs moisture and when weather permits, said Bernhard Leinauer, Extension turfgrass specialist.

"If homeowners learn to irrigate efficiently and plant proper grasses, they can save substantial amounts of water without converting their landscapes into rock gardens," Leinauer said. "At these workshops, we taught people how to maintain grass despite drought."

Research shows that even when homeowners replace grass with xeric plants, they don't always save water because many still irrigate inefficiently, Leinauer said. In San Antonio, Texas, for example, municipal authorities surveyed homes in 2003 to determine how much water was saved after years of encouraging people to switch to xeric landscapes. The survey showed only 25 percent of homeowners saved water, about 50 percent used the same amount as before, and 25 percent actually used more water than when they had grass, Leinauer said.

"There was a zero sum gain in water savings," Leinauer said. "People didn't know how much water their turf needed in the first place so they over watered, and they continued to over water even after planting xeric plants."

To address the problem, Extension specialists now emphasize irrigation efficiency as an alternative for homeowners who want grass, Leinauer said.

"We need to revisit our approach to conserving water," he said. "There's been a big push in Albuquerque and Santa Fe to replace traditional backyard turf with xeric plants, but many homeowners would do just as well by keeping their grass and instead learning to irrigate with less water."

To do that, people need to adopt new technology and watering techniques, said Joran Viers, horticulture agent with the Bernalillo County Extension office.

"By using drip irrigation and learning to water only as much as the grass actually needs, people can still have nice green lawns," Viers said. "We want to teach homeowners to apply these techniques."

Subsurface drip systems use about 30 percent less water than sprinklers, said Leinauer, who showed how to install drip irrigation step-by-step. He taught participants to access NMSU's online weather station to schedule irrigation when there is no rain and little wind. He also discussed low-water-use turf to encourage homeowners to select varieties that are better adapted to dry climates, such as Bermuda and buffalo grasses. The workshop included visits to residences with sprinkler systems for hands-on demonstrations on how to reduce water use even without drip irrigation.

Leinauer's research and these workshops are part of his efforts under the Rio Grande Basin Initiative.

Bernhard Leinauer, turfgrass specialist with NMSU's Cooperative Extension Service, examines grass plots at NMSU's Fabian Garcia Research Center in Las Cruces where he is measuring the water requirements of different turf varieties. Photo courtesy of J. Victor Espinoza.

Special Section

Highlighting Texas and New Mexico county program administrators

by

Danielle Supercinski

Texas Cooperative Extension and New Mexico Cooperative Extension Service have a key role in the Rio Grande Basin Initiative (RGBI). Extension administrators, county agents and specialists all contribute to the overall efforts of RGBI by taking their educational materials and demonstrations to all citizens in the basin.

"A critical component of RGBI is collectively the county educational programs being developed and delivered by Extension agents and specialists at local levels," said Dr. Bill Harris, RGBI project director and Texas Water Resources Institute associate director. "With the goal of expanding adoption of water conservation practices, based on best available science, local programming is most important. Strong administrative support make these programs happen."

In this "Special Section" we would like to recognize the Texas and New Mexico Extension administrators who are in RGBI districts supporting the work of county agents and specialists in their area.

Jeff Bader, Bernalillo County Extension program director in Albuquerque, New Mexico, is involved in water conservation and water quality educational programs.

"The RGBI has funded two of the projects in Bernalillo County with hopefully a third to be funded soon," Bader said. "Two projects involve Xeriscape demonstration gardens which provide demonstration sites for proper irrigation, plant material selection and mulching techniques."

The majority of agricultural work is in horticulture.

"There is a great demand by both commercial and private entities for non-biased, research-based information on plant selection, drip irrigation and landscape design for the Xeriscape garden," he said.

Another project, recently completed by an Extension home economist, supported a larger statewide program in which low flow water appliances and devices were installed in the homes of volunteer families to measure the impact these devices have on water consumption.

"Possibly more important than funded projects is the information that is obtained from RGBI research and education projects that is utilized by faculty for water programming across the state," Bader said. "With water being the most important factor affecting the growth and viability of the Middle Rio Grande Valley of New Mexico, it makes sense for New Mexico State University and its Extension Service to do all it can to provide sound research and educational programs on water quality and conservation."

Brenda Rue, district Extension administrator at Fort Stockton, Texas, supports and supervises county agents in District 6 which includes El Paso, Culberson, Hudspeth, Crockett, Val Verde, Brewster, Pecos, Presidio, Reeves, Terrell, Ward, Jeff Davis, Crane, Loving and Winkler counties. RGBI county agents have ongoing efforts in most all of these counties.

"Sixteen counties in the West Region are in the Rio Grande Basin and have utilized over $40,000 to enhance county programs that addressed water issues in 2005," Rue said. More than 5,000 contacts were made through group educational methods. An additional 200,000 contacts were made through individual contacts and mass mailings, she said.

"Water quantity and quality are essential to sustain our population and provide for growth and development," Rue said. "Because we are a desert area, we must look for innovative ways to capture water for our homes, livestock and wildlife. Our citizens are learning ways to do this through RGBI educational programs."

Renee Sanders, regional program director for family and consumer sciences (FCS) at San Angelo, Texas, advises FCS agents about their RGBI projects. She connects agents to FCS specialists who provide

subject-matter information and training.

Nine counties in District 6 and one county in District 10 are served by FCS agents in the RGBI program. Sanders said five of these FCS agents are presently conducting in-home water conservation projects in El Paso, Crockett, Val Verde and Ward counties.

"The in-home water conservation projects which have been conducted by FCS agents are educating county residents about ways to conserve water in the home, particularly in the bathroom, with use of water-saving shower heads and commodes," Sanders said.

Cheryl Mapston, District 10 Extension administrator for family and consumer sciences at Uvalde, Texas, provides supervision of agents involved in the RGBI project and works with agents to develop a program interpretation plan for communicating RGBI program results to key stakeholders. RGBI programs are active in three of the 21 counties in the district.

Programs conducted over the past few years include irrigation result demonstrations, water well testing, watershed management, in-home water conservation, educational tours, establishment of weather stations and providing information to the media for the general public on water conservation.

"Participation in RGBI has provided agents with top-quality training opportunities and resources necessary to complete projects and educational programs that provide valuable information to producers and clientele to help them make wise decisions on water-use," Mapston said.

Marvin Ensor, regional program director for agriculture and natural resources (ANR) at San Angelo, Texas, works with agents in RGBI counties during program planning. He also assists agents in developing plans and securing resources to conduct educational programs.

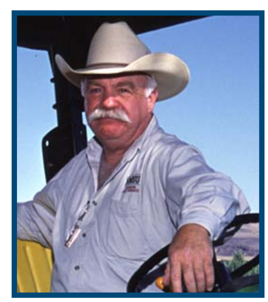
Water programming in the West Region includes groundwater and wastewater management, watershed management, rainfall harvesting, in-home water conservation, irrigation efficiency, water quality issues and management and youth water education to name a few. Additionally, the Precision Irrigators Network began during 2005 in seven counties.

"Agents in the RGBI counties provide the educational programs needed to address the water issues," Ensor said. "The funds received through the RGBI have greatly enhanced our educational efforts and the program impacts on our clientele."

Charlie Siepel, Southwest District department head for New Mexico Cooperative Extension Service, serves as mentor, financial monitor and RGBI project supporter. He covers Socorro, Sierra, Dona Ana, Luna, Lincoln, Otero, Catron, Grant and Hidalgo counties.

The RGBI allows county faculty to provide demonstrations on water-use as it relates to crop and livestock production and urban utilization. Projects currently under way are addressing irrigation efficiency, rain water storage and use, urban landscape, and residential water-use and conservation.

"RGBI is allowing a basinwide effort to address the critical issues of water utilization from agriculture water use shortfalls to increasing urban water demands," Siepel said.



Mike English serves as superintendant of the Los Lunas, New Mexico Agricultural Experiment Station. He provides administrative and technical support to the RGBI. English facilitates several RGBI research projects, as well as implements his own water conservation projects.

Terry Lockamy serves as regional program director for ANR for District 12. Lockamy is located at the Texas A&M Agricultural Research and Extension Center at Weslaco, Texas. He is responsible for developing and maintaining quality ANR programs in the South Region's 56 counties and provides oversight and support to the RGBI county programs.

Results Are In

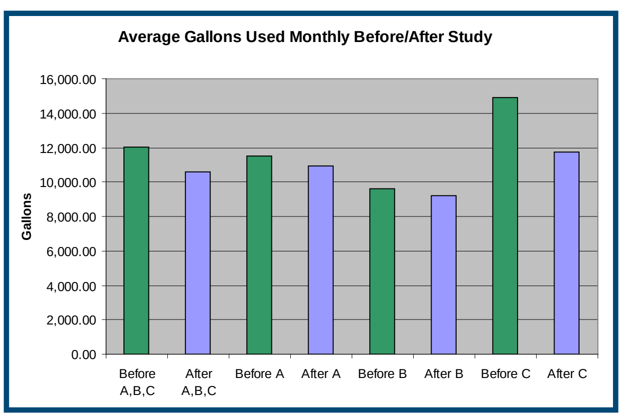
by
Danielle Supercinski

Savings from in-home water conservation project

Water-saving equipment has been available for 14 years for homeowners to conserve water used in their homes. Janie Harris, Texas Cooperative Extension housing and environment specialist, said research has shown that households can save as much as 25 gallons per person per day with water-conserving equipment and changed behaviors.

Twenty-six households throughout nine counties in Texas participated in the 2006 in-home water conservation project led by Harris and other Texas Cooperative Extension agents and specialists. Three households in Webb, Pecos, Starr, Ward, Val Verde, Crockett, Hidalgo, El Paso and Cameron counties participated in the study, which took place during January through April.

Each household received a different level of water conservation training. Household A received education only; Household B received education and recommendations for specific changes; and Household C received education, recommendations and retrofitted toilets, shower heads and faucet aerators. Results showed 5 percent water savings for those in A, 4 percent water savings for B and 21 percent water savings for C. A graph containing the average gallons of water used monthly before and after the study is below.



Pilot project and economic model analyze cost of producing water

Cities and rural communities throughout Texas are faced with many issues limiting their sustainable potable water supply. However, a pilot project in Cameron County and an economic model developed by Texas Cooperative Extension and Texas Agricultural Experiment Station economists provides a more cost efficient analysis of desalinating brackish water.

Drought, water supply issues, and increasing pressure for limited water supplies with economic and population growth are just a few of the major problems Texans face. An abundance of brackish water, which is more salty than freshwater but not as salty as seawater, tops the list of issues.

Desalination of brackish water is one option to make use of this otherwise unusable water, but it's not that simple. While desalination is capable of increasing the available local water supply, high costs and volume constrain its uses.

A pilot project was developed to analyze the economic and financial life-cycle costs of desalination of brackish groundwater for South Texas using primary construction and ongoing costs for an actual desalination facility. The study is limited to an existing facility near the Gulf of Mexico and the Texas-Mexico border just outside of Brownsville, Texas, termed the Southmost Desalination Facility.

The life-cycle cost of providing an acre-foot of desalinated water is of keen interest. Therefore, the Excel® spreadsheet model DESAL ECONOMICS© has been developed. This model analyzes and provides life-cycle costs (dollars per acre-feet per year) for up to eight individual functional expense areas, as well as for the entire facility. For the Southmost Facility, the cost of producing 1,000 gallons of water per year equated to approximately $1.70, whereas the charges assessed by municipalities in other areas of Texas can range from $1.80 to $4.

To read the full stories covering these projects and their results, please visit http://riogrande.tamu.edu under the "What's New" section.

Save the Dates

by
Sara Alarcon & Danielle Supercinski

Plans for the 2007 New Mexico technical conference

"River Terrace & Flood Plain Hydrology," a Rio Grande Basin Initiative technical conference, will be held at the Hotel Encanto de Las Cruces (formally Hilton) February 28, 2007 through March 1, 2007. Conference goals include: assessing the state of the science in river terrace and floodplain hydrology, exploring river flow and water quality linkages, examining integrative measurement and modeling methods, sharing information among researchers, identifying knowledge gaps and future research directions, and producing a special journal issue from submitted papers. Additional conference information is available at http://nmwater.nmsu.edu.

2007 Rio Grande Basin Initiatives conference announcement

Based on the majority of responses from the post-conference survey, the 2007 Rio Grande Basin Initiatives Conference will be held at South Padre Island, Texas. The conference is scheduled for May 15, 2007 through May 17, 2007, at the Radisson Resort. Please continue to check the joint conference Web site at http://riogrande-conference.tamu.edu. More information will be posted as the conference gets closer.

Please put these dates on your calendar, and we look forward to seeing you there.

Faces of RGBI

Administrative assistant takes care of business

by
Danielle Supercinski

Anyone who has called the Texas Water Resources Institute at some time or another has probably heard her voice answering on the other end of the line. Tamaron Stewart has worked for TWRI for the past 4 years. She has not only answered the phones, but has also taken care of travel, office supply orders, work orders, coordinating meetings, ordering business lunches and keeping the office well-organized.

Tamaron has also had a major hand in helping out with the administrative side of RGBI. When accomplishment reporting time comes around, she has always been willing to jump in and help write summaries and edit the big book of progress and accomplishments for the year. Believe me, this would have been even more of an overwhelming job without all the help she provided!

Past RGBI conference speakers and moderators may also recognize Tamaron's name, as she has been one of the key contacts involved in organizing the conference agenda and getting information to those on the agenda. She has coordinated printing of RGBI materials (including this newsletter) and has played a vital role in assisting with pre-registration, check-in and helping with all other aspects involved at the conference.

Unfortunately for us, as of July 21, Tamaron left the TWRI "family" to begin the first step in her own family – marrying Kyle Hunt and moving to Plano, Texas! Although we will miss Tamaron and all the things she did for us, we are very happy for her and wish her all the best in this new phase in her life.

Tamaron, thank you for all you have done for TWRI and RGBI over these past 4 years. Your organization, assistance, cheerfulness and friendship will be greatly missed!

Increasing Irrigation Efficiency in the Rio Grande Basin through Research and Education

Through Extension and research efforts, the Texas Agricultural Experiment Station and Texas Cooperative Extension and counterparts at New Mexico State University are implementing strategies for meeting present and future water demands in the Rio Grande Basin. These strategies expand the efficient use of available water and create new water supplies. This federally funded initiative is administered by the Texas Water Resources Institute and the New Mexico State University Water Task Force with funds from the Cooperative State Research, Education and Extension Service.

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Rio Grande Basin Initiative

OUTCOMES

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New Mexico State University
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For these and other stories, please visit:
http://riogrande.tamu.edu

Interactive Mapping

NMWRRI develops 'sister' Web sites for New Mexico and Texas

by
Sara Ash

New Mexico Water Resources Research Institute (NMWRRI) and Texas A&M University Spatial Sciences Laboratory (SSL) are working on a joint Rio Grande Basin Initiative (RGBI) project to develop sister Web sites which will provide interactive mapping and analytical services for both states.

The SSL currently has several products serving the needs of Texas counties included in the RGBI. Similar mapping and analysis services are being developed for New Mexico RGBI counties under the auspices of NMWRRI.

To expedite the progress of the New Mexico project, the SSL provided NMWRRI with the programs and configuration files developed for Texas. NMWRRI will modify the SSL system for use in New Mexico in two phases. The first phase of development will incorporate environmental and natural resources data, the second socioeconomic and health-related data. Dr. Bobby Creel, NMWRRI associate director, manages the project, and Susanna Glaze, NMWRRI GIS technician, collects data and implements the programs.

"The project is now in the first phase," Glaze said. "Right now we're gathering data, the bulk of which is digital imagery." Glaze will collect data for all the counties in New Mexico which have some area in the Rio Grande drainage.

Sara Ash works to bring the RGBI and SSL Web sites together as sister Web sites.

"This means we will include 27 of New Mexico's 33 counties into the system," Creel said. "We had data for the nine main-stream counties, but they were from 1992 and 1996. When we decided to include more counties, we wanted to gather new data for 2005."

This has delayed the project somewhat, but Glaze has been working diligently to complete data acquisition. She conducts web searches for data, mostly on government Web sites. Once she finds what she needs, she downloads and organizes it.

"I am focusing on the Lower Rio Grande Valley right now, because there is a large amount of data to download," Glaze said. "Downloading is time-consuming, because the file sizes are large."

Most of the information can be found online, but on occasion she cannot find what she needs. "The EPA listed three toxic release inventories without coordinates," Glaze said. "I couldn't find the coordinates anywhere online. I took the GPS down to the Santa Teresa area, found the sites myself and plotted the points," she laughed about her fieldwork.

Once all data have been collected, Glaze will use ESRI's ArcIMS software to provide the interactive mapping services online.

"I will set up a geodatabase and map, then load them into the ArcIMS software," she said.

"The ArcIMS systems that we develop are quite easy for the public to use," Creel added. The counties are clickable, and the maps are self-explanatory. The accessibility and simplicity of the systems mean that people with average computer skills can use the maps without any extra training or software.

Once the mapping service is online, researchers, stakeholders and the public will have access to environmental data, such as superfund sites; natural resources data, such as digital orthophoto quads; socioeconomic data, consisting of Census of Agriculture and Census Bureau information; and health-related data, including medical facilities and Department of Health indicator information.

"Right now we are focusing on environmental and

*See **NMWRRI** on page 5*

Market-Based Approach to Conservation

Management of water shortages through water transfer mechanisms

by
Nargiza Rakhimova

Large dams and reservoirs built on major rivers to mitigate water shortages are no longer economically or environmentally feasible, however, the competition for water is increasing.

Socioeconomic and political aspects of water conservation are current hot topics, as many people realize the importance and inherent difficulty in allocating this scarce resource among the diverse range of water users. One way to address this issue is to encourage water-users to improve water-use efficiency through a market-based transfer mechanism where price is a result of demand and supply interaction.

A three-year research program to assess the potential for the development of a water market in the Lower Rio Grande Basin of New Mexico and to determine what type of water transfer mechanisms would be most effective in the basin, has been initiated by a team of investigators under the supervision of Ereney Hadjigeorgalis, assistant professor at New Mexico State University.

The program was developed based on a three-stage evaluation aimed to:

1) Identify economic disincentives to water trades in the current institutional framework for both short-term trades and permanent transfers of water-use-right titles;
2) Determine the factors that influence farmers' willingness to participate in water markets and the specific type of water transfer mechanism that is most suitable; and
3) Design a working draft of a water transfer mechanism that would reduce wasted water and encourage conservation by efficiently allocating scarce water resources among farmers during times of drought, while still protecting third party interests specific to the basin.

Results obtained from research to date are encouraging. Findings show that while farmers were interested in participating in water markets, they prefer short-term transfer mechanism and spot water markets over water banks, thereby giving them the ability to negotiate price between transacting parties. In addition, there was little interest in 'option markets', due to their complexity and institutional constraints, i.e., the water users currently do not have secured water rights and well-defined property rights to water.

This year, the research program is focused on the current institutional framework in the basin such as transaction costs associated with water leasing and sales, and the potential impact on third parties from increased water transfers. These findings will assist the program in determining various aspects and structures of the water markets and find the most appropriate approaches in the Rio Grande Basin case.

A wide range of municipal, industrial, agricultural, recreational and other water-users must factor into a water marketing scheme.

Pecanigator©

Improving irrigation efficiency in New Mexico pecan production

by
Craig Runyan

A simplified, handheld calculator to help determine when established pecan orchards should be irrigated is being developed by a team at NMSU.

The 'Pecanigator' is a Rio Grande Basin Initiative funded effort targeting "primarily pecan growers whose enterprise is an important part of their income," said John Mexal, NMSU horticulturist and leader for the project.

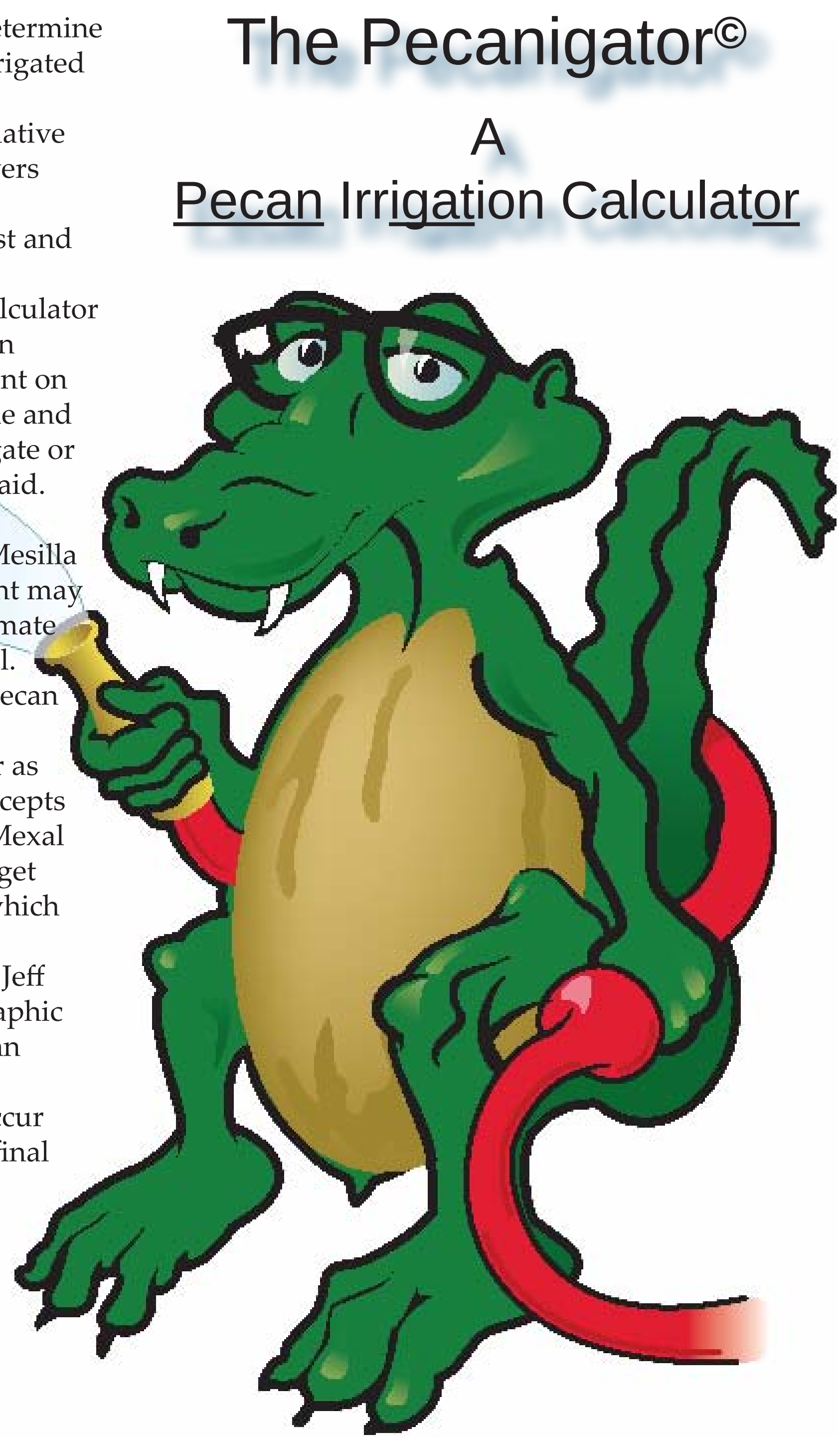
Although using the irrigation scheduling calculator could be useful to the small and medium pecan producer, Mexal added that "more management on their part may be required with additional time and labor." Small scale producers often under-irrigate or schedule irrigation intervals too far apart, he said.

The current Pecanigator prototype is being developed from climate data collected in the Mesilla Valley of New Mexico. Additional development may expand its usefulness to other areas if local climate and soil data were incorporated into the model.

Richard Heerema, New Mexico Extension pecan specialist, is a part of the team developing this irrigation tool. Heerema views the Pecanigator as an "introduction, for some growers, to the concepts behind science-based irrigation scheduling." Mexal concurs, adding that "the long-term goal is to get more producers using real-time information which will increase irrigation efficiency even more."

Other members of the Pecanigator team are Jeff Kallestad, research specialist; Jerry Downs, graphic artist; Ted Sammis, state climatologist; and John White, Dona Ana Extension agent.

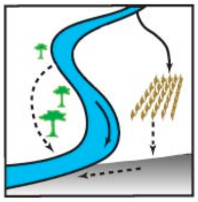
Pilot testing of the device prototypes will occur over the next few months. Distribution of the final product is expected to begin by March 2007.



Event Updates

Speakers selected to address quality and quantity of river flows

by
Sara Alarcon



The Rio Grande Basin Initiative will address quality and quantity of river flows at the *River Terrace & Flood Plain Hydrology* symposium Feb. 28 and March 1 at Hotel Encanto, Las Cruces, NM.

The main focus of the conference will be on connections between surface water and groundwater sources in river valley ecosystems. The symposium will assess the state of science in river hydrology, river flow and water quality linkages. The convention will also examine integrative measurement and modeling methods, and share research to help identify knowledge gaps and future research directions.

Of particular interest are situations where surface water moves underground and subsequently returns to the river. The symposium will evaluate implications of existing research and chart future directions for needed work, as well as provide a better understanding of river valley hydrology and related management strategies.

Contributing to the symposium are speakers from the Universidad de Concepcion, New Mexico Tech, Sandia National Laboratory, New Mexico State University, Sul Ross State University and the U.S. Environmental Protection Agency.

The Web site is now available for registration and additional information concerning the Symposium. Please visit http://nmwater.nmsu.edu for more information.

Congressman Bonilla recognized at Uvalde Water Day

by
Danielle Supercinski

The Texas A&M University Agricultural Research and Extension Center at Uvalde held a Water Day on Monday, Oct. 16 to recognize Representative Henry Bonilla's leadership on critical water issues.

Speakers highlighted water programs implemented under the Rio Grande Basin Initiative and announced the new Beef Improvement program headquartered at the Uvalde Center.

Walt Smith, appropriations associate for Representative Henry Bonilla, met with local citizens and producers earlier that afternoon. Dr. Bill Holloway, center resident director of research; Congressman Bonilla; Dr. Elsa Murano, vice chancellor, dean of agriculture and life sciences and director of Texas Agricultural Experiment Station for Texas A&M University; and Dr. Ed Smith, associate vice chancellor for agriculture and life sciences, spoke at the meeting.

Dr. Leo Sayavedra, vice chancellor for academic and student affairs of Texas A&M University System; John Bellinger, chairman of the U.S. Meat Exportation Federation; and Dr. Wendy Gramm and Ida "Weisie" Clement Steen, both members of the Texas A&M Board of Regents, were also in attendance and said a few words.

"We need to make sure we are doing everything we can through science to ensure we are protecting this precious natural resource," Murano said. "I believe the Rio Grande Basin Initiative will help us maximize the availability of this precious natural resource."

NMWRRI

continued from page 2

natural resources data," Creel said. "In the second phase of the project, we will start gathering health data and incorporating it into the system."

The project covers such a "wide scope of information. It will be useful to a lot of people," Glaze said.

The mapping service will be hosted from one of the WRRI servers at http://water.nmsu.edu.

Keeping the Rain Out

Evaluating 60-day drought survival in turfgrass

by

Danielle Supercinski

The Rio Grande Basin Initiative helped establish a new, state of the art facility for determining the 60-day drought survival of various established turfgrass species and cultivars to provide background data for a San Antonio Water System (SAWS) ordinance that will go into effect in January 2007.

"The Rio Grande Basin Initiative supported this work through the time and effort of Extension associates Chris Braden, David Flahive and Wayne LePori who provided design and construction oversight," said Dr. Guy Fipps, Extension agricultural engineer and Irrigation Technology Center director. "This (rainout shelter) facility will be used for years to come to determine irrigation requirements of landscape and horticultural plants."

Construction of a 5,000 square foot rainout shelter at the research site was completed on July 25, 2006. The rainout shelter will cover the research plot area during times of rainfall to maintain a 60-day summer drought period. Two Campbell Scientific rain gauges are mounted 6 feet off the ground on both sides of the storage shed. When both rain gauges detect 0.01 inches of rain, the rainout shelter will deploy; in less than two minutes it will be able to cover the turf test plots.

San Antonio's new ordinance will require new home construction to have at least 4 inches of topsoil in place prior to lawn establishment and plant grasses that are most likely to survive a 60-day drought.

"The ordinance will provide some drought capacity for homeowners who have very little control over the landscape and soil put in by their builder before they take over the house," said Karen Guz, director at SAWS Conservation Department.

Dr. Chris Braden, Extension associate at the Irrigation Technology Center at San Antonio, said, "The addition of a high quality topsoil will increase the water holding capacity and rooting depth, thus increasing the ability to better withstand long-term drought conditions."

Grasses at the research site are planted on 4 inches of native soil over an impermeable plastic barrier to simulate the 4-inch topsoil requirement in the SAWS ordinance. In addition, grasses are planted on native soil without restriction to rooting to represent drought survival on unrestricted soil depth.

Plots have been sodded with 25 different turfgrasses solicited by SAWS and the Turfgrass Producers of Texas (TPT) on the basis of either the grass having a presence in the San Antonio market or as a result of a producer wishing to pay to enter a grass in the test. These grasses have been evaluated from their planting date in September 2005 through the July 22, 2006, establishment period. Data is being collected weekly for turfgrass quality, density, color and leaf firing due to moisture stress. SAWS will then use this data to formulate an initial list of "drought-tolerant" grasses.

"The drought study started on July 23, 2006, and the shelter will be in operation mode for 60 days," Braden said. After the 60-day drought period, the grasses will be allowed to recover with irrigation for another 60 days.

Braden and other Texas Cooperative Extension soil and crop sciences and agricultural engineering faculty have entered into an agreement with SAWS Conservation Program and the TPT for a two-year research project.

"Next year we will repeat the study and the shelter will once again be in operation mode for 60 days," Braden said. The second-year plot area is currently under construction for an anticipated sodding in mid-September 2006.

Additional funding for supplies and materials were provided by SAWS and TPT as part of the 60-day drought recovery program.

For more information and pictures, please visit http://itc.tamu.edu/rainout.php.

Faces of RGBI

Financial support role of NMSU bookkeepers

by

Nargiza Rakhimova

(L to R) Sally Baeza, Pat Zapien, Mary Acosta, Donna Ebler, Sandra Day, Eva Cortez, Kristine Kitchens, Beth Chorey and Leeann DeMouche.

Bookkeepers play an important role working in partnership with other staff and faculty on sponsored accounts. Often in daily program activities, however, our bookkeepers are often 'left out of the loop.' Craig Runyan, New Mexico RGBI project coordinator, said it is "sometimes difficult for bookkeepers to establish a rapport with staff professionals due to time constraints.

"It's useful to keep track of everyone's activities, and often staff forgets that it is important to keep the bookkeeper apprised of what they're doing," said Runyan when greeting New Mexico State University (NMSU) staff at the Department Bookkeepers Luncheon, organized as a part of New Mexico's RGBI project activities. "It should be recognized that bookkeeping is far more than simply entering data."

As every other successful project or business, the RGBI project at NMSU owes its ceaseless progress in implementing its various project components, in part, to the outstanding performance of the department's bookkeepers. They provide key support links in the effective management of all RGBI projects. Their distinguished performance is characterized by their flexibility and ability to adjust to unusual circumstances and communicate with the other members of the project and/or research staff. Their goal is to resolve financial issues without detrimental consequences or delays to the research. Improved communications and closer relations with faculty and technical staff increases support and appreciation for the role bookkeepers have in the project. Department bookkeepers are indeed an important link between research efforts and RGBI's progress in the region pursuing the goal to ensure efficient irrigation for water conservation in the Rio Grande Basin.

NMSU "water guy"

by

Leeann DeMouche

On the New Mexico State University campus R. Craig Runyan is known as the "Water Guy." Since 1990, he has served as Extension water quality specialist in the NMSU Extension Plant Sciences Department, and currently devotes his time as Water Task Force Coordinator and state director of the Southern Region Watershed Resource Management Project. His professional interests include: watershed management, pollution risk assessment and water resources development.

Craig began his career in agriculture growing broilers in East Texas while earning a bachelor's degree at Stephen F. Austin State University. He taught vocational agriculture in Texas before he joined NMSU's Yemen project in 1981 as a farm manager and mechanization specialist. Craig earned a master's degree in Agricultural and Extension Education at NMSU and was assistant professor of agricultural mechanization.

"Craig has been a great partner and NMSU leader for the Rio Grande Basin Initiative, and his broad knowledge of water and his professionalism have fostered significant project outcomes," said Bill Harris, RGBI project director. "Craig is a pleasure to work with and is a champion of interstate collaborations."

While not working in the water world Craig loves playing with his two boys, working with his bird dogs and enjoys bird hunting – quail being his favorite.

Increasing Irrigation Efficiency in the Rio Grande Basin through Research and Education

Through Extension and research efforts, the Texas Agricultural Experiment Station and Texas Cooperative Extension and counterparts at New Mexico State University are implementing strategies for meeting present and future water demands in the Rio Grande Basin. These strategies expand the efficient use of available water and create new water supplies. This federally funded initiative is administered by the Texas Water Resources Institute and the New Mexico State University Water Task Force with funds from the Cooperative State Research, Education and Extension Service.

Rio Grande Basin Initiative Outcomes
November 2006, Vol 5. No. 4

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http://riogrande.tamu.edu

Special thanks to NMSU guest writers:
Sara Ash, NM Water Resources Research Institute
Nargiza Rakhimova, NMSU graduate student
Sara Alarcon, NMSU student writer

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Rio Grande Basin Initiative

OUTCOMES

February 2007, Vol. 6, No. 1

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For these and other stories, please visit:
http://riogrande.tamu.edu

Pulling the Plug

Grass carp and chemicals used to control aquatic weeds

by
Danielle Supercinski

Demonstrations to control non-native aquatic weeds have been instituted with collaborating irrigation districts in the Lower Rio Grande Valley to unclog and manage weed-infested irrigation canals and conserve water.

Species such as hydrilla (*Hydrilla verticillata*), water lettuce (*Pistia stratiotes*) and water hyacinth (*Eichornia crassipes*) are most commonly found in the Lower Rio Grande Valley, and they cause numerous problems in irrigation canals.

According to Dr. Michael Masser, professor and Texas Cooperative Extension fisheries specialist in the Department of Wildlife and Fisheries Sciences at College Station, hydrilla is the most problematic of these aquatic weeds because it severely plugs canals. Therefore, irrigation districts and producers have to pump more water so it will lay down the hydrilla to push water over it, resulting in increased pumping costs, Masser said. In addition, there is more percolation and seepage losses.

These aquatic weeds create other issues as well. They form small pools of water in the vegetation that then serve as breeding grounds for mosquitoes, which is problematic with the West Nile Virus situation, he said. In addition, water hyacinth is also known to cause an increase in water evaporation, known as evapotranspiration, causing a higher loss of irrigation water.

Triploid grass carp are used to control hydrilla that clog irrigation canals and other water bodies.

There is a myriad of treatment options. "Historically, there was just physical or mechanical removal of aquatic weeds plugging canals. Now we've come along with (triploid) grass carp and herbicides," Masser said.

To control and manage these aquatic weeds, as well as conserve water, Masser has sought effective controls of these plants.

In April 2002, Masser began his first demonstration under the "Environment, Ecology and Water Quality Protection" task of the Rio Grande Basin Initiative. The first demonstrations utilized triploid grass carp to control hydrilla at Brownsville Irrigation District and Hidalgo County Irrigation District No. 1.

In 2005, Masser started additional hydrilla projects with Santa Cruz Irrigation District No. 15 and Hidalgo County Irrigation Districts No. 1 and No. 2. Currently, approximately five grass carp demonstrations are ongoing.

"The bottom line from these demonstrations is that grass carp readily consume hydrilla and offer long-term (5 to 7 years), economical control," he said.

Triploid grass carp have been scientifically proven to be the most effective biological control for hydrilla. As "triploid," genetically altered grass carp, their life expectancy is 10 to 12 years with an estimated 20 percent annual mortality rate, he said. They also are infertile and do not reproduce.

"We see losses every year past about year three," Masser said. "We've only had to do a little supplemental restocking because of districts draining canals and canals rupturing; of course there is always a loss of fish when there is no water. Also, by year five we have to do some restocking – the fish are getting really large and not eating much causing the cumulative mortality issue."

At other locations, hyacinth and lettuce have been controlled using chemical herbicides.

"Other researchers have tried biological control on hyacinth, but that is equivalent to treating fleas on a


Reward herbicide treatments were used to control water lettuce (left) at Cameron County Irrigation District No. 6. Within three days after treatment all plants contacted were killed (right), representing an approximate 16,000 gallon per day savings.

dog; it slows the hyacinth down but doesn't control it. You can see damage (to hyacinth) everywhere, but it's not controlling it," Masser said. "There is no good biological control for water hyacinth or lettuce; therefore, we use herbicides to control them."

Water lettuce demonstrations with herbicide control began in 2003 and continued into 2004 with Cameron Irrigation District No. 6. Reward™ herbicide was used, and all plants contacted by the herbicide were killed within three days.

"This represents a water savings by reducing plant transpiration of 30 percent," Masser said. "In this case, this would represent a water savings of approximately 20,000 gallons per day."

Prior to using grass carp and herbicides, irrigation districts removed these aquatic weeds by mechanical methods. Mechanical control proved to be very expensive – several thousand dollars an acre – and labor intensive, whereas biological control is much cheaper.

"Mechanical control is like mowing the grass; (weeds) keep coming back, so you don't get good control," Masser said. "Compared to grass carp on a per acre basis, we're not spending $200 an acre."

Irrigation districts have saved in excess of $500,000 per year from on-going demonstrations of the biological control of submerged aquatic weeds in canals and resacas, he said. Removal of submerged aquatics has reduced labor costs, pumping costs and water loss from evapotranspiration and percolation/seepage from the canals.

"For example, Hidalgo County Irrigation District No. 1 was spending more than $130,000 per year on mechanical control," Masser said. "After one stocking of grass carp, the hydrilla was under control in about three months."

Masser sends an annual newsletter to irrigation districts with recent demonstrations and their progress and results. As far as planned demonstrations in the future, "it is up to the districts and depends on whoever takes advantage of it," he said.

"I plead with the irrigation districts to please utilize me; that is what I'm here for," Masser said. "I make several trips a year to the Lower Valley to work with the people and irrigation districts to help with their aquatic weed problems. I enjoy working in the Valley and would be glad to take on some more demonstrations. As an Extension specialist, I'm available to everyone."

Masser has also built the AQUAPLANTS Web site that is available for anyone who is unsure of what aquatic weed is in their canal. By looking on the Web site and working with Masser, irrigation district managers or landowners can make sure they know what plant they're dealing with and identify how best to manage it. The pages can easily be printed off to use as a reference. Visit the AQUAPLANTS Web site at http://aquaplant.tamu.edu.

Silvery Minnow Preservation

Graduate prepares photo essay of RGBI project and progress

by
Sara Alarcon

In efforts to preserve the silvery minnow of the Rio Grande, Michelle Marusek, a recent graduate of Fine Arts, has been tailing Dr. David Cowley, professor in the Department of Fishery and Wildlife Sciences at NMSU, and his students. Cowley's RGBI project, "Agricultural Irrigation Systems and Conservation of Native Fishes," is focused on recovering the silvery minnow in the Middle Rio Grande Conservancy District around the Albuquerque area.

Marusek is preparing a photo essay of Cowley's project and progress. Many photos were taken while Cowley and his students worked to develop refugial fish habitats. The photo essay is a work in progress with hopes of publication in 2007.

A portion of this photo essay is currently on display at the NMSU College of Agriculture and Home Economics dean's office. For additional silvery minnow project photos please visit Marusek's Web site at http://nmsu.edu/~marusek.

The photos accompanying this article are a few examples selected from the photo essay.

When stretches of the Rio Grande go dry, biologist Michael Hatch of the Silvery Minnow Rescue Operation oxygenates Rio Grande water containing silvery minnows so they can be relocated to a stretch of the Rio Grande that is still flowing.

Biologist Michael Hatch inspects the contents of a net he pulled through the small finger of the Rio Grande remaining in the riverbed.

Dr. David Cowley, professor at NMSU's Department of Fishery and Wildlife Sciences, conducts a species survey in a drainage canal near the Isleta Reach. His findings suggest the Rio Grande silvery minnow makes a year-round home of the drainage canals.

NMSU Department of Fishery and Wildlife Sciences students record the temperature of a drainage canal where Rio Grande silvery minnows were collected.

Award Winning Project

RGBI closes out 2006 like a champ

by
Danielle Supercinski

Several award nominations were submitted for the *Efficient Irrigation for Water Conservation in the Rio Grande Basin* project, also known as RGBI, toward the end of 2006, and we are pleased to announce that RGBI has won two award categories.

Drs. Juan Enciso, Ari Michelsen, Giovanni Piccinni, Edward Rister, Zhuping Sheng and Bob Wiedenfeld were selected by the Texas Water Resources Institute (TWRI) Awards Committee to represent the research side of RGBI. This research team was nominated for and won the *2006 TAMUS Vice Chancellor's Awards in Excellence: Award in Research* for their numerous project efforts and accomplishments. These representatives received the award at the 2007 Texas A&M Agriculture Conference award ceremony on Jan. 9, 2007.

RGBI was also nominated for and won the U.S. Department of Agriculture–Cooperative State Research, Education and Extension Service (USDA–CSREES) *National Water Program 2007 Awards in the Outstanding Integrated Activities for Water Resources*. The award was presented to Drs. Allan Jones and Bill Harris of TWRI and Craig Runyan of NMSU at the USDA–CSREES National Water Conference in Savannah, GA, Jan. 30, 2007.

The selected recipients accepted these awards on behalf of all RGBI participants and collaborators. RGBI is a winner because of the hard work, dedication and collaboration of all participants involved in the project working with each other and other universities, agencies and individuals to make this project a success. Congratulations to all RGBI participants!

Photo courtesy of James Lyle

(L to R) Drs. Elsa Murano (Vice Chancellor for Agriculture and Life Sciences), Bob Wiedenfeld, Ed Rister, Juan Enciso, Zhuping Sheng, Ari Michelsen, Giovanni Piccinni and Bill Dugas (associate director for operations, Texas Agricultural Experiment Station).

Optimizing Beneficial Water Use

Joint effort studying ag water consumption in Southern New Mexico

by
Nargiza Rakhimova

In a region with limited fresh water resources, the growing population in Southern New Mexico is facing fierce competition for water.

According to the Elephant Butte Irrigation District (EBID), which serves 90,640 acres of agricultural and urban water users, irrigation is the largest consumer of water, yet the consumptive use by agricultural crops is often not reliably quantified. As the demand for water to meet municipal, recreational, irrigation and environmental requirements is increasing, it is becoming extremely important to plan and prepare for future water use.

Therefore, more accurate estimates of agricultural consumption or evapotranspiration (ET, the true loss from a hydrologic basin) are necessary.

A research team at New Mexico State University, led by Dr. Zohrab Samani and Dr. Salim Bawazir, civil engineering professors; Dr. Rhonda Skaggs, agriculture economics professor; undergraduate civil engineering student Brad Kirksey, and Max Bleiweiss, scientist for the Center for Applied Remote Sensing Agriculture, Meteorology and Environment, is tackling this research problem.

*See **Water Use** on page 7*

New Mexico Woody Landscape Manual

Plant information to be used in interactive, searchable database

by
Leeann DeMouche

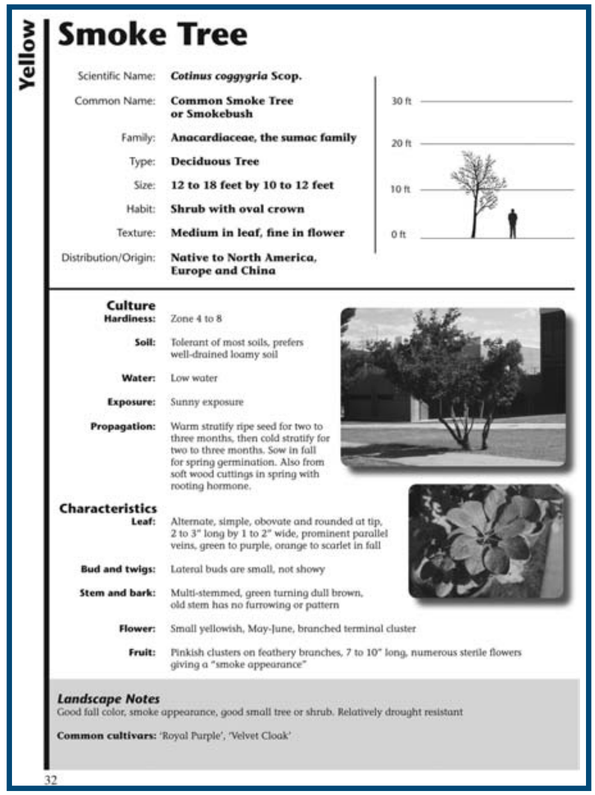
New Mexico State University's (NMSU) current landscape horticulture and garden design courses on ornamental plants will be receiving a new online manual for students in August 2007, sponsored by the Rio Grande Basin Initiative.

For the past year Dr. Rolston St. Hilaire, assistant professor for plant and environmental sciences at NMSU, has been working with Kerry Krumirne, landscape designer and former Las Cruces nursery owner, to develop and produce a high quality image database that provides definitive identification and use of common landscape trees and shrubs suitable for water conserving landscapes. The manual is being produced in both print and electronic forms. Students will be able to access a secure Web site and download the electronic and interactive course manual.

The manual's courses, which will lead the student to receiving a bachelor of science in the College of Agriculture and Home Economics Horticulture Degree (Landscape Design Option), includes Plant Materials classes I & II. Presently, the manual used in the courses includes two bound paper texts with no plant images. Students currently access plant images via a separate image database. The new manual will include a graphic design layout for landscape and a colored graphic picture of the plants. Each plant will be identified by scientific and common name with additional information on culture, characteristics and landscape notes.

"Landscape horticulture, as a career and a hobby, is growing dramatically," St. Hilaire said. "The market for our course material is greatly needed in the arid western states. Using the Internet, we can extend an excellent educational experience to our students at NMSU and other satellite landscape programs across New Mexico."

What's in store for the future? St. Hilaire hopes that the plant information he is collecting will be used on an interactive, searchable database that will assist not only his students, but landscape architects, master gardeners, landscape designers and the general public.



Yellow

Smoke Tree

Scientific Name: ***Cotinus coggygria* Scop.**
Common Name: **Common Smoke Tree or Smokebush**
Family: **Anacardiaceae, the sumac family**
Type: **Deciduous Tree**
Size: **12 to 18 feet by 10 to 12 feet**
Habit: **Shrub with oval crown**
Texture: **Medium in leaf, fine in flower**
Distribution/Origin: **Native to North America, Europe and China**

Culture
Hardiness: Zone 4 to 8
Soil: Tolerant of most soils, prefers well-drained loamy soil
Water: Low water
Exposure: Sunny exposure
Propagation: Warm stratify ripe seed for two to three months, then cold stratify for two to three months. Sow in fall for spring germination. Also from soft wood cuttings in spring with rooting hormone.

Characteristics
Leaf: Alternate, simple, obovate and rounded at tip, 2 to 3" long by 1 to 2" wide, prominent parallel veins, green to purple, orange to scarlet in fall
Bud and twigs: Lateral buds are small, not showy
Stem and bark: Multi-stemmed, green turning dull brown, old stem has no furrowing or pattern
Flower: Small yellowish, May-June, branched terminal cluster
Fruit: Pinkish clusters on feathery branches, 7 to 10" long, numerous sterile flowers giving a "smoke appearance"

Landscape Notes
Good fall color, smoke appearance, good small tree or shrub. Relatively drought resistant

Common cultivars: 'Royal Purple', 'Velvet Cloak'

32

The new manual includes photos of landscape plants along with their identification by scientific name and common name, and information on culture, characteristics and landscape notes.

RGBI Conference Reminder

by
Danielle Supercinski

The annual Rio Grande Basin Initiatives Conference will be held at South Padre Island, Texas, May 14 to 17, 2007 at the Radisson Resort.

This will be another joint meeting of Texas and New Mexico Agricultural Experiment Stations and Cooperative Extension, Texas State University System and the University of Texas at Austin. Early registration and hotel reservations must be made by Friday, April 13.

Continue to visit the conference Web site at http://riogrande-conference.tamu.edu as more information will be posted as the event gets closer.

Water Use

continued from page 5

The team uses state-of-the-art technology (eddy covariance technique) to measure pecan and cotton ET on the ground. They also quantify the consumptive use of water by crops throughout New Mexico's Lower Rio Grande region using 2002 remote sensing data.

This research is also receiving collaborative support through the National Science Foundation-Experimental Program to Stimulate Competitive Research (NSF-EPSCoR), New Mexico's Office of State Engineer, Governor Richardson's Water Innovation Fund II Project and the New Mexico Water Resources Research Institute.

According to Samani, the preliminary outcomes of this collaborative, field-level research have already produced interest.

"Last November our poster with the results of the crop ET study for Dona Ana County received second place in the 19th annual EPSCoR National Conference at Lexington, Kentucky," Samani said. "Brad Kirksey, the only undergraduate student to compete in the conference, received an Award of Excellence for outstanding research."

The team believes that this innovative research will provide invaluable knowledge about water consumption in Southern New Mexico. The team plans to extend their research to other regions and vegetation types.

Faces of RGBI

Economists can save you money

by

Danielle Supercinski

Economists play an integral part in RGBI by working to save irrigation districts (IDs), municipal water suppliers, stakeholders and farmers money. Spreadsheet models, surveys, workshops and publications are just a few of the tools produced by Texas and New Mexico RGBI economists to determine effects on the cost of delivering water and how much money can be saved by making economic adjustments.

RGBI economists include Dr. Ron Lacewell, Dr. Ari Michelsen, Dr. Luis Ribera, Dr. Edward Rister and Allen Sturdivant for Texas; and Leeann DeMouche, Rhonda Skaggs and Frank Ward for New Mexico.

These economic teams work together through RGBI tasks 1 and 3, "Irrigation District Studies" and "Institutional Incentives for Efficient Water Use." Some of their numerous efforts and accomplishments to date can be found online at http://riogrande.tamu.edu under "Featured Articles."

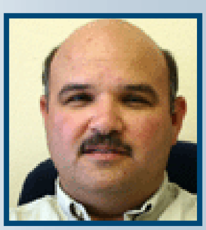
Thank you, economists, for all your efforts and keep up the good work!

Dr. Ronald Lacewell

Dr. Ari Michelsen

Dr. Luis Ribera

Dr. Edward Rister



Allen Sturdivant

Leeann DeMouche

Dr. Rhonda Skaggs

Dr. Frank Ward

Increasing Irrigation Efficiency in the Rio Grande Basin through Research and Education

Through Extension and research efforts, the Texas Agricultural Experiment Station and Texas Cooperative Extension and counterparts at New Mexico State University are implementing strategies for meeting present and future water demands in the Rio Grande Basin. These strategies expand the efficient use of available water and create new water supplies. This federally funded initiative is administered by the Texas Water Resources Institute and the New Mexico State University Water Task Force with funds from the Cooperative State Research, Education and Extension Service.

Texas Agricultural Experiment Station
THE TEXAS A&M UNIVERSITY SYSTEM

Texas Cooperative EXTENSION
The Texas A&M University System

Texas Water Resources Institute
make every drop count

NM STATE UNIVERSITY

Rio Grande Basin Initiative Outcomes
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Student Support

Student Support					
Category	Section 104 Base Grant	Section 104 NCGP Award	NIWR-USGS Internship	Supplemental Awards	Total
Undergraduate	1	0	0	0	1
Masters	3	2	0	0	5
Ph.D.	7	1	0	0	8
Post-Doc.	0	0	0	0	0
Total	11	3	0	0	14

Notable Awards and Achievements

Publications from Prior Projects

None