Texas Water Resources Institute
Annual Technical Report
FY 2005

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 some 150 faculty members from across the state with more than $13.5 million in funding.

The institute maintains joint projects with 14 Texas universities and four in other states; nine federal agencies; five state agencies; seven consulting engineering firms; 30 water districts; four river authorities; five 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 graduate student research projects for 2005-06 conducted by graduate students and researchers at Texas A&M University (6 projects), Rice University (1), Texas A&M University Kingsville (1), Baylor University (1), and the University of Texas at Austin (1).

The research projects covered several broad subjects, including the following: stormwater analysis/control (2 projects); irrigation scheduling (1); using zerovalent iron to reduce nitrate mobility (1); saltcedar control (1); groundwater management (1); watershed development (2); environmental flows and estuarine function (1); ecosystem functions (1); water purification; (1) and the soil and water assessment tool (1). Note that several projects include more than one topic.

Lindsay Birt, of Texas A&M Universitys Biological and Agricultural Engineering Department, focused on the evaluation of standards for compost blankets in stormwater control.

Josh Bynum of Texas A&M University studied the use of the biotic model to focus on the evolution of irrigation scheduling.

In the department of civil and environmental engineering at Rice University, Zhen Fang worked to enhance a distributed hydrologic model for stormwater analysis within the GIS framework in an urban area.

Omar Harvey, Texas A&M University graduate student, worked to assess the potential of zerovalent iron to reduce nitrate mobility.

Jeremy Hudgeons, Texas A&M University graduate student, focused his research on determining the efficacy of biological control of saltcedar on the Colorado River of Texas.

Texas A&M University at Kingsville graduate student, Muthukumar Kuchanur, focused on a decision support system to develop sustainable groundwater management policies for a multi-county single aquifer system.

Marc Russell, University of Texas at Austin graduate student, investigated watershed development and climate change effects on environmental flows and estuarine function.

Baylor University graduate student, Thad Scott, worked with spatial patterns in wetland nutrient biogeochemistry: implications for ecosystem functions.

Civil engineering graduate student, Sanjay Tewari of Texas A&M University, studied carbon aerogel electrodes: absorption-desorption and regeneration study for purification of water.

Texas A&M University forest science graduate student, Xuesong Zhang evaluated spatial hetergeneity of a watershed through HRU concept using the Soil and Water Assessment Tool (SWAT).

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 Guadalupe Estuary (Texas): The importance of Freshwater Pulses

Research Progress Report
(March 1, 2005 through February 28, 2006)

Submitted to:

National Institutes of Water Resources

Through:

Dr. C. Allan Jones
Texas Water Resources Institute
MS 2118
Texas A&M University
College Station, TX 77843-2118

By

Stephen E. Davis, III
Daniel L. Roelke
Department of Wildlife & Fisheries Sciences
MS 2258
Texas A&M University
College Station, TX 77843-2258

USGS Project ID# 2003TX112G
TAMU Account No. 57136800

June 26, 2006

Introduction

In accordance with the reporting policies established by the National Institutes of Water Resources, this report describes the activities undertaken by researchers at Texas A&M University from March 1, 2005 through February 28, 2006 for project ID # 2003TX112G. Please refer to the accompanying portable document file entitled SanAntonioBay.pdf for figures (i.e. slides) referenced throughout the report.

The San Antonio Bay system is a lagoonal estuary located along the Texas coastal bend. It is approximately 500 km^2 in area and is fed by the Guadalupe River, that accounts for approximately 70% of gauged, freshwater inflows to the bay system. This amounts to an average of about 2 million acre-feet of freshwater inflow each year. The region immediately around the estuary is mostly agricultural with littler residential development (**Slide 1**). Aransas National Wildlife Refuge is located within this estuary as are the wintering grounds of the only naturally migrating population of whooping cranes (*Grus americana* L.) in the world (currently numbering 216 birds).

Reduced freshwater inflow is a problem facing many bay systems in Texas. Unfortunately, there are still many unknowns regarding the importance of freshwater inflows in driving estuarine loadings, water quality patterns, and estuarine function. The overall goal of this project is to understand how this particular estuarine system responds to a range of inflow characteristics (pulse magnitude, pulse duration, pulse frequency, etc.) from the Guadalupe River. We anticipate our findings from this research will be helpful in developing future water management plans for this region that protect necessary habitat for commercially important species such as blue crabs, shrimp, and oysters in addition to protecting marsh habitat for whooping cranes.

Accomplishments

We conducted monthly samplings this past year as a part of this continuing research in San Antonio Bay. During each trip seven fixed-location stations were sampled (plus an 8th site along the lower Guadalupe River; see **Slide 2**), and the entire system was mapped using an onboard flow-through system (DataFlow, see **Slide 3**). During 2005, we witnessed increasing drought-like conditions, as high inflows at the beginning of the year transitioned to low flows at the end of the year (**Slide 4**).

At fixed stations, parameters measured included:

1. Phytoplankton biomass (chlorophyll *a*)
2. Phytoplankton composition (photopigments and microscopy)
3. Zooplankton biomass (microscopy)
4. Zooplankton composition (microscopy)
5. Primary productivity (light/dark bottle technique)
6. Community respiration (dark bottle technique)
7. Dissolved inorganic nutrients (NO3, NO2, NH4, PO4, TP, SiO3)
8. Total suspended solids
9. Secchi depth
10. Water quality parameters (temperature, dissolved oxygen, pH, salinity, turbidity, oxidation-reduction potential)

These fixed station data reflect patterns found in Dataflow samplings and will be analyzed to understand the effect of inflow patterns along the estuarine salinity gradient (**Slides 97-108**)

Parameters measured during our high-resolution spatial mapping of the entire system each month included:

1. Transmissivity
2. In-vivo chlorophyll *a*
3. Fluorescent dissolved organic matter
4. Temperature
5. Salinity/conductivity
6. Photosynthetically active radiation

For the collection of high-resolution spatial mapping data, we sampled approximately 160 linear miles of San Antonio Bay and collected more than 5000 rows of data. We also followed the same set of transects in order to best capture variability across samplings (**Slide 5**). At the conclusion of each run, all data were transferred from the datalogger to a computer. They were subjected to a thorough QA/QC check, archived in MS-Excel format, and were backed-up multiple times to prevent loss. Maps for each parameter from each sampling were generated in Surfer using standard interpolation (e.g. nearest neighbor) techniques. See **Slides 6-90** for monthly maps of different water quality parameters.

All gauge data from relevant USGS river gauge stations (http://waterdata.usgs.gov/tx/nwis/rt) and the Texas Coastal Ocean Observation Network (TCOON; http://lighthouse.tamucc.edu/overview/031) bay monitoring sites have been acquired and incorporated into our project database (see USGS discharge data in **Slides 4, 92, and 96** and TCOON wind data in **Slide 92**). **Slide 91** provides examples of Dataflow maps for a few parameters and illustrates the co-variation we have seen through time. Spatio-temporal patterns in these parameters seem to be tied to inflows from the Guadalupe River; however, wind patterns (direction and speed) also need to be considered in this shallow, micro-tidal system that is dominated by SE winds (**Slides 92 and 93**)

We also established and sampled continuously a saltwater barrier site along the lower Guadalupe River. This site has also been sampled continuously since November 2004. Our work at this site focused solely on water quality and nutrient loading into the head of the estuary. The refrigerated water sampler at this site has been visited at least once per month for retrieval of water samples (see **Slides 94 and 95**). Nutrient data from this site are just starting to come into the lab, but have not been checked for quality. Total suspended solids data from these water samples were checked through and corresponded with discharge patterns along the lower Guadalupe River (**Slide 96**).

To make this data readily available to other scientists, resource managers, and lay people, we developed a web-based system where users can quickly access the data. The fixed station data is in two formats. The first format shows the data with emphasis on spatial trends, and the second format with emphasis on temporal trends. A sample of our web-based data access system is provided in this report (see **Slides 109-112**). The URL address for these web pages is http://www.wfsc.tamu.edu/roelkelab/SABproj.htm.

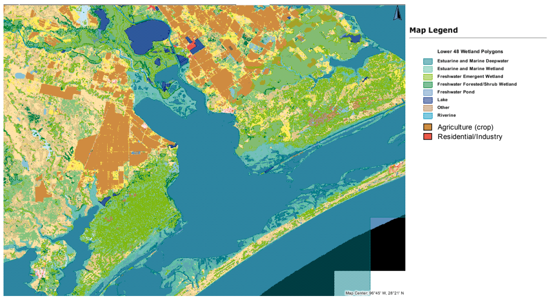
Project Impact

This projected supported three graduate students this past year (George Gable, M.S.; Hsiu-Ping Li, Ph.D.; and Carrie Miller, M.S.), produced 13 presentations, and two manuscripts that are in preparation. It is also led to other sources of funding that will generate many more peer-reviewed publications and presentations.

Researchers imported a technology from Florida, i.e., Dataflow, that invloves ship-board, flow-through sensors. The technique is 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.

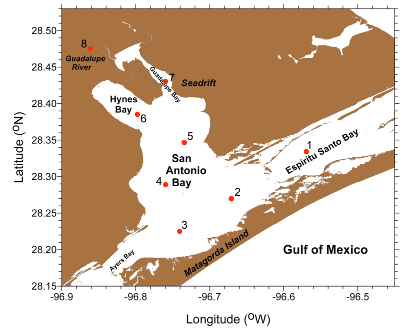
Researchers developed a web-based data access system were users can quickly view monthly data being collected in San Antonio Bay, which includes fixed station data and high-resolution spatial maps of the entire bay stsrem (see above for parameters measured). This service, after being properly advertised, 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.

Land-Use and Wetland Area Around the San Antonio Bay System



1

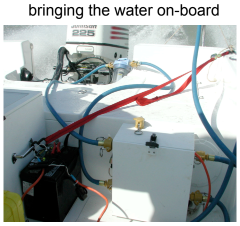
Fixed Sampling Stations in San Antonio Bay and along the Lower Guadalupe River



2

Dataflow in Action

bringing the water on-board

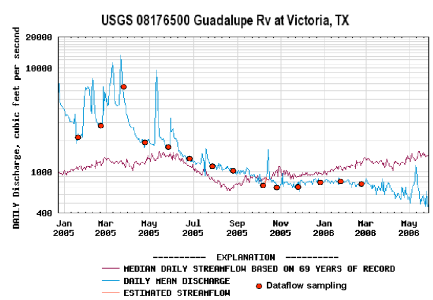


sensor array and datalogger

Measures GPS coordinates, Temperature, Salinity/Conductivity, Beam Transmittance, Chlorophyll *a*, CDOM, Depth, and PAR at approximately 8 second intervals from a vessel running at 20 kts.

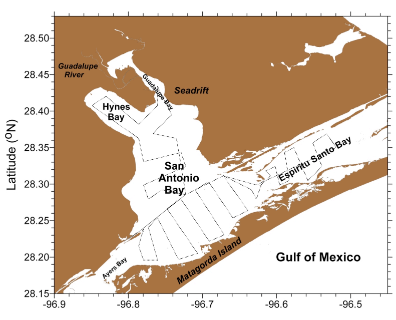
3

Mean Daily Discharge (December 2004–June 2006) in Lower Guadalupe River



4

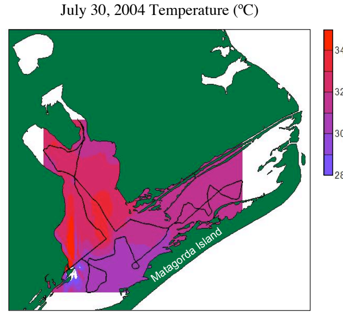
Example of Transects Followed in Sampling San Antonio Bay with Dataflow



5

Temperature in San Antonio Bay

July 30, 2004 Temperature (°C)

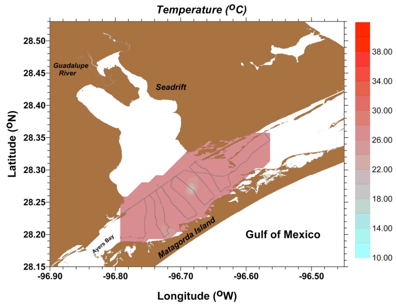


6

Temperature in San Antonio Bay

San Antonio Bay, Oct 04

Temperature (°C)

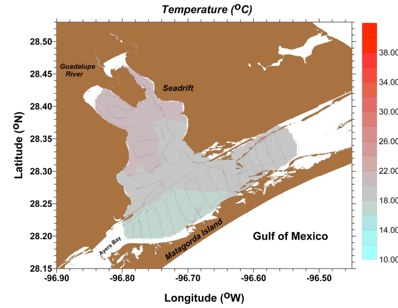


7

Temperature in San Antonio Bay

San Antonio Bay, January 05

Temperature (°C)

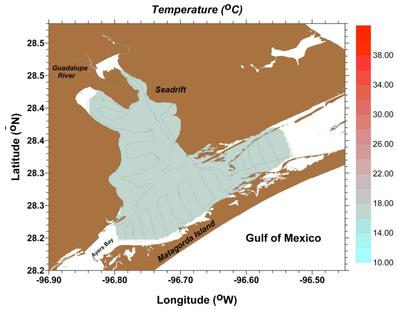


8

Temperature in San Antonio Bay

San Antonio Bay, February 05

Temperature (°C)



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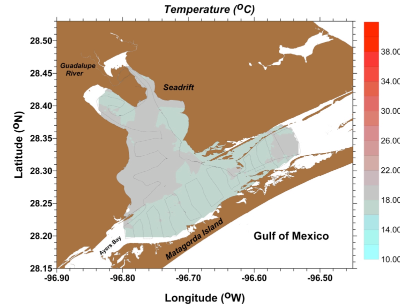
Temperature in San Antonio Bay

San Antonio Bay, March 05

Temperature (°C)

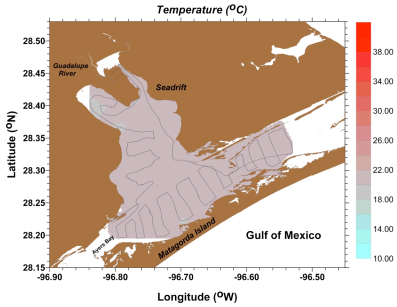


10

Temperature in San Antonio Bay

San Antonio Bay, April 05

Temperature (°C)

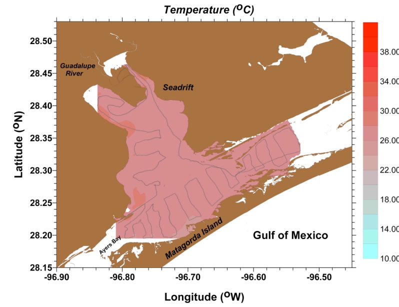


11

Temperature in San Antonio Bay

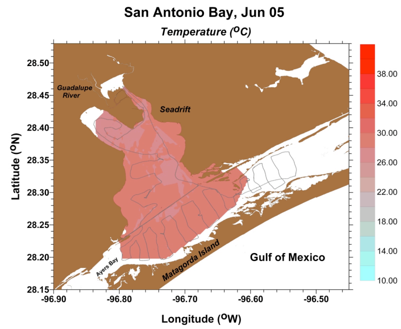
San Antonio Bay, May 05

Temperature (°C)



12

Temperature in San Antonio Bay



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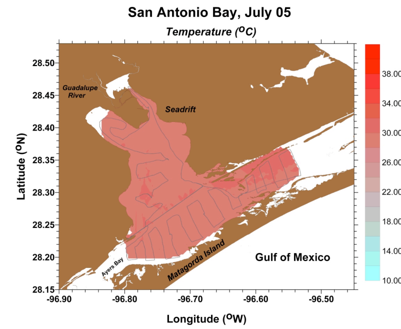
Temperature in San Antonio Bay



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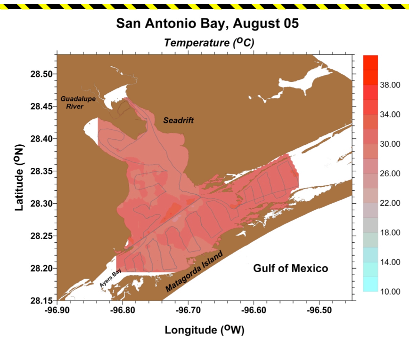
Temperature in San Antonio Bay



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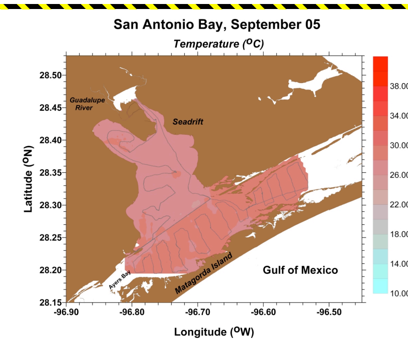
Temperature in San Antonio Bay



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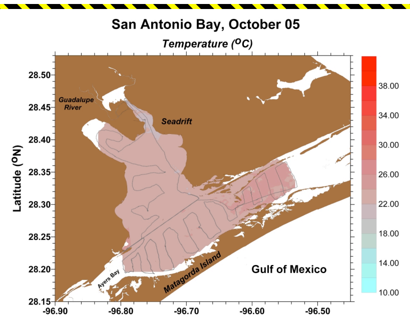
Temperature in San Antonio Bay



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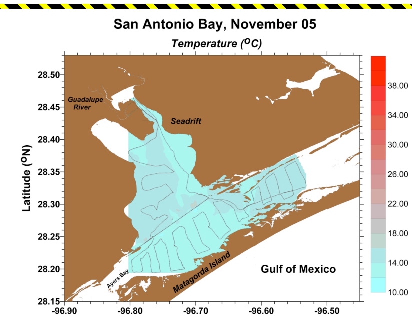
Temperature in San Antonio Bay



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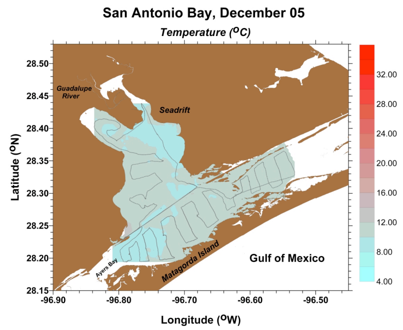
Temperature in San Antonio Bay



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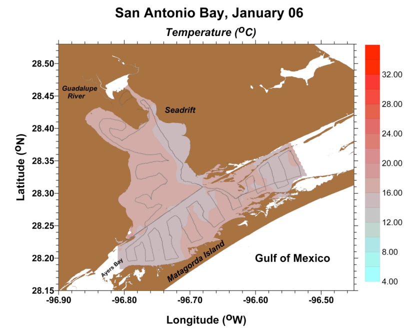
Temperature in San Antonio Bay



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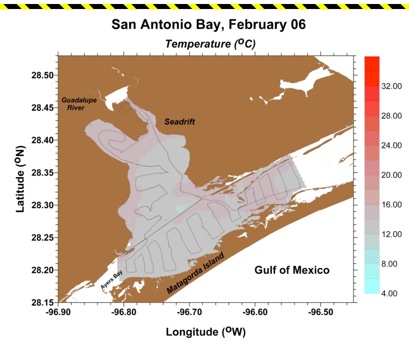
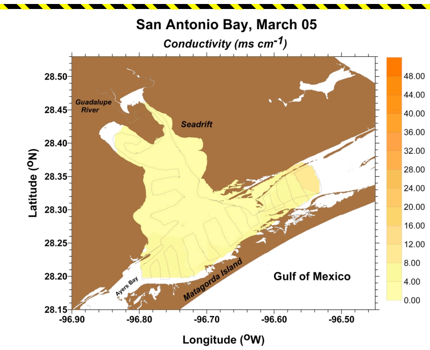
Temperature in San Antonio Bay



21

Conductivity in San Antonio Bay



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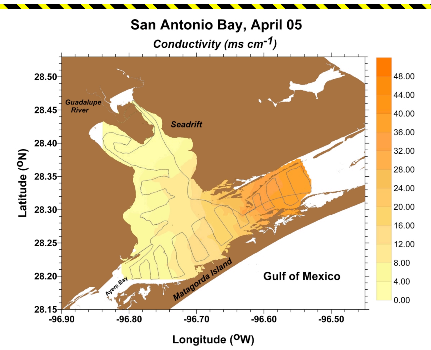
Conductivity in San Antonio Bay



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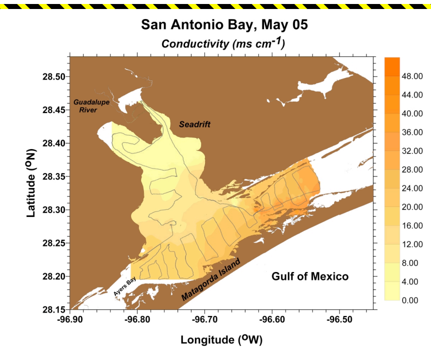
Conductivity in San Antonio Bay



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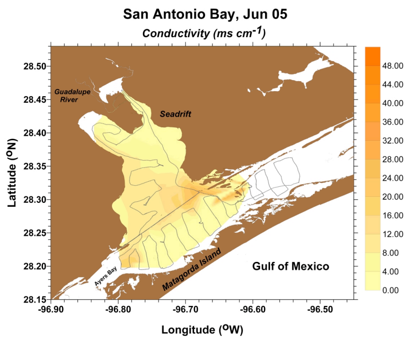
Conductivity in San Antonio Bay



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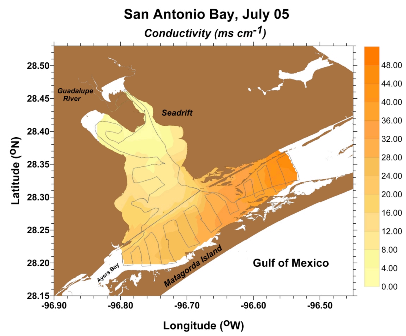
Conductivity in San Antonio Bay



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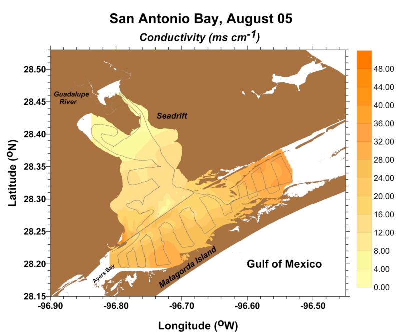
Conductivity in San Antonio Bay



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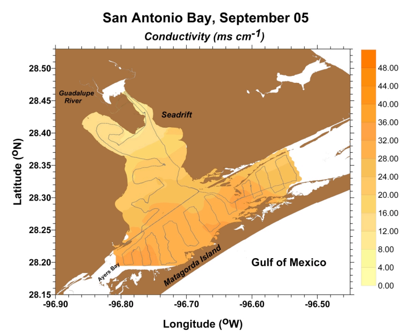
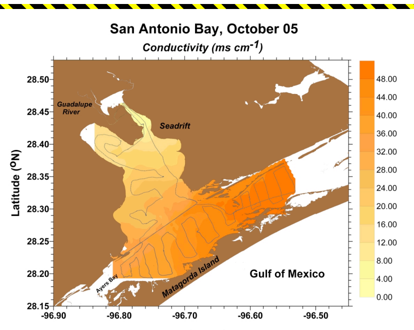
Conductivity in San Antonio Bay



28

Conductivity in San Antonio Bay



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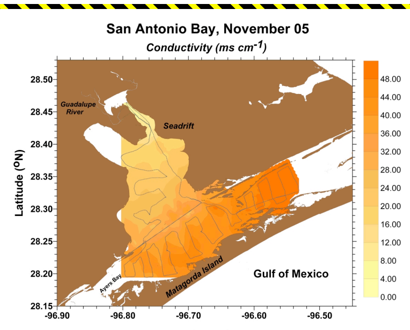
Conductivity in San Antonio Bay

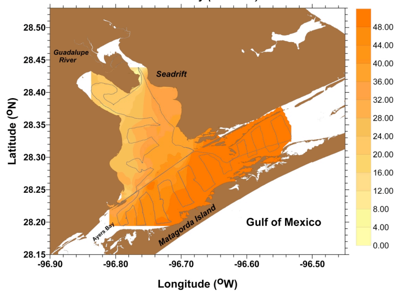


30

Conductivity in San Antonio Bay

San Antonio Bay, December 05

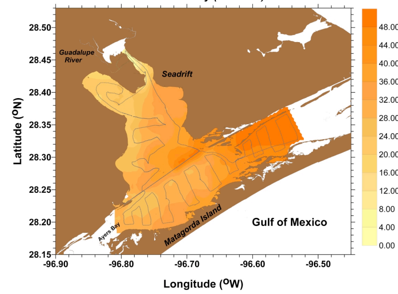
Conductivity (ms cm^{-1})



Conductivity in San Antonio Bay

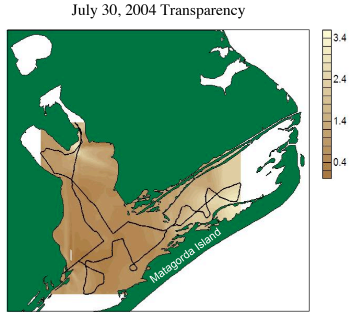
San Antonio Bay, February 06

Conductivity (ms cm^{-1})



Beam transmittance* in San Antonio Bay

July 30, 2004 Transparency

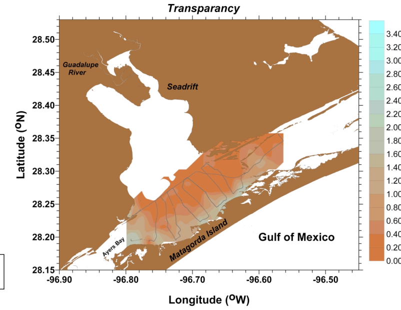


* higher value indicates water of higher clarity

Beam transmittance* in San Antonio Bay

San Antonio Bay, Oct 04

Transparancy

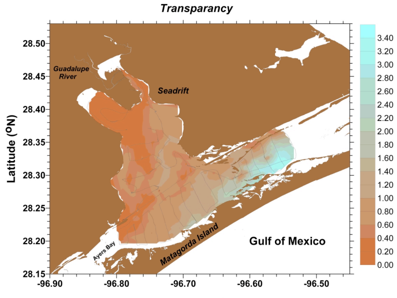


* higher value indicates water of higher clarity

Beam transmittance* in San Antonio Bay

San Antonio Bay, January 05

Transparancy

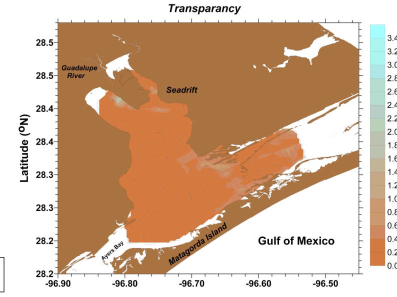


* higher value indicates water of higher clarity

Beam transmittance* in San Antonio Bay

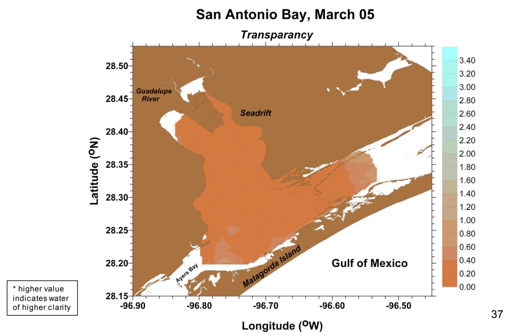
San Antonio Bay, February 05

Transparancy



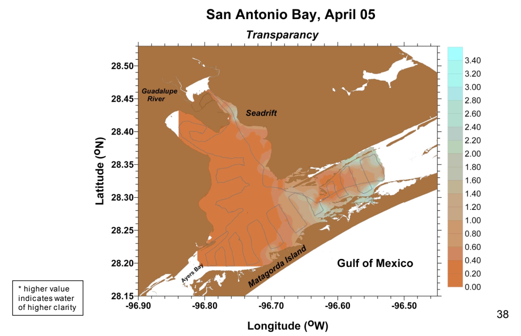
* higher value indicates water of higher clarity

Beam transmittance* in San Antonio Bay



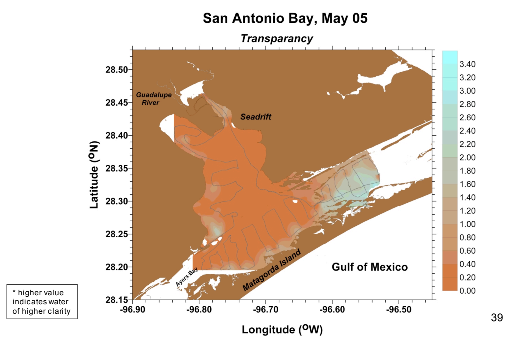
37

Beam transmittance* in San Antonio Bay



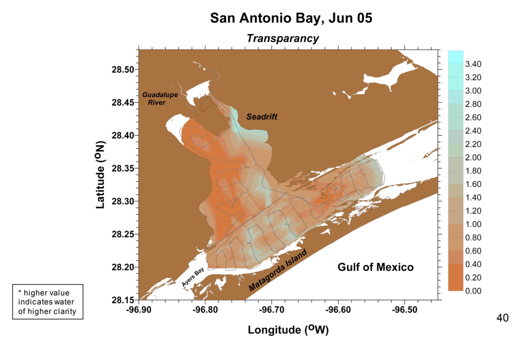
38

Beam transmittance* in San Antonio Bay



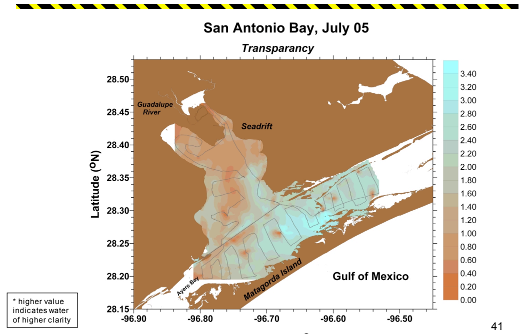
39

Beam transmittance* in San Antonio Bay



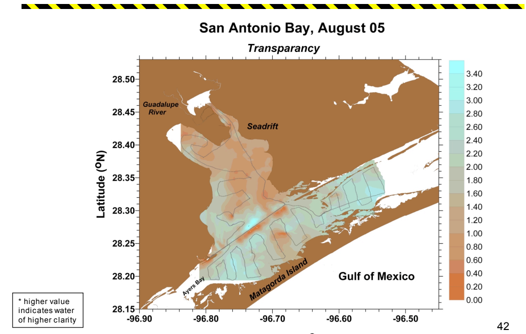
40

Beam transmittance* in San Antonio Bay



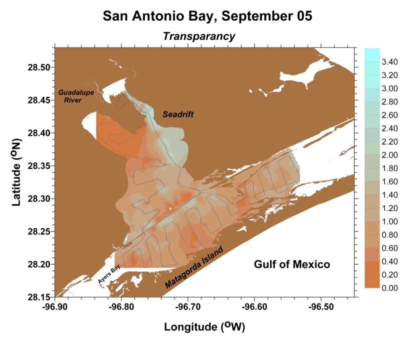
41

Beam transmittance* in San Antonio Bay



42

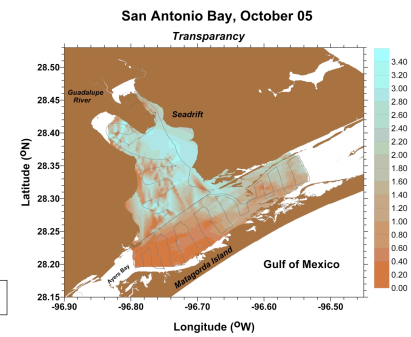
Beam transmittance* in San Antonio Bay



* higher value indicates water of higher clarity

43

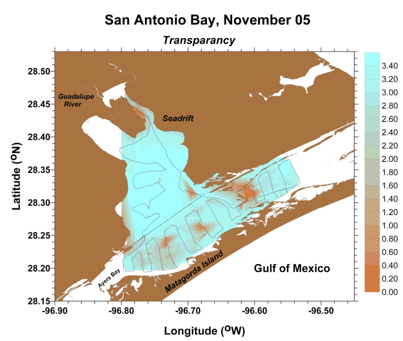
Beam transmittance* in San Antonio Bay



* higher value indicates water of higher clarity

44

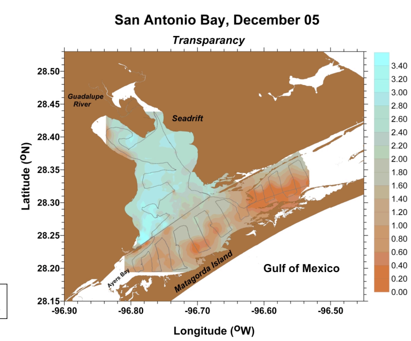
Beam transmittance* in San Antonio Bay



* higher value indicates water of higher clarity

45

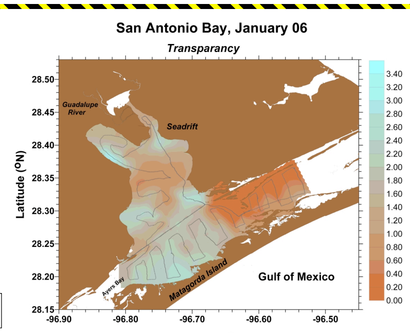
Beam transmittance* in San Antonio Bay



* higher value indicates water of higher clarity

46

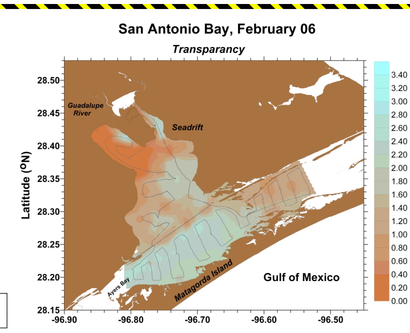
Beam transmittance* in San Antonio Bay



* higher value indicates water of higher clarity

47

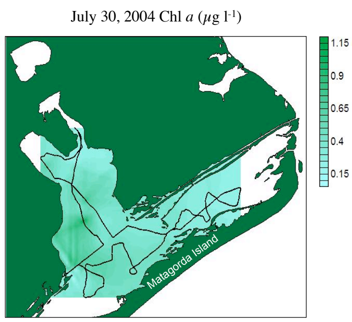
Beam transmittance* in San Antonio Bay



* higher value indicates water of higher clarity

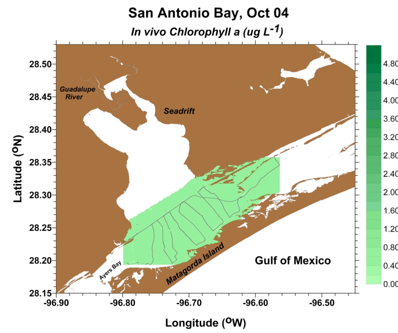
48

Chlorophyll *a* in San Antonio Bay



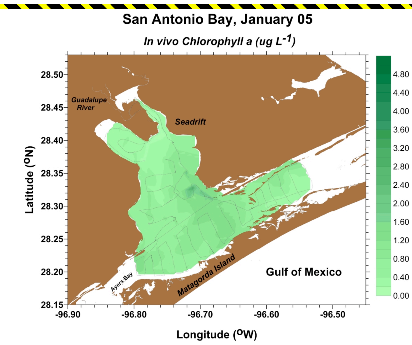
49

Chlorophyll *a* in San Antonio Bay



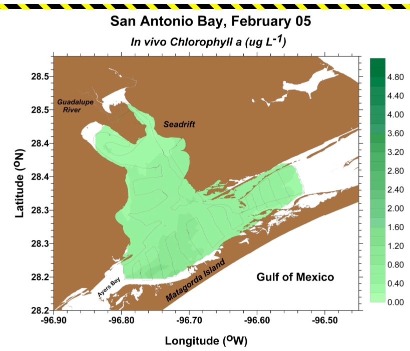
50

Chlorophyll *a* in San Antonio Bay



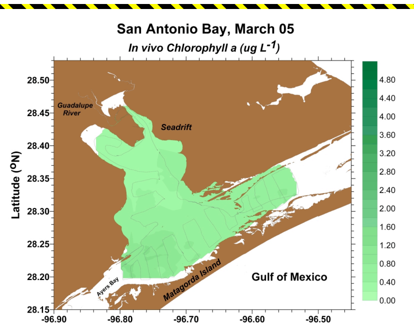
51

Chlorophyll *a* in San Antonio Bay



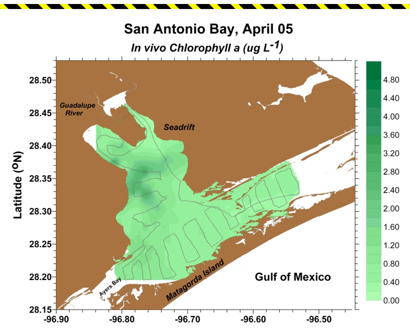
52

Chlorophyll *a* in San Antonio Bay



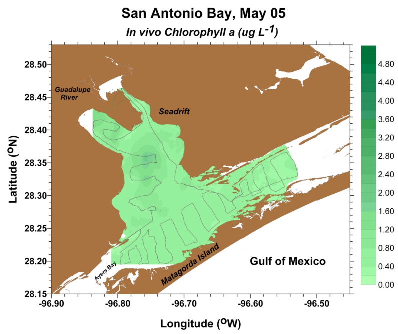
53

Chlorophyll *a* in San Antonio Bay



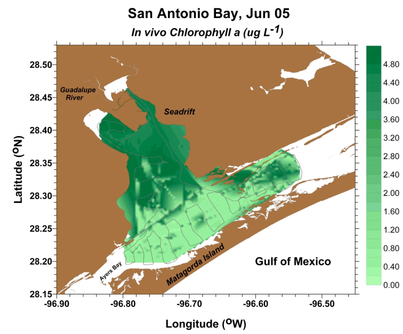
54

Chlorophyll *a* in San Antonio Bay



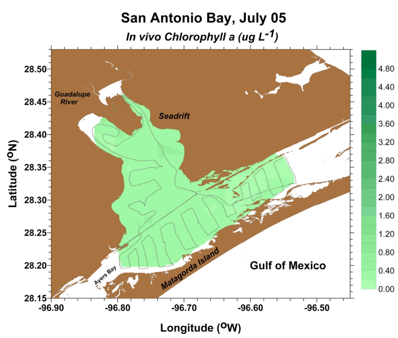
55

Chlorophyll *a* in San Antonio Bay



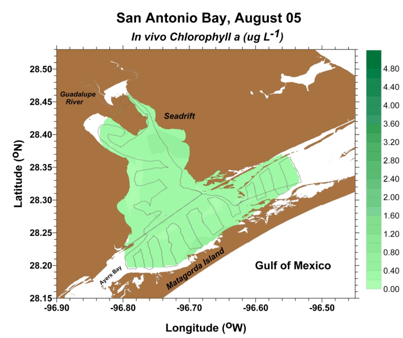
56

Chlorophyll *a* in San Antonio Bay



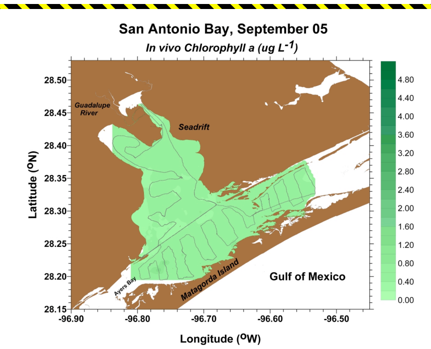
57

Chlorophyll *a* in San Antonio Bay



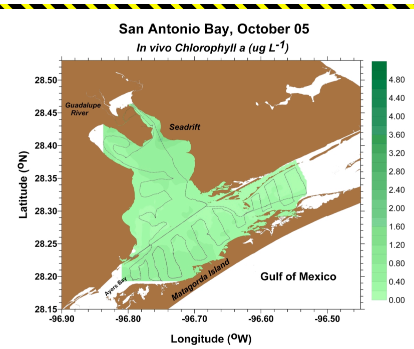
58

Chlorophyll *a* in San Antonio Bay



59

Chlorophyll *a* in San Antonio Bay

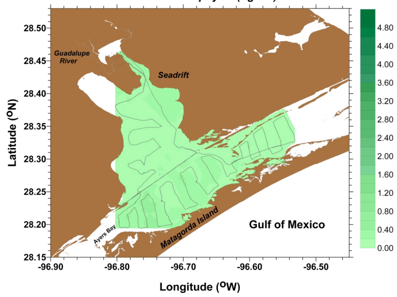


60

Chlorophyll *a* in San Antonio Bay

San Antonio Bay, November 05

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

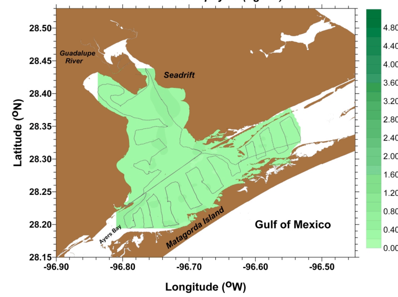


61

Chlorophyll *a* in San Antonio Bay

San Antonio Bay, December 05

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

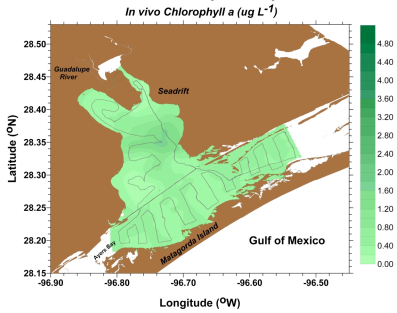


62

Chlorophyll *a* in San Antonio Bay

San Antonio Bay, January 06

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

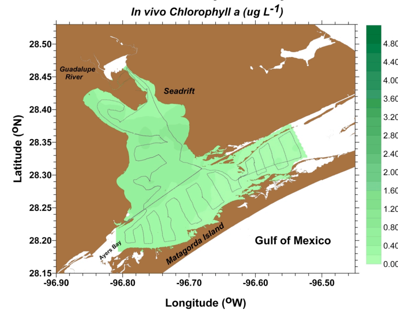


63

Chlorophyll *a* in San Antonio Bay

San Antonio Bay, February 06

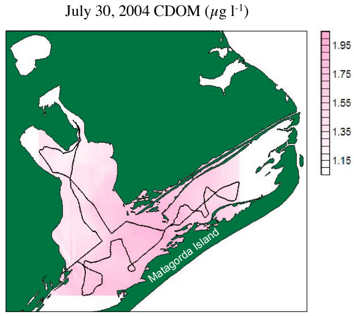
In vivo Chlorophyll a (ug L^{-1})



64

CDOM in San Antonio Bay

July 30, 2004 CDOM (μg l^{-1})

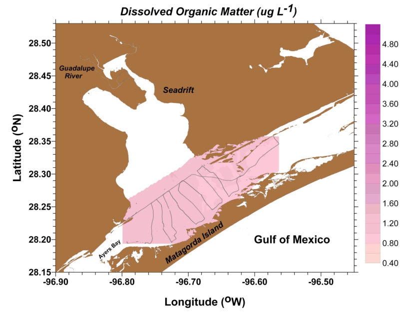


65

CDOM in San Antonio Bay

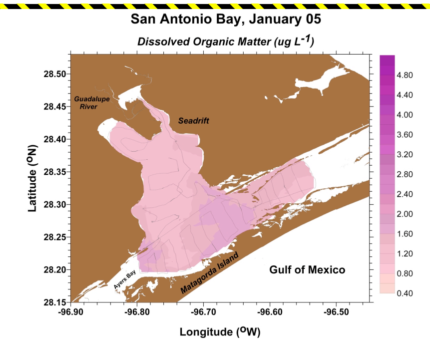
San Antonio Bay, Oct 04

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



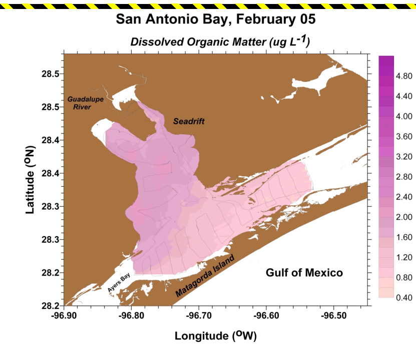
66

CDOM in San Antonio Bay



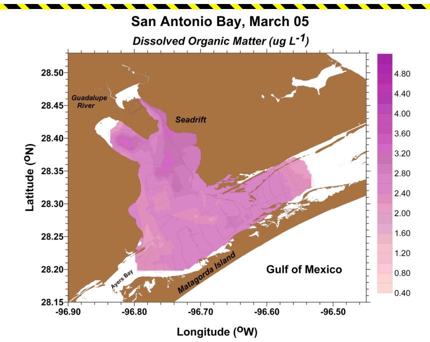
67

CDOM in San Antonio Bay



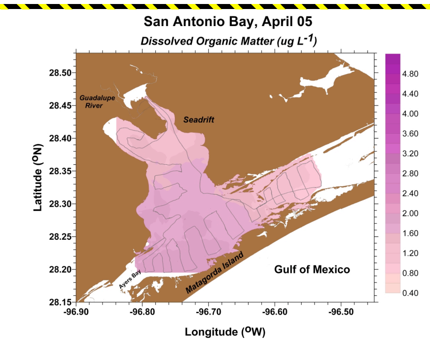
68

CDOM in San Antonio Bay



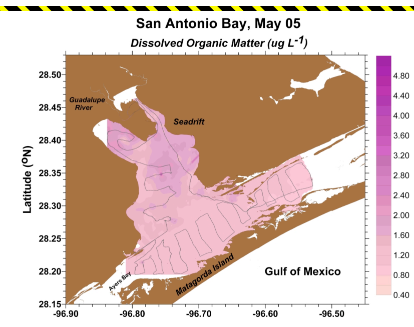
69

CDOM in San Antonio Bay



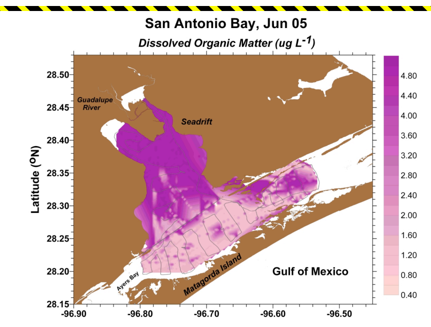
70

CDOM in San Antonio Bay



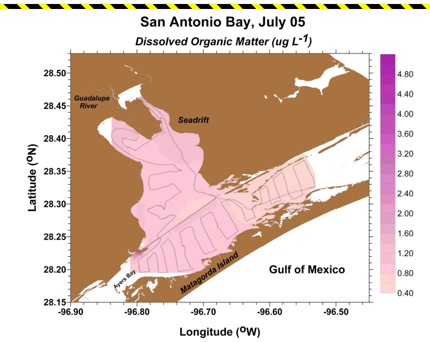
71

CDOM in San Antonio Bay



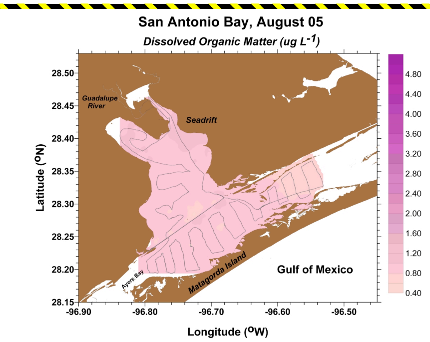
72

CDOM in San Antonio Bay



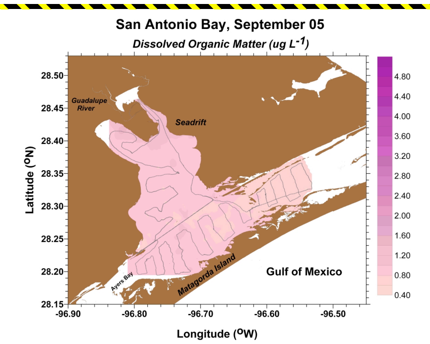
73

CDOM in San Antonio Bay



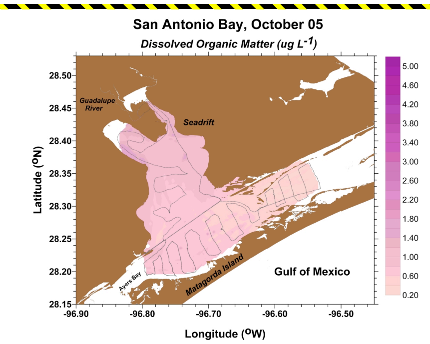
74

CDOM in San Antonio Bay



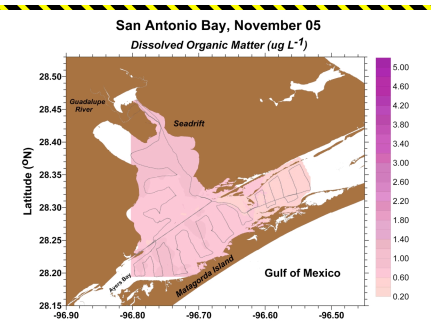
75

CDOM in San Antonio Bay



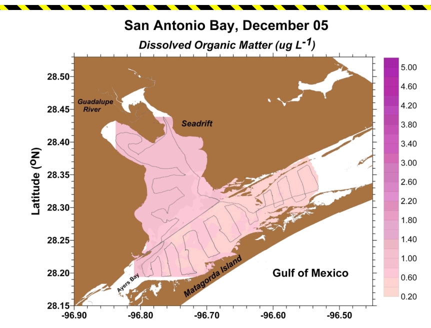
76

CDOM in San Antonio Bay



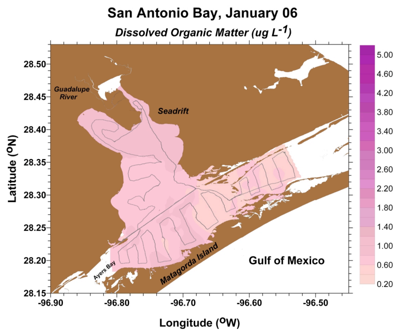
77

CDOM in San Antonio Bay



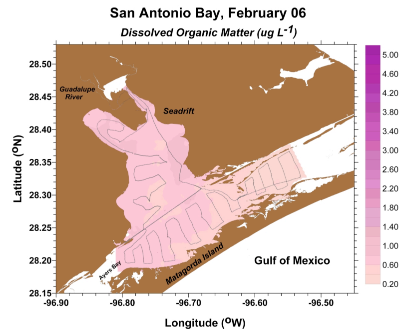
78

CDOM in San Antonio Bay



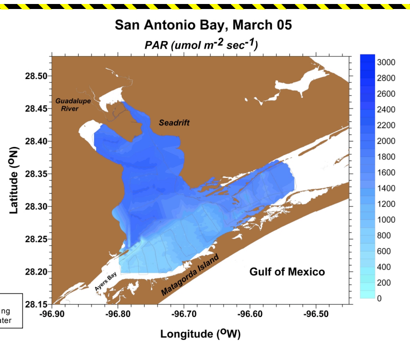
79

CDOM in San Antonio Bay



80

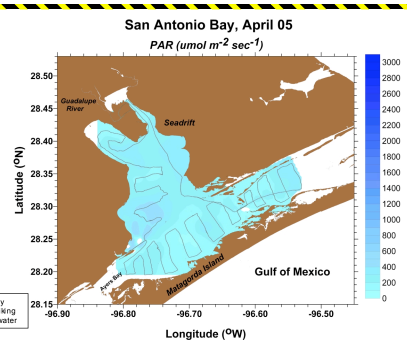
PAR* striking San Antonio Bay



* Photosynthetically active radiation striking the surface of the water

81

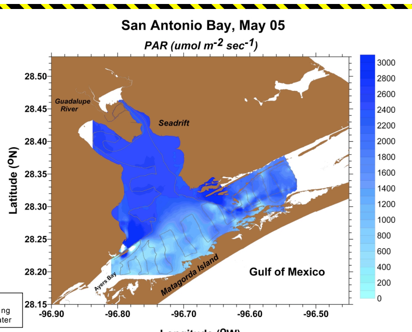
PAR* striking San Antonio Bay



* Photosynthetically active radiation striking the surface of the water

82

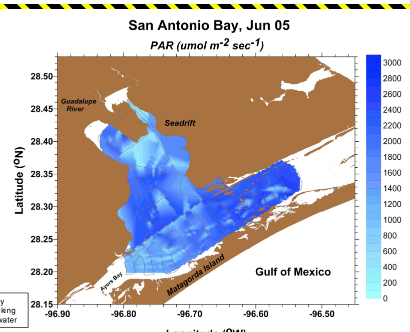
PAR* striking San Antonio Bay



* Photosynthetically active radiation striking the surface of the water

83

PAR* striking San Antonio Bay



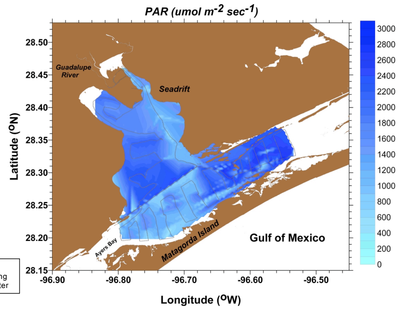
* Photosynthetically active radiation striking the surface of the water

84

PAR* striking San Antonio Bay

San Antonio Bay, July 05

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



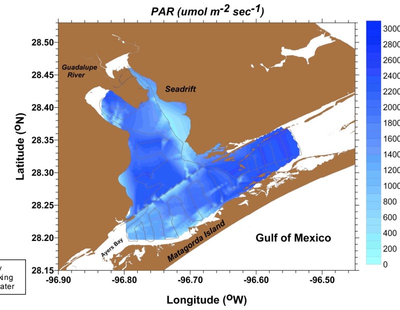
* Photosynthetically active radiation striking the surface of the water

85

PAR* striking San Antonio Bay

San Antonio Bay, August 05

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



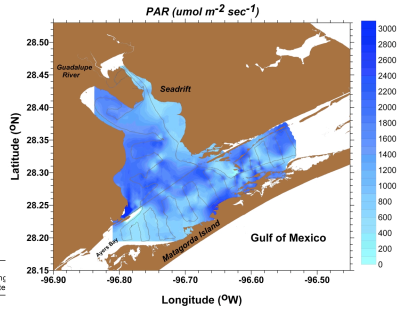
* Photosynthetically active radiation striking the surface of the water

86

PAR* striking San Antonio Bay

San Antonio Bay, September 05

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



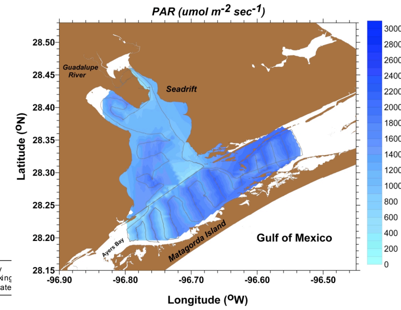
* Photosynthetically active radiation striking the surface of the wate

87

PAR* striking San Antonio Bay

San Antonio Bay, October 05

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



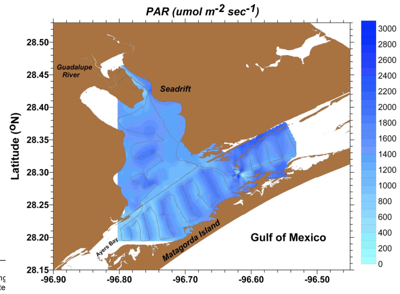
* Photosynthetically active radiation striking the surface of the wate

88

PAR* striking San Antonio Bay

San Antonio Bay, November 05

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



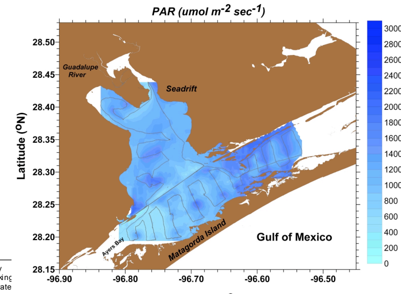
* Photosynthetically active radiation striking the surface of the wate

89

PAR* striking San Antonio Bay

San Antonio Bay, December 05

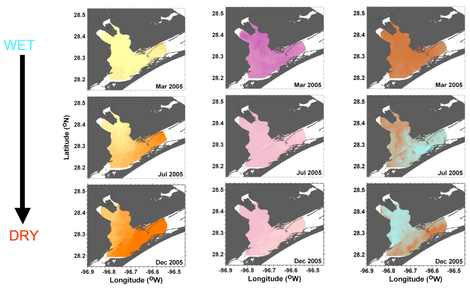
PAR (umol m^{-2} sec^{-1})



* Photosynthetically active radiation striking the surface of the wate

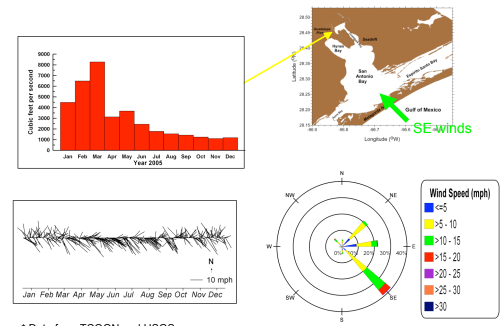
90

San Antonio Bay: 2005 Trends



91

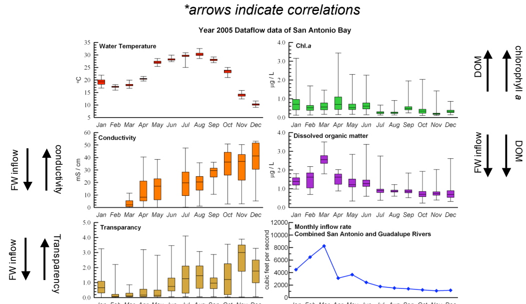
Inflows and Wind from 2005*



* Data from TCOON and USGS

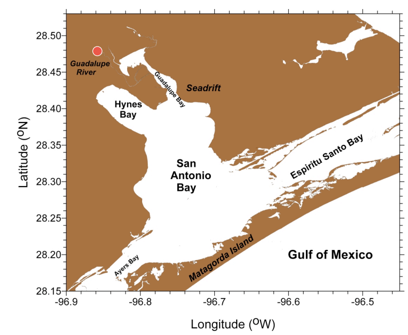
Monthly Variability in San Antonio Bay*

arrows indicate correlations



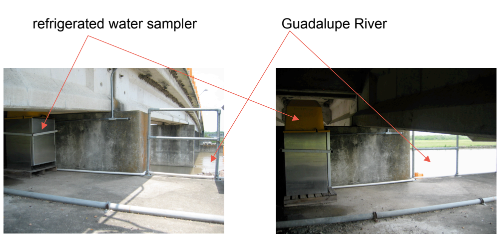
93

Fixed Sampling Station at the Saltwater Barrier of the Lower Guadalupe River



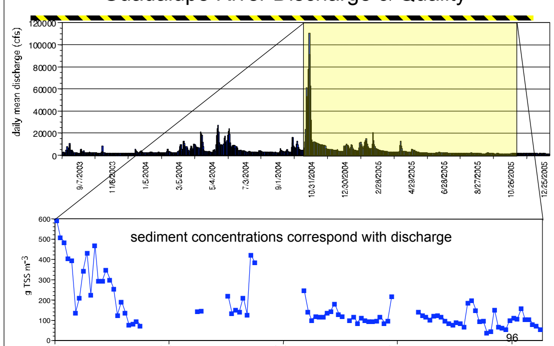
94

Sampling Station at the Saltwater Barrier of the Lower Guadalupe River



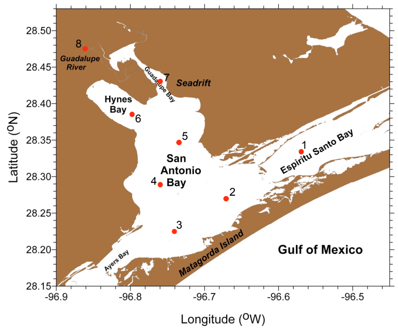
95

Guadalupe River Discharge & Quality



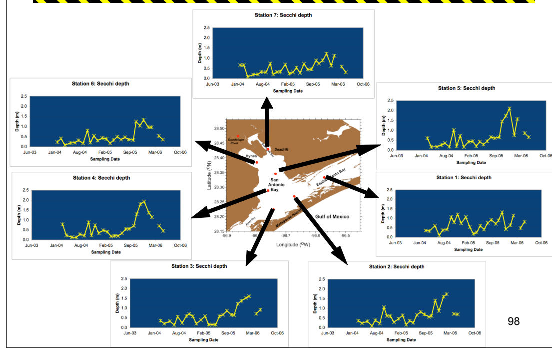
96

Fixed Sampling Stations in San Antonio Bay and along the Lower Guadalupe River



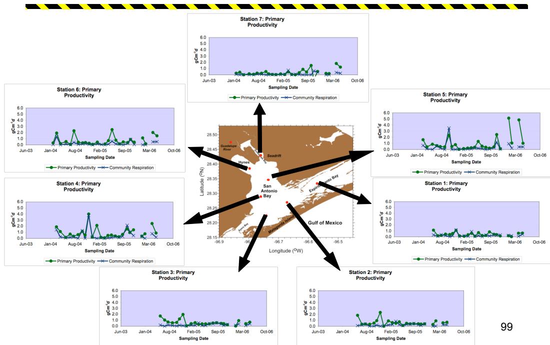
97

Secchi Depth at Fixed Sampling Stations in San Antonio Bay



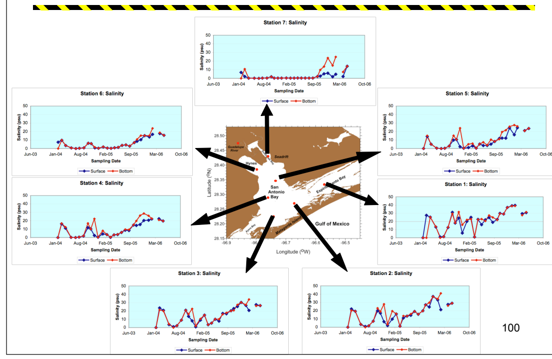
98

1º Productivity and Community Respiration at Fixed Sampling Stations in San Antonio Bay



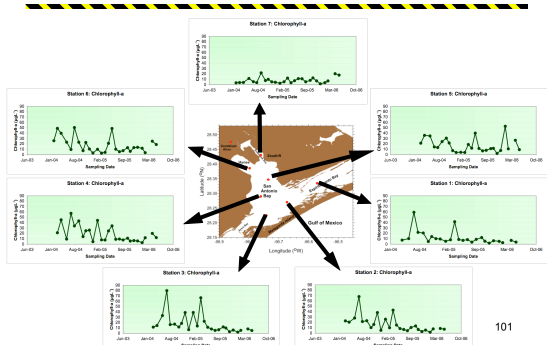
99

Salinity at Fixed Sampling Stations in San Antonio Bay



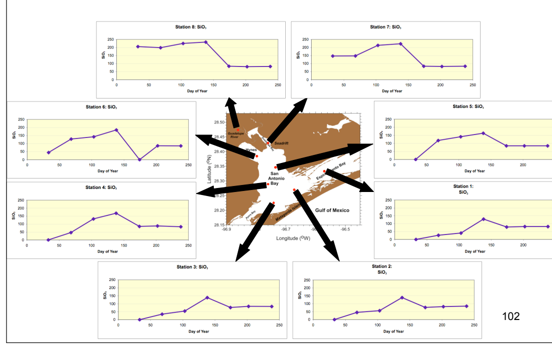
100

Chlorophyll a at Fixed Sampling Stations in San Antonio Bay



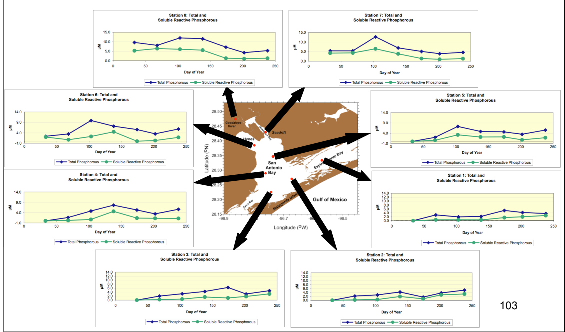
101

[SiO_3] at Fixed Sampling Stations in San Antonio Bay



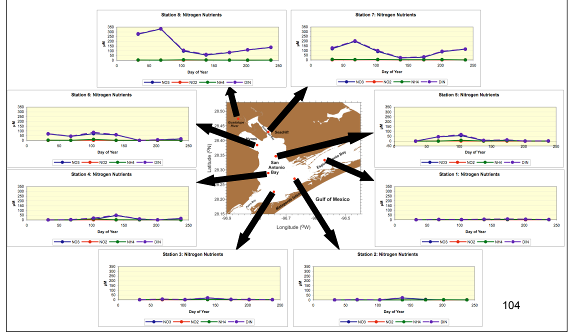
102

[TP] and [SRP] at Fixed Sampling Stations in San Antonio Bay



103

[DIN] at Fixed Sampling Stations in San Antonio Bay



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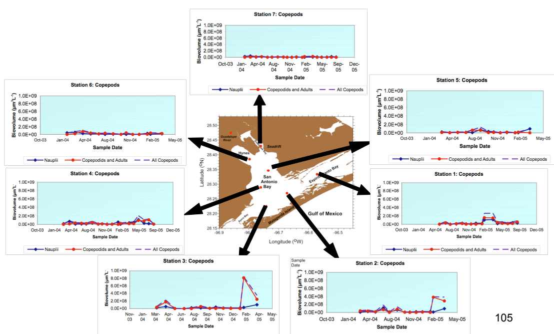
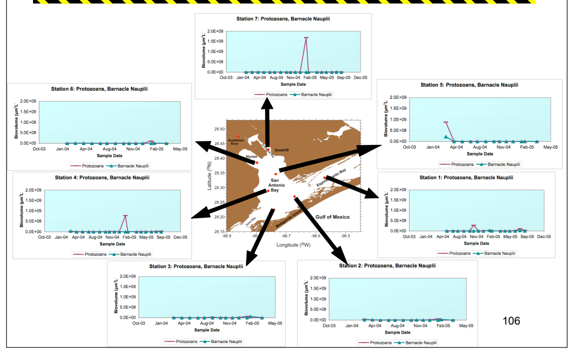
Copepod Biovolume at Fixed Sampling Stations in San Antonio Bay



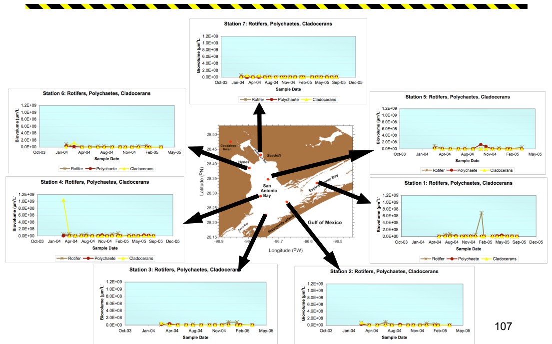
105

Biovolume of Protozoans and Barnacle Nauplii at Fixed Sampling Stations in San Antonio Bay



106

Biovolume of Rotifers, Polychaetes, and Cladocerans at Fixed Sampling Stations in San Antonio Bay



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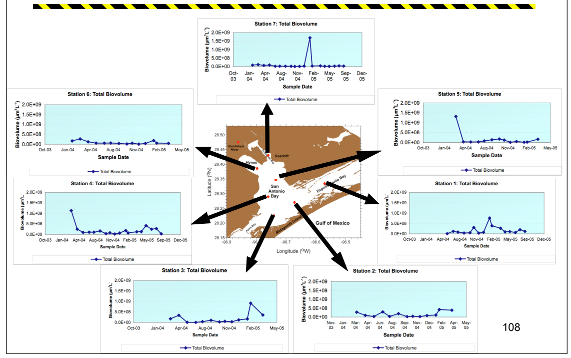
Zooplankton Biovolume at Fixed Sampling Stations in San Antonio Bay



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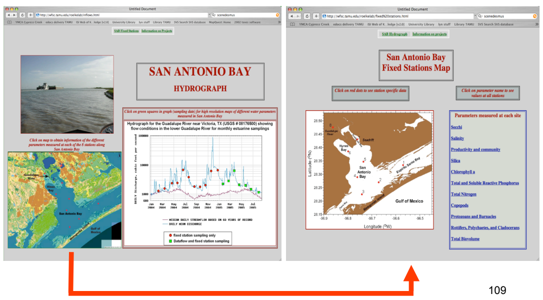
On-line Access To Data (http://wfsc.tamu.edu/davislab)



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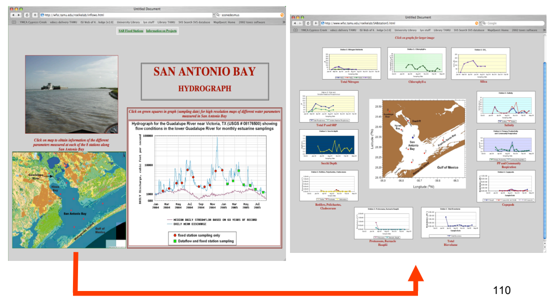

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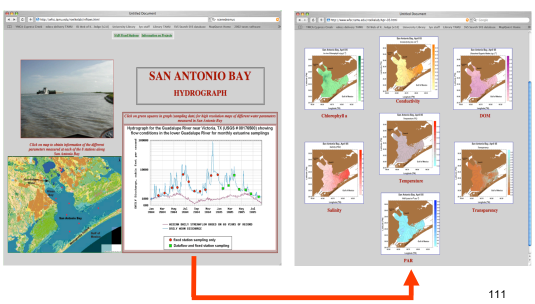

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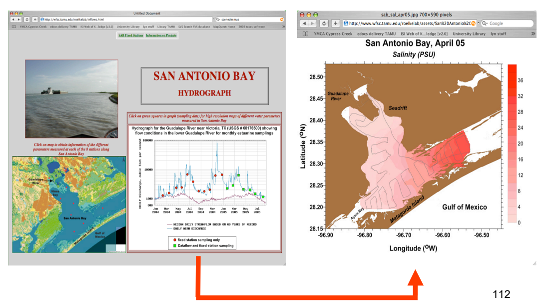
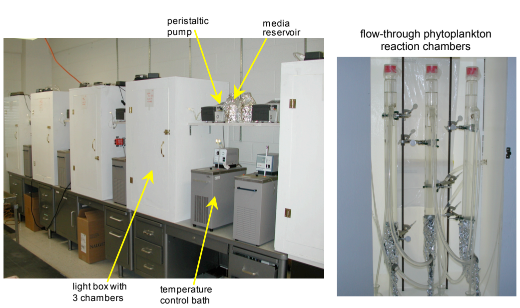
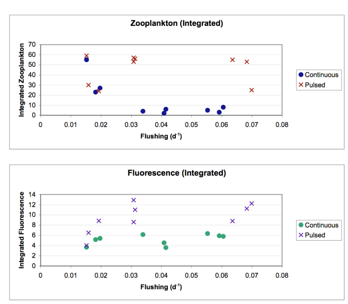


Plankton Incubation Chamber Set-up



Zooplankton and Phytoplankton (fluorescence) Response to Continuous vs. Pulsed Mode of Delivery Under Different Hydrologic Flushing Rates



Evaluation of Standards for Compost Blankets in Stormwater Control

Basic Information

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Principal Investigators:	Lindsay Birt, Russell Persyn

Publication

Evaluation of Standards for Compost Blankets in Stormwater Control-Part 1: Interrill Erosion and Runoff

L. N. Birt, R.A. Persyn, P. K. Haan

Lindsay N. Birt, ASABE Member, Department of Biological and Agricultural Engineering, Texas A&M University, Graduate Research Assistant, **Dr. Russell Persyn, ASABE Member,** Assistant Professor, Department **Agricultural & Biosystems Engineering**, South Dakota State University, Brookings, South Dakota, **Dr. Patricia Haan, ASABE Member,** Associate Professor, Department of Biological and Agricultural Engineering, Texas A&M University, College Station, TX,

ABSTRACT: Runoff rates, solid detachment, and interrill erodibility rates were determined and compared across seven blanket treatments applied at 5 cm and 1.3 cm depth. An indoor rainfall simulator was used to apply an average rainfall intensity of 92 mm/hr to aluminum pans with each treatment at a 3:1 slope. The mean runoff for CMT-1.3, CMT-5, and TS treatments were similar whereas, the mean runoff for HS, ECC-5, ECC-1.3, and GUC-5 were similar in values. The log-transformed geometric means of interrill erodibility resulted in CMT-1.3, CMT-5, and TS treatments had similar means whereas, the mean runoff for HS, ECC-5, ECC-1.3, and GUC-5 were similar in values. The interrill erodibility had the same mean comparison results as the runoff rates. Overall, the depth of application had no significant affect on the runoff, detachment, or interrill erodibility. Yet, coarser materials (i.e. woodchips and hydro seeding), absorb reduced the amount of runoff and minimized detachment and interrill erodibility.

KEYWORDS: Compost blankets, detachment, interrill erodibility

OBJECTIVES

The overall objective of this study was to determine the effectiveness of using compost rather than the conventional hydroseeding application to reduce erosion and nutrient load from roadside construction. Blanket applied compost was used in seven treatment applications at 5 cm and 1.3 cm depths for this research. The treatments were: untreated woodchips, composted yard trimmings, topsoil, and fertilizer-paper mulch blend as the hydroseeding. Runoff rates, solid detachment, and interrill erodibility rates were determined and compared across the six treatments. The specific objectives of the study were:

- Determine the effect of treatment on runoff rate, detachment, and interrill erodibility

- Determine the optimal application depth of compost to minimize runoff from treatment plots.

LITERATURE REVIEW

In 1987, the Clean Water Act was revised to require all states to investigate non-point sources of sediment and determine strategies to minimize the sources. Currently, the United States Environmental Protection Agency (EPA) regulates stormwater from construction activities as part of the National Pollution Discharge Elimination System (NPDES) (US EPA, 1995). The Texas Department of Transportation (TxDOT) has approved and promoted the use of compost as stormwater BMPs during highway construction. Recent studies have shown that compost application will reduce erosion (Persyn et al., 2004; Demars et al., 2000; Storey et al.,1996), improve re-vegetation (Richard et al., 2003), and minimize costs for construction companies (TxDOT, 2004).

Composting is a process of breaking down organic materials into an aerobic biodegradable blend (EPA, 1995). Compost is typically applied one of the three ways for erosion control; incorporated with topsoil, as a blanket, or as a filter berm.

Mukhtar (2004) conducted a study on the effects of using dairy manure compost for controlling erosion and revegetation on steep slopes. They reported that dairy manure compost resulted in less runoff with fewer total solids than a commercial fertilizer. They recommended manure compost be applied to highway construction for erosion control.

Persyn et al. (2004) studied erosion along Iowa highways using three different composts blanket; biosolids compost, yard waste compost, and bio-industrial compost, applied at 5 cm and 10 cm depths. The report sited mulch blanket compost at the 5 cm application as an efficient application to reduce runoff and erosion.

Interrill erosion is the amount of sediment is detached from surface after rainfall impact. Recent work by Persyn et al. (2004) as developed for the Water Erosion Prediction Project model to describe interrill erosion mechanics is shown below.

$$D_i = K_i I q S_f \qquad (3)$$

where

D_i =steady-state interrill erosion rate (mass of soil eroded/unit area/unit time)

K_i =interrill erodibility (mass-time/length^4)

I=rainfall intensity (depth/unit time)

q=runoff rate (depth of solids eroded/time)

$S_f = 1.05 - 0.85\exp(-4\sin\theta), \theta$ is the slope angle (unit-less)

The steady-state interrill erosion rate, D_i , equals the weight of sample collected divided by the surface area of the aluminum pan divided by the time interval of each sample collection. The rainfall intensity, I, was determined by averaging the five rain depths taken within 60 minutes. The slope factor, S_f, is calculated using 18.43 as the angle for theta. Interrill erodibility was then calculated for each sample (Eq. 4).

$$K_i = D_i \big/ I q S_f \qquad (4)$$

METHODS AND MATERIALS

The experiment was conducted in the Water Quality Laboratory at the Department of Biological and Agricultural Engineering at Texas A&M University. An indoor rainfall simulator was used in an effort to control both rainfall intensity and climatic conditions.

Experimental Design

The aluminum soil pans were built using NSERL Hydraulics Lab specifications (Norton et al., 1996). The height, width, and length dimension for each pan was 0.2 m (8 in.), 0.33 m (13 in.), and 0.45 m. (18 in) respectively (fig.1).

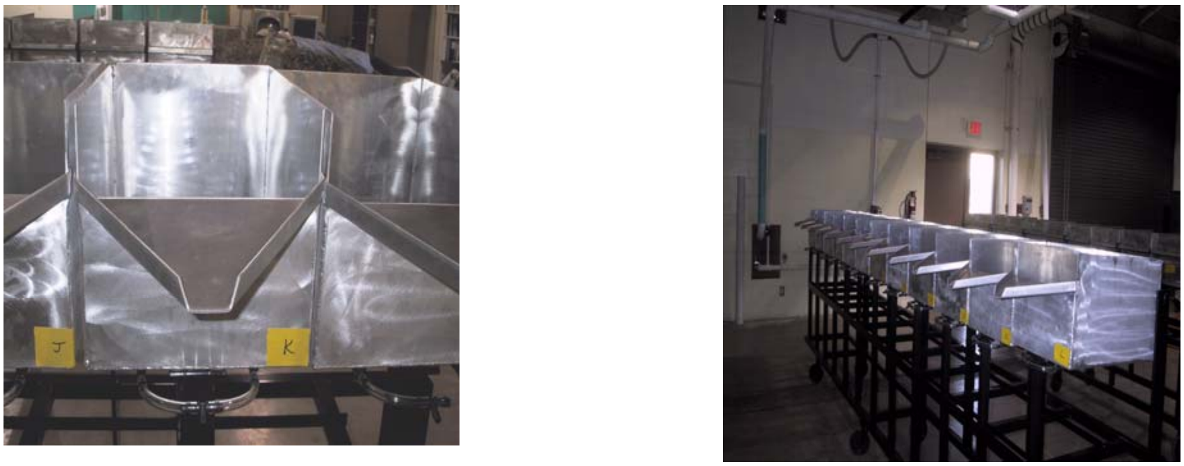

Figure 1: Experimental Setup for treatments

Each pan was set on a 3 to 1 slope. Four layers were placed in each aluminum soil pan; gravel, fabric, topsoil, and treatment (fig. 2).

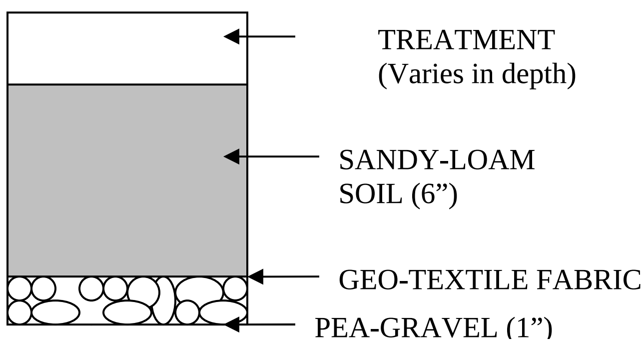

Figure 2: Plot setup for each of the six treatments

Treatments

Seven total treatments were tested: a compost/topsoil blend at a 5 cm depth, a woodchip/compost blend at 5 cm and 1.3 cm depths, 100% compost at 5cm and 1.3 cm depths and two controls (hydro seeding at a 5cm depth and topsoil at 5cm depth). Specifics on each treatment are provided in Table 1. Compost was obtained from the Brazos Valley Solid Waste

Management Authority (BVSMA) in Bryan, Texas. The BVSMA composting facility is a Seal of Testing Assurance Facility as outlined by the United States Composting Council.

Table 1: Seven treatments used in interrill erosion analysis

Treatment	Characteristic	Application
Compost Manufactured topsoil (CMT-5)	75% topsoil, 25% compost	5 cm (2 inches)
Erosion Control Compost (ECC-5)	50% untreated wood chips, 50% compost blend	5 cm (2 inches)
General Use Compost (GUC-5)	100% Compost	5 cm (2 inches)
Dispersion Treatment of Erosion Control Compost (ECC-1.3)	50% untreated wood chips, 50% compost blend	<1.3 cm (1/2 inch)
Dispersion Treatment of Compost Manufactured topsoil(CMT-1.3)	75% topsoil, 25% compost	<1.3 cm (1/2 inch)
Hydroseeding (HS)	Paper mulch with fertilizer and Bermuda grass seeds.	5 cm (2 inches)
Topsoil (TS)	100% topsoil	5 cm (2 inches)

Compost Characteristics

A chemical and physical analysis of each raw material was conducted by the Texas Cooperative Extension /Soil, Water, and Forage Testing Laboratory at Texas A&M University. A list of multi-nutrient analysis is found in Table 2 and Table 3.

Table 2: Chemical characteristics of samples

Sample ID	pH	Conductivity [umho/cm]	Nitrate-N [ppm]	Phosphorus (P) [ppm]	Potassium (K) [ppm]	Calcium (Ca) [ppm]	Magnesium (Mg) [ppm]	Sulfur (S) [ppm]	Sodium (Na) [ppm]
TS	7.8	81	1	3	53	974	116	9	190
TS	8.8	173	4	3	31	11051	100	12	255
CMT	7.9	250	7	190	183	2001	184	43	283
GUC	7.1	718	5	156	848	1733	279	44	326
GUC	7.2	1128	103	695	753	2802	297	129	414
ECC	6.8	1197	84	813	1032	3376	370	158	518

Table 3: Physical characteristics of samples

Sample ID	Sand [%]	Silt [%]	Clay [%]	Texture
TS	86	4	10	Loamy Sand
TS	86	4	10	Loamy Sand
CMT	86	6	8	Loamy Sand
GUC	n/a	n/a	n/a	n/a
GUC	n/a	n/a	n/a	n/a
ECC	n/a	n/a	n/a	n/a

Rainfall Simulator

The simulator was operated using specifications described by Meyer and Harmon (1979) which included using VeeJet 80100 nozzles at a height of 5m operating at a pressure of 41 kPa. Rainfall was applied at an average rainfall intensity of 92 mm/hr. A completely randomized design was selected to compare four samples of each of the seven treatments (28 treatments/sample combinations). Yet, to reduce the risk of splashing from one treatment to another, a maximum of six plots were tested under the rainfall simulator per repetition. The design was set up for seven replicates of each sample per rainfall simulation depth with at least hydroseeding or topsoil control treatment in each run, as shown in Table 4.

Table 4: Completely randomized design of the runoff

			RUNS			
1	2	3	4	5	6	7
ECC-5	TS	ECC-1.3	GUC-5	GUC-5	ECC-1.3	CMT-5
GUC-5	CMT-5	HS	CMT-1.3	CMT-5	CMT-5	CMT-1.3
TS	CMT-1.3	GUC-5	CMT-5	ECC-1.3	HS	ECC-1.3
ECC-1.3	ECC-1.3	ECC-5	ECC-1.3	ECC-5	CMT-1.3	HS
CMT-1.3	GUC-5	CMT-1.3	ECC-5	HS	ECC-5	GUC
CMT-5	ECC-5	CMT-5	HS	CMT-1.3	GUC	ECC-5

**Acronyms: GUC-5:General Use Compos (5 cm), ECC-5 :Erosion Control Compost (5 cm), CMT-5:Compost Manufactured Treatment, ECC-1.3: Dispersion Treatment ECC, CMT-1.3: Dispersion Control GUC, HS-Hydro-seeding, TS-topsoil

Data Collection

Data collection procedures were similar to those outlined in Persyn et al. (2004). Rainfall intensity of 100 mm hr^{-1} was controlled by a rainfall simulator. Five rain gauges were placed under the rainfall simulator; one at each of the four corners and another rain gauge directly in the center of the rainfall simulator distribution area. Each gauge collected rainfall for the entire 60 minutes of rain application. To analyze steady-state erodibility, samples were collected every five minutes; the first two minutes was a solid sample analysis, the next two minutes was a nutrient analysis, then a one minute break was taken. This process was repeated six times over the last 30 minutes time span with a total of 5 samples collected for solid sample analysis.

RESULTS

Statistics

The arithmetic means were computed for runoff, detachment rate, and interrill erodibility. The mean for runoff had a normal distribution and IID (Fig.3)

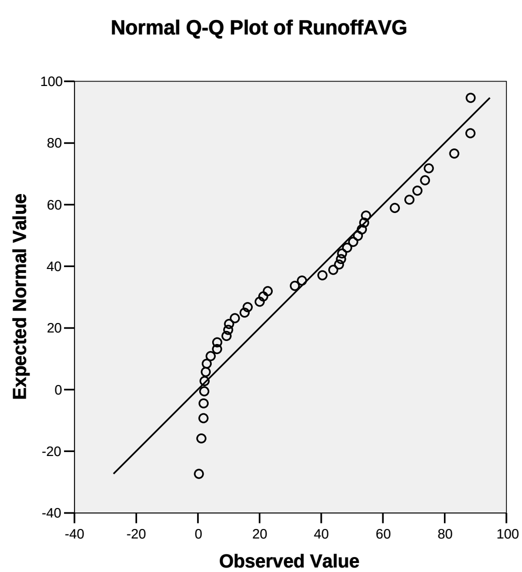

Figure 3: Normal distribution of mean runoffs using Q-Q plot

The arithmetic means of detachment and erodibility were not normally distributed, so the log-transformed geometric mean was computed for normality test (Fig. 4 and 5). To compare the difference in means for runoff, detachment, and erodibility the Analysis of Variance test (ANOVA) was computed. Using a 95% confidence interval, ANOVA tested the hypothesis of equal variances among all seven treatments.

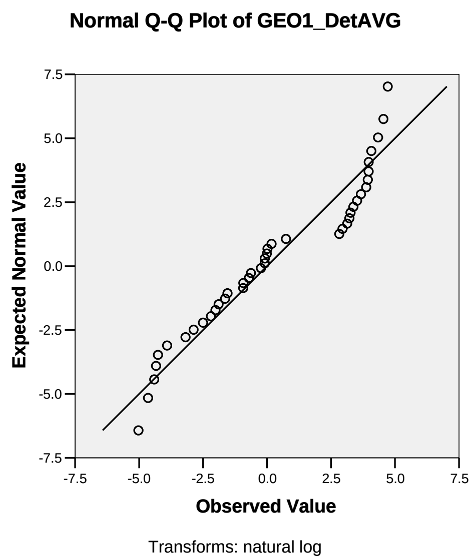

Figure 4: Log-Normal distribution of geometric mean detachment using Q-Q plot

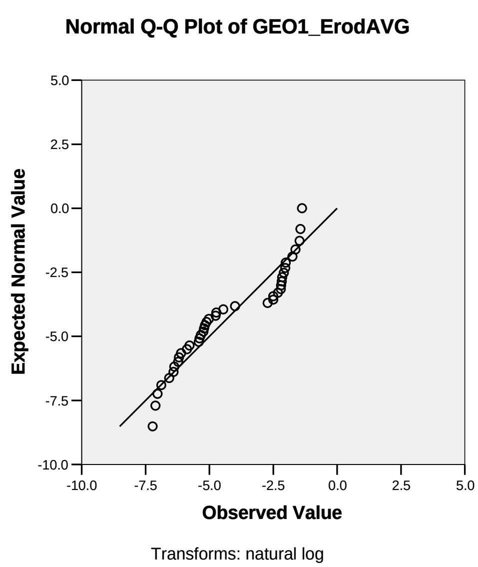

Figure 5: Log-Normal distribution of geometric mean erodibility using Q-Q plot

Runoff

Runoff was calculated using the runoff rate (mm^3/hr) divided by the surface area of the aluminum pan for all seven treatments. The arithmetic mean and standard deviation was then computed (Table 5). ANOVA determined p-values of 0.00, meaning there was significant difference in means for the runoff of each treatment.

Table 5: Arithmetic mean of runoff (mm/hr) for 5 compost treatments and 2 controls

Treatment	N	Mean	Std. Deviation
CMT-1.3	7	$61.78^{d,e,f,g}$	16.91
CMT-5	7	$65.96^{d,e,f,g}$	15.69
TS	2	$58.47^{d,e,f,g}$	14.26
HS	4	$2.44^{a,b,c}$	2.62
ECC-5	7	$13.93^{a,b,c}$	17.97
ECC-1.3	7	$18.87^{a,b,c}$	14.65
GUC-5	7	$18.55^{a,b,c}$	14.47

*Means with difference using 95% confidence interval are designated with letters. CMT1.3=a, CMT-5=b, TS=c, HS=d, ECC-5=e, ECC-1.3=f, GUC-5=g

According to Tukey's pair-wise comparison, the mean runoff for CMT-1.3, CMT-5, and TS treatments were similar whereas, the mean runoff for HS, ECC-5, ECC-1.3, and GUC-5 were similar in values.

Detachment

The detachment rate, also known as the interrill erosion rate, was determined for each treatment. Table 6 lists the geometric mean for each treatment and their standard deviation. The geometric means of zero value were considered missing values during the ANOVA, because a value of zero can not be used in calculations. Therefore, the ANOVA p-value of zero for detachment resulted in a significant difference in means for detachment rates.

Table 6: Geometric mean of Detachment (mg/m^2-sec) for 5 compost treatments and 2 controls

Treatment	N	Mean	Std. Deviation
CMT-1.3	7	42.49^{c,d,e,f,g}	32.63
CMT-5	7	44.96^{c,d,e,f,g}	20.25
TS	2	73.73^{a,b,d,e,f,g}	29.49
HS	4	0.14^{a,b,c}	0.18
ECC-5	7	0.35^{a,b,c}	0.39
ECC-1.3	7	0.69^{a,b,c}	0.78
GUC-5	7	0.41^{a,b,c}	0.40

*Means with difference using 95% confidence interval are designated with letters. CMT1.3=a, CMT-5=b,

Using the log-transformation of geometric means, the pair-wise comparison resulted in treatments CMT-5 and CMT-1.3 were similar in means, whereas HS, ECC-5, ECC-1.3, and GUC-5 were similar in means. However, the topsoil control treatment (TS) was significantly different from all other treatments.

Interrill Erodibility

The interrill erodibility was calculated for all seven treatments. The geometric mean and standard deviation were computed (Table 7). The ANOVA results concluded that all treatments were significantly different in means.

Table 7: Geometric mean of Interrill Erodibility (kg-sec/m^4)*(10^{-6}) for 5 compost treatments and 2 controls

Treatment	N	Mean	Std. Deviation
CMT-1.3	7	0.13^{d,e,f,g}	0.06
CMT-5	7	0.13^{d,e,f,g}	0.03
TS	2	0.24^{d,e,f,g}	0.02
HS	4	0.01^{a,b,c}	0.01
ECC-5	7	0.00^{a,b,c}	0.00
ECC-1.3	7	0.00^{a,b,c}	0.00
GUC-5	7	0.00^{a,b,c}	0.00

*Means with difference using 95% confidence interval are designated with letters. CMT1.3=a, CMT-5=b, TS=c, HS=d, ECC-5=e, ECC-1.3=f, GUC-5=g

Applying Tukey's pair-wise comparison for the log-transformed geometric means of interrill erodibility resulted in CMT-1.3, CMT-5, and TS treatments had similar means whereas, the mean runoff for HS, ECC-5, ECC-1.3, and GUC-5 were similar in values.

CONCLUSION

In summary, the mean comparison for runoff rates concluded the more topsoil added to the treatment increased the runoff rate. Hydro seeding resulted in the lowest runoff depth of 2.44 mm/hr. For interrill erosion (i.e. detachment) results, the topsoil had the highest detachment rate of 73.73 mg/m^2-sec. Topsoil also had the highest interrill erodibility rate of 0.24 kg-sec/m^4*(10^{-6}). Depth of application had no significant affect on the runoff, detachment, or interrill erodibility. Yet, coarser materials (i.e. woodchips and hydro seeding), absorb the impact of splashing due to interrill erosion which may have reduced the amount of runoff and minimize detachment and interrill erodibility.

FUTURE WORK

- Repeat treatment comparison for runoff rate, detachment and interrill erodibility for first flush
- Evaluate the water quality implications of using nutrient rich source materials
- Determine the rill erosion mechanics for compost blankets

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Evaluation of Irrigation Scheduling Using the Biotic Model

Basic Information

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Focus Category:	Agriculture, Irrigation, Conservation
Descriptors:	None
Principal Investigators:	Joshua Brian Bynum, Tom Cothren

Publication

Evaluation of Irrigation Scheduling Using the Biotic Model

Josh Bynum

Many producers are faced with irrigation decisions that greatly impact their production and economics. The primary purpose of irrigation is to alleviate crop water stress by the timely application of supplemental water. Current irrigation practices involve monitoring soil moisture, atmospheric parameters, and plant measurements such as leaf water potential and stomatal resistance. The above procedures require considerable time and effort in directly attaining soil or plant water status, or the requirement of implementing decision based software for determining irrigation. A universal theme in the current irrigation practices is that the assessment of irrigation is based indirectly. The development of infrared thermometers has made it possible to directly measure plant canopy temperature.

BIOTIC (Biologically-Identified Optimal Temperature Interactive Console) is a novel process and device for managing irrigation. BIOTIC provides a management tool by which irrigation events/timings can be improved by using a device that utilizes a thermal kinetic window (TKW). TKW is defined as a temperature range that permits normal enzyme function in plants. The estimated TKW for cotton is 23.5^0 - 32^0 C (2). Within the TKW, plants are able to cool themselves through transpiration. When the crop canopy temperature exceeds the TKW for a duration of two hours, the BIOTIC device will use a signal as an indicator for irrigation. Regardless of the ambient temperature, crop canopy temperatures may be affected by atmospheric humidity. High humidity levels may retard the transpiration cooling process to which a signal for an application of irrigation from the BIOTIC device would not be effective in reducing crop canopy temperatures.

Thus far, the BIOTIC device has been successfully researched by USDA-ARS and implemented in the Lubbock surrounding area. BIOTIC irrigation scheduling has proven to be effective on the Southern High Plains of Texas (SHPT) over multiple years. On the SHPT irrigation is generally carried out under a deficit condition in which irrigation frequency and amount are not generally sufficient to replace moisture used by the plant. In the College Station region, irrigation capacity and rainfall are generally sufficient to supply the needs of the plant and irrigation frequency should be reduced compared to the SHPT. BIOTIC irrigation uses a pair of threshold values to generate irrigation signals; a temperature threshold and a time threshold.

1) The temperature threshold is based on the thermal dependence of the metabolism of the plant, 28°C for cotton.

2) The time threshold is calculated on the basis of the evaporative environment in the irrigation region. Multiple years of weather data from College Station was provided by the USDA/ARS. Weather data was used to calculate the temperature threshold for the College Station region.

3) A BIOTIC instrument package was assembled and installed in College Station. The device was used to monitor irrigation status for comparison to commonly used irrigation scheduling. Data was collected during the growing season.

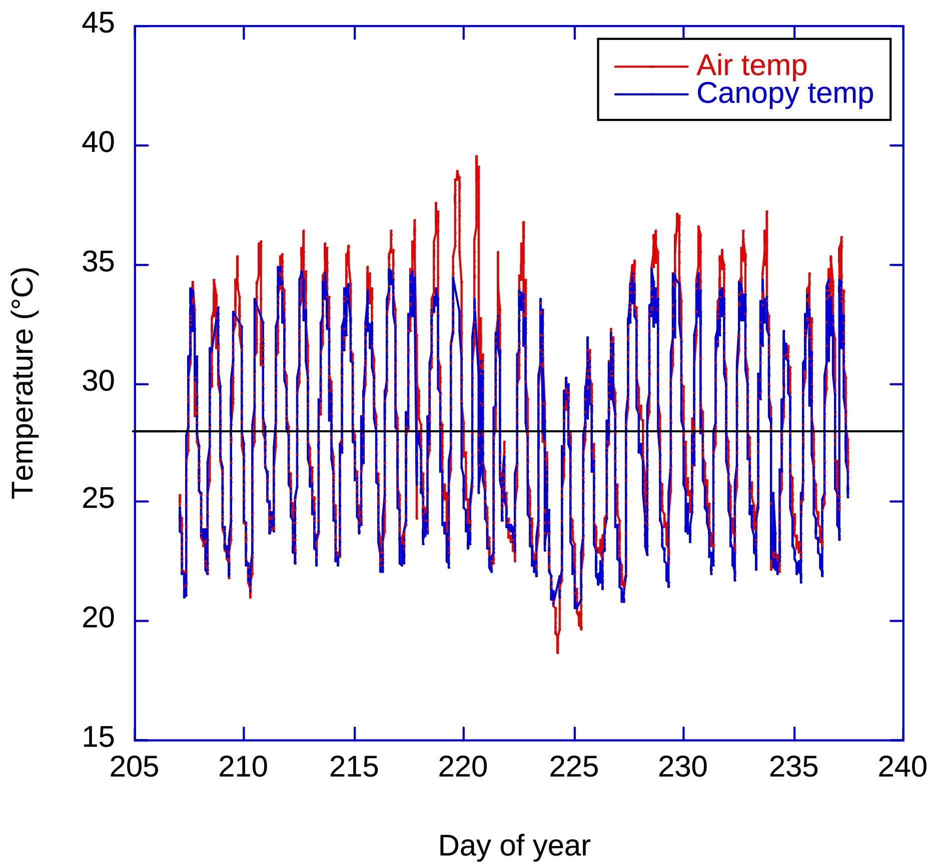
4) Humidity in the College Station region is generally higher than that on the SHPT and the BIOTIC results must be corrected for high humidity. Efforts are underway to calculate a humidity factor to account for the elevated relative humidity.

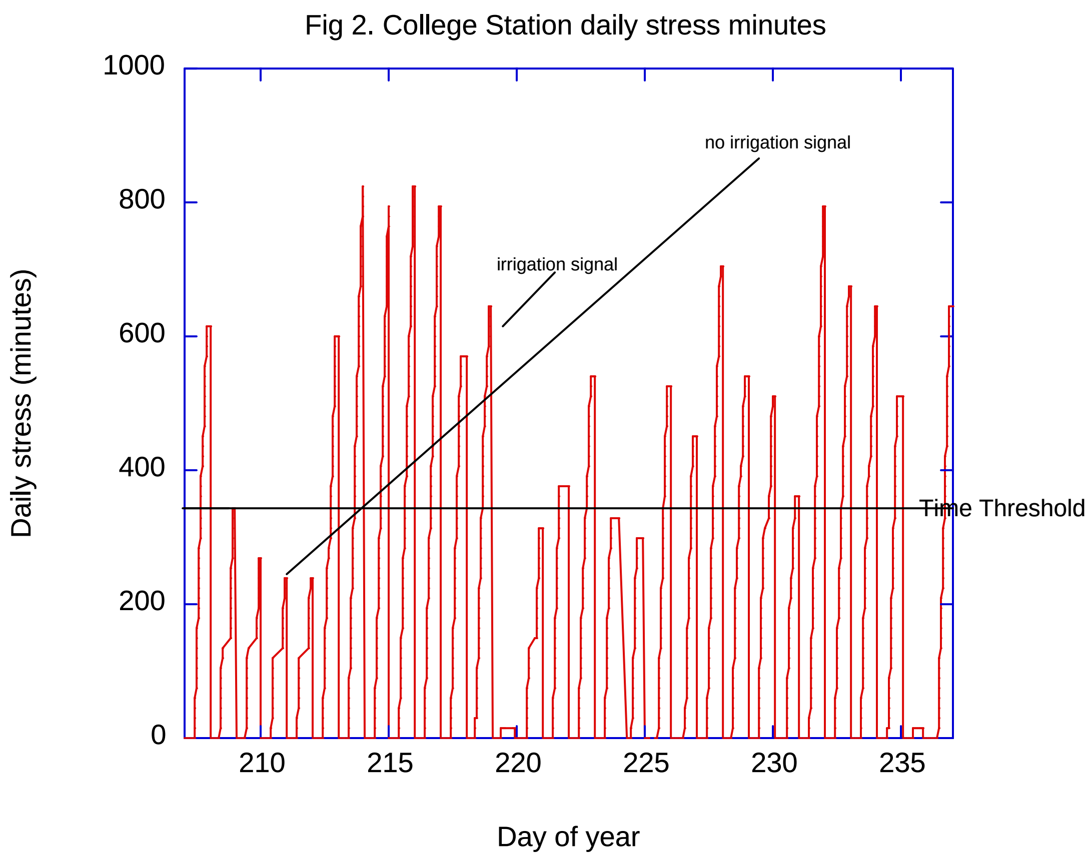
Figure 1 shows air and canopy temperature data collected for a 30-day period in College Station. The horizontal black line indicates the 28°C temperature threshold for irrigation. Canopy temperatures in excess of the temperature threshold indicate a possible water deficit condition.

Figure 2 shows the daily accumulation of stress time over a 30-day period in College Station. The horizontal black line indicates the 330 minute time threshold for irrigation. Stress accumulation in excess of the threshold indicates the need for irrigation. In this period irrigation signals were generated for 20 of 30 days.

The time threshold and relative humidity values will be modified based on improved estimates to determine the effect on irrigation scheduling.

Fig 1. College Station air and canopy temperature





Significance

The research of developing improved irrigation strategies is of great importance due to our depleshing water supply. The advantages of using this irrigation prediction model could impact growers statewide. Identifying the adaptation of this model to various climates will assist researchers in continuing the improvement of irrigation strategies, by determining more precise application timings and optimizing water use at time of application. Temperature and time thresholds set in 2005 triggered irrigation at unrealistic time intervals. These frequent irrigation triggers are not properly accounting for high humidity levels. Efforts are underway to calculate a humidity factor to account for the elevated relative humidity.

Enhancing A Distributed Hydrologic Model for Storm Water Analysis within a GIS Framework in an Urban Area

Basic Information

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Principal Investigators:	Zheng Fang, Philip B. Bedient

Publication

1. Fang, Z.; E., Safiolea; P. B., Bedient; B. E., Vieux, 2005, Enhanced Flood Alert System for Houston, 2005 National Hydrologic Warning Council Conference: Flood Warning Systems, Technologies and Preparedness. Sacramento, California, May 16-20, 2005.
2. Fang, Z.; P. B., Bedient; R., Hovinga, 2006, Prediction of Severe Storm Flood Levels for Houston Using Hurricane Induced Storm Surge Models in GIS Frame, American Water Resource Association 2006 Spring Specialty Conference: GIS and Water Resources IV, Houston, Texas, May 8-10, 2006.
3. Fang, Z.; E., Safiolea; P. B., Bedient, 2006, Enhanced Flood Alert and Control Systems for Houston, Proceedings of 25th American Institute of Hydrology Conference: Challenges of Coastal Hydrology and Water Quality, Baton Rouge, Louisiana, May 21-24, 2006.
4. Bedient, P. B.; A., Holder; J. F., Thompson; Z., Fang, 2006, Modeling of Stormwater Response Under Large Tailwater Conditions for the Texas Medical Center, Journal of Hydrologic Engineering, ASCE. 2006 (Submitted).

Enhancing a Distributed Hydrologic Model: Addition of Storm Water Pipe Analysis within a GIS Framework in an Urban Area

Zheng Fang

Abstract

The City of Houston has been facing flood problems of a serious nature, some of which occurred in 1989, 1992, 1994, 1998, 2001, and 2003. Tropical Storm Allison in June 2001 created the most extensive urban flood damage in U.S. history ($5 billion). Urban flood problems have repeatedly brought attention to the need for improved urban drainage design and flood prediction, as in the case of the Texas Medical Center flooding in 2001. In order to improve flood alert capabilities for highly urbanized areas with dense drainage systems, the physics-based distributed model, VfloTM, was chosen because it preserves the spatial variability by dividing the model domain into small, interconnected cells to better represent watershed features. VfloTM has been tested with a number of rainfall events that affected the Houston area from 1998 to 2003. Incorporation of NEXRAD radar rainfall data, GIS databases, and detailed storm water system data with enhanced distributed hydrologic modeling tool (VfloTM) enables us to develop an advanced storm water modeling system in highly urbanized Harris Gully area to provide decision makers of TMC with more accurate flooding warning information in order to initiate timely evacuation plans under severe weather conditions. The original VfloTM model represented this network as overland flow model elements with only a short, trapezoidal channel reach draining into Brays Bayou. An updated hydrologic model for Harris Gully has been set up by feeding both higher spatial and temporal resolution precipitation data into an enhanced distributed hydrologic model of the same spatial resolution that more fully represents the storm water drainage network for Harris Gully. In the updated model, a much more extensive representation of the actual drainage network has been used by including channels to represent the sewer and road systems within the basin. Using channel elements to simulate overland flow along the road and sewer network has typically resulted in a better fit with respect to peak discharge magnitude and timing. It has been carefully calibrated against 6 historical rainfall events. This innovative flood modeling system will provide more accurate data on problematic flow areas in storm sewer systems and associated watersheds. The increased information and accuracy of flood levels will provide TMC decision-makers with more accurate flood warning information, enabling them to initiate timely evacuation plans under severe weather conditions. In addition, it will build a solid foundation for a future real-time flood alert system for areas as small as Harris Gully.

Introduction

Flooding is considered the number one natural disaster in the United States in terms of damage cost. According to the National Oceanic and Atmospheric Administration and National Climatic Data Center data for the period between 1980 and 2004, 28 out of 60 disasters that occurred in the 1990s were directly flood related (NCDC, 2004). Today the average for flood damage costs in the United States has risen to over $4 billion annually (NWF, 1998). The type of floods that cause the greatest damage and loss of life are flash floods associated with intense rainfalls in urban areas. Damages can be excessive due to insufficient preparation and lack of lead-time available for emergency response personnel. This indicates the severity of the flood problem at the national level, even after the years of investment in flood control (Bedient and Huber, 2002).

The City of Houston has been facing flood problems of a serious nature, some of which occurred in 1989, 1992, 1994, 1998, 2001, and 2003. Ninety percent of Houston rainfall events are convective storm systems (Schwertz, personal communication, 1998). Typical summer convective storms are extremely variable in space and time (Schell et al., 1992) and can produce very intense rainfall rates that lead to localized flooding (Doswell et al., 1997).

Harris Gully watershed, a subwatershed of Brays Bayou, drains approximately 14.2 km2 (5.5 mi2) and flows in large box-culverts underneath the Texas Medical Center (Figure 1). The TMC was extensively flooded during TS Allison in June of 2001; storm water in Harris Gully overflowed, causing flooding of the streets and buildings around the TMC. This flooding was due to high urbanization, flat slope, clayed-soil characteristics, and backwater effects at the downstream of Harris Gully caused by high flows in Brays Bayou, and it resulted in millions of dollars in damages. The hydrology and hydraulics of Harris Gully are complex due to large channelization into conduits below street level, particularly in its lower reaches directly underneath the TMC. In order to improve flood forecasts further for the TMC, we focused on development of an enhanced distributed hydrologic model for Harris Gully that better represents the storm water drainage network than the existing one does.

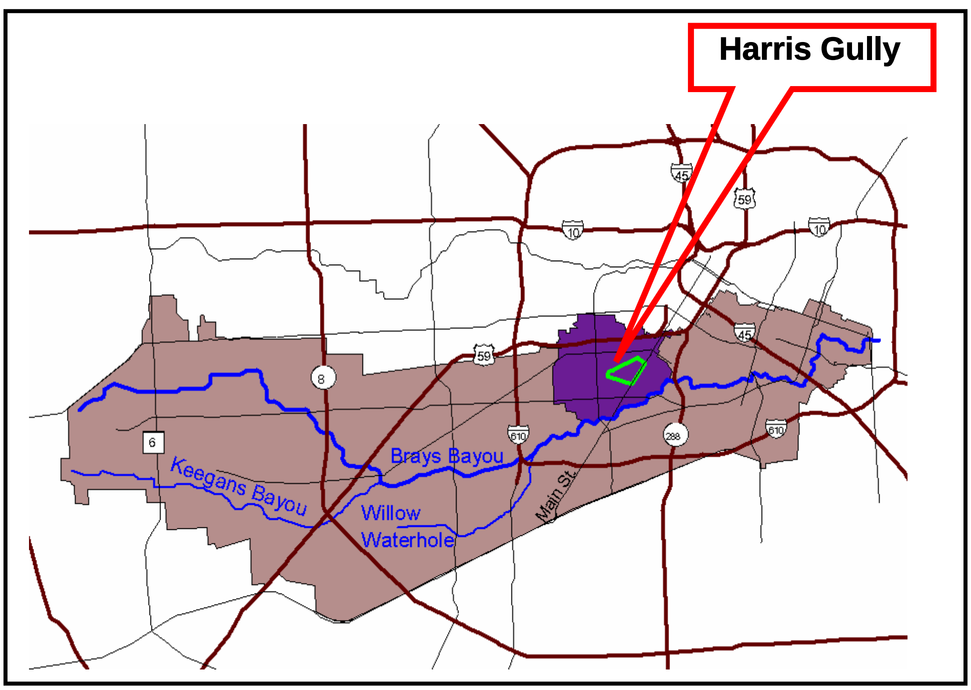

Figure 1: Brays Bayou (334 km2), and Harris Gully (purple shading 20.7 km2)

The availability of NEXRAD radar data, GIS databases, accurate distributed hydrologic modeling tools, and detailed storm water system data has made the development of advanced storm water modeling systems possible. Incorporation of NEXRAD radar rainfall data, GIS databases, and detailed storm water system data with enhanced distributed hydrologic modeling tool (VfloTM) enables us to develop an advanced storm water modeling system in highly urbanized Harris Gully area to provide TMC decision-makers with more accurate flooding warning information, enabling them to initiate timely evacuation plans under severe weather conditions.

Research Needs

Urban flood problems have repeatedly brought attention to the need for improved urban drainage design and flood prediction, as in the case of the Texas Medical Center (Vieux and Bedient, 2004) after the Tropical Storm Allison flood of June, 2001. This flood was reported by the National Oceanic and Atmospheric Administration as the most damaging urban flood in U.S. history, dropping nearly 15.2 inches of rainfall in three hours over much of the lower section of Brays Bayou and downtown Houston. An estimated $5 billion in damages and about 50,000 damaged structures were reported throughout Harris County. The TMC alone accounted for nearly $1.5 billion in damages resulting from flooding in Harris Gully near Brays Bayou. Until more permanent solutions are found, it is vital to develop real-time hydrologic models as platforms for early warning flood systems to provide the warnings that public and private entities are demanding. Modeling of both storm water pipes and overland flow in an urban system can produce more accurate runoff hydrographs at various points in the watershed. This would provide emergency personnel with more useful information to determine exact locations of flood- prone areas and design deficiencies, especially in highly-urbanized settings. However, one of the critical problems is that storm water sewer systems (pipes) are generally not modeled as part of hydrologic flood analyses for urban watershed areas. Although the Storm Water Management Model (SWMM) developed by the EPA is capable of simulating storm water pipes, it is difficult to handle overland flow and distributed data such as rainfall radar data and Light Detection And Ranging (LiDAR) data. Furthermore, SWMM cannot run easily in real time, which is an obstacle for future development of real-time flood warning systems. Therefore, we enhanced an existing distributed hydrologic model (VfloTM) for overland flow by adding in the ability to analyze the storm water system of pipes.

The primary objective of the research was to achieve more accurate and timely flood forecasts for Harris Gully area by adding pipe flow effects into an existing hydrologic distributed model (VfloTM) in a GIS framework and by using pre-calibrated NEXRAD radar rainfall data for 6 historical events.

Methodology

Distributed Hydrologic Model (VfloTM)
Currently, two general classes of models are available; they are classified as lumped or distributed depending on how the model handles spatial variability (Vieux et al., 2002). In this research, the physics-based distributed model with a commercially available hydrologic modeling package (VfloTM) developed by Vieux & Associates, Inc. has been chosen to simulate

runoff from radar rainfall input. Because lumped models such as HMS are limited by their failure to account for small-scale variations of the hydrologic processes (Muzik, 1996), VfloTM is used to solve the kinematic wave method for both overland and channel flood routing in a finite element mesh. Distributed models preserve spatial variability by dividing the model domain into small, interconnected cells, which makes them suitable for distributed hydrologic forecasting to better represent watershed features. VfloTM has been tested by a number of rainfall events that affected the Houston area from 1998 to 2003 (Bedient et al., 2003). Stewart (2003) built the first distributed hydrologic model using radar rainfall data on Brays Bayou watershed in Houston, Texas. Moreover, Safiolea and Bedient (2004) applied VfloTM to address land use and subsidence impacts on the White Oak Bayou watershed northwest of Houston.

NEXRAD

Given the extremes that can occur in spatial and temporal rainfall variability in the Texas Gulf Coast region, it is difficult to detect floods at the watershed level with sparsely placed rain gauges. A study by Johnson and Dallman (1987) found that rain gauges have limited ability to detect rainfall with enough response time, which is needed for flood prediction and warning. However, the availability of the new WSR-88D (NEXRAD) weather radar for use in rainfall estimation and flood prediction greatly improves the spatial and temporal coverage of a watershed for prediction purposes. Smith et al. (1996) and Johnson et al. (1999) both examined the contrasting detection capabilities of the NEXRAD and rain gauge networks. WSR-88D or Next Generation Radar Rainfall (NEXRAD) radar allows for the tracking of storms in space and time up to 230 km away from a radar installation. The central Houston area is located approximately 45 km from KHGX radar installation, an optimum distance for the hydrologic application of radar rainfall data (Crum et al., 1993). The system proved its worth when applied to rapidly responding highly urbanized watersheds such as Brays Bayou, where the NEXRAD/GIS-based system allowed for more accurate flood prediction than could have been possible using more traditional monitoring approaches. Therefore, calibrated radar rainfall data for historical rainfall events from NEXRAD were chosen to feed into the updated hydrologic model due to its higher accuracy.

GIS

A hydrologic analysis using spatially-oriented radar data, defined watershed boundaries, and other spatial hydrologic parameters is greatly enhanced by the use of GIS. The linkage of NEXRAD and a GIS system makes estimation of rainfall that has fallen over a specific watershed area feasible. These rainfall estimates can create a powerful system for storm prediction and flood alerts using distributed-parameter models (VfloTM) (Vieux, 2001).

LiDAR

Distributed models depend on accurate descriptions of the drainage network. Elements of the drainage network such as slope, flowpath, and drainage density are usually derived from a raster digital elevation model (DEM). DEMs are utilized in delineating watershed boundaries to yield more accurate hydrologic basin models than traditional approaches. In this research, the database developed by Harris County LiDAR released in 2002 was used as input to the application area for the model.

The availability of NEXRAD radar data, GIS databases, accurate distributed hydrologic modeling tools, and detailed storm water system data has made the development of advanced storm water modeling systems possible. Since late 2003, the distributed hydrologic model has been used with RTHEC-1 as an ensemble for real-time flood alert systems (FAS2) for Brays Bayou and Texas Medical Center (TMC). Moreover, it has been applied to address land use and subsidence impacts on White Oak watershed northwest of Houston. Incorporation of NEXRAD radar rainfall data, GIS databases, and detailed storm water system data with enhanced distributed hydrologic modeling tool (VfloTM) enables us to develop an advanced storm water modeling system in the highly- urbanized Harris Gully area to provide TMC decision-makers with more accurate flooding warning information enabling to initiate timely evacuation plans under severe weather conditions.

Developing a new element of stormwater pipe system in the commercial modeling package (VfloTM) and embedding the very dense drainage systems (sewers and streets) within Harris Gully into the existing distributed hydrologic model are very complex processes. Since it is time- and effort-consuming to develop stormwater pipe element alone in VfloTM., the existing channel elements within VfloTM have been converted into stormwater pipe elements with minimum adjustments at this point to enhance the existing distributed hydrologic model for Harris Gully.

The primary focus of the research was to set up an improved hydrologic model for Harris Gully by feeding both higher spatial and temporal resolution precipitation data into a distributed model of the same spatial resolution that more fully represents the storm water drainage network for Harris Gully. The Harris Gully drainage network consists entirely of a series of buried pipes and box-culverts. The original VfloTM model represented this network as overland flow model elements with only a short, trapezoidal channel reach draining into Brays Bayou. In the updated model, a much more extensive representation of the actual drainage network has been used by including channels to represent the sewer and road systems within the basin (Figure 2). Using channel elements to simulate overland flow along the road and sewer network has typically resulted in a better fit with respect to peak discharge magnitude and timing. This improved distributed hydrologic model has been carefully calibrated against 6 historical rainfall events.

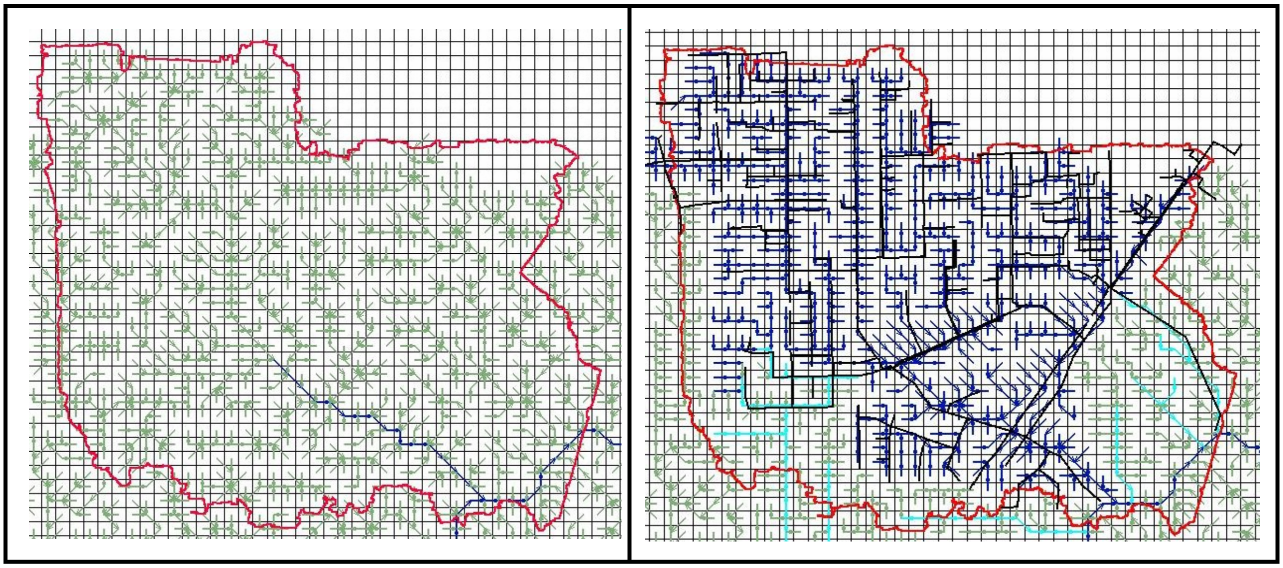

Figure 2 VfloTM Finite Element grid for (a) “Original” Harris Gully Model, a single short box culvert (left); (b)“Improved” Model, an extensive representation of the actual sewer and street network (right)

Results

Several sensitivity analyses have been performed to compare simulation results from the existing distributed model and the improved model. Firstly both models were fed a 24-hour 100-year design rainfall; simulation results from both models for this design event indicate that the improved VfloTM model of Harris Gully is more sensitive to rainfall than the existing model (**Figure 3**).

Secondly, VfloTM model results for T.S. Frances from four combinations of precipitation data and model setup were compared to the observed stage and flow data. Table 1 summarizes the different model runs and provides some comparative statistics describing the results. Results from this table indicate that local rain gage data (HG400) are higher than total rainfall estimated from NEXRAD radar for T.S. Frances. Therefore the runoff depth value from the same model (either original or improved model) using rain gage data is always higher than that from the model using radar rainfall data. Peak runoff values from the improved model generally produced fewer errors than the original did. Additionally, the improved model produced fewer timing errors than the original model did.

Figure 4 depicts modeling results for the August 2002 event with four hydrographs: the flow calculated from the observed stage data recorded in the Harris Gully culvert, the flow modeled using the improved model (solid black line), the flow modeled using a bias correction factor applied to the radar precipitation data of 1.06 (calculated by Baxter Vieux) (dashed blue line), and the flow modeled using the original model (green line). The improved VfloTM model better captures the magnitude of the runoff peak as well as the shape of the first hydrograph rise. The peak, however, is still underestimated, perhaps due to backwater effects which are not accounted for.

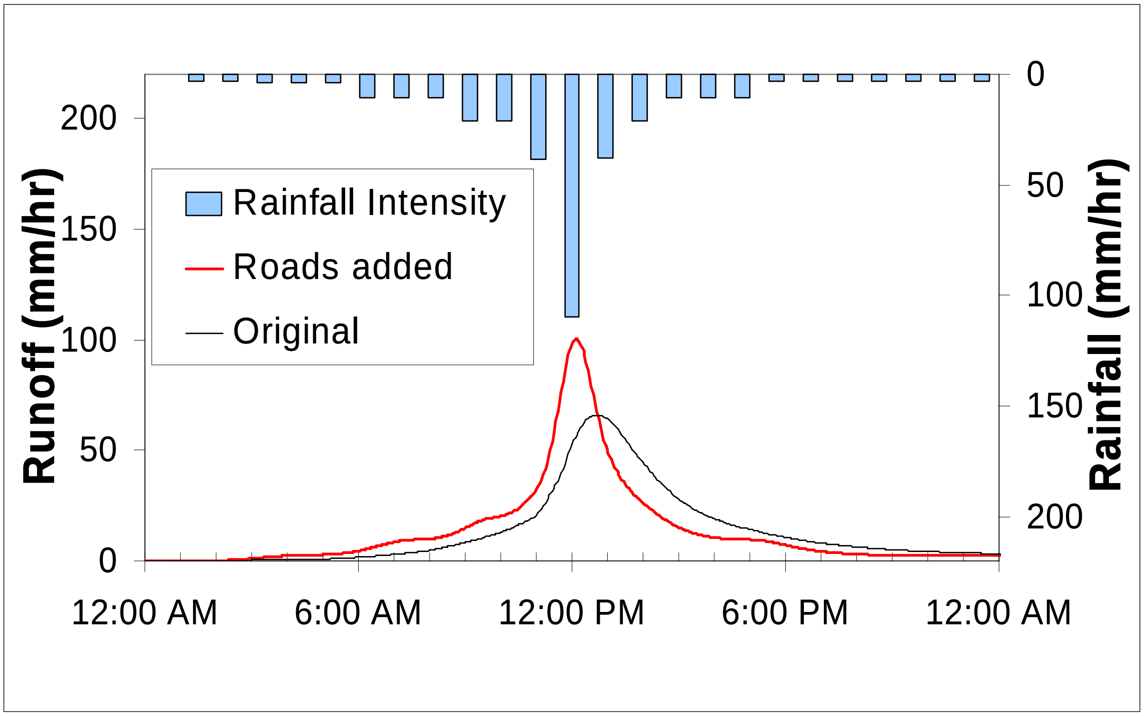

Figure 3 Sensitivity Analysis of VfloTM existing model and upgraded model for Harris Gully

Table 1: Summary of TS Frances modeling runs

Run No.	Rainfall source & (Total (mm))	VfloTM model	Runoff depth (mm) up to 11:24 (error in parenthesis)	Peak runoff error (%)	Timing error to 7ft
1	HG 400 (239.5)	Original	87.6 (-5.2)	-10.3	4 hr 47 mins
2	NEXRAD (218)	Original	73.1 (-20.9)	-4.5	3 hr 55 mins
3	HG 400 (239.5)	Improved	97.2 (+5.2)	5.57	27 mins
4	NEXRAD (213)	Improved	85.1 (-7.9)	4.57	1 hr 14 mins

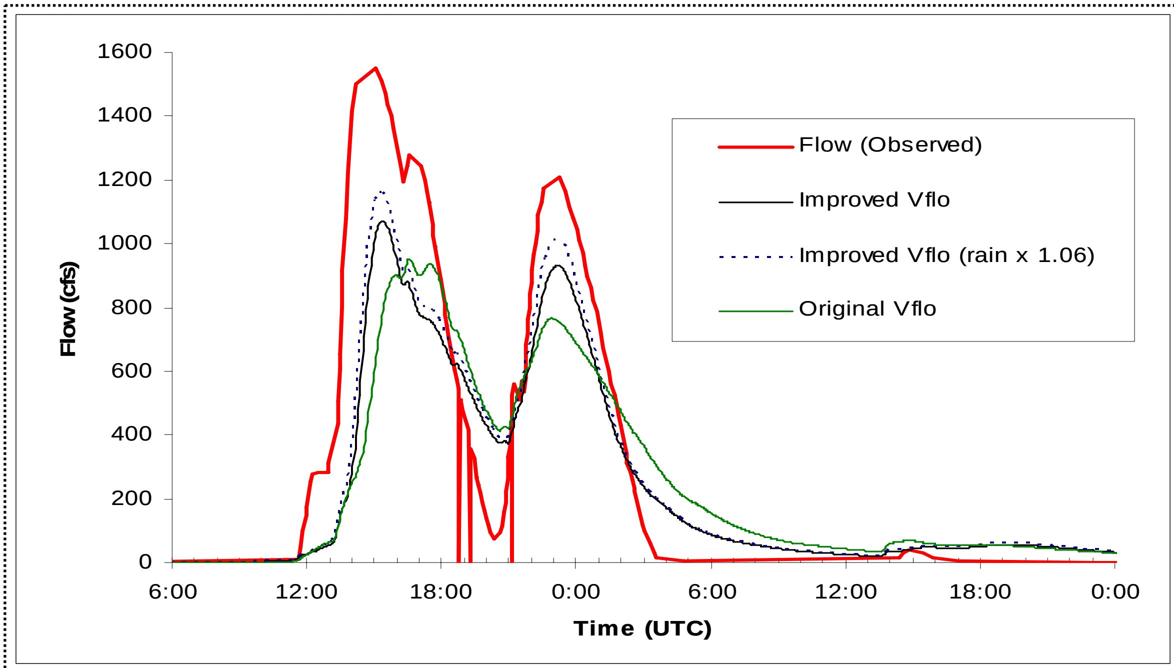

Figure 4 Modeling Results for Harris Gully in August 2002 Event

Conclusions

This research helps us better understand the hydrologic and the hydraulic response of Harris Gully relative to Brays Bayou under severe weather conditions. Finer grid resolution of the enhanced distributed model that fully accounts for Harris Gully with similar resolution radar rainfall data as input can improve flood forecasting capabilities in terms of timing, duration, peak flow, and volume. Six historical rainfall events were used to calibrate the enhanced distributed model.
It has been found that using channel elements to simulate overland flow along the road and sewer network typically results in a better fit with respect to peak discharge magnitude and timing. However, for some events peak flows are still underestimated, likely due to a combination of backwater and surcharge effects not currently accounted for.

Modeling both the storm water pipes and overland flow in an urban system produces more accurate runoff hydrographs at various points in the watershed based on characteristics of distributed models. This modeling can provide emergency personnel with more useful information to determine exact locations of flood-prone areas and design deficiencies, especially in highly urbanized settings.
Because the enhanced distributed hydrologic model provides more accurate flood warning information than the existing model, the results of this research can be grafted into the advanced flood alert system for the TMC with better understanding of the dynamic response of Harris Gully and more accurate flood forecasting capabilities.

Based on more timely and accurate information from this enhanced distributed hydrologic model for Harris Gully, TMC decision-makers are capable of initiating a better evacuation plan. Results from this research are going to ease hundreds of thousands of patients and their relatives in the TMC and even saves their lives. Furthermore, damages caused by flooding within Harris Gully area can be economically diminished to the minimum due to more preparations done during the longer lead-time given by this enhanced distributed model and due to finer resolution certainties of floodplain delineation.

Even though Harris Gully was initially chosen as our research test bed, the technologies and methodology used in this research can be beneficially applied to any coastal areas which are frequently impacted by severe rainfall events and tropical hurricanes.

Future Work

Firstly, a new VfloTM model of this smaller subcatchment will be developed based on a finer grid resolution than the current Brays Bayou model (122m×122m grids). Results from the Harris Gully stand-alone model will be compared with those from an existing urban hydrologic model, for example SWMM. Secondly, simple modifications are going to be made to the model so that it can simulate some of the features typically found in urban areas. These include buried channels (which become drainage culverts) and an anthropogenic drainage network consisting of ditches, manholes, etc. to route the runoff into the subsurface drains (as opposed to a "natural" drainage network where overland flow is routed uniformly across the ground surface into a channel element).

The sensitivity of the modeled (VfloTM) runoff hydrographs to these two-staged changes will be investigated, and the benefits of each stage in terms of the improvement in the model predictions will be quantified. In addition, model accuracy for storms with different characteristics such as duration and direction of movement with respect to the watershed will be investigated. It is hoped that the staged improvements will help the model to accurately forecast moderate (in addition to extreme) hydrologic events that are more sensitive to spatial and temporal variations in precipitation rate, antecedent soil conditions, and the explicit representation of the urban drainage network.

Additionally, Harris Gully area is frequently influenced by the backwater effects caused by high flows of Brays Bayou and severe coastal hurricane surges, which causes the storm water pipe system to be under the pressured flow circumstances that VfloTM cannot address precisely. However, updated hydrologic models provided by TSARP for Harris Gully, when incorporated with HEC-RAS, could generally account for the backwater issue and delineate floodplains in local scale under storm surge scenarios

Acknowledgements

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Determining the Efficacy of Biological Control of Saltcedar (Tamarix spp.) on the Colorado River of Texas

Basic Information

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End Date:	2/28/2006
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Congressional District:	17th
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Focus Category:	Ecology, Surface Water, Invasive Species
Descriptors:	None
Principal Investigators:	Jeremy L. Hudgeons, Allen E. Knutson

Publication

Determining the Efficacy of Biological Control of Saltcedar (Tamarix spp.)

Jeremy L. Hudgeons

Saltcedar are deciduous trees indigenous to arid, riparian habitats of Eurasia. Several species of saltcedar (*Tamarix* spp., Family Tamaricaceae) were introduced into North America during the 19th and 20th centuries. Upon their importation into the US, these trees were released from the pressures of most of the natural enemies found in their native range. Partly as a consequence of their natural enemy release, saltcedar has become highly invasive in arid ecosystems of the western United States. An estimated 2 million acres of riparian ecosystems in the US, including 500,000 acres in Texas alone, are infested with saltcedar. Saltcedar displaces native vegetation, reduces stream flows, increases soil and water salinity, and consumes significant quantities of groundwater. Saltcedar is widely distributed along most of the watersheds of western Texas including the Brazos, Colorado, Pecos and Rio Grande Rivers. Many of these river basins are beginning to suffer from severe water shortages. More than 21,000 acres of the Colorado River are infested with saltcedar. The Colorado River Municipal Water District estimates that existing stands of saltcedar in the Upper Colorado River basin may be consuming more than 90,000 acre-feet of water annually.

The release of a biological control agent can be highly specific to saltcedar, relatively inexpensive, and may provide long term suppression in areas susceptible to re-infestation. After extensive host-specificity studies by USDA-ARS scientists, the saltcedar leaf beetle, *Diorhabda elongata* (Coleoptera: Chrysomelidae), has been approved for open field releases in Texas. The purpose of this study was to evaluate the efficacy of using the saltcedar leaf beetle as a biological control agent in Texas. We studied two release sites within the Colorado River watershed to determine beetle establishment and dispersal rates. In addition, we studied the impact of beetle defoliation on the tree starch reserves and the propensity of trees to regrow following defoliation.

Objectives

The objectives of this project were to:

(1) Monitor the open field establishment of *Diorhabda elongata* beetles and describe their dispersal from release sites along the Upper Colorado River.

(2) Characterize the impact of beetle feeding on saltcedar trees by measuring the changes in starch storage and amount of regrowth of the trees subjected to beetle herbivory.

Progress and Results

Beetle Establishment and Dispersal

Beetles were released at two locations within the Upper Colorado River basin in 2004. Trees along transects were surveyed monthly for beetle presence and degree of tree defoliation during the 2005 growing season (May-September). Beetles established at one of two release sites. No beetles were detected at the Lake Thomas (Scurry Co.) site in 2005. Beetles did establish and disperse at the Beals Creek site (Howard Co.). By September 2005, beetles were detected on 29 of 45 trees surveyed, and on some trees, beetle numbers were high enough to result in tree defoliation (Figure1). Beetles were found on the furthest trees surveyed, 200meters from the point of release, and over 200 trees were completely defoliated by beetles by the end of the 2005 season (Image1).

Beetle Feeding

The saltcedar leaf beetle feeds exclusively on the leaves of the target trees which can result in large-scale tree defoliation. However, field observations to date have shown that defoliation does not immediately kill the trees. Biological control of saltcedar is expected to be a gradual process as trees become less competitive due to repeated defoliation by *D. elongata*. Field cage and natural experiments were used to test the hypothesis that defoliation due to beetle feeding decreases starch reserves and tree regrowth.

Field cage experiments conducted at Lake Thomas indicate that trees defoliated late in the growing season stored slightly less starch when compared to control trees, though this difference was not statistically significant (Figure2) due in part to the limits of experimental replication. However, the same defoliated trees in the experiment grew significantly less spring foliage when compared to control trees (Figure3).

In cooperation with colleagues at USDA-ARS laboratory in Reno, Nevada, a natural experiment was conducted at a site near Lovelock, Nevada. Beetles released by the Nevada Department of Agriculture successfully established at this site in 2001. Each year since the 2001 release, the beetles dispersed further from the release point defoliating more saltcedar trees in their wake. By 2005, over two thousand hectares of saltcedar had been defoliated. Core samples from the root crown were taken from trees that had been fully defoliated for three, two, one and zero seasons. Samples were analyzed for starch concentrations. The results clearly indicate that trees defoliated for at least one growing season have a significant reduction in starch reserves (Figure4). These data further support our hypothesis that beetle feeding results in decreases in starch reserves which in turn may lead to less tree growth.

Project Implications:

Biological control is only one tool in the arsenal being employed to combat the saltcedar invasion. An integrated management program is necessary for effective saltcedar control. For saltcedar control along the Colorado River and other river basins, large-scale herbicidal treatments have been initiated. While an effective control strategy, herbicide treatments are expensive and impractical in some situations. Biological control potentially offers an effective supplement to control methods based on herbicide treatments.

To effectively assist in the management of saltcedar, the saltcedar leaf beetle, *Diorhabda elongata*, must be able to establish and disperse in areas of introduction. Secondly, the beetle must make an appreciable impact on the target pest. Our studies show that *D.*

elongata is establishing and dispersing from release sites in the Upper Colorado River basin. Additionally, field cage and natural experiments indicate that beetle defoliation is reducing tree starch reserves and subsequent tree regrowth.

The results from this study are adding to our understanding of how *D. elongata* survives and impacts saltcedar and will help us make decisions regarding the integration of biological control into an area-wide program for saltcedar management in Texas.

Education:

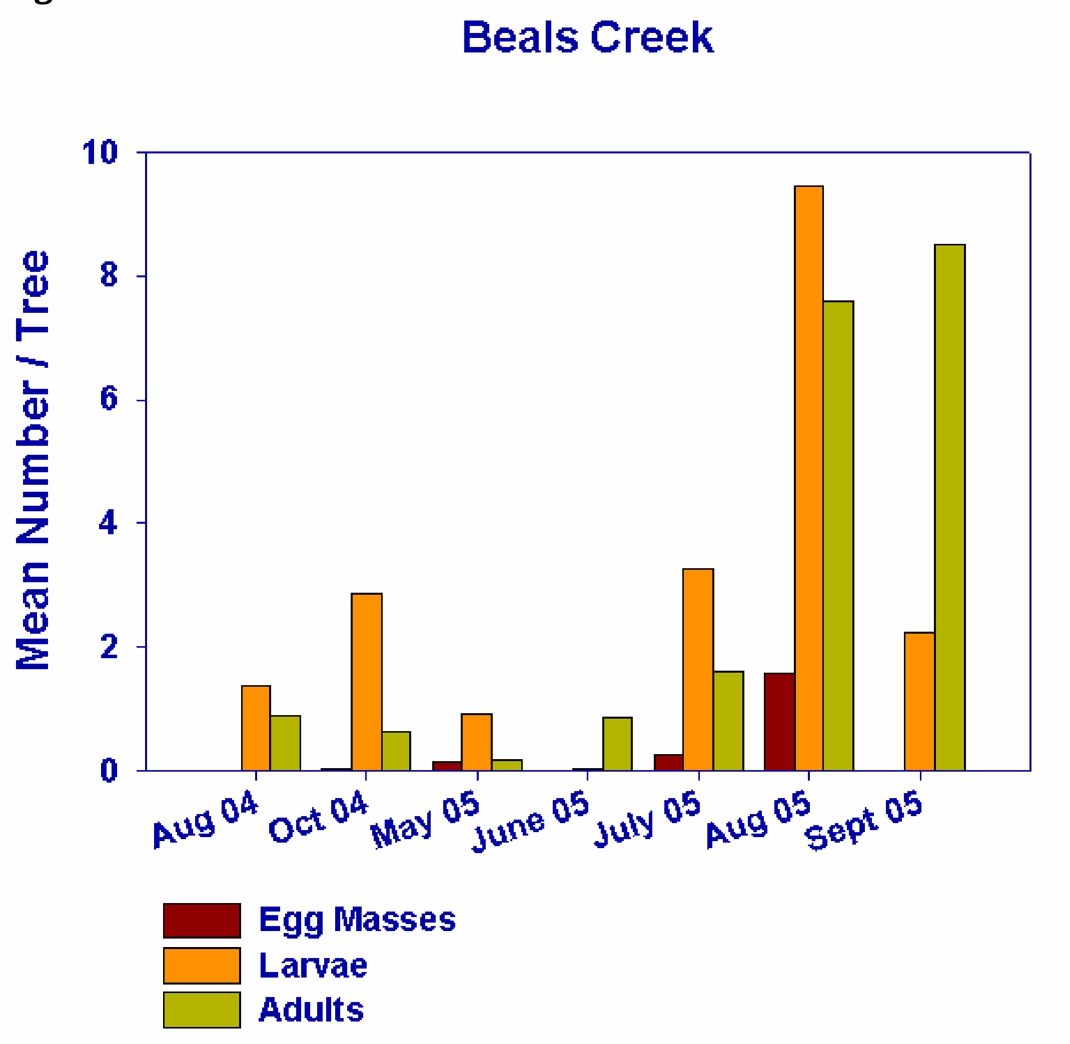
This work was presented at several local and regional forums during the granting period:

TAMU Student Research Week (March 2005, College Station, Texas)
Aquatic Plant Management Society Meeting (July 2005, San Antonio, Texas)
Dept. of Entomology Graduate Student Forum (August 2005, College Station, Texas)
SW Branch of the Entomological Society of America (February 2006, Austin, Texas)
Saltcedar Biological Control Consortium (March 2006, Austin, Texas)

Additionally, this project and related work were featured in two Texas newspapers in July 2005: the Lubbock Avalanche Journal and the San Antonio Express. Parts of the San Antonio Express article were circulated in additional newspapers throughout the state. These articles can be found at the following link:
http://insects.tamu.edu/feature/saltcedar/

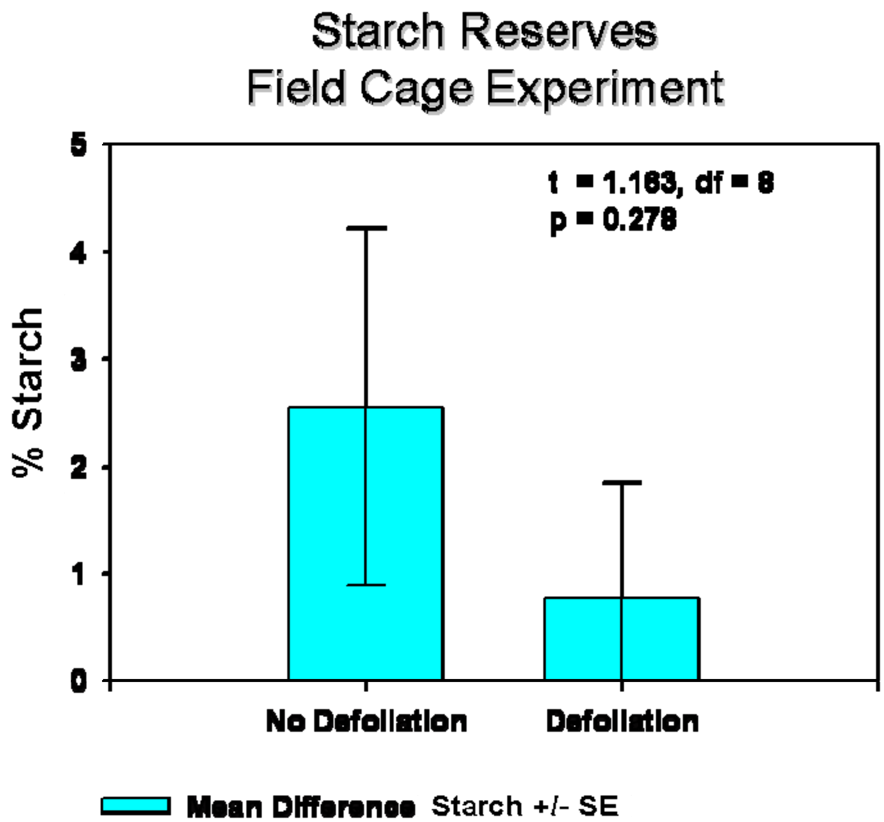
Beals Creek, September 2005

Figure 1



Beals Creek
Mean Number / Tree
10
8
6
4
2
0
Aug 04
Oct 04
May 05
June 05
July 05
Aug 05
Sept 05
Egg Masses
Larvae
Adults

Figure 2



Starch Reserves
Field Cage Experiment
t = 1.163, df = 8
p = 0.278
% Starch
5
4
3
2
1
0
No Defoliation
Defoliation
Mean Difference Starch +/- SE

Figure 3

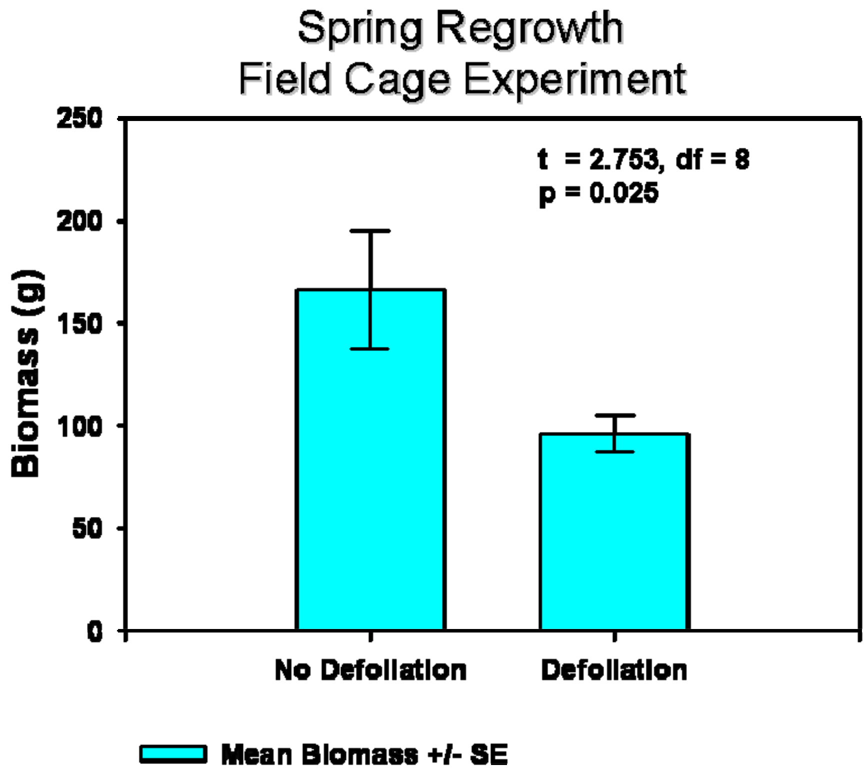
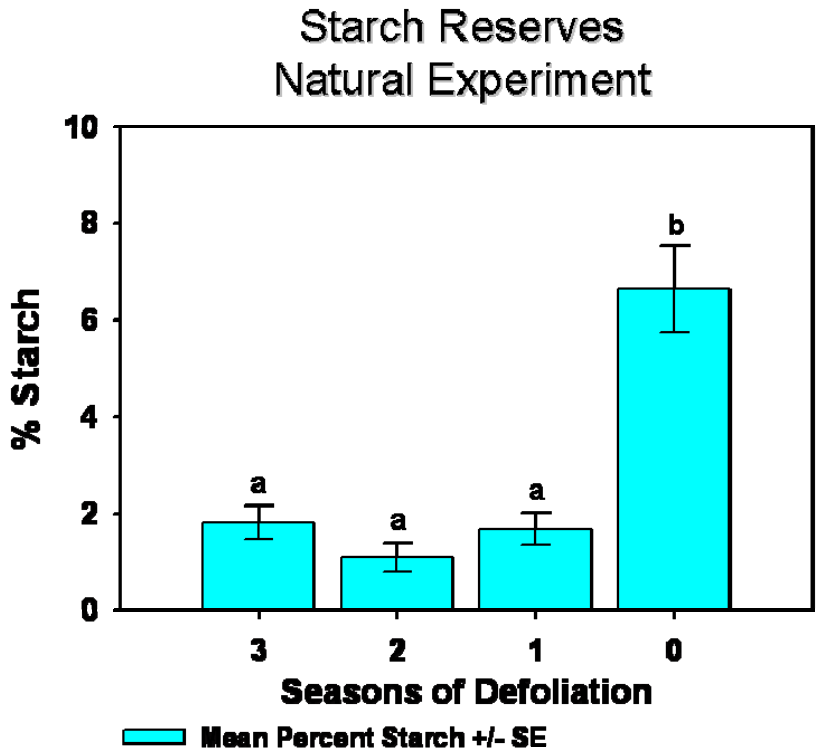

Spring Regrowth
Field Cage Experiment
t = 2.753, df = 8
p = 0.025
250
200
150
100
50
0
Biomass (g)
No Defoliation
Defoliation
Mean Biomass +/- SE

Figure 4



Starch Reserves
Natural Experiment
% Starch
10
8
6
4
2
0
b
a
a
a
3
2
1
0
Seasons of Defoliation
Mean Percent Starch +/- SE

Assessing the Potential of Zero-Valent Iron to Reduce Perchlorate and Nitrate Mobility in Soils

Basic Information

Title:	Assessing the Potential of Zero-Valent Iron to Reduce Perchlorate and Nitrate Mobility in Soils
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Principal Investigators:	Omar R. Harvey, Cristine Morgan

Publication

Assessing the Potential of Zero-valent Iron to reduce Nitrate Mobility in Soils

Omar Richard Harvey

Abstract

Finding ways to reduce non-point nitrate pollution of groundwater is of major significance because of the potential economic and environmental implications such contamination has on communities that rely on groundwater for drinking water. Much of this contamination is largely due to the high mobility of nitrate in the environment, particularly in soils. Reducing the mobility of nitrate in soils is therefore critical in controlling nitrate contamination. In this study an abiotically-mediated reduction approach using zero-valent iron as a nitrate reductant is being assessed as a potential method for reducing nitrate mobility in soils. A series of laboratory-scale batch and column experiments were designed and are currently being conducted to determine important factors for developing larger plot- and field-scale studies. Results so far indicate that in the presence of zero-valent iron, nitrate is reduced to ammonium. The ammonium produced is partitioned between the soil surface and the solution phase. The amount of ammonium partitioned to the soil surface is dependent on the cation exchange capacity of the soil as well as the concentration of ammonium in the solution phase. For a given rate of zero-valent iron, nitrate reduction was greater for a soil containing system compared to a soil-free system. Nitrate reduction was also accompanied by a decrease in dissolved oxygen (for closed system) and an increase in pH with the magnitude and rate of change being dependent on the amount of nitrate reduction and zero-valent iron in the system. In addition to ammonium as a product of reduction, visual observation indicated iron-oxide formation. No detectable quantity of iron was found in solution except in the presence of the complexing agent EDTA. Addition of EDTA also resulted in increased nitrate reduction.

1. Introduction

Recent studies of nitrate concentrations in Texas groundwater wells show that nitrate levels, particularly in the western half of the state, were substantially higher than the maximum contamination limit (10 mg NO_3-N/ L) [1]. Hudak (1999), suggested a surface origin for the nitrate contamination in at least six of nine aquifers tested, most likely from agricultural land use which occupies 77% of land statewide [2]. The results of this are consistent with those of numerous studies worldwide [3, 4, 5] with inorganic nitrogen fertilizers and soil organic N believed to be the primary sources of nitrate contamination. Best management practices including irrigation and fertilizer management have received significant attention as ways to control nitrate loss but their effectiveness is often significantly affected by rainfall and or farmers' hesitancy to change management practices. Alternative approaches are therefore worth studying. Jia et al. (2004) reported an electro-kinetic approach to retaining nitrate in the root zone. In the current proposed research an abiotically-mediated reduction approach will be investigated.

The ability of zero-valent iron (Fe^0) to chemically reduce nitrate and chlorinated organic contaminants has long been known [7, 8] and has been successfully utilized in several pilot-scale and full-scale groundwater remediation efforts to remove these contaminants [9]. Nitrate reduction by Fe^0 is a redox reaction in which the oxidation of Fe^0 to Fe^{2+}or Fe^{3+} releases electrons which are accepted by nitrate, leading to the reduction of nitrate to ammonium [10, 11, 12]. Nitrate reduction to ammonium of 70 -100 % has been reported in groundwater [12, 13]. It is the Fe^{2+} or Fe^{3+} and NH_4^+ produced during the reaction and their fate that are significant in the retardation of N mobility.

Soils generally have significantly higher cation-retention capacity than anion-retention capacity, and therefore, would retain NH_4^+ more readily than NO_3^-. Hence ammonium is less likely to leach in soils. Ammonium is also preferentially fixed by micro-organisms, rendering the NH_4^+ unavailable for leaching. The NH_4^+ can also enhance microbial denitrification. The Fe^{2+} produced can be further oxidized to less soluble Fe^{3+}, providing more electrons for nitrate reduction. Additionally, the Fe^{2+} or Fe^{3+} can be easily hydrolyzed and precipitated to form reactive Fe-(hydroxides) which can enhance reduction as well as increase the soil retention capacity of nutrients. Complexation of Fe^{2+} or Fe^{3+} by organic matter can result in complexes that are more resistant to mineralization of organic-N.

Little is known about abiotically-mediated nitrate reduction in soils. To our knowledge, this is the first study seeking to evaluate the potential use of zero-valent iron to reduce nitrate mobility in soils. Initial work will therefore be geared towards determining factors important for developing plot-scale or field-scale studies.

2. Research Objectives

As previously mentioned much of this work is and will be primarily focused on determining important factors for the development of larger scale experiments. The objectives are to:

(a) Determine the rate of nitrate reduction and subsequent production of ammonium and oxidized iron in soils.
(b) Quantify nitrate reduction as a function of nitrate input concentration and zero-valent iron application rate.
(c) Estimate reducing longevity (“life”) of zero-valent iron in the soil.
(d) Determine the fate of residual zero-valent iron and the products of reduction.
(e) Develop a mass balance for nitrate, zero-valent iron and reduction products.

3. Materials and Methods

Six soils from varying geographical locations across Texas and having different properties (Table 1) were selected for this study.

Table 1. Summary of soil properties. *Courtesy: Soil Characterization Laboratory, TAES.*

	pHH_20	CEC[1] cmol/kg	B. D.[2] g/cm^3	B. sat[3]	Clay	Sand	Silt	O.C.[4]
				------------	------------	-----% -----	------------	------------
Soil 1	4.6	23.5	1.46	74	31.5	22.2	46.3	0.13
Soil 2	4.8	6	1.37	27	7.9	36.1	56	1.79
Soil 3	8.3	31.3	1.42	100	48.3	30.3	21.4	0.43
Soil 4	8.0	53.3	1.29	100	56.5	8.9	34.6	2.20
Soil 5	9.1	2.8	1.52	100	3.3	92.5	4.2	0.13
Soil 6	6.0	2.4	1.41	71	2.7	91.9	5.4	0.31

[1] Cation exchange capacity
[2] Bulk density
[3] Base Saturation
[4] Organic Carbon

3.1 Chemicals

All chemicals used were reagent grade. For preparation of nitrate solution, pre-determined quantities of KNO_3 were dissolved in a 50 mM KCl background electrolyte solution. The electrolyte solution, rather than deionized water, was used because it was more representative of the natural soil environment. In experiments where EDTA was used, the 50mM KCl was substituted with an equivalent concentration of EDTA. No effort was made to control oxygen level in these current experiments presented. Zero-valent iron (H-200, HEPURE[sm]) was obtained from Hepure Technologies; physical properties of the zero-valent iron are summarized in Table 2. A Na^+-saturated cation exchange resin was used as an additional exchange surface for comparison with the soil. The Na^+-saturated resin was prepared via Na^+-H^+ ion exchange of an H^+-saturated resin (550 $cmol^-$/ kg) under alkaline pH.

Table 2. Physical properties of H-200 zero-valent iron. *Courtesy of Hepure technology*

Apparent Density (g/ cm^3)	2.55
Surface area (m^2/g)	0.1
Particle size	
< 45 µm	10 %
< 85 µm	50 %
< 140 µm	90 %

3.2 Batch Experiments

Two types of batch experiments were conducted: (a) open-system and (b) closed-system batch experiments. In the open-system experiments 250 ml centrifuge bottles were used as batch reactors. Two holes were punched into the cap of each reactor to facilitate gaseous exchange with the external environment. In the closed-system experiment, no such gaseous exchange was facilitated. Additionally, for the closed system depending on the total volume of solution used, either 250 ml centrifuge bottles or 50 ml tubes were used as batch reactors.

In nitrate reduction experiments, predetermined quantities of zero-valent iron, soil and nitrate solution were added to the batch reactors and allowed to equilibrate for varying time intervals on a rotary shaker at 250 rpm. At each interval, a reactor was sacrificed, and the pH and dissolved oxygen of the suspension was measured. The suspension was subsequently centrifuged at 2500 rpm for 5 minutes and an aliquot of supernatant filtered through 0.45 µm nylon syringe filters and refrigerated for analysis of nitrate, ammonium and dissolved iron. The remaining supernatant was discarded and a known quantity of 2M KCl was added to the residual (soil or resin + residual Fe^0) and shaken for 30 minutes to determine the quantity of ammonium and or nitrate partitioned to the exchange sites of the soil or exchange resin. The resulting residual + 2M KCl suspension was centrifuged and filtered as described above; an aliquot was saved and stored at 4 ^oC for later analysis.

3.3 Column Experiments

While much of the methods for the batch experiments have been completed, methodology for the column experiments is still being refined; hence, the methods described below include conceptual ideas that have been completed.
Eighteen inch long vertically mounted columns will be used. The internal diameter of the columns was approximately 1 inch. Each column will be packed to a depth of 8 inches according to its respective bulk density (Table 1). A predetermined quantity of Fe^0 will be incorporated into the top 5 inches of soil before being added to the column. For each soil type, a blank and three Fe^0 iron-containing columns (triplicates) will be used. Filter paper will be put at the base of the column to prevent loss of soil and at the on top of the soil to prevent sealing of pores upon impact of water. Nitrate solution will be applied in two pore volume intervals to the top of the column at a rate consistent with different rainfall intensities. The columns will be allowed to drain freely and drainage solution will be collected at the base of the column and refrigerated for analysis of ammonium and nitrate. The pH of the drainage solution will also be measured. After each two pore volumes the column will be flushed with a known volume of 50mM KCl to remove nitrate and ammonium from the soil pores. The drainage solution from flushing will also be collected and stored for analysis. At the end of the leaching experiments the soil in the column will be sectioned into different depth intervals. The nitrate and ammonium on the soil surface will be measured by extracting ammonium and nitrate with 2M KCl and analyzing the extract.

Nitrate-N and Ammonium-N were and will be analyzed colorimetrically using a Technicon II autoanalyzer. Released iron was measured using atomic absorption spectroscopy. pH and dissolved oxygen (DO) was measured using an accumet pH-DO meter.

4. Results and Future Work

4.1 Nitrate Reduction by zero-valent iron using batch experiments

Nitrate in soils can be completely reduced to ammonium in the presence of zero-valent iron (Figure 1). Figure 1 also suggests that the rate reduction increases as the Fe0: soil ratio increases. For example, after 5 h, nitrate concentration was reduced from an initial concentration of 60 mg/L to below 10 mg/L by a Fe^0: soil ratio of 1:1 (5:5) comparing to about 30 mg/L for a ratio of 1:9. The reduction from NO_3-N to NH_4-N appears to be direct with a stoichometric conversion ratio of 1:1. This can be seen more clearly in Figure 2 where at any given time total N (NH_4-N + NO_3-N) remained at 60 mg/L the concentration of the input nitrate solution. Nitrate reduction to ammonium was also accompanied by an increase in pH and a decrease in DO concentration (Figure 3) indicating a consumption of H^+ and O_2.

It was not initially clear whether the change in pH and DO was due to the actual reduction process or whether it was due to the fact that these initial experiments were conducted in the closed-batch system. Table 3 shows the results of an open-batch system. These results suggest that although the reduction process may consume both H^+ and oxygen in an open-system the oxygen can be replenished, maintaining the DO concentration. The consumption of H^+ is most likely utilized in the formation of NH_4^+ from NO_3^-. Table 3 also shows that nitrate reduction is possible at much lower Fe^0:soil ratio than those shown in Figure 1.

Further work will be conducted to determine the lowest, as well as the most economically feasible Fe^0: soil ratio. One major consequence of reducing the Fe^0: soil ratio is the increase likelihood of surface passivation effects arising from iron-oxide precipitation. Figure 4 shows the effect of the addition of the metal complexing agent EDTA to the system. In contrast to KCl, in the presence of EDTA no precipitation of iron was observed. The lack of iron precipitation is due to the complexation of the iron to form a Fe-EDTA complex, which is confirmed by analysis of solutions for total iron using atomic absorption spectroscopy. No Fe was detected in the presence of KCl while as much as 1000 ppm Fe was detected in the presence of EDTA. There was evidence indicating that in the presence of EDTA nitrate reduction may increase several folds (Figure 5).

Also apparent from Figure 5 is the fact that even in the presence of KCl, nitrate reduction was several folds higher than that in exchange resin and Fe-only samples. The actual reason for this is not definitive. One possible explanation is that the Fe released during nitrate reduction is precipitated onto the surface of the soil rather than the residual zero-valent iron; and therefore, passivation effects are reduced. Further evidence is needed to prove this. Selective dissolution technique will be used to compare pre-reduction and post reduction soil iron content.

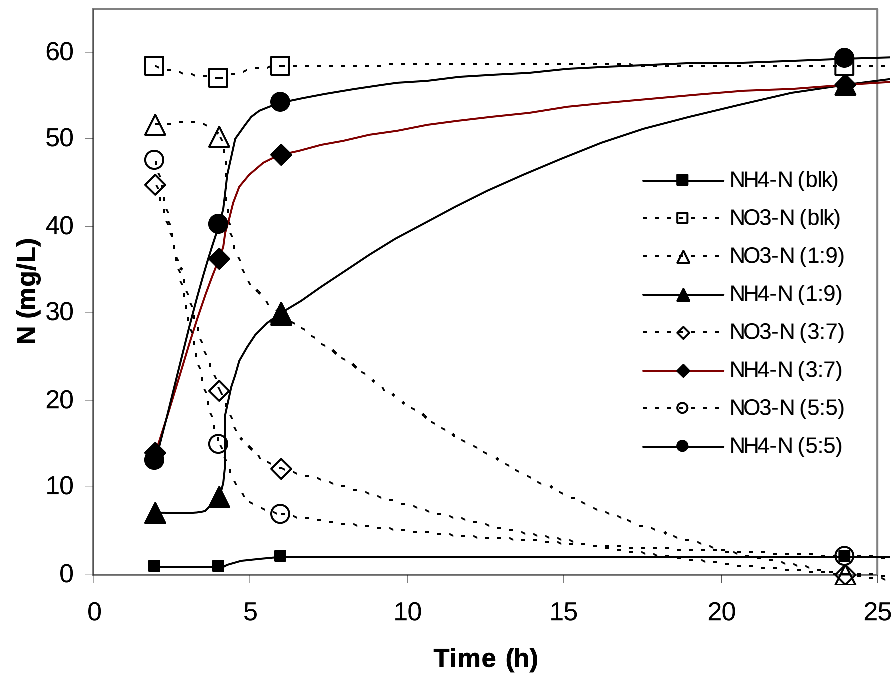

Figure 1. Nitrate-N reduction and accompanied Ammonium-N production in Soil 1 at different Fe^0:soil ratio.

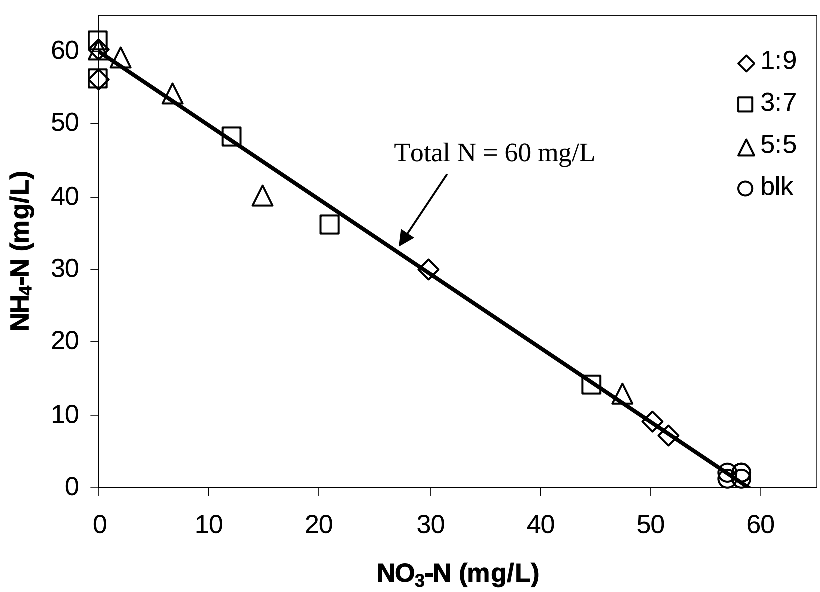

Figure 2. Total NH_4-N in Soil 1 system as a function of total NO_3-N. The fact that point follow 60 mg/L line is suggest direct conversion of NO_3-N to NH_4-N.

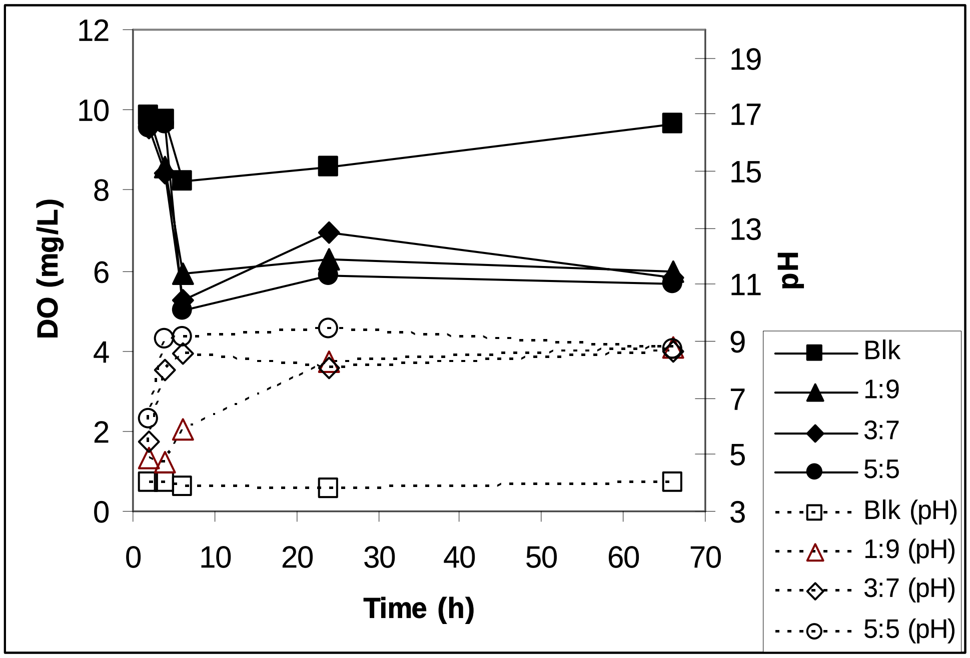

Figure 3. Changes in pH (broken lines) and DO (solid lines) with time for Soil 1 system.

Table 3. Measured pH ,nitrate-N, ammonium-N, and DO concentrations in a open-batch system using Soil 1. Input nitrate-N concentration = 40 mg/L.

Fe^0 : Soil	pH	DO	NO_3-N	NH_4-N	ex-NH_4-N[2]
		--------------------------mg/L---------------- ------			
(g : g)					
0:10	3.8	8.3	40.4	nd[1]	nd
1:100	4.2	8.2	40.4	2.1	nd
1:40	5.8	8.0	21.6	19.3	2.1
1:20	7.3	8.1	nd	38.7	3.4

[1]below detection limit
[2]Ammonium-N on exchange sites

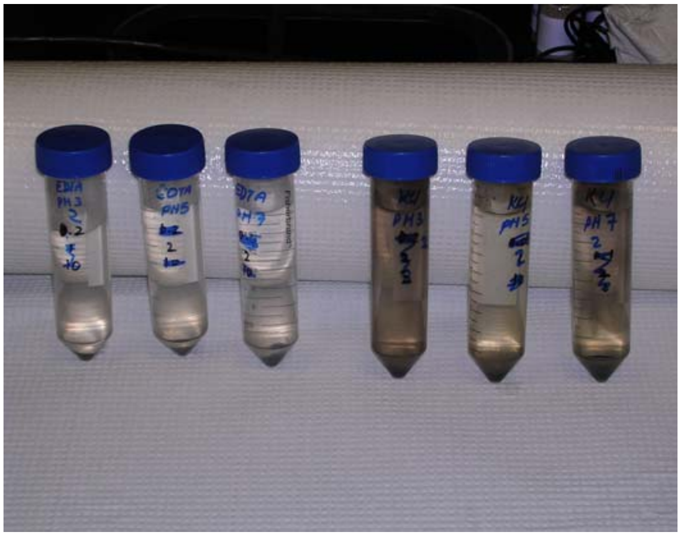

Figure 4. Effect of EDTA on iron-oxide precipitation. Cloudiness in tubes to the right (KCl as background electrolyte) is due to precipitation of iron-oxide. Tubes on the left (EDTA as electrolyte) show no evidence of precipitation.

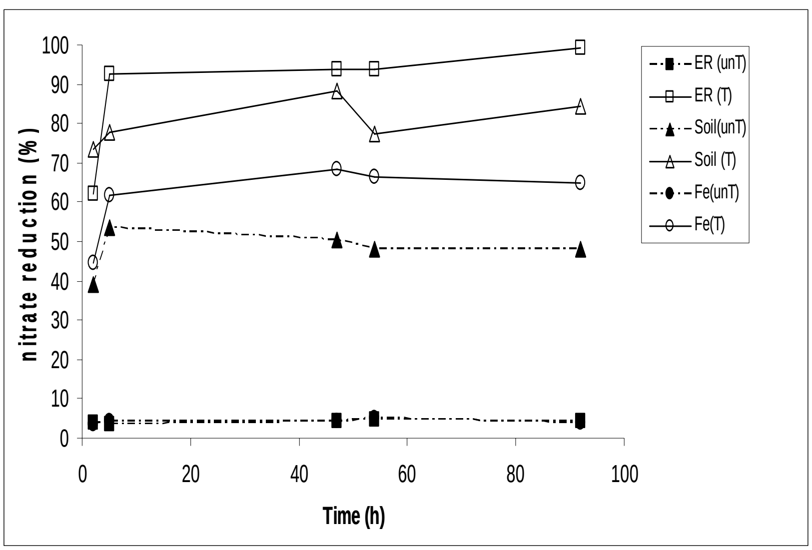

Figure 5. Effect of EDTA on nitrate reduction. ER- exchange resin; Soil – Soil 1; Fe- zero-valent iron without soil; unT- in the presence of KCl; T- in the presence of EDTA.

4.2. Ammonium partitioning between solution and soil surface

Figure 6 shows that over time the concentration of ammonium on the exchange surface increases. This is consistent with an increase in nitrate reduction and ammonium production. Figure 7 indicates that the concentration of ammonium-N on the soil exchange surface is negatively related to the nitrate and positively related to ammonium-N concentration. This indicates that as reduction proceeds, ammonium is partitioned to the soil surface exchange sites and can be trapped. There is also the potential for this ammonium to become fixed in the interlayer of some clays.

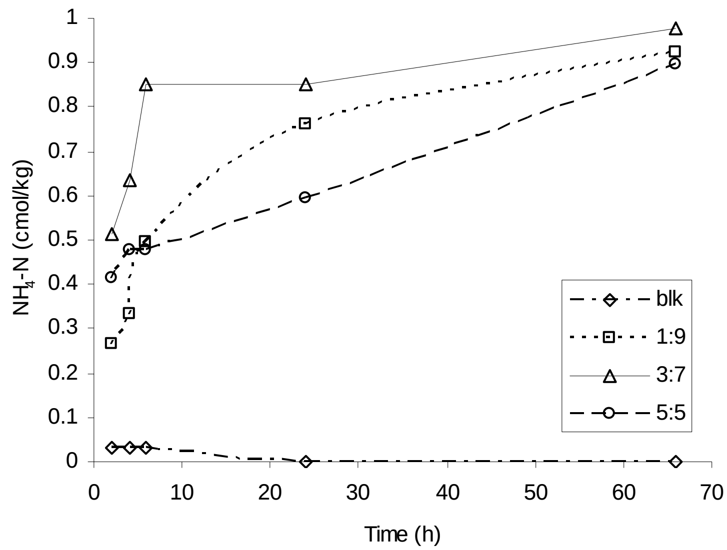

Figure 6. Concentration of ammonium-N on the soil surface.

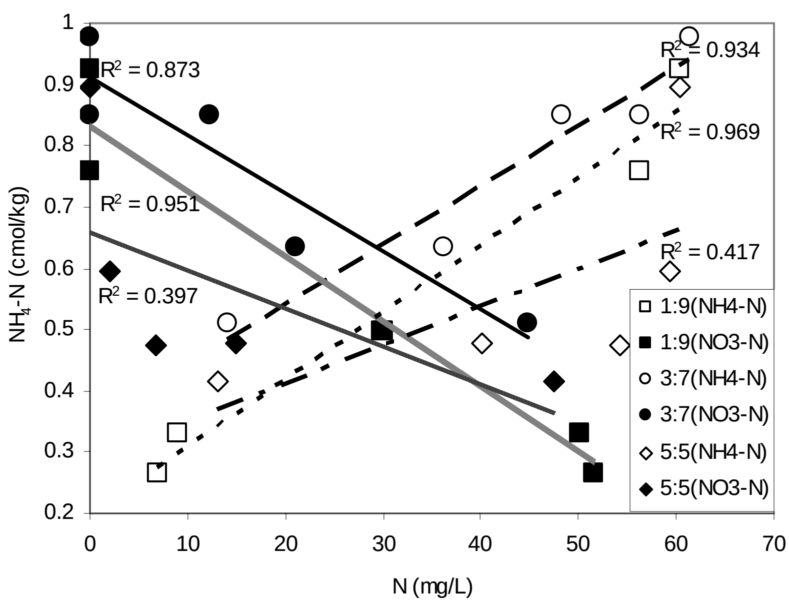

Figure 7. Correlation between N in solution and ammonium-N on the exchange sites.

4.3 Nitrate reduction in column studies

Nitrate concentration as a function of pore volumes is shown in Figure 8. Total reduction of a 160 mg/L nitrate solution was accomplished after 8 pore volumes indicating that even in the absence of stirring nitrate reduction is significant. Comparison with the blank shows that that there was some evidence of nitrate reduction even in the blank. This was probably due to microbially-mediated denitrification. Autoclaving of sample or the use of a biocide will bee used in up coming experiments for comparison. Even in the considering the reduction in the blank column there is an addition loss of 80 mg/L which was clearly attributable to the presence of the zero-valent iron (Figure 9).

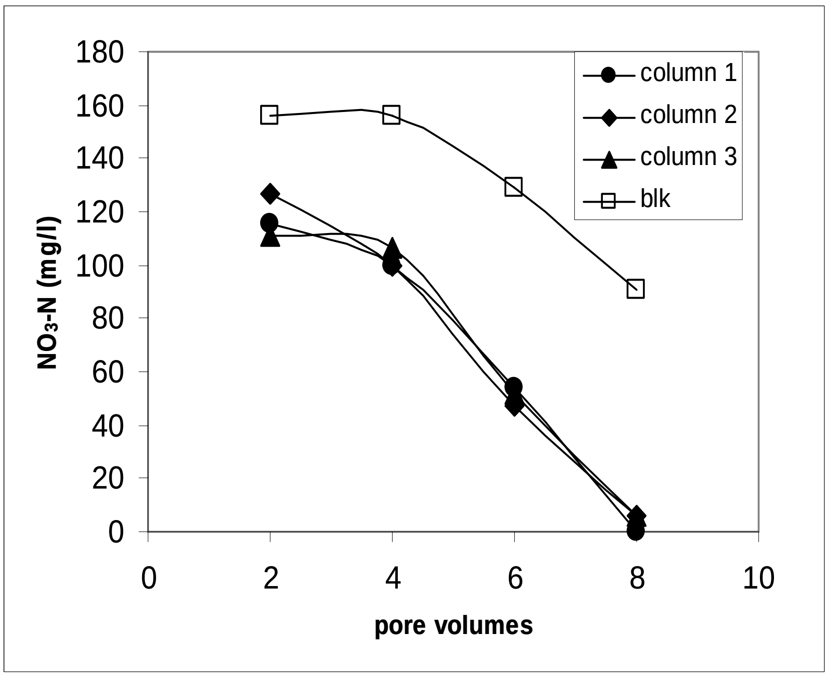

Figure 8. Concentration of nitrate in column discharge for Soil 2.

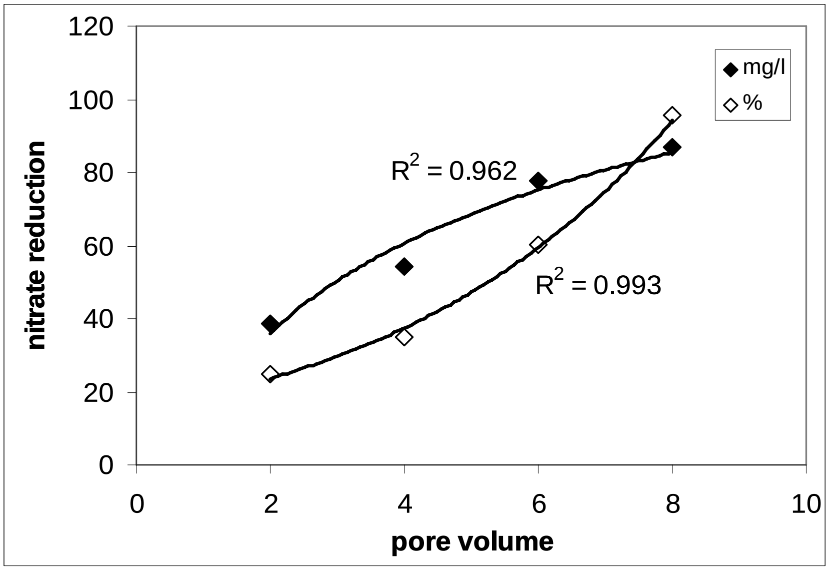

Figure 9. Nitrate concentration in nitrate discharge excluding reduction observed in blank.

Conclusion

Zero-valent iron reduction shows potential for reducing nitrate mobility in soils through the partitioning of the produced ammonium-N to soil surface exchange sites. Further work is needed to determine optimal parameters for nitrate reduction in these systems as it appears to be different than in a pure Fe^0-solution system.

We anticipate that much of the remaining work will be completed by years ending and by then we should have finalized our conclusions and be ready to move on to the next phase of research.

Acknowledgements

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Watershed Development and Climate Change Effects on Environmental Flows and Estuarine Function

Basic Information

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Descriptors:	None
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2. Russell, M. J., and P. A. Montagna. Spatial and Temporal Variability and Drivers of Net Ecosystem Metabolism in Western Gulf of Mexico Estuaries. Submitted 2006. Estuaries and Coasts.

Watershed Development and Climate Change Effects on Environmental Flows and Estuarine Function

Marc Russell

Introduction

Coastal environments, as the receiving ecosystems of freshwater inflow from watersheds, have the potential to be greatly influenced by anthropogenic and climatic watershed modifications (Jørgensen 1980, Officer et al. 1984, Rosenberg 1985, Andersen and Rydberg 1988, D'Avanzo et al 1996, Montagna et al. 2002a). Ecosystem ecologists are searching to find suitable indicators of estuarine ecosystem response to changing environmental conditions so that watershed management can, with some degree of certainty, maintain estuaries within an acceptable range of conditions. The dynamic nature of watershed landscape modification, land use/ land cover, and the uncertainties of regional meteorological changes due to climate change require scientists to find an indicator of ecosystem response that integrates at the watershed level scale. The inherent variability in coastal ecosystems such as estuaries, however, requires scientists to find an indicator of estuarine response that is sensitive enough to respond to watershed changes on various spatial and temporal scales, but is simple and efficient enough to make spatial and temporal assessment under highly variable conditions possible (Russell 2005). Here it is proposed that net ecosystem metabolism (NEM) is a good indicator for assessment of the influence of anthropogenic and climatic watershed modifications on coastal environments because NEM has been shown to respond to highly variable spatial and temporal environmental conditions in estuaries (Russell 2005).

Climatic changes and anthropogenic watershed modifications during the next one hundred years will change freshwater inflow and environmental conditions in coastal areas. The Union of Concerned Scientists (Twilley et al. 2001), in their regional summary of the Intergovernmental Panel on Climate Change findings for the Gulf of Mexico (Houghton et al. 2001), reports that precipitation over Texas coastal watersheds will increase from 5-25%. This precipitation will be delivered in higher magnitude freshwater inflow pulses. The incidence of heavy precipitation events and high river flows are estimated to increase by 7.5% and 21% respectively. Anthropogenic watershed development may reinforce this increase in higher magnitude freshwater inflow pulses, because impervious surfaces reduce the infiltration capacity of the soil (U.S. Soil Conservation Service 1986). This decreased infiltration capacity results in a higher percentage of precipitation becoming runoff, which leaves less precipitation to become groundwater. Population in Texas increased by 17.8 million people during the 20th century (US Census 2000). Counties in coastal watersheds, such as San Patricio and Bee counties, have had 14.3% and 28.7% population growth respectively between the years 1990 and 2000, and are predicted to triple over the next one hundred years. The combination of increased magnitude precipitation events and a reduced infiltration capacity due to urbanization will result in freshwater inflow delivered in higher magnitude but shorter duration pulses. Decreased groundwater may result in smaller river flows during the interval between precipitation events (Houghton et al. 2001, Twilley et al. 2001). Thus, even with more predicted precipitation, average conditions may be closer to drought conditions. Thus, precipitation is estimated to be more variable with higher magnitude pulses interspersed with longer dry periods (Houghton et al. 2001, Twilley et al. 2001). Soil moisture is predicted to increase by up to 25% but this is dependant on estimates of evaporation. The predicted climatic changes and watershed development and the resulting modifications to freshwater inflow and environmental conditions could affect coastal estuarine ecosystem metabolic processes.

The purpose of the present study was to create models to assess how predicted climate and watershed changes might affect freshwater inflow and ecosystem function as indicated by NEM in Texas estuaries. First, freshwater inflow, salinity, and temperature's influence on NEM was modeled in two separate bay systems. Then, a hydrological model was developed to estimate freshwater inflow under the wide range of observed and predicted precipitation conditions. Finally the NEM and hydrological models were linked to provide the means to estimate NEM under various land cover/ land use development and climate change scenarios. Estimates of NEM during inflow events under predicted future climate and watershed development conditions were compared to present day NEM. Comparisons between present and future NEM were used to assess whether predicted changes will result in a more heterotrophic or autotrophic estuarine ecosystem.

Methods and Materials

Study site.

The Texas lagoonal estuarine system contains seven distinct bay systems (Longley 1994). Most of these systems incorporate a primary bay with either a direct or indirect opening to the Gulf of Mexico, and a smaller secondary bay that receives most of the freshwater inflow from rivers. The primary and secondary bays are partially separated by a land constriction at the mouth of the secondary bay. Freshwater inflow thus has a greater influence on secondary bays. One of these secondary bays, Copano Bay, Texas (28^{o} 6.9' N, 97^{o} 1.5' W) and its watershed have unique characteristics that made it particularly attractive for the current research goals. The Aransas River, which drains into Copano Bay, drains a relatively small (2,172 km^2) watershed. The watershed can be broken down into three sub-basins with different land use/ land cover and soil type characteristics (Fig. 1). The Aransas River watershed is one of only a few south Texas river systems that are currently unimpeded by dams. Copano Bay is a shallow, micro-tidal, meso-haline, lagoonal coastal plain estuary with wind dominated mixing (Longley 1994). Mean daily freshwater inflow over the past 40 years from the Aransas River equals 28 $m^3 s^{-1}$ (NOAA 1997). Freshwater is mainly delivered during spring and early summer freshets. Lavaca Bay, located about 100 km to the northeast of Copano Bay (28^{o} 38.4' N, 96^{o} 36.6' W), receives most of its freshwater inflow from the Lavaca River watershed (2,110 km^2). Lavaca Bay receives about 4-6 times the amount of freshwater inflow that Copano Bay does. Lavaca Bay also encountered a wider range of freshwater inflows in 2004 than Copano Bay, and thus provided a model system for addressing salinity effects on ecosystem metabolism.

Sampling design.

Water quality and environmental condition data were collected from field studies and public websites. Water quality parameters were also sampled at one station in upper Copano Bay for one week each month in 2004, and at three synoptically sampled stations out from the river mouth for one week during five different months in 2004 (Russell 2005). Samples were taken at both surface (0.5 m from surface) and bottom depths (0.25 m from bottom). Sampling in upper Lavaca Bay took place between 2002 and 2004 (Russell 2005, Russell et al In Press). Daily freshwater inflow from the Aransas River was downloaded from the United States Geological Survey (USGS) (USGS station 08189700 Aransas River near Skidmore, TX). Daily freshwater inflow into Lavaca Bay was determined from flow gauges in the Lavaca River, Placedo Creek, and Garcitas Creek which are numbered USGS 08164000, 08188800, and 08164600 respectively. Wind speed was downloaded from the Texas Coastal Ocean Observation Network for stations in Port Aransas, and Sea Breeze, Texas.

Water quality measurements.
During field sampling, dissolved oxygen and other water quality parameters were measured every 15 minutes at surface and bottom depths, or at mid-depth, using YSI series 6 multiparameter data sondes. Models 6920-S and 600XLM data sondes with 610-DM and 650 MDS display loggers were used. The series 6 parameters have the following accuracy and units: temperature (± 0.15^{o}C), pH (± 0.2 units), dissolved oxygen (mg l^{-1} ± 0.2), dissolved oxygen saturation (% ± 2%), specific conductivity (± 0.5% of reading depending on range), depth (± 0.2 m), and salinity (± 1% of reading or 0.1 ppt, whichever is greater). Salinity was automatically corrected to 25^{o}C.

NEM Model.
The goal was to produce NEM models for Copano and Lavaca Bay that could be used to predict NEM changes due to currently available climate change and watershed development predictions. A suite of environmental conditions, driven mainly by temperature, salinity, and freshwater inflow, have already been estimated to explain up to 70% of the total environmental variability at four Texas estuarine sites (Russell 2005). Dissolved oxygen and dissolved oxygen percent saturation could not be included in the NEM model as they are used in the calculation of NEM and would lead to circular reasoning. Other parameters, such as pH and chlorophyll-a had to be avoided because they can be affected by biological processes linked to NEM. This left freshwater inflow, salinity, and temperature as the main candidates for inclusion in the NEM model. The relationships between temperature, salinity, freshwater inflow, and NEM in Copano and Lavaca Bay have been previously analyzed using linear regression analysis (Russell 2005). In Copano Bay, temperature, salinity, and freshwater inflow were found to not have a linear relationship with NEM, but a non-linear trend was evident for freshwater inflow. NEM tended to increase to a peak and then decrease as freshwater inflow increased. Thus, the relationship between freshwater inflow and NEM was examined with a non-linear model based on a model used to explain biological structure characteristics at different cumulative freshwater inflows (Montagna et al. 2002b). The assumption behind the model is that NEM values peak at some maximum value with small increases from base freshwater inflows and NEM values decline prior to and after this peak. The shape of this curve can be predicted with a three-parameter, log normal model:

$$Y = a (\exp (-0.5 (\ln (X/c)) /b)^2)),$$

where Y is NEM, X is freshwater inflow, and as explained in Montagna et al. (2002b) the three parameters characterize different attributes of the curve, where "a" is the maximum value, "b" is the skewness or rate of change of the response as a function of freshwater inflow, and "c" is the location of the peak response value on the freshwater inflow axis.

The model was fit to data using the Regression Wizard in SigmaPlot, which uses the Marquardt-Levenberg algorithm to find coefficients (parameters) of the independent variables that give the best fit between the equation and the data (SigmaPlot 2000).

Lavaca Bay results implied a multiple-linear relationship between temperature, salinity, freshwater inflow, and NEM (Russell 2005). The linear response in Lavaca Bay, not found in Copano Bay, may be due to the wider range of environmental conditions influencing Lavaca Bay during 2004. For example, the range of salinity during 2004 sampling in Lavaca Bay was 0-23 ppt while Copano Bay was only 1-12 ppt. Thus, a multiple linear regression analysis was used to create an empirical NEM model for Lavaca Bay that would respond to temperature, salinity, and freshwater inflow.

The fit of the Copano NEM model curve to observed NEM values was assessed using a range of cumulative daily freshwater inflow. An analysis of R^2's using one to twenty-one days of cumulative freshwater inflow into Copano Bay was run and the best fit used for NEM model calibration. This analysis allows for assessment of how many previous days inflow influence NEM in Copano Bay, and provides justification for adjusting the previously used ten-day cumulative freshwater inflow calculation (Russell 2005, Russell et al In Press).

NEM results from Copano Bay (Russell 2005) were fitted to the conceptual non-linear model. NEM results were previously calculated using the dissolved oxygen diurnal curve method as detailed in Chapter 2. The entire set of NEM results from Copano Bay was used for calibration, except those results from April when an abnormally large freshwater inflow event occurred (> 30 million m^3 in ten days). April results were analyzed separately for temporal trends in NEM occurring as this freshwater inflow event subsided (Russell 2005).

The NEM model is comprised of three parameters; a, b, and c. Sensitivity of the model to each of the parameters was assessed by varying one while holding the other two constant. Validation of the both NEM models was completed by comparing observed to simulated NEM results for 2002-2004 and model estimation error was quantified.

Hydrological model.

One goal was to assess the influence of precipitation and watershed land use/ land cover characteristics on NEM. To facilitate this analysis a simple hydrological model for the Aransas River watershed was produced based on the soil conservation service (SCS) curve number method (US Soil Conservation Service 1986) and NEXRAD precipitation data. This hydrological model converted spatially and temporally dynamic precipitation inputs into runoff. The model also adjusted runoff by factoring in watershed soil types and land use/ land cover of the receiving terrestrial landscape by applying the appropriate curve numbers (McCuen 1998). The model served two purposes. It was used to assess the relationship between precipitation and runoff under present day land use/ land cover conditions. It was also used to estimate runoff from simulated precipitation events using predicted land use/ land cover and climate change conditions. Freshwater inflow into Lavaca Bay was adjusted, using the Aransas River watershed as a reference, to reflect the estimated effects of climate change and watershed development.

Precipitation – Nexrad.

Daily Nexrad precipitation shape files for the year 2004 were downloaded from the National Weather Service website in an undefined geographic projection. Each file was then unzipped four separate times to yield a daily shapefile of precipitation points on a 4 km by 4 km grid for the entire Southeastern United States. The projection for each precipitation shapefile was defined according to the Hydrologic Rainfall Analysis Project (HRAP) coordinate system using ArcInfo 9.0. The point shapefiles were then cropped to the extent of the Texas state border and subsequently spatially joined to a HRAP coordinate grid using their HRAP coordinates. This resulted in a gridded polygon shapefile with each cell's precipitation value taken from the point located at its center. The precipitation polygon file was then cropped to the extent of the Aransas River watershed which had been previously delineated from a digital elevation map. The precipitation polygon file was finally converted to a Raster grid file on a 30 m by 30 m scale which was bounded by the Aransas River watershed polygon.

Watershed characteristics.

Two components of the watershed were needed to convert precipitation to runoff. The first component was the land use/ land cover characteristics of the Aransas River watershed. Land use/ land cover data was downloaded as a Raster grid file from the United States Geological Survey's (USGS) 1992 National Land Cover Dataset. The USGS land use/ land cover data has 30 m by 30 m grid cells. The land use/ land cover data was converted to a polygon shapefile on a scale of 300 m by 300 m. The second component was the soil types in the Aransas River watershed. This data was retrieved from the National Resource Conservation Service's State Soil Geographic (STATSGO) database website as a polygon shapefile. The soil polygon shapefile was cropped to the extent of the Aransas River watershed and split into one shapefile per soil type (Fig. 4.1). The Aransas River watershed soils are characterized into three types: soil type B (silt loam or loam), soil type C (sandy clay loam) and soil type D (clay loam, silty clay loam, sandy clay, silty clay or clay). The land use/ land cover polygon data set attribute table was then edited so that curve number (CN) estimates (McCuen 1998) for each land use/ land cover type were added for each soil type. A polygon shapefile of CN's for each soil type was created and cropped to the extent of each soil type within the watershed. These CN by soil type shapefiles were converted to Raster grid files on a 30 m by 30 m scale and then the mosaic function of ArcInfo 9.0 combined them into one CN Raster grid file for the entire Aransas River watershed (Fig. 4.2).

Runoff.

Calculations of runoff take into account both precipitation and the CN of the receiving land surface. Runoff depth was calculated in every 30 m by 30 m grid cell for each day of 2004 using the following equations:

$Q = (P – 0.2\ S)^2 / (P + 0.8\ S)$
$S = (1000/CN) – 10$
$Q = 0$ at $P < I_a$

Where Q is runoff depth in inches d^{-1}, P is precipitation in inches d^{-1}, I_a is the initial abstraction number, and S represents the proportion of precipitation that will runoff from a particular land use/ land cover located on a particular soil type, with CN being the curve number.

Runoff depths in inches d^{-1} were converted to runoff in $m^3\ d^{-1}$ by multiplying them by a conversion factor of inch to meter of 0.0254 and by 900 m^2 (the area of each 30 m by 30 m grid cell). Each cells daily runoff was then summed to calculate total daily runoff from the entire Aransas River watershed and also from just the portion of the watershed that drains to the point where USGS has a river flow gauge.

Hydrological model verification.
The hydrological model runoff results were compared to observed river flow rates in the Aransas River (USGS gauge 08189700 near Skidmore, TX). Daily averaged river flow rates in $ft^3\ s^{-1}$ were converted to an average river flow in $m^3\ d^{-1}$ by multiplying by 2445.12. Daily modeled runoff was assumed to be delivered to the river gauge location with no lag interval. Each daily runoff sum above the gauge was compared to that same day's average river flow using linear regression analysis. This analysis allowed a comparison of runoff estimates to observed river flows. A close fit between simulated runoff and observed river flow allows prediction of freshwater inflow in the Aransas River under various climatic and watershed development scenarios.

Climate change scenarios.
Climate change predictions estimate a 5-25% increase in precipitation over the next hundred years (Houghton et al. 2001, Twilley et al. 2001). This precipitation is predicted to arrive in more intense pulses increasing the incidence of high river flows by up to 21%. Temperature is predicted to increase between 2.5 ^{o}C and 5 ^{o}C with a larger change in summer months than in winter (Houghton et al. 2001, Twilley et al. 2001). To assess the affect of these climate change predictions, NEM was simulated during average 2004 daily precipitation event conditions (1.63 cm) over the Aransas River watershed. Freshwater runoff magnitudes were then adjusted to reflect potential climate change effects on precipitation (average daily precipitation event increased to 2.45 cm) during the next one hundred years and NEM simulated under the modified conditions. These simulations will allow assessment of the effects of climate change on NEM during inflow events.

Watershed development scenarios.
Watershed development over the next one hundred years could result in more land becoming impervious as land use/ land cover is modified to accommodate the growing housing and agricultural needs of an increasing human population. Population in Texas increased by 17.8 million people between the year 1900 and 2000 (US Census 2000). This constitutes a 100-200% increase per 50 years. Texas population densities are now between 75 and 200 people $mile^{-2}$. San Patricio and Bee counties, which are located in the Aransas River watershed, had 14.3% and

28.7% population growth respectively between 1990 and 2000. Population numbers in San Patricio County, which is located in the lower portion of the Aransas River watershed, was predicted to double from around 60000 to 120000 people between 1990 and 2050. Actual population numbers in San Patricio County increased as predicted from 58749 to 67138 people between the years 1990 and 2000. Population densities in the Aransas River watershed portion of San Patricio and Bee counties are approximately 40 people mile^{-2} (US Census 2000). The national average is 80 people mile^{-2}, and urbanized watersheds such as those in Maryland have population densities as high as 542 people mile^{-2}. Thus the Aransas River watershed is considered rural and has < 2% urbanized land cover. Urbanization with increased population numbers produces more impervious surfaces and results in more water running off into the river and stream systems of a watershed during precipitation events (US Soil Conservation Service 1986). During large precipitation events in unrestricted coastal watersheds without dams most of this runoff will flow downstream to become freshwater inflow to estuaries. The influence of watershed development on NEM was assessed by simulating a present day precipitation event (1.63 cm) under current land use/ land cover characteristics in the upper Aransas River watershed. Precipitation was related to runoff using the hydrological model for the Aransas River watershed. Land use/ land cover was then adjusted to simulate 100% and 200% increases in urbanization in the upper watershed (Fig. 3) yielding approximately 3 % and 4.5 % urbanized land cover. This percent urbanization can still be considered rural as most urbanized watersheds have >10 % urbanized land cover. NEM response to urbanization was then simulated under present day precipitation event conditions and compared to present day simulated results.

Combined effects of potential climate change and watershed development.
The effects on NEM from predicted modifications of freshwater inflow due to the combination of climate change and watershed development were assessed. Predicted freshwater inflows during precipitation events may be up to 25 % higher than today, and could increase by greater than 25 % as freshwater inflow arrives in larger pulses due to urbanization (US Soil Conservation Service 1986, Houghton et al. 2001, Twilley et al. 2001). NEM during predicted average freshwater inflow event conditions into Copano Bay, due to the combined effects from potential climate change and urbanization, were simulated and compared to present day NEM results. The ratio of present day to predicted freshwater inflow into Copano Bay was then used to assess potential changes in Lavaca Bay NEM due to similar ratios of change in freshwater inflow to that bay. Estimates of the predicted change in Lavaca Bay NEM also incorporate the potential 5 ^{o}C increase in temperature predicted by climate change models for Texas coastal areas (Houghton et al. 2001).

Results

Environmental conditions.
Temperatures followed a seasonal cycle with lows during winter months and highs during summer (Table 1). Daily average water temperature ranged from a low of 16 ^{o}C in Copano Bay and 13 ^{o}C in Lavaca Bay during January to a high of 30 ^{o}C in both bays during July. Water temperatures during deployments tended to remain stable, but some weeks had daily temperature changes of about 1 ^{o}C, and on a few occasions temperatures decreased by as much as 7 ^{o}C in 24-hours. Rapid daily temperature changes were mostly associated with decreasing salinity (-2 ppt

d^{-1}) during April storm events. Salinity was highest during January-March 2004. Large freshwater inflows (up to 44×10^6 m^3 d^{-1}) beginning in April and continuing through May in Copano Bay and June in Lavaca Bay resulted in large decreases in salinity (down by as much as 22 ppt) in Copano and Lavaca Bays. Salinity was at or near zero by May. Copano Bay remained relatively fresh throughout the year with an annual average salinity of 6 ppt. Freshwater inflow into Copano Bay decreased back to base flow levels (~2×10^5 m^3 d^{-1}) in June and was low throughout most of the remaining year. Salinity did not recover to pre-spring levels until September due to the long residence time in Copano Bay. High freshwater inflow into Lavaca Bay started in April and continued through the beginning of July, reaching an average inflow of 86×10^5 m^3 d^{-1} in June.

NEM response to environmental conditions.

Copano Bay had fairly stable NEM values (mean = -1.12 mg O_2 l^{-1} d^{-1}, SE = 0.10 mg O_2 l^{-1} d^{-1}) over a range of temperatures (16-30 ^oC) (Fig. 4a). Copano Bay NEM results were not significantly related to temperature ($p = 0.4869$, $R^2 <0.01$), and showed little response over a range of salinity (0-14 ppt) ($p = 0.1131$, $R^2 = 0.01$) (Fig. 4b). NEM in Copano Bay increased from a basal value of around -1 mg O_2 l^{-1} d^{-1} during the lowest inflows to around 0 mg O_2 l^{-1} d^{-1} at ten-day cumulative inflows less than 2×10^6 m^3 (Fig. 4c). Less data exists for evaluating NEM under ten-day cumulative inflows above 2×10^6 m^3, but the results show a decreasing trend in NEM down to values around -4 mg O_2 l^{-1} d^{-1} as cumulative inflow increased to 7×10^6 m^3. The limited samples collected at ten-day cumulative freshwater inflows above 7×10^6 m^3 in Copano Bay occurred during one particularly large inflow event in April (Fig. 4c). NEM was initially autotrophic during the first day of the freshwater pulse and then dropped to around -4.00 mg O_2 l^{-1} d^{-1} after a peak one-day inflow on April 12th around 600×10^3 m^3 d^{-1} and then became autotrophic again (1.00 mg O_2 l^{-1} d^{-1}) for a day or two as one-day freshwater inflow subsided to around 150×10^3 m^3 d^{-1} (Fig. 5). NEM values then returned to more normal values (-1 to -2 mg O_2 l^{-1} d^{-1}) as freshwater inflow slowed to 80×10^3 m^3 d^{-1}.

Lavaca Bay NEM results from 2002-2004, when combined, had significant linear relationships with temperature, salinity, and cumulative ten-day freshwater inflow (Fig. 6a-c). Salinity, however, was strongly influenced by ten-day cumulative freshwater inflow with an exponential drop from around 22 ppt to 5 ppt as ten-day cumulative freshwater inflow increased from base flows of 1×10^6 m^3 to around 20×10^6 m^3 ($p < 0.001$, $R^2 = 0.76$) (Fig. 7a). Also, salinity above 20 ppt mainly occurred during winter months when water temperatures were below 15 ^oC (Fig. 7b). Since these three factors are interrelated, a multiple linear-regression analysis was used to assess each factors influence on NEM while accounting for the influences from the other factors. Salinity alone accounted for 40% ($p < 0.001$, $R^2 = 0.40$) of the variance in NEM explained by the multiple linear-regression model ($R^2 = 0.45$). Temperature ($p = 0.073$, additional $R^2 = 0.03$) and cumulative 10-day freshwater inflow ($p = 0.071$, additional $R^2 = 0.02$) together accounted for another 5% of the variance in NEM. The combination of these three factors, thus, explained 45% of the variability in Lavaca Bay NEM and estimates of NEM using the complete three-parameter model had a standard error of 1.64 mg O_2 l^{-1} d^{-1} (Fig. 8).

Copano Bay NEM model calibration.

The fit of the non-linear conceptual model to observed Copano Bay NEM values was assessed under various days of cumulative inflow (Fig. 9). It was determined that a 17-day cumulative inflow provided the best model fit ($R^2 = 0.15$) to observed NEM values in Copano Bay. Adjustment of the previously used 10-day cumulative inflow value in chapter 1 and 2 did not change the pattern of response of NEM to increased freshwater inflow, but changing to a 17-day cumulative flow helps to reduce the error of estimates made from the NEM model. Even with this adjustment, the predictive power of the Copano Bay NEM model remained very low and large changes in NEM would be needed to find significant differences in NEM due to the effects of different environmental conditions.

NEM results from Copano Bay were used for parameter calibration.

NEM (mg O_2 l^{-1} d^{-1}) = (f_x) $\sum$ 17-day cumulative freshwater inflow (m^3)
NEM (mg O_2 l^{-1} d^{-1}) = a (exp (-0.5 (ln (X/c)) /b^2))
a = 9.3465 (mg O_2 l^{-1} d^{-1})
b = 2.512 (mg O_2 l^{-1} d^{-1})
c = 960396 (m^3)
X = cumulative 17-day freshwater inflow (m^3)

Parameters were set to values derived from the fit between the non-linear model and observed NEM over the observed freshwater inflows range. Using these parameters, simulated NEM increases from -1.37 mg O_2 l^{-1} d^{-1} at cumulative 17-day freshwater base flow conditions of 352586 m^3 to a peak of -0.65 mg O_2 l^{-1} d^{-1} at 955003 m^3 (Fig. 10). As cumulative 17-day freshwater inflow continues to increase, NEM steadily decreases to an estimated low of -5.50 mg O_2 l^{-1} d^{-1} at cumulative 17-day inflows close to 20×10^6 m^3. This agrees well with the most heterotrophic values observed during the largest Copano Bay freshwater inflow event that occurred in April 2004 (Fig. 5) as well as the heterotrophic values observed using alternative methods for quantifying respiration and NEM (Russell 2005).

Copano Bay NEM model sensitivity.

The sensitivity of the NEM model was assessed by comparing the shapes of the curves relating NEM over a range of freshwater inflow conditions (17-day cumulative inflow between 100,000 – 15 million m^3) while modifying each parameter separately. The shape of the NEM response curve was calculated at the following range of parameter values: a = 5, 10, and 15 (mg O_2 l^{-1} d^{-1}); b = 1.5, 2.5, and 3.5 (mg O_2 l^{-1} d^{-1}); and c = 500000, 1000000, and 1500000 (m^3). Parameter "a" controls the peak value of NEM with higher values yielding more autotrophic conditions (Fig. 11a). Parameter "b" controls the skewness of the curve and how fast NEM declines from its peak value with increased inflow (Fig. 11b). Parameter "c" controls which freshwater inflow value peak NEM will be located at (Fig. 11c).

Copano Bay NEM model estimation error.

Simulated NEM results were compared to those observed at Copano Bay during 2004 (Russell 2005). The overall fit of the non-linear model to observed NEM results was relatively low ($R^2 = 0.15$) but the relationship was significant ($p < 0.0001$). The standard error of estimating NEM using the model was 1.46 mg O_2 l^{-1} d^{-1}. This standard error requires a minimum change of ± 2.39 mg O_2 l^{-1} d^{-1} to produce a significantly different NEM result with a 95% confidence interval.

Precipitation.

Precipitation over the Aransas River watershed varied widely during 2004 (Fig. 12). Daily precipitation, falling over the sub-basin above the USGS river gauge 08189700, ranged from zero measurable precipitation up to as much as 11 cm d^{-1} (4.33 inches). Large daily precipitation values occurred mostly during April and May storm events. Precipitation was notably low during the first three months of 2004. Precipitation events (>1.65 cm d^{-1}) occurred seven times between June and December.

Runoff potential.

The interaction of soil types with land use/ land cover characteristics within the Aransas River watershed yielded distinct areas of potential precipitation infiltration. The three soil types influenced infiltration potential within each of their respective areas. This is especially evident in the upper Aransas River watershed (Fig. 3). Infiltration potential was assessed using initial abstraction (I_a) values for each 30 m by 30 m grid cell. Values for I_a ranged from 0 to 1.4, with 1.4 being the highest infiltration potential. Soil type B (silt loam or loam) yielded an I_a value (mean ± standard error) of $0.84 \pm 0.66\times10^{-3}$. Soil type C (sandy clay loam) yielded an I_a value of $0.59 \pm 0.525\times10^{-3}$. Soil type D (clay loam, silty clay loam, sandy clay, silty clay or clay) yielded an I_a value of $0.23 \pm 0.584\times10^{-4}$. Infiltration potential of different land use/ land cover types also influenced runoff potential. Values for I_a ranged between 0 in urbanized areas to 1.4 in forested or shrub land areas.

Simulated runoff and observed river flow.

Simulated runoff and observed river flow from the Aransas River watershed area draining to the USGS gauge location had a wide range during 2004. Simulated runoff during precipitation events ranged between 4×10^3 m^3 d^{-1} and 4.4×10^6 m^3 d^{-1}. Observed river flows during the same precipitation events ranged from 20×10^3 m^3 d^{-1} to 3.3×10^6 m^3 d^{-1}. Simulated monthly runoff matched up well with monthly observed river flow ($p < 0.0001$, $R^2 = 0.99$) (Fig. 13). The river flow response to increased runoff was more scattered at lower flows ($p = 0.0035$, $R^2 = 0.68$). This may be due to differences in the effects of evaporation during smaller precipitation events. The average present day runoff event was calculated as 1,378,730 m^3 d^{-1}. Assuming events last for 3 days with one event during every 17 days; these runoff events would yield a total 17-day cumulative simulated river flow of around 4×10^6 m^3 passing the USGS gauge in the Aransas River watershed before it flows into Copano Bay.

Simulated runoff from the area draining towards the USGS river flow gauge also compared well with simulated total watershed runoff ($p < 0.0001$, $R^2 = 0.91$) (Fig. 14a). Outliers influenced this relationship and so the analysis was re-run without them. The relationship between simulated gauged runoff and simulated total watershed runoff suggests that actual river inflow into Copano Bay is approximately 3-4 times larger than observed USGS river flow. This is not surprising, considering the USGS gauge only measures river flow from about a third of the total area of the Aransas River watershed. Estimated freshwater inflows from the entire Aransas River watershed are, thus, roughly equivalent to those measured from the Lavaca River watershed, which has its gauge much closer to the point of river discharge than the one in the Aransas River. A slightly less strong, but still significant relationship existed with the outliers removed ($p < 0.0001$, $R^2 = 0.54$) (Fig. 14b). More scatter existed as runoffs increased, implying that as a larger proportion of the watershed receives precipitation, differences between sub-basin land use/land cover, soil types, and their influence on runoff may become magnified. Thus, spatially variable precipitation patterns, such as provided by Nexrad, may be even more important for basin scale runoff estimates than those from smaller sub-basins.

Climate change scenarios.

NEM was simulated under upper Aransas River watershed present day cumulative 17-day freshwater event conditions of 4,136,190 m^3 and predicted future event conditions 91% higher at 7,915,263 m^3 (Table 2). This assumes an average three days of precipitation of 1.65 cm d^{-1} and an average three days of predicted precipitation of 2.46 cm d^{-1} occurring in a 17-day period. The resulting simulated present day and predicted NEM values were not significantly different at -2.11 and -3.43 mg O_2 l^{-1} d^{-1} respectively (t-test, $p > 0.1$). The model, however, suggests the potential of 60% more heterotrophic conditions with increased precipitation. To produce significantly different present day and predicted NEM results with a 95% confidence interval, 17-day cumulative freshwater inflow conditions would have to reach 10×10^6 m^3. This would require another 21% increase in cumulative 17-day freshwater inflow above those predicted in this study.

Watershed development scenarios.

Urbanized areas in the Aransas River watershed currently equal 1.5% (1975 of 134399, 900 m^2 cells) of the total area. These urbanized areas are mostly surrounded by land use/ land cover areas with I_a values of 0.2 to 0.4. The city of Beeville, Texas, which is located in the upper Aransas River watershed, is surrounded by land with higher infiltration potential (I_a from 0.8 to 1.4) (Fig. 3). Increased urbanization would result in a 0 - 71% decrease in infiltration potential in converted lands. The percent decrease depends on which soil type is developed. A present day average precipitation runoff event of 1.63 cm (0.64 inches) homogeneously applied over the upper Aransas River watershed would result in runoffs of 1378730, 1406269, and 1642889 m^3 d^{-1} under present day, low urbanization, and high urbanization conditions respectively (Table 3). These daily flows would yield, again assuming a three-day precipitation event with no other events occurring in the previous 17 days, a cumulative 17-day freshwater inflow of 4136190, 4218807, and 4928667 m^3 respectively (increases of 2% and 19%). NEM is estimated to change from a present day value of -2.11 mg O_2 l^{-1} d^{-1} to -2.14 and -2.44 mg O_2 l^{-1} d^{-1} (1% and 16% more heterotrophic) during low and high urbanization scenarios respectively in the upper Aransas River watershed. This represents a non-significant change in NEM with urbanization (t-test, $p > 0.1$)

Combined effects of climate change and watershed development.

Urbanization and climate change have similar effects on NEM in that they both tend to increase freshwater inflow. The combined influence of increased precipitation and increased impervious surfaces due to urbanization in the Aransas River watershed could potentially increase freshwater inflow to Copano Bay. NEM was simulated under future cumulative 17-day freshwater inflow conditions, due to the combination of climate change and watershed urbanization, of 9431796 m^3

(an 128% increase) (Table 2). The simulated NEM under these predicted conditions is 81% more heterotrophic at -3.82 mg O_2 l^{-1} d^{-1}. The combination of urbanization and climate change, thus, almost causes enough freshwater inflow to produce a significantly more heterotrophic ecosystem. An NEM 8% more heterotrophic than predicted (-3.98 mg O_2 l^{-1} d^{-1}) would be significantly different from a present day average event NEM of -2.11 mg O_2 l^{-1} d^{-1} (t-test, $p < 0.1$).

Predicted NEM in Lavaca Bay.
The Lavaca Bay NEM model is influenced by not only freshwater inflow, but also salinity, and temperature. A similar analysis of how many days cumulative freshwater inflow produce the best model fit showed little improvement (Data not shown) from changing from the previously used 10-day period (Russell 2005). The calibrated NEM model equation for Lavaca Bay is as follows:

$$\text{NEM (mg } O_2 \text{ } l^{-1} \text{ } d^{-1}) = -1.82 \text{ (mg } O_2 \text{ } l^{-1} \text{ } d^{-1}) + 2.62\times10^{-8} \text{ (mg } O_2 \text{ } l^{-1} \text{ } d^{-1} \text{ } m^{-3}) \text{ FW} - 0.07 \text{ (mg } O_2 \text{ } l^{-1} \text{ } d^{-1} \text{ } ^{o}C^{-1}) \text{ T} + 0.21 \text{ (mg } O_2 \text{ } l^{-1} \text{ } d^{-1} \text{ ppt}^{-1}) \text{ S}$$

Where FW is cumulative 10-day freshwater inflow (m^3), T is temperature (^{o}C), and S is salinity (ppt).

Average cumulative 10-day freshwater inflow conditions in Lavaca Bay are around 10×10^6 m^3 (Fig. 7). Salinity at this average present day inflow is approximately 15 ppt (Fig. 7). Application of a proportional increase in freshwater inflow to Lavaca Bay inflow, as calculated from predicted climate change and watershed development conditions in Copano Bay, results in a predicted future event inflow into Lavaca Bay of around 20-30$\times10^6$ m^3. With more precipitation over the Lavaca Bay watersheds, however, the infiltration capacity of soil there will become saturated more often. This could potential increase the runoff and subsequent inflow into Lavaca Bay during the predicted increased precipitation events. A predicted future freshwater inflow event was, thus, estimated to produce around 40×10^6 m^3 over a 10 day period, which is within the range of those observed during 2004 (Fig. 7). This magnitude of freshwater inflow can drop salinity to around 0-2 ppt (Fig. 7). A 5 ^{o}C temperature increase as predicted for this region by climate change model predictions (Houghton et al. 2001, Twilley et al. 2001), was also applied to the model. The multiple linear-regression Lavaca Bay NEM model predicts an NEM of -0.16 mg O_2 l^{-1} d^{-1} during present day environmental conditions and an NEM 1563% more heterotrophic at -2.66 mg O_2 l^{-1} d^{-1} during predicted future environmental conditions due to climate change and watershed development (Table 3). The more heterotrophic simulated NEM value during future conditions, however, is not significantly different than simulated present day NEM (t-test, $p > 0.1$). Similar to what was found in Copano Bay, a 7% more heterotrophic NEM value than predicted by the Lavaca Bay NEM model (-2.85 mg O_2 l^{-1} d^{-1}) is required to produce a significantly different NEM than present day. All that would be required to produce a significantly more heterotrophic NEM would be to model the predicted salinity as 0 ppt instead of the 1 ppt used in this study. Thus, with the large amount of variability observed in these systems, the potential for more heterotrophic conditions in Lavaca Bay exists.

Discussion

NEM models.

Observed NEM values from Copano Bay followed the shape of the conceptual NEM model (Fig. 10). NEM data, however, fit the conceptual model better when they where compared to cumulative freshwater inflow from multiple previous days (Fig. 9). A 10-day period was previously identified as the time interval needed to capture the response of estuarine benthic community structure to freshwater inflow events (Kalke and Montagna 1991; Montagna and Kalke 1992). The current research identified the 17-day period as the best time interval to capture the response of estuarine metabolism to freshwater inflow events in Copano Bay.

Copano Bay had an initially increasingly autotrophic NEM with increased freshwater inflow (Fig. 10). This type of ecosystem response to increased inflow is likely indicative of increased nutrient loading. Photosynthetic organisms, which produce oxygen as they produce energy during photosynthesis, can combine this energy with nutrient loads to produce more biomass. Increased loading of nutrients was concluded to result in more autotrophic NEM's in marine mesocosms (Oviatt et al. 1986) and in natural systems with high nutrient inputs (D'Avanzo et al. 1996). NEM was significantly more autotrophic under conditions of higher nitrogen loading in a study of 42 sites in 22 National Estuarine Research Reserves (Caffrey 2004).

The initially increasingly autotrophic NEM in Copano Bay, with increased freshwater inflow, was followed by a peak and then a subsequently decreasing NEM trend as freshwater inflow continued to increase (Fig. 10). Heterotrophic ecosystem responses have been found in systems dominated by organic carbon loading (Smith and Hollibaugh 1993, 1997, Cai et al. 1999, and Raymond et al. 2000). NEM was heterotrophic in these organic matter dominated systems. Overall, Copano Bay remained relatively heterotrophic throughout 2004. This result was also found at most NERR sites (Caffrey 2004). Copano Bay, thus, follows the general trend of shallow water estuaries being net heterotrophic.

NEM model results were significantly related to observed NEM values in Copano Bay but the non-linear relationship had a lot of scatter ($p < 0.0001$ $R^2 = 0.15$) (Fig. 10). The large amount of dispersion in observed NEM values, especially during low freshwater inflow conditions, may be due to factors not included in the model. One factor that may influence NEM during low freshwater inflow periods is turbidity. The balance between primary production and respiration could be influences by reduced light availability due to high turbidity in Copano Bay. High turbidity conditions exist for the majority of the year in Texas bays (NOAA 1997). Higher turbidities and subsequent lower available photosynthetically active radiation (PAR) with depth usually exist in water close to river discharge as compared to water closer to an estuary mouth (Kennish 1986). Secchi depths in Copano Bay ranged between 0.5 m during winter to 0.2 m during summer (personal observation). Surface irradiance, and thus PAR, also varied with season, and on shorter time scales associated with clouds (Russell 2005). Surface irradiance levels dropped markedly during the April and May storm events (Russell 2005), but little effect was observed on NEM. Turbidity and in-situ irradiance measurements need to be compared to simultaneously calculated NEM values before these relationships can be added to the model.

Another factor that may influence NEM could be the balance between nutrients and organic matter in freshwater inflow. A determining factor of the balance between autotrophy and heterotrophy is the balance between organic carbon and nutrient loading (Kemp et al. 1997, Eyre and McKee 2002). Nutrient and organic matter loads in the micro-tidal estuaries of Texas are mainly delivered through freshwater inflow (Whitledge 1989a, 1989b, Longley 1994). The pulsing nature of freshwater inflow sporadically delivers nutrients and organic matter at high magnitudes but for short durations. As freshwater inflow increases, the ratio of nutrients to organic matter within the inflow will also change, decreasing as more terrestrial organic particulates are eroded from the watershed (Jones et al. 1986, Parker et al. 1989). The NEM model predicts an increasing NEM with small increases from base freshwater inflow conditions (Fig. 10). The model then predicts more heterotrophic conditions with increasing flow. It is possible that a shift from high to low nutrient to organic matter ratios occurs as freshwater inflow increases from base flow levels. Quantification of nutrient and organic matter loading during a range of freshwater inflow conditions would be an important addition to the NEM model.

NEM event dynamics during a very high magnitude freshwater inflow in Copano Bay resulted in a similar response, overall, to that of NEM during increased cumulative flow (Fig. 5). Days with net heterotrophic rates as large as -5 mg O_2 l^{-1} d^{-1} (Fig. 5) dominated the ecosystem response when all daily NEM were averaged (average NEM = -1.37 mg O_2 l^{-1} d^{-1}). Copano Bay exhibited an initial autotrophic response the day the freshwater pulse began and then became relatively heterotrophic as freshwater inflow rates continued to increase. This response may be due to an initial phytoplankton response to dissolved nutrient inputs followed by large magnitude benthic respiration rates as organic matter loads become the main constituent in freshwater inflow. Within a few days as the freshwater pulse subsided, however, the system became relatively autotrophic again, even becoming net autotrophic for a few days. This response suggests that the more marine planktonic community may have been flushed downstream during the large freshwater pulse and an autotrophic response by phytoplankton may not have occurred until the planktonic community reestablished itself as inflow subsided. These event dynamics may be responsible for some of the observed scatter in NEM values from Copano Bay as enough days of sampling (n = 69) were completed there that various events must be included in the results.

Copano Bay receives freshwater inflow from three point sources. Error in the NEM model may relate to freshwater influences from other point sources than just the Aransas River. This study focused on the influence of the Aransas River, however, and so stations were located close to its discharge point. Copano Creek discharges into the far northeast section of Copano Bay. Freshwater inflow from Copano Creek would have to travel approximately 16 km directly across the bay in order to influence the results of the present study. The Mission River discharges into the tertiary Mission Bay before freshwater inflow can have any influence on the northwestern area of Copano Bay. Water from the Mission River would have to travel approximately 8 km before it could have any influence on the closest station in the present study. By comparison, the Aransas River discharges directly into southeastern Copano Bay, and this discharge is less than one km from the closest station in the present study and is less than 3 km from the farthest station. The Aransas (8.10 cm) and Mission River (8.47 cm) watersheds receive similar amounts of annual precipitation (Quenzer 1998). The Aransas and Mission River watersheds, however, have rather different agriculture (58% and 25% respectively) and rangeland land use (38% and

73% respectively). Even with these differences in land use, though, nutrient loads from the two rivers are remarkably similar. Total nitrogen loads for Aransas and Mission River are 213,314 and 239,843 kg yr^{-1} respectively, and phosphorus loads are 60,900 and 57,801 kg yr^{-1} (NOAA 1997). Tidal range in Copano Bay is severely dampened by the distance from the Gulf of Mexico, and is usually less than one-half meter (Powell et al. 1997). Residence time in Copano Bay has been calculated to be as high as 3 years (Longley 1994) suggesting that water circulation and replacement by river inflows is very slow. Thus, the influence of the Mission River freshwater inflow on the area of station locations in the present study is significantly reduced by the combination of retention in Mission Bay, little tidal circulation, and the long distance between discharge and station locations. The influence that Mission River freshwater inflow could have on the results of the present study could potentially increase during precipitation events producing increased inflows. Any increase in potential influence from the Mission River, however, would coincide with a similar increased inflow from the Aransas River which would push water away from the present study station locations. Thus, the influence of Copano Creek and the Mission River on NEM results in the present study is assumed to be insignificant when compared to that from the Aransas River.

Lavaca Bay NEM results were similar to Copano Bay results in that they generally became more heterotrophic at higher freshwater inflows. The dominant factor explaining changes in NEM was salinity ($R^2 = 0.40$), with more heterotrophic conditions during low salinities (Fig. 6a). Temperature and freshwater inflow, which were somewhat interrelated to salinity (Fig. 7), added a small ($R^2 = 0.05$), but significant, amount of explanatory power to the overall NEM model (Fig. 6b-c). With 45% of the variability in NEM explained by these three factors, the Lavaca Bay NEM model provides much more confidence in estimates of NEM during changing environmental conditions than the Copano Bay NEM model. It is interesting to note, however, that the two models generally agree about the consequences of increases in freshwater inflow due to climate change and watershed development. The Lavaca Bay NEM model was calibrated with NEM values measured over a much wide range of environmental conditions, especially salinity, than those in Copano Bay. This suggests that the relationship between NEM and salinity in Copano Bay may not have been observed due to lack if sampling over a wider range of conditions. A comparison of the shape of the Lavaca Bay and Copano Bay model curves illustrates the similarities and differences of the two ecosystems. Copano Bay, although overall it is more heterotrophic than Lavaca Bay, shows an autotrophic response at moderate flows. A combination of nutrient ratios, organic carbon loads, and residence times may explain this difference. Lavaca and Copano Bays have very similar phosphorus inputs, but nitrogen loads are higher in Lavaca than Copano Bay. Thus, the nitrogen to phosphorus ratio of nutrients loads into Lavaca Bay is higher (6.63) than that in Copano Bay (4.88) (Longley 1994). The low residence time of Lavaca Bay (77 days) as opposed to Copano Bay (1102 days), however, means that nitrogen is much more available in Copano Bay (residence time weighted nitrogen = 5.83 g m^{-3} yr^{-1}) than Lavaca Bay (residence time weighted nitrogen = 0.66 g m^{-3} yr^{-1}) (Longley 1994). The ratio of organic carbon to nitrogen loads, which are identical in Lavaca and Copano Bays (C:N = 6.16), become much lower in Copano Bay (2.06) than Lavaca Bay (29.70) when nitrogen load availability is adjusted to reflect the differences in residence time between the two bays. The slight autotrophic response at moderate flows in Copano Bay may be due to this higher availability of nutrients which may dominate metabolic processes until organic carbon loads increase during higher freshwater inflows (Jones et al. 1986, Parker et al. 1989).

Hydrological model.
The hydrological model links spatially and temporally dynamic precipitation data with spatially variable landscape characteristics to produce runoff and freshwater inflow to the downstream estuary. This model was created for the Aransas River watershed. The thrust of this modeling effort was to estimate freshwater inflow into Copano Bay under predicted future climate change and watershed development conditions.

The SCS curve number method (US Soil Conservation Service 1986) for transforming precipitation to runoff was originally designed to assess flooding events due to large magnitude precipitation events in urban watersheds. The original SCS curve number method is stated to have less accuracy when runoff is less than 0.5 inch. The method also assumes zero runoff at precipitation less than the initial abstraction value (I_a), which here is assumed to be S multiplied by 0.2. The SCS curve number method does not account for changing I_a values, which are dependent on soil moisture content (US Soil Conservation Service 1986). Soil moisture content may have significantly changed in the Aransas River watershed during 2004, especially considering the large spatial and temporal variability in precipitation that was observed. Even with the potential short comings of using the SCS curve number method for this type of modeling, the rainfall-runoff model performed quite well. Simulated monthly runoff was strongly related to monthly observed river flows ($p < 0.0001$, $R^2 = 0.99$) (Fig. 13). The model showed more error when simulated monthly runoff and observed river flow were compared while excluding the very high inflow months of April and May ($p = 0.0035$, $R^2 = 0.68$). This increased error could have arisen due to the lack of an evaporation term in the rainfall-runoff model. The significant fit between precipitation, runoff, and observed river flow indicates that the combination of Nexrad precipitation data and the SCS curve number method can be used to model freshwater inflow under various climate change and watershed development scenarios.

Climate change and watershed development.
NEM in Copano Bay was more heterotrophic (mean = -3.43 mg O_2 l^{-1} d^{-1}), but not statistically significantly so, during predicted future precipitation conditions than during present day conditions (mean = -2.11 mg O_2 l^{-1} d^{-1}) (Table 3). NEM becomes approximately 63% more heterotrophic with a 91% increase in cumulative 17-day freshwater inflow. Watershed development had less of an effect on net ecosystem metabolism than climate change (Table 3). It is important, however, to realize that the model only accounts for changes in water quantity arising from urbanization. It does not take into account changes in constituent concentrations in that inflow or water quality. It also does not take into account future water diversions or ground water flows.

The level of urbanization in the Aransas River watershed is very low (currently 1.5%). This is one of the many reasons Copano Bay provides a good study site for assessing the consequences of potential watershed development. The NEM model predicts that Copano Bay NEM, after an average precipitation event, is currently around -2.11 mg O_2 l^{-1} d^{-1} and could change to -2.44 mg O_2 l^{-1} d^{-1} with a 200% increase in urbanization in the upper Aransas River watershed. This is not a statistically significant change but these estimates of NEM in Copano Bay provide a baseline for comparison to other more urbanized watersheds. It is also important to realize that the present study does not attempt to integrate changes in constituent loads into estimates of NEM. Increased agricultural runoff or sewage treatment discharge both effect the response of an estuary to freshwater inflow. For example, the trend of increased extreme heterotrophic or autotrophic conditions with increased urbanization is supported by findings from urbanized watersheds such as those flowing into the Nueces River Estuary (Borsuk et al. 2001), Chesapeake Bay estuaries (Kemp et al. 1997, Hale et al. 2004), the Husdon River Estuary (Howarth et al. 1992 and 1996), San Francisco Bay (Jassby et al. 1993), and Tomales Bay (Smith et al. 1991). Many of these estuaries and bays have greater than 20% urbanized land in the corresponding watersheds, and eutrophication was concluded as the most influential factor on metabolic rates in these estuaries. Dissolved inorganic nitrogen to total organic carbon ratios in heterotrophic estuaries that act as carbon sinks are typically < 0.5 (Kemp et al. 1997). Texas estuaries fall well within this range at 0.16-0.33 (Longley 1994, Russell 2005). Extremely autotrophic estuaries tend to be carbon sources and usually have dissolved inorganic nitrogen to total organic carbon rations > 0.5. Dissolved oxygen conditions, in the receiving water bodies of heavily urbanized watersheds, often become hypoxic (Kemp et al. 1992). Summertime anoxia/hypoxia in the bottom waters of Chesapeake Bay has occurred since the mid-1930's (Newcombe and Horne 1938), and has spatially and temporally increased in recent decades (Heinle et al. 1980, Officer et al. 1984). Historical increases in spatial and temporal occurrences of hypoxic events are attributed to anthropogenic inputs in many coastal regions (Jørgensen 1980, Rosenberg 1985, Andersen and Rydberg 1988). Years with higher freshwater inflows support elevated respiration as a result of nutrient loading, phytoplankton assimilation, and subsequent organic matter remineralization, which can lead to rapid depletion of dissolved oxygen (Boynton et al. 1982). The present study provides evidence that, as relatively undeveloped watershed become urbanized; NEM becomes more heterotrophic as a consequence of increased freshwater inflow. Increased constituent loading of either nutrients or organic matter, would, undoubtedly modify this response. Future research efforts should explore the relationships between climate change, watershed development, and constituent loading to Texas estuaries.

The degree of change in freshwater inflow from both climate change and watershed development combined to determine the magnitude of heterotrophy in Copano Bay (Table 2). Copano Bay exhibited more heterotrophic conditions (mean = -3.82 mg O_2 l^{-1} d^{-1}), with the combination of relatively modest urbanization of the Aransas River watershed and predicted precipitation increases due to climate change, than from each individually. This estimate of heterotrophy, especially when the standard error of 1.46 mg O_2 l^{-1} d^{-1}, could push Copano Bay dissolved oxygen consumption past the assimilation capacity afforded by diffusion (Russell 2005). This large standard error means that NEM values as heterotrophic as -6 mg O_2 l^{-1} d^{-1} are within the 95% prediction confidence interval. On calm days with average wind speeds less than 2 m s^{-1} daily diffusion from the atmosphere in Texas bays reach a maximum rate of approximately 5 mg O_2 l^{-1} d^{-1}. Thus, an NEM value of -6 mg O_2 l^{-1} d^{-1} would result in a decrease of dissolved oxygen concentrations of around 1 mg O_2 l^{-1} which could quickly lead to dystrophic conditions and hypoxia in the warm, salty Texas bays where dissolved oxygen concentrations at 100%

saturation can already be as low as 6 mg O_2 l^{-1}. It is fortunate that this combination of conditions (i.e. high freshwater inflow and calm winds) is currently rare in Texas.

Conclusions

The model predicts non-significant changes to NEM in Copano and Lavaca Bays over the next one hundred years of climate change and watershed development. However, if variability in model estimates is accounted for, Copano Bay may become so heterotrophic after increased precipitation events that it might suffer from increased occurrences of hypoxia. Increased urbanization, above the 200% increase modeled in this study, could also push NEM in Copano and Lavaca Bay to significantly more heterotrophic values after precipitation events. It is difficult to model NEM during intervals between precipitation events because of the large variability at low freshwater inflows (Fig. 10). Also, assessment of significant changes in NEM on the time scales of climate change and watershed development is hampered by the large variability in daily freshwater inflows. Daily freshwater inflow into Copano Bay, for example, changed as much as 30 million m^3 in 2004, which is much greater than the predicted 1-2 million m^3 d^{-1} increase in inflow due to climate change and watershed development. With uncertainties that exist during attempts to model physical and biological parameters on watershed level scales, it is important to view the simulated NEM results as possible trends arising from possible future conditions. The simulated results suggest a trend towards more heterotrophic conditions in Copano and Lavaca Bay metabolic rates with predicted climate change and watershed development.

Recommendations for Future Research

NEM model results were significantly related to observed NEM values in Copano Bay but the non-linear relationship had a lot of scatter. The large amount of dispersion in observed NEM values, especially during low freshwater inflow conditions, may be due to factors not included in the model. One factor that may influence NEM during low freshwater inflow periods is turbidity. The balance between primary production and respiration could be influences by reduced light availability due to high turbidity in Copano Bay. High turbidity conditions exist for the majority of the year in Texas bays (NOAA 1997). Higher turbidities and subsequent lower available photosynthetically active radiation (PAR) with depth usually exist in water close to river discharge as compared to water closer to an estuary mouth (Kennish 1986). Secchi depths in Copano Bay ranged between 0.5 m during winter to 0.2 m during summer (personal observation). Surface irradiance, and thus PAR, also varied with season, and on shorter time scales associated with clouds (Russell 2005). Surface irradiance levels dropped markedly during the April and May storm events (Russell 2005), but little effect was observed on NEM. Turbidity and in-situ irradiance measurements need to be compared to simultaneously calculated NEM values before these relationships can be added to the model.

Another factor that may influence NEM could be the balance between nutrients and organic matter in freshwater inflow. A determining factor of the balance between autotrophy and heterotrophy is the balance between organic carbon and nutrient loading (Kemp et al. 1997, Eyre and McKee 2002). Nutrient and organic matter loads in the micro-tidal estuaries of Texas are mainly delivered through freshwater inflow (Whitledge 1989a, 1989b, Longley 1994). The pulsing nature of freshwater inflow sporadically delivers nutrients and organic matter at high magnitudes but for short durations. As freshwater inflow increases, the ratio of nutrients to organic matter within the inflow will also change, decreasing as more terrestrial organic particulates are eroded from the watershed (Jones et al. 1986, Parker et al. 1989). The NEM model predicts an increasing NEM with small increases from base freshwater inflow conditions. The model then predicts more heterotrophic conditions with increasing flow. It is possible that a shift from high to low nutrient to organic matter ratios occurs as freshwater inflow increases from base flow levels. Quantification of nutrient and organic matter loading during a range of freshwater inflow conditions would be an important addition to the NEM model.

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Table 1 Copano Bay (CB) and Lavaca Bay (LB) average daily water temperatures (Temp) (^{o}C), and salinity (ppt) during deployments, and United States Geological Survey average gauged daily freshwater inflow (FW) (10^5 m^3) during 2004.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
CB Temp	16	17	20	21	24	29	30	29	28	28	22	18	24
LB Temp	13			21			30			27			23
CB Salinity	9	11	12	4	1	1	1	2	6	7	7	7	6
LB Salinity	22			8			0			8			10
CB FW	3	3	2	13	16	1	4	3	4	2	7	2	5
LB FW	12	15	15	26	71	86	21	3	2	8	106	5	31

Table 2 Present day and predicted daily precipitation (Precip), total precipitation depths, and freshwater inflows during events due to potential scenarios of climate change, urbanization, and their combination in the upper Aransas River watershed.

Scenario	Precip (cm d^{-1})	Precip Depth (cm d^{-1})	Freshwater Inflow (m^3 d^{-1})	Cumulative Event Inflow (m^3)	NEM ± SE (mg O_2 l^{-1} d^{-1})
Present Climate	1.63	91	1378730	4136190	-2.11 ± 1.46
Predicted Climate	2.46	137	2638421	7915263	-3.43 ± 1.46
Present Urbanization	1.63	91	1378730	4136190	-2.11 ± 1.46
100% Increase in Urbanization	1.63	91	1406269	4218807	-2.14 ± 1.46
200% Increase in Urbanization	1.63	91	1642889	4928667	-2.44 ± 1.46
200% Increase in Urbanization and Predicted Climate	2.46	137	3143932	9431796	-3.82 ± 1.46

Table 3 Present day and predicted environmental conditions due to climate change and watershed development. NEM is a function of cumulative ten-day freshwater inflow (FW), salinity (S), and temperature (T).

$$\text{NEM (mg } O_2 \text{ l}^{-1} \text{ d}^{-1}) = -1.82 + 2.62\times10^{-8}\ FW - 0.07\ T + 0.21\ S$$

Scenario	Cumulative Event Inflow (m^3)	Salinity (ppt)	Temperature (^oC)	NEM ± SE (mg O_2 l^{-1} d^{-1})
Present Day	10×10^6	15	25	-0.16 ± 1.64
Predicted Climate and 200% Urbanization	40×10^6	1	30	-2.66 ± 1.64

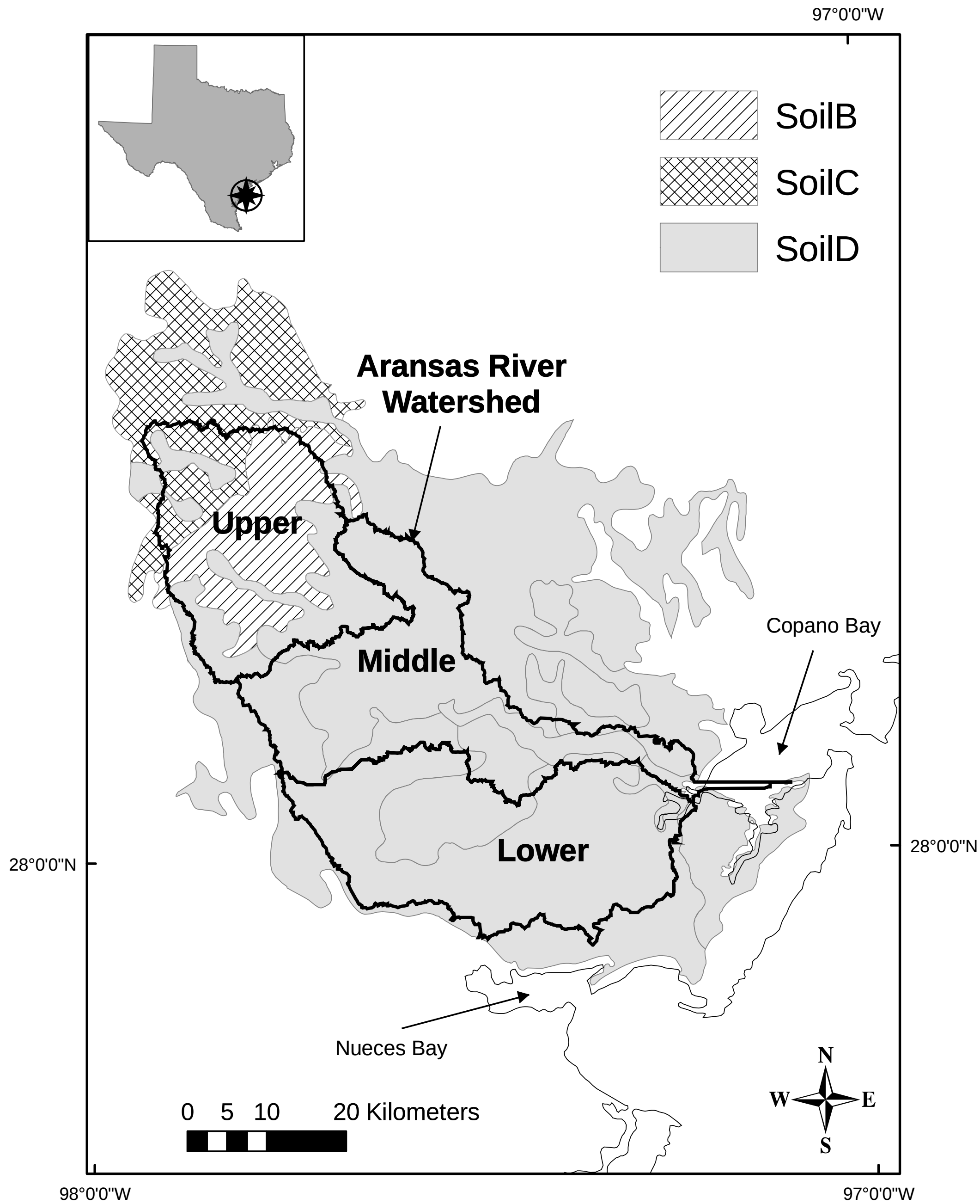

Figure 1 Soil groups in the three regions of the Aransas River watershed draining into Copano Bay. The Aransas River watershed soils are grouped into three types: soil type B (silt loam or loam), soil type C (sandy clay loam) and soil type D (clay loam, silty clay loam, sandy clay, silty clay or clay).

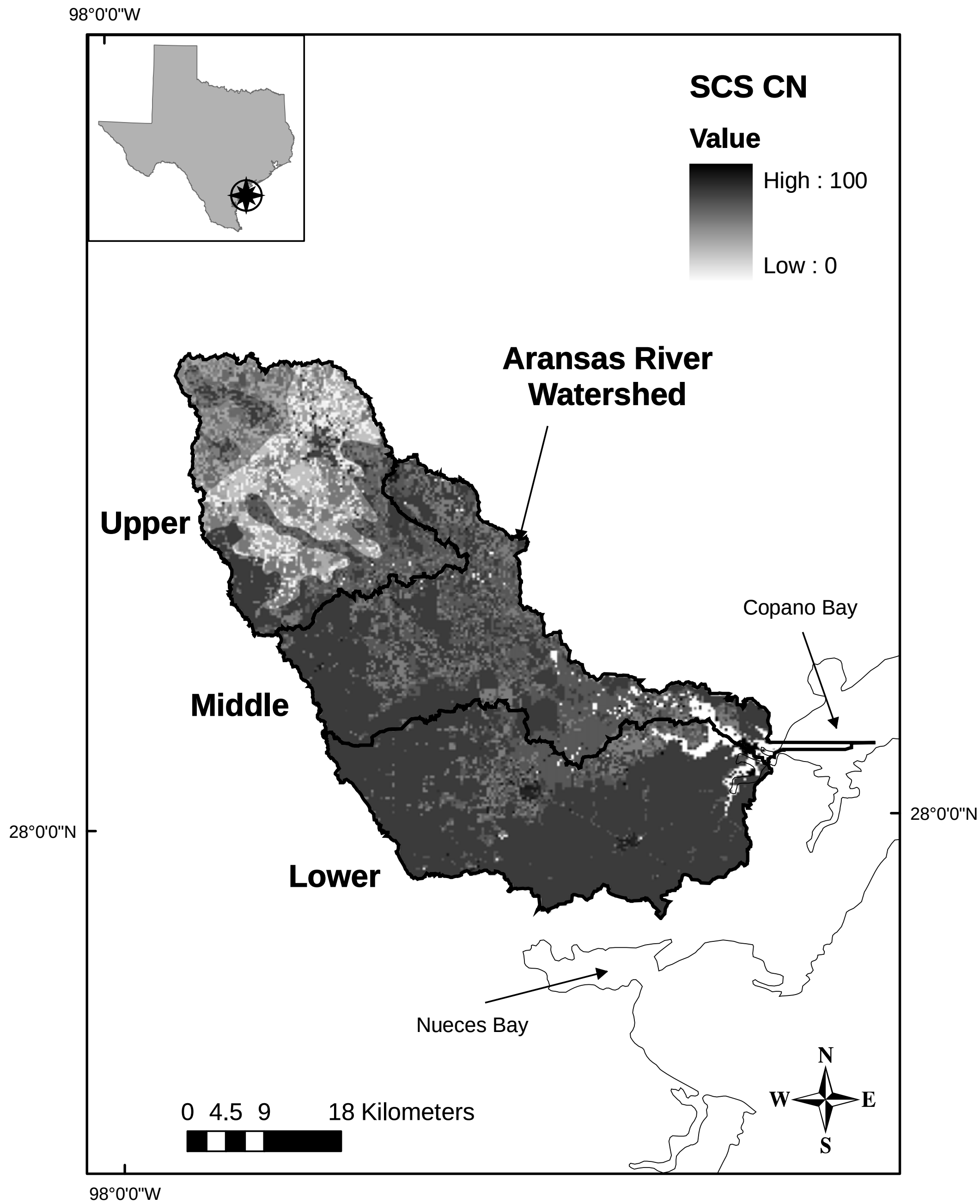

Figure 2 Curve numbers by soil type in the Aransas River watershed. Urbanized and cropland yield the highest CN numbers. Areas with high CN numbers have less precipitation infiltration capacity.

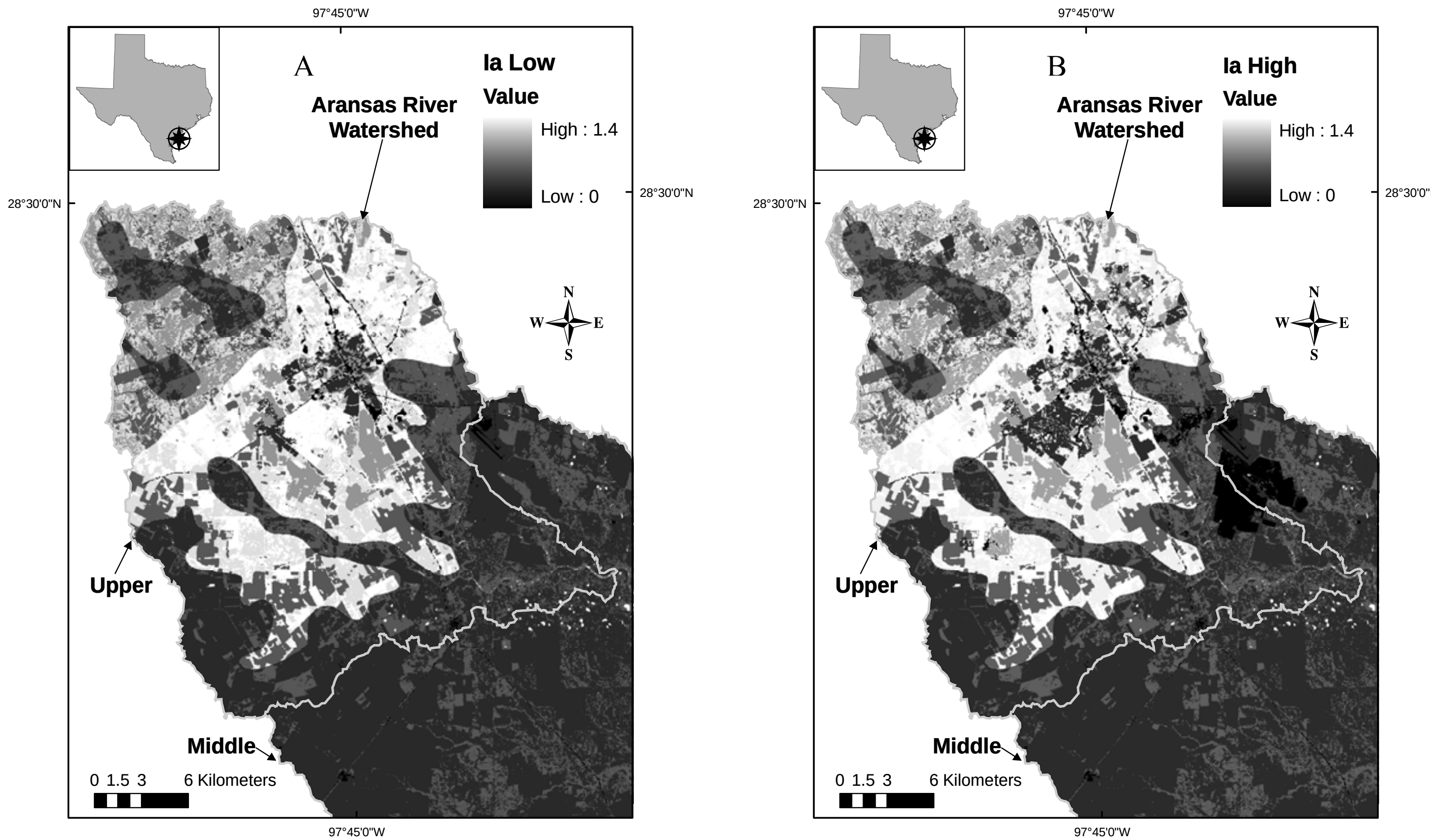

Figure 3 Estimated land use / land cover due to two different percent increases in upper Aransas River watershed urbanized areas with initial abstraction values used in watershed development scenarios. A) 100%. B) 200%.

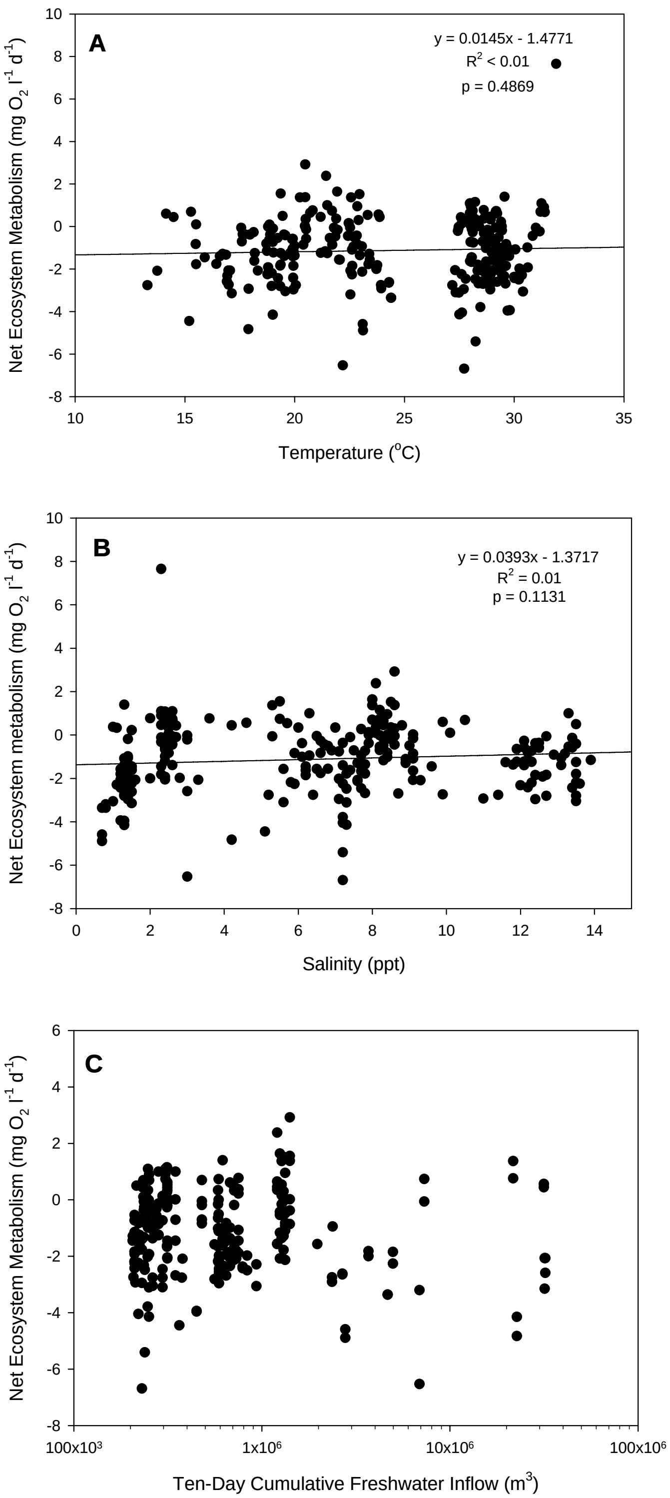

Figure 4 The response of net ecosystem metabolism to changing environmental conditions in Copano Bay. A) Temperature. B) Salinity. C) Freshwater inflow.

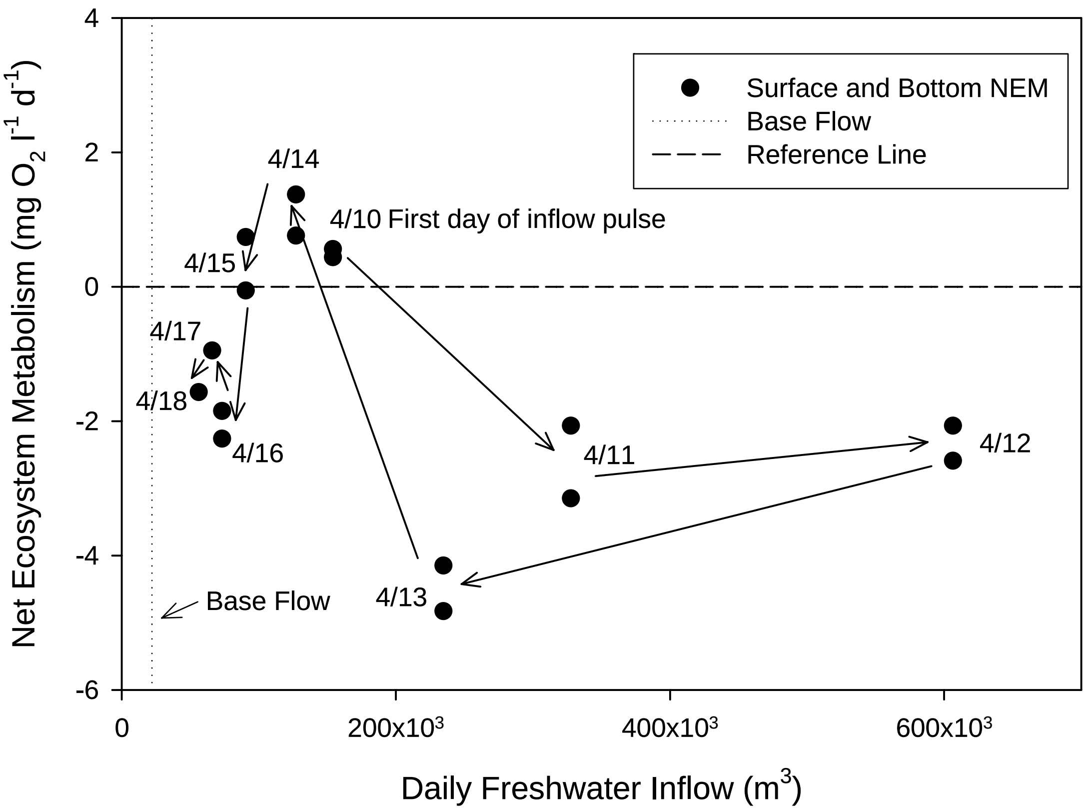

Figure 5 The temporal response of net ecosystem metabolism to rapidly changing daily freshwater inflow. Net ecosystem metabolism is autotrophic during the first day of increased inflow, is net heterotrophic over the following three days, and then becomes autotrophic again for a couple of days before returning to more typical heterotrophic values during base flow conditions (Aransas River 2002-2005 USGS median gauged freshwater inflow $= 22\times10^3$ m^3 d^{-1}).

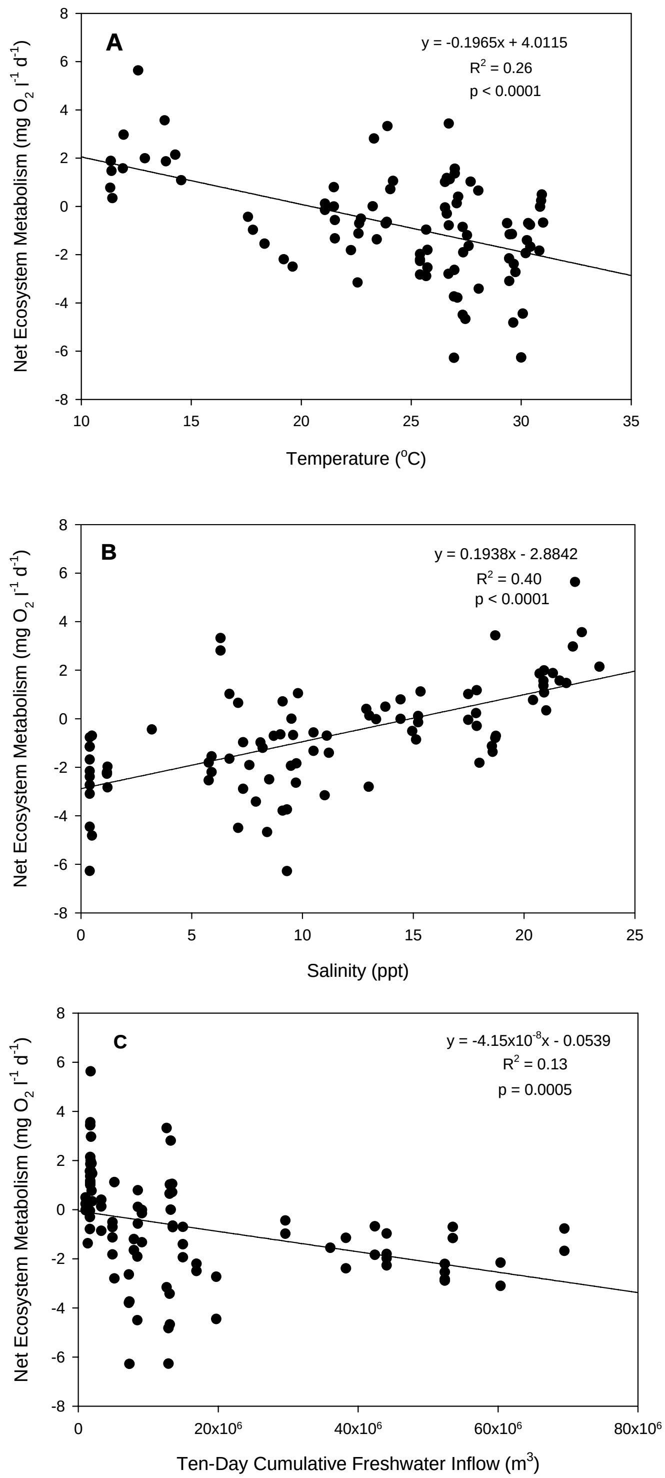

Figure 6 The response of net ecosystem metabolism to changing environmental conditions in Lavaca Bay. A) Temperature. B) Salinity. C) Freshwater inflow.

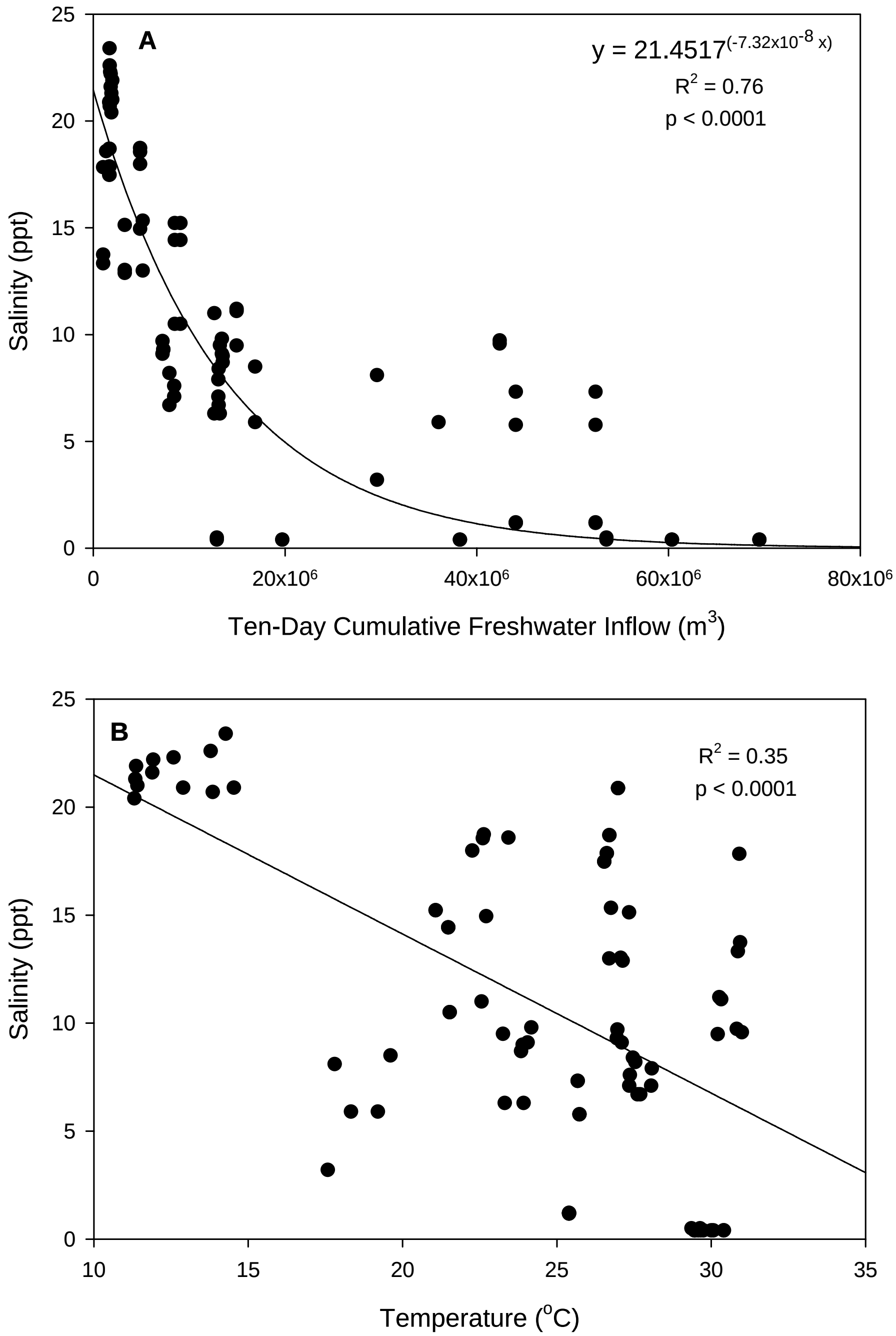

Figure 7 Relationships between A) freshwater inflow and salinity, and B) temperature and salinity in Lavaca Bay

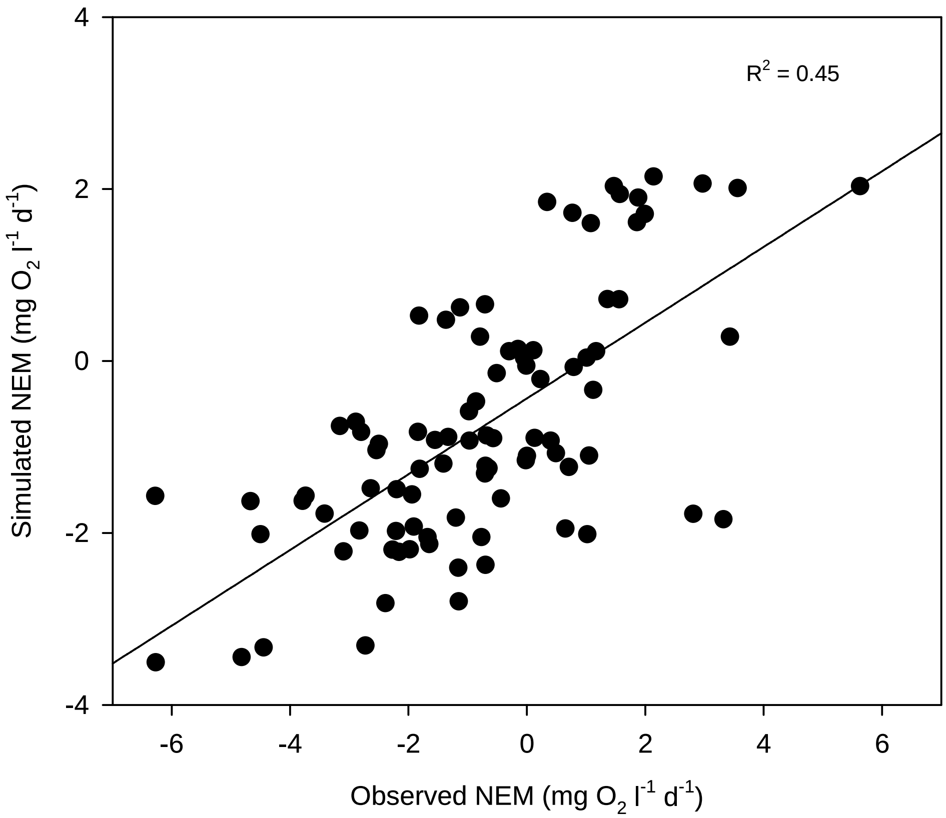

Figure 8 Lavaca Bay NEM model. Simulated NEM values match fairly well with those observed during 2002-2004.

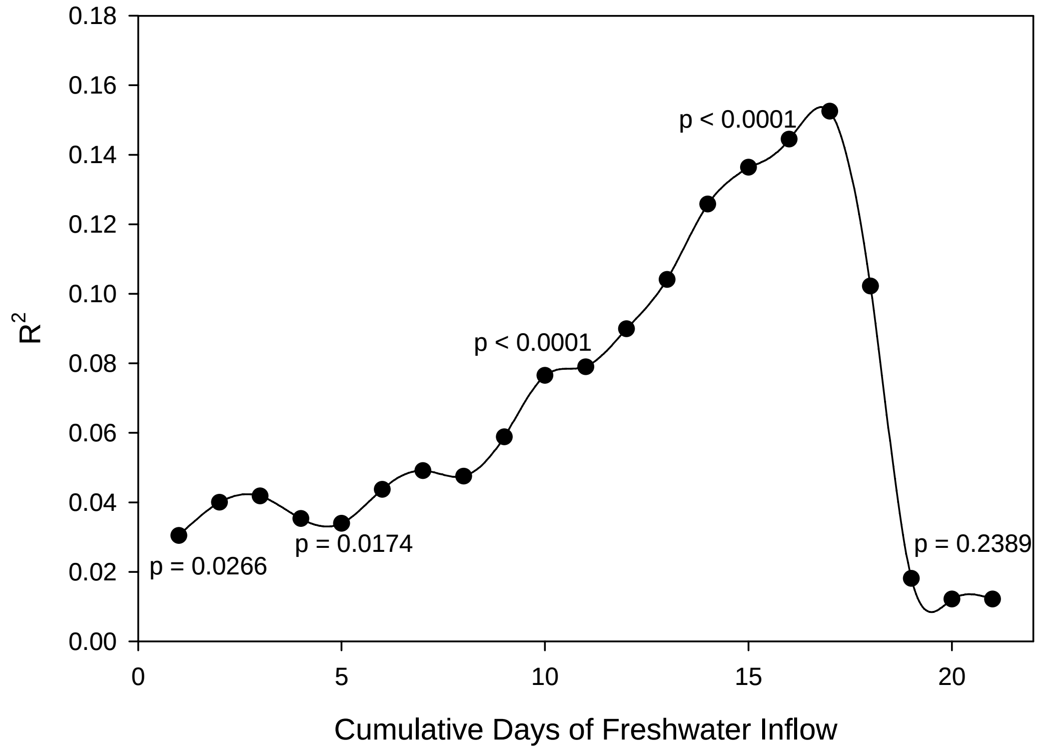

Figure 9 The fit of the model to observed NEM results in Copano Bay was assessed at one to twenty-one days of cumulative freshwater inflow. The best fit was obtained when the model was fit to NEM results at 17-day cumulative flow.

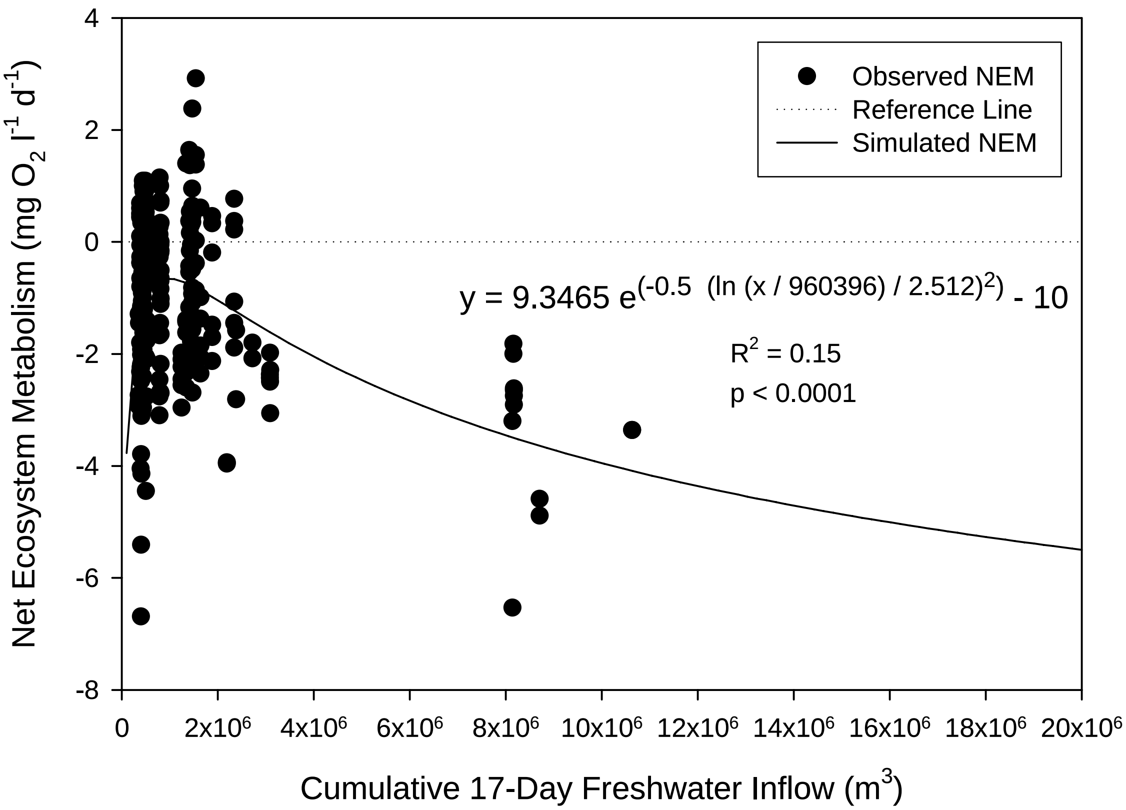

Figure 10 The relationship between observed and model predicted net ecosystem metabolism in Copano Bay, 2004. The non-linear net ecosystem metabolism model curve increases, peaks, and then steadily decreases as 17-day cumulative freshwater inflows increase.

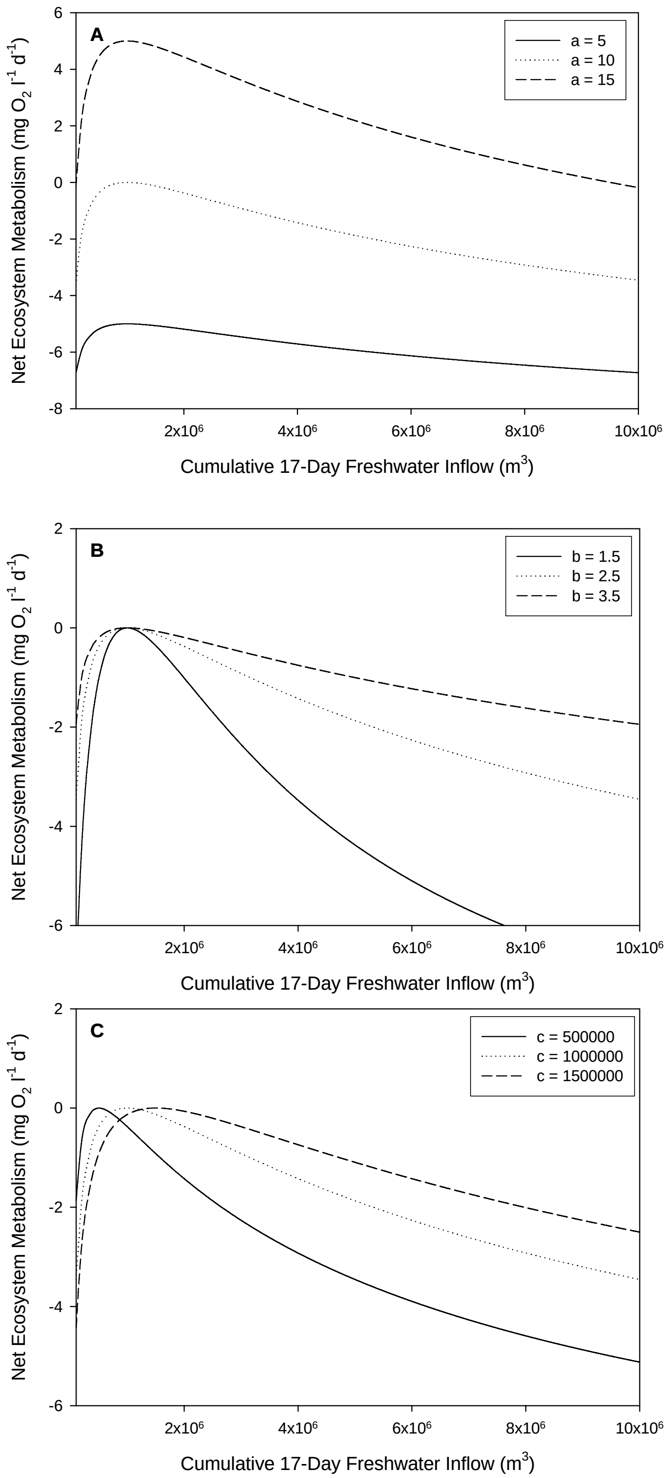

Figure 11 Sensitivity analysis of the three parameters in the net ecosystem metabolism model over a range of 17-day cumulative freshwater inflows. A) Parameter a. B) Parameter b. C) Parameter c.

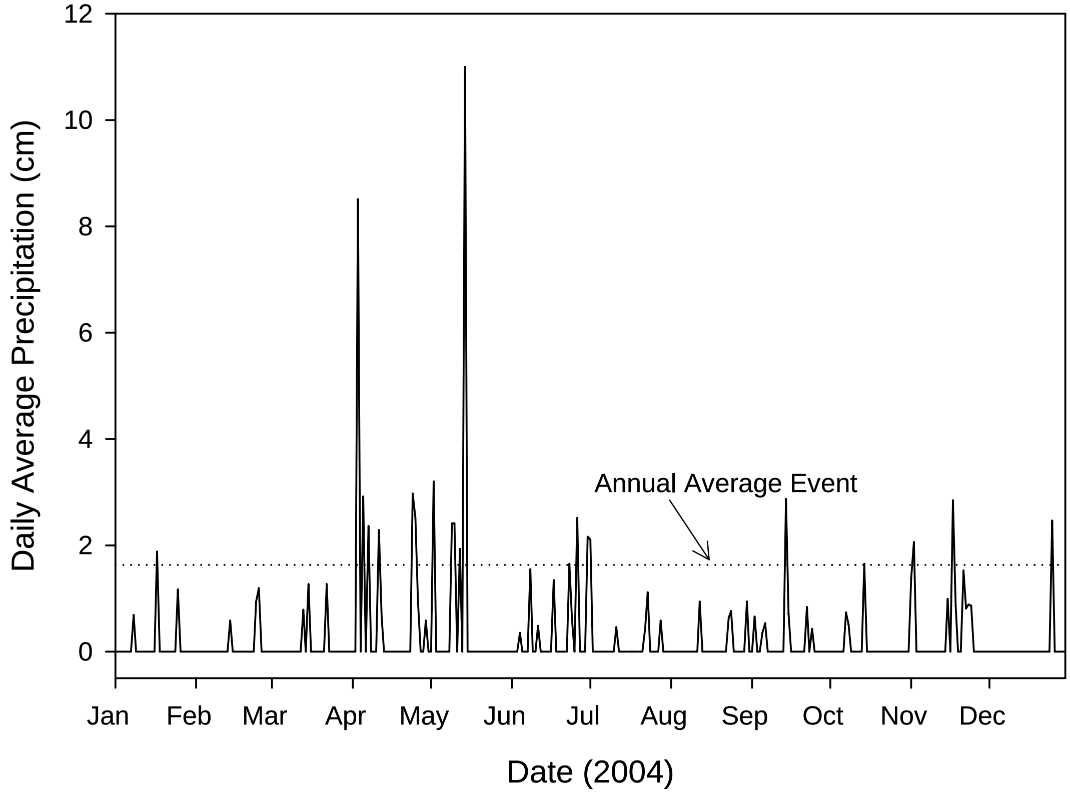

Figure 12 Daily average upper Aransas River watershed precipitation calculated from Nexrad data. Annual average precipitation (1.63 cm d^{-1}) during events denoted by dotted line.

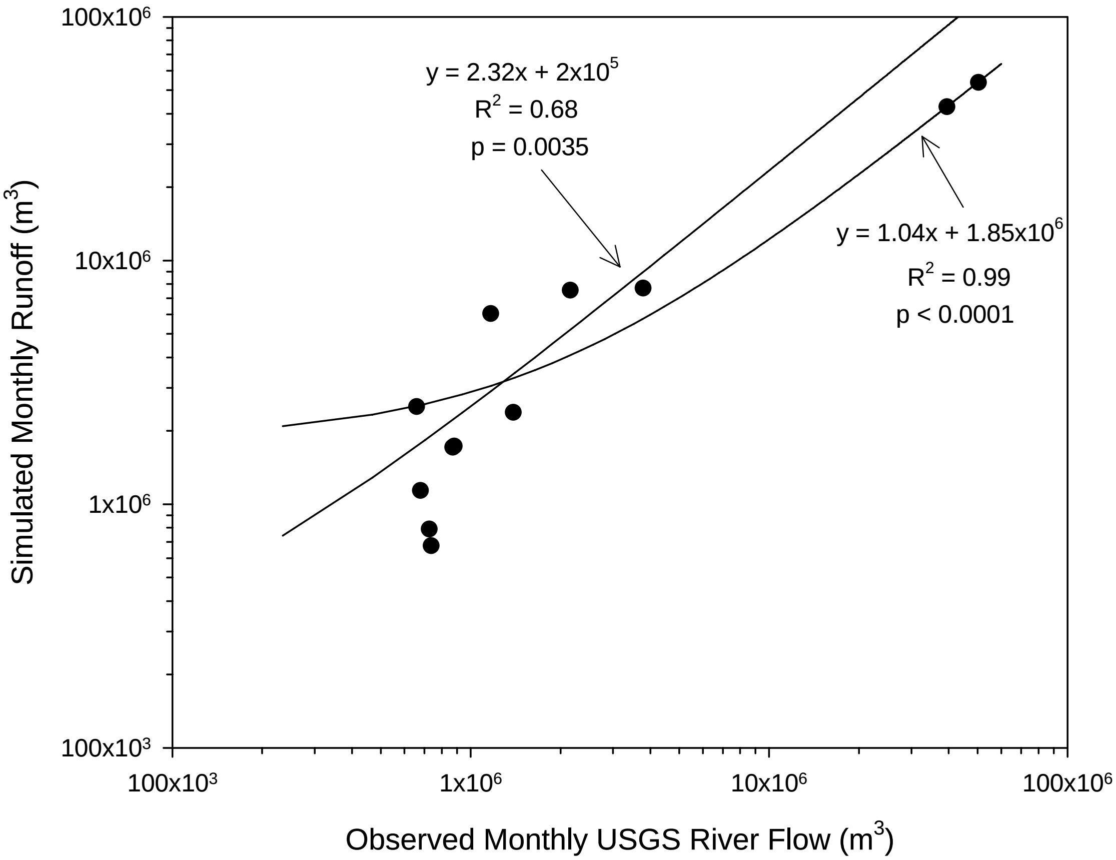

Figure 13 A comparison of simulated monthly runoff from the upper Aransas River watershed and observed monthly Aransas River flow. The best fit line is shown with ($R^2 = 0.99$) and with out ($R^2 = 0.68$) inclusion of the two extreme flow events. More scatter is present at lower flows, possibly due to the effects of differences in evaporation rates of runoff.

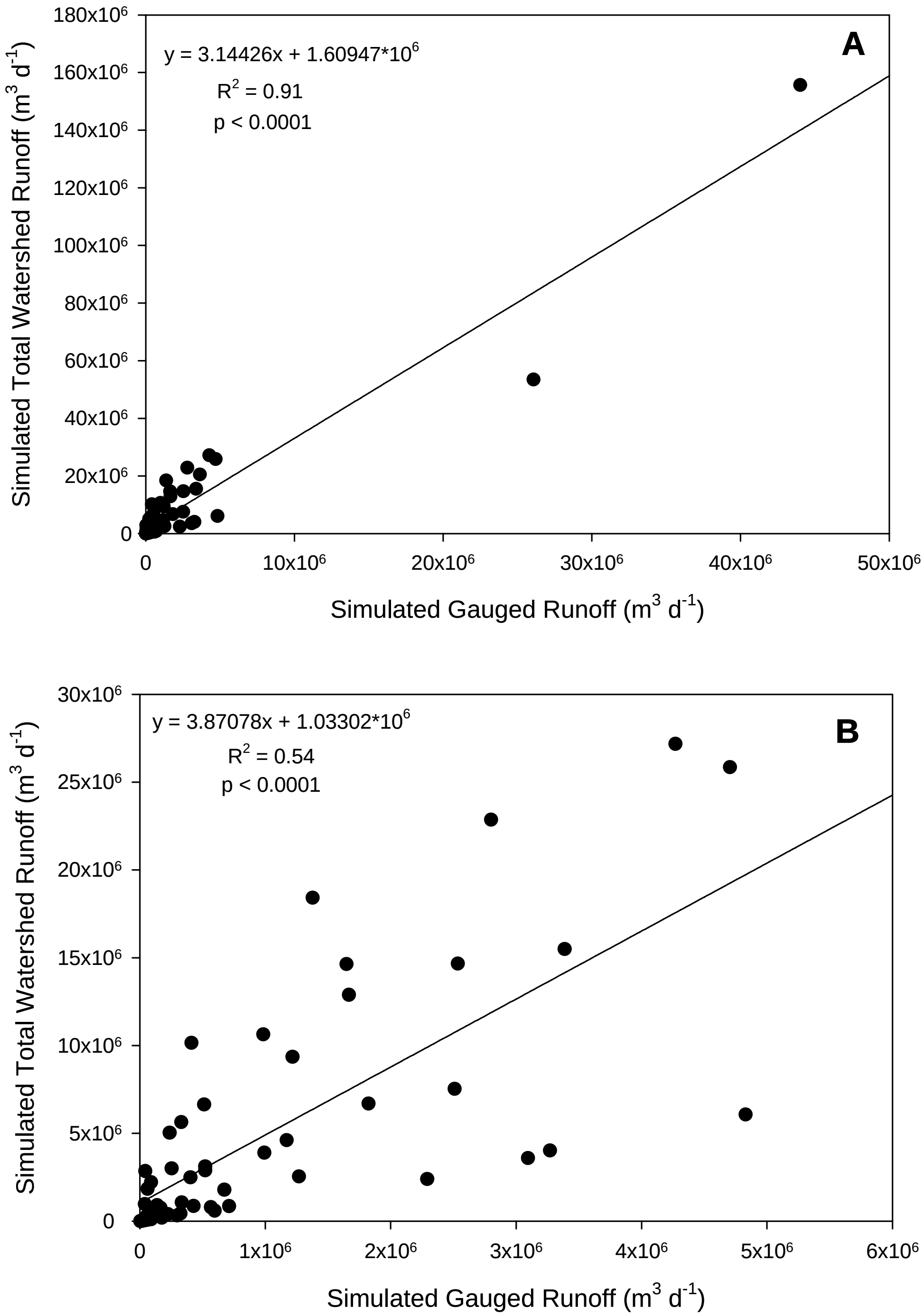

Figure 14 Comparison of simulated runoff in the upper sub-basin and simulated runoff from the entire Aransas River watershed. A) Full data-set. B) Without outliers.

Spatial Patterns in Wetland Nutrient Biogeochemistry: Implications for Ecosystem Functions

Basic Information

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4. Scott JT and Doyle RD. N2 fixation and the natural abundance of N isotopes in a wetland periphyton community. Society of Wetland Scientists International Cogress, July 2006, Cairns, Queensland, Australia.

Spatial Patterns in Wetland Nutrient Biogeochemistry: Implications for Ecosystem Functions

Thad Scott

Abstract

The role of nitrogen (N_2) -fixation in balancing N supply to a wetland periphyton mat was assessed by comparing measurements of primary production with elemental, isotopic, and enzymatic correlates. Measurements of primary production, N_2 fixation (acetylene reduction (AR)), phosphatase activity, C:N:P content of periphyton, and N isotopic composition of periphyton were made along a nutrient availability gradient in a freshwater marsh during May through September 2004. Periphyton primary production was correlated with inorganic N availability in the spring, but became more closely correlated (inversely) with phosphatase acitivity during the remainder of the summer. Nitrogen fixation and phosphatase activity in periphyton were negatively correlated with inorganic N and P availability, respectively. Elemental imbalance appeared to shift from N imbalance (C:N > 15 by mass) in spring to P imbalance in the summer (C:P ≥ 150 by mass). The percent contribution of N_2 fixation to total N uptake, determined from AR measurements and estimates of gross N assimilation, was highest in the spring (0 – 50 % in May 2004) and decreased throughout the summer (0 – 25% in July 2004 and 0 – 10 % in September 2004). However, N isotopic data suggested the sustained importance of an atmospheric N_2 source throughout the summer. This discrepancy is likely explained by the seasonal accumulation and retention of sequestered N supplies. When periphyton primary production was normalized to periphyton N content, production rates for the entire growing season were strongly inversely correlated with periphyton phosphatase activity ($r^2 = 0.78$). Results of the study suggest that N_2 fixation may adequately supplement community N supplies in wetland periphyton mats over short-time scales (weeks), thereby causing limitation by other elemental resources such as P.

Introduction

Primary production in freshwater aquatic ecosystems will proceed until limited by resource availability. In general, photoautotrophs become limited by either the availability of light energy or elemental resources (*e.g.* nitrogen (N) or phosphorus (P)). When elemental resources are sufficient, photoautotrophs will grow until their own biomass decreases the amount of available light energy or until nutrients have been exhausted. Schindler (1977) suggested that N resources of lakes could only be exhausted temporarily and therefore P would limit primary production in these systems over extended time scales. This hypothesis was based on the ability of planktonic heterocystous cyanobacteria to fix atmospheric N (N_2) at a rate sufficient to supplement the N supply to an ecosystem. Cyanobacterial N_2 fixation rates, and conditions controlling the establishment of cyanobacteria and initiation of N_2 fixation, have since been widely described for a variety of aquatic habitats (see reviews by Howarth et al. 1988a and 1988b) with the greatest attention given to planktonic systems (Vitousek 2002). Although Schindler's hypothesis (1977) did not hold true for estuarine and marine systems (due to trace element limitation of the nitrogenase enzyme; see Howarth et al. 1988b for details), "evolving" P-limitation in phytoplankton has often since been assumed for freshwater systems. However, the rate at which

N_2 fixation can supplement ecosystem N supply has not been rigorously tested, even for planktonic systems.

Howarth et al. (1999) derived a mechanistically-based simulation model to test the interacting effects of molybdenum-limitation and zooplankton grazing on cyanobacterial exclusion from estuarine phytoplankton. Although the model could accurately predict the timing and magnitude of N_2 fixing cyanobacterial blooms in lakes, the model did not include a mass balance term that would suppress N_2 fixation in response to N accumulation. In that and subsequent papers, the authors suggested the need to refine the model to include the inherent feedback of N accumulation in the N_2-fixing community (Howarth 1999, Vitousek et al. 2002). Although many studies have identified dissolved inorganic N (DIN) concentrations at which cyanobacterial N_2 fixation diminishes (see Horne et al. 1979, Doyle and Fisher 1994, and Scott et al. 2005), few studies, if any, have characterized how feedback conditions such as N accumulation might suppress N_2 fixation or even stimulate P-limitation of primary production.

In wetland and shallow lake environments (lentic ecosystems), periphyton communities can dominate microbial primary production. In particular, floating periphyton mats or "metaphyton" (Stevenson 1996), which form by fragmentation of epipelic, epilithic, or epiphytic communities, can be highly productive and radically alter ecosystem nutrient cycling (Wetzel 1996). These communities often efficiently retain and recycle sequestered nutrient stocks. However, nutrient-limitation of periphyton primary production has been widely demonstrated in enrichment experiments utilizing both whole-system (McDougal et al. 1997, Havens et al. 1999, McCormick et al. 2001) and diffusion substrate approaches (Fairchild et al. 1985, Scott et al. 2005). Many of these studies demonstrated periods of N and/or P-limitation, and/or periods of N+P co-limitation. Co-limitation describes a scenario whereby only combined enrichments of N and P (and possibly other micronutrients as well) resulted in growth stimulation. When N or both N and P are in low supply and cyanobacteria are present, N_2 fixation should commence when the energetic costs of N-limitation (*i.e.* unrealized primary production) exceed the energetic cost of N_2 fixation. When N stocks have been replenished, N_2 fixation will cease as its energetic cost begins to exceed the potential production achievable solely with DIN (Tyrell 1999).

To our knowledge, no studies have assessed the impact of N accumulation derived from N_2 fixation in lentic periphyton communities. In fact, few studies on periphyton nutrient limitation have included N_2 fixation measurements at all. Scott et al. (2005) found that periphyton were increasingly N-limited and exhibited increasing N_2 fixation potential along the longitudinal axis of a created wetland. However, that study did not attempt to quantify N accumulation within the periphyton community. In a Florida Everglades periphyton community, Inglett et al. (2004) found that N accumulated with increasing N_2 fixation throughout the summers of 1998 and 1999 and that periphyton N content was always greatest in September when N_2 fixation rates began to decline. Although these results suggest that N_2 fixation may have been sufficient to balance periphyton N content within one summer season, this study did not assess the limitations to periphyton primary production over any time scale.

Interestingly, N_2-fixing periphyton communities are conspicuous in tropical and sub-tropical marshes, such as the Florida Everglades, which are generally considered strongly P-limited. For instance, Rejmánková et al. (2000) found that P enrichment increased periphyton primary production but that N enrichment did not change periphyton primary production in three marshes of northern Belize. In two of the three marshes where P enrichment increased primary production, a simultaneous increase in N_2 fixation rates and decrease alkaline phosphatase activity (APA) were observed. This suggests that P availability may have limited primary production but that P enrichment may have resulted in an N deficiency. Additionally, periphyton N content was generally higher in the third marsh where N_2 fixation and APA did not change when enriched with P, than it was in the two marshes where N_2 fixation and APA responded to P enrichment. This further suggests that N rich periphyton did not waste energy on N_2 fixation to bring N supply into balance, which is in general agreement with trends observed in phytoplankton (Tyrell 1999). Considered collectively, the results of Rejmánková et al. (2000) suggest that cyanobacterial N_2 fixation could have been sufficient to maintain N balance during the 10 day experimental period but the process was only initiated under relatively low periphyton N content.

If we are to understand the role of nutrient limitations to primary production in any ecosystem, it is imperative that we have a complete understanding of the role of biological N_2 fixation in ecosystem production (Vitousek 2002). Aquatic ecosystems, and periphytic communities in particular, provide a unique opportunity to study the role of N_2 fixation in alleviating N-limitations to community production. In this study, we attempted to quantify the seasonal role of periphytic N_2 fixation in balancing community N stocks and inducing P-limitation to primary production. Specifically, the objectives of the study were to: 1) quantify periphyton primary production along a nutrient availability gradient, 2) quantify rates of biological N_2 fixation relative to periphyton primary production and nitrogen content, 3) quantify periphyton phosphatase activity relative to primary production, and 4) describe both short-term (instantaneous) and long-term (seasonal) limitations to periphyton primary production.

Materials and methods

Site Description

The study was conducted at the Lake Waco Wetland (LWW) complex, near Waco, Texas, USA (Figure 1). The complex is an 80-ha off-channel constructed marsh that receives water pumped from the North Bosque River. Water meanders through five wetland cells before flowing back into the North Bosque River. The average depth of the wetland is approximately 0.5 meters and the hydraulic residence time ranges between 10 to 30 days. During the course of

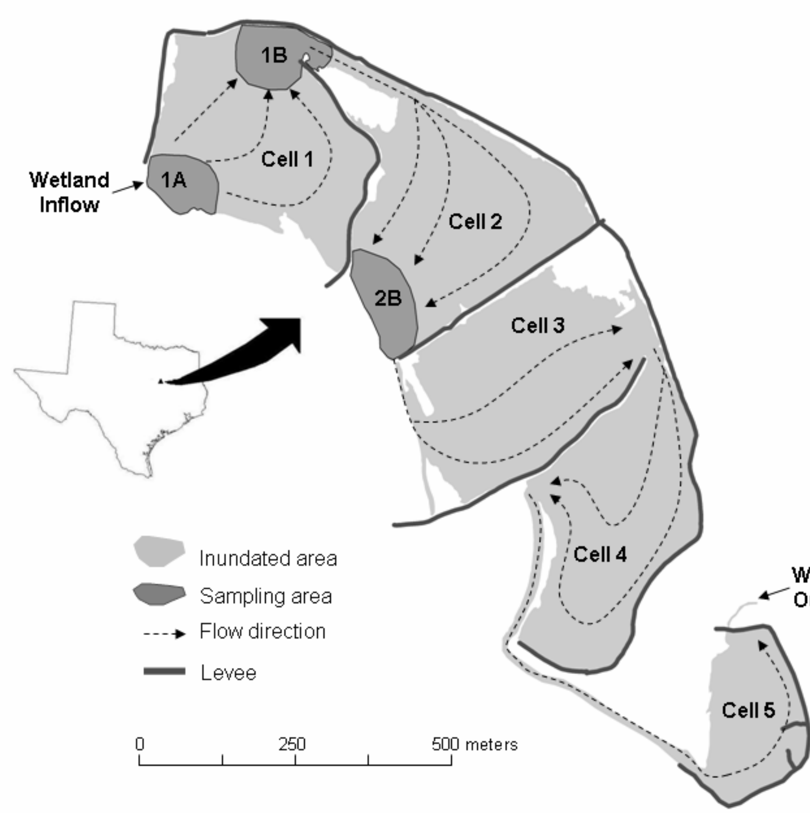

Figure 1. Lake Waco wetland, near Waco, Texas, USA. Periphyton samples were collected in May, July, and September 2004 from random locations with areas 1A, 1B, and 2B. Water chemistry was measured biweekly from May – September 2004 in each sampling area.

this study, the mean pumped inflow rate was 6.0 million gallons per day (range = 0 to 11 MGD) and the average hydraulic residence was 17.5 days.

A floating periphyton community generally occurs in the relatively deep (≥ 1m), open-water areas of this wetland. This community is comprised of green algae (*Hydrodiction* sp., or *Cladophora* sp.) and a consortium of attached microbiota including diatoms, cyanobacteria, and heterotrophic bacteria (Scott, unpubl.). Scott et al. (2005) demonstrated that the periphyton community in the downstream areas of the LWW was strongly N-limited and exhibited high N_2 fixation potential. Furthermore, periphytic N_2 fixation was light-dependent and generally carried out by heterocystous cyanobacteria or diatoms with cyanobacterial endosymbionts such as *Epithemia adnata* and *Rhopalodia gibba*. Near the inflow however, periphyton were either co-limited by N and P or not limited by nutrients at all. N_2 fixation potential in the periphyton community near the inflow was always zero. Given these trends, the LWW provides a well documented gradient where available inorganic nutrients decrease in the downstream direction. Therefore, the LWW exhibits ideal conditions to test hypotheses regarding evolving P-limitation and the role of N_2 fixation in balancing periphyton N content.

Periphyton mat samples were randomly collected from areas 1A, 1B, and 2B of the LWW (Figure 1) in May, July, and September 2004. These sampling areas were positioned along the gradient of nutrient availability which corresponds to the flow path of water (Figure 1; see Scott et al. 2005). Approximately 400 cm^2 of periphyton mat were harvested, placed into a plastic container with site water, and transported to the laboratory. Eight replicate samples were collected from each area on all dates. In the laboratory, periphyton mat samples were subsampled for measurements of primary production, N_2 fixation via acetylene reduction, phosphatase activity, C, N, and P content, and $\delta^{15}N$ composition. In addition to periphyton samples, four liters of water were collected on each sampling date to use as incubation water in laboratory bioassays for primary production and N_2 fixation. Water samples were also collected in each sampling area on a biweekly basis during the course of the study for water chemistry analysis.

Primary Production

Periphyton primary production was determined by measuring the rate of O_2 production in high-light, low-light, and dark incubations (Wetzel and Likens 2000). Three small subsamples (≤ 1 cm^2) were cut away from each periphyton sample. Two portions were transferred into transparent BOD bottles with 300 ml site water and the third portion was transferred into an opaque BOD bottle with 300 ml site water. The concentration of dissolved O_2 was determined to a precision of 0.1 ppm before incubation with a YSI 5000 dissolved O_2 meter. Prior to addition to BOD bottles, dissolved O_2 concentration of incubation water was reduced to ~ 3.0 ppm by bubbling with N_2 gas amended with 350 ppm CO_2. All BOD bottles were placed in a water bath incubation set to *in-situ* temperature conditions. One transparent bottle was incubated under high-light intensity (~ 390 - 460 µmol m^{-2} s^{-1}) and the other under low light intensity (~ 45 - 55 µmol m^{-2} s^{-1}). Samples were incubated until dissolved O_2 concentrations increased by ~ 1 to 1.5 ppm in low light incubations (~ 1-4 hours). Final dissolved O_2 concentration, incubation time, and photon flux density were recorded at the end of incubation. The photon flux density encountered by each incubation bottle was determined by measuring irradiance at the location of each bottle in the water bath with a LI-COR LI-250 light meter equipped with a spherical sensor. In addition to periphyton samples, samples containing only site water from each sampling location were incubated in duplicate at each light level to account to photosynthesis and respiration by plankton.

Following incubation, the samples were filtered onto a pre-washed, -dried, and –weighed glass fiber filter then oven-dried at 60 °C overnight. The dry weight of sample was calculated as the final weight of the sample and filter minus the original filter weight. Gross photosynthesis for samples at each light level was calculated as:

$$GP = \frac{[(O_{2e} - O_{2r}) \times 0.375 \times 0.3]}{(PQ) \times (t) \times (DW)}$$

where *GP* is the rate of gross photosynthesis (mg C g DW^{-1} h^{-1}), O_{2e} is the change in dissolved O_2 concentration (mg O_2 L^{-1}) in the transparent bottle over time *t*, O_{2r} is the change in dissolved O_2 concentration (mg O_2 L^{-1}) in the opaque bottle over time *t*, *PQ* is the photosynthetic quotient (dimensionless constant = 1.2; see Wetzel and Likens 2000), and *DW* is the dry weight of the sample in grams. The constant 0.375 represents the ratio of carbon fixed to oxygen generated during photosynthesis, and the constant 0.3 was the incubation volume in liters. Low-light photosynthetic rates were standardized to the average low-light condition by dividing the photosynthetic rate by the measured incubation light intensity and multiplying by the average low-light incubation condition (40 µmol m^{-2} s^{-1}). Standardized low-light gross photosynthesis was multiplied by 8 hours, light-saturated (determined from high-light incubations) gross photosynthesis was multiplied by 4 hours, and these rates were summed to derive an estimate of daily periphyton primary production expressed as mg C g DW^{-1} day^{-1}.

N_2 fixation

Acetylene reduction was used to estimate the rate of N_2 fixation in periphyton samples. In this assay, acetylene is reduced to ethylene by the nitrogenase enzyme at a rate proportional to the reduction of N_2 to NH_4^+ (Flett et al. 1976). The measurement is indicative of N_2 fixation in a sample at a given point in time (*i.e.* instantaneous N_2 fixation). In the laboratory, three small subsamples (≤ 1 cm^2) were cut away from each periphyton sample and placed into Popper Micromate syringes with 30 ml site water. One syringe was wrapped in foil for dark incubation while the other two were used for high-light and low-light incubations. Five milliliters of acetylene gas were injected into each syringe which was then gently mixed to allow rapid dissolution of acetylene. Syringes were incubated as described above for primary production. At the end of incubation, 15 ml of air were drawn into each syringe which was then vigorously agitated to establish equilibrium conditions of gases between aqueous and vapor phases. Water and vapor volumes were recorded to account for partitioning between phases and ethylene concentration of the vapor was determined using a Carle AGC Series gas chromatograph (GC). The GC was equipped with a flame-ionization detector and a 1.8 m column packed with 80% Porapack N and 20% Porapack Q (80/100 mesh). The column temperature was 70 °C, helium was used as the carrier gas, and 10 ppm ethylene standards were used to calibrate the instrument daily. For each light level (dark, low-light, high-light), the hourly ethylene production rate was converted to an hourly N_2 fixation rate assuming that the production of 3 µmol ethylene was equivalent to the fixation of 1 µmol N_2 (Flett et al. 1976). Low-light N_2 fixation rates were standardized to average low-light conditions and used with light-saturated N_2 fixation rates to derive estimates of daily periphyton N_2 fixation (µg N g DW^{-1} day^{-1}) following the same method described above for primary production.

Phosphatase Activity

Phosphatase activity may be used as an indicator of P-limitation in periphyton. Organisms will increase phosphatase production in an attempt to increase P availability. In this study, phosphatase activity in periphyton was measured fluorometrically using methylumbelliferone phosphate (MUP) as a substrate. In the presence of phosphatase enzymes the phosphate group on MUP is hydrolyzed yielding methylumbelliferone (MU). MU fluoresces when irradiated at 365 nm wavelength. In samples saturated with MUP, the rate of increasing fluorescence is proportional to the rate of MU production, and subsequently, phosphatase activity (Petterson 1980). Periphyton subsamples were transferred into 15 ml culture tubes with 9 ml 1.2 % TRIS buffer (pH 8.3). One milliliter of 10^{-4} mol L^{-1} MUP was added to each tube and samples were mixed gently. Samples were incubated at room temperature under ambient indoor lighting. Fluorescence was measured after 5, 15, and 45 minutes on a Turner 10 AU fluorometer calibrated with 50, 100, 250, 500, and 1000 ppb MU standards. Dry weight of all samples was determined as previously described and phosphatase activity expressed as nmol P_{ase} g DW^{-1} min^{-1}.

Periphyton Elemental and Isotopic Composition

A subsample of each periphyton sample was oven-dried overnight at 60 °C and ground to a fine powder for determination of C, N, and P content and N isotopic composition. C and N content were determined simultaneously using a Thermo Finnigan FlashEA 1112 elemental analyzer. Phosphorus content was determined colorimetrically on a Lachat Quickchem 8500 following a 3 hour digestion in concentrated H_2SO_4 at 370 °C (Clesceri et al. 1998). Nitrogen isotopic composition was measured using a continuous flow isotope ratio mass spectrometer connected to a Carlo Erba NA1500 elemental analyzer. Measured $^{15}N/^{14}N$ ratios are expressed in delta notation (δ):

$$\delta^{15}N_{sample} = \left[\left(\frac{R_{sample}}{R_{air}}\right) - 1\right] \times 1000$$

where $\delta^{15}N_{sample}$ is the isotopic composition of the sample expressed in units of per mil (‰), R_{sample} is $^{15}N/^{14}N$ ratio measured in the sample, and R_{air} is the $^{15}N/^{14}N$ ratio of air.

Contribution of N_2 fixation to total N uptake

We estimated the contribution of N_2 fixation to total N uptake by periphyton using two separate methods: 1) acetylene reduction measurements with gross N assimilation estimates, and 2) $\delta^{15}N$ composition of periphyton. Estimates from acetylene reduction assays were derived by dividing the rate of N_2 fixation measured by acetylene reduction by the rate of gross N assimilation. Gross N assimilation was estimated by multiplying the rate of primary production of a sample by its measured ratio of N:C. The quotient of N_2 fixation, expressed as mg N g DW^{-1} h^{-1}, and gross N assimilation, also expressed as mg N g DW^{-1} h^{-1}, is the percent contribution of N_2 fixation to total N uptake.

The use of $\delta^{15}N$ as an indicator of the contribution of N_2 fixation to total N uptake is based on the general isotopic difference between atmospheric N_2 and DIN. Atmospheric N_2 has a constant N isotopic composition. When air is used as the reference standard in mass spectrometry (as is usually done for N), $\delta^{15}N$ of atmospheric N_2 is 0 ‰. The isotopic composition of DIN in freshwaters however, is usually relatively heavy ($\delta^{15}N \approx 5 - 15$ ‰; Heaton 1986). Because N isotopic composition of autotrophs will usually reflect the isotopic composition of their inorganic N source (Lajtha and Marshall 1994), it is often possible to estimate the relative contribution of DIN and atmospheric N_2 to autotrophic communities that can utilize either N source by measuring the N isotopic composition of the community itself (Gu and Alexander 1993; France et al. 1998).

For our purposes, a two-end member mixing model was developed to predict the relative contribution of N_2 fixation to total N uptake by periphyton. The model was constructed as follows:

$$\delta^{15}N_{periphyton} = \left[\left(C_{N_2}\right)\times\left(\delta^{15}N_{N_2} + f_{N_2}\right)\right] + \left[\left(C_{DIN}\right)\times\left(\delta^{15}N_{DIN} + f_{DIN}\right)\right]$$

where $\delta^{15}N_{periphyton}$ is the N isotopic composition of periphyton, C_{N_2} is the percent contribution of atmospheric N_2 to total nitrogen uptake by periphyton, $\delta^{15}N_{N_2}$ is the isotopic composition of N_2 (0 ‰), and f_{N_2} is the fractionation value associated with N_2 fixation (assumed to be -2.0 ‰ based on the value of fractionation reported for cyanobacterial cultures using N_2 as their sole source of N (Gu and Alexander 1993)), respectively. C_{DIN} is the percent contribution of DIN to total N uptake which was set equal to $1 - C_{N_2}$ in this mixing model. $\delta^{15}N_{DIN}$ is the isotopic composition of DIN in waters flowing into the LWW (assumed to be 9.7 ‰; from Dworkin 2003), and f_{DIN} is the fractionation value associated with DIN uptake. In general, fractionation with DIN uptake will occur only when DIN is in relatively abundant supply and should approach zero when DIN availability is at limiting or near-limiting levels (see Fogel and Cifuentes 1993). Because DIN has been shown to limit periphyton production in the LWW (Scott et al. 2005), f_{DIN} was assumed to be 0 ‰ in this study.

Periphyton δ^{15}N, along with the previously stated assumptions, were used to solve the mixing model for the percent contribution of N_2 fixation to total N uptake (C_{N_2}). An important assumption inherent within the model was that N was not efficiently retained and recycled within the periphyton community. Predicted values of C_{N_2} calculated by the model were compared to estimates of the percent contribution of N_2 fixation to total N uptake derived from acetylene reduction assays and N uptake estimates using linear regression analysis in Sigma Plot 9.0 (Sigma Plot 2005).

Water Chemistry

Biweekly water chemistry samples were collected in acid-washed 1 liter polyethylene bottles and returned to the laboratory for analysis of nitrite-nitrogen plus nitrate-nitrogen (NO_2-N+NO_3-N), ammonia-nitrogen (NH_3-N), and soluble reactive phosphorus (SRP). NO_2-N+NO_3-N was determined colorimetrically on a Beckman DU 650 spectrophotometer following cadmium reduction (Clesceri et al. 1998). NH_3-N and SRP were also determined colorimetrically using the phenate and molybdenum blue methods, respectively (Clesceri et al. 1998). Water temperature, specific conductance, and pH were measured during sample collection with a YSI 6600 multiparameter datasonde.

Results

Water Chemistry

Average water chemistry conditions observed during the study are provided in Table 1. Conductivity was generally greatest at site 1A (wetland inflow), diminished at site 1B, and lowest at 2B, except in September when this pattern was reversed. Both NO_2-N+NO_3-N and NH_3-N followed a similar pattern of decreasing concentration along the flow path of water. However, this pattern was not observed in SRP. In May and July, SRP concentrations were generally similar amongst all sites. In September, average SRP concentration was highest at site 1B, followed by sites 1A then 2B. However, all differences observed in SRP concentrations between sites were minor when compared to differences observed in dissolved inorganic nitrogen (DIN = NO_2-N+NO_3-N + NH_3-N). The ratio of DIN:SRP consistently decreased along the flow path of water during all months.

Periphyton Primary Production and Enzyme Activity
Periphyton primary production did not follow a consistent pattern among sites and dates (Table 2). In May, production was highest at site 1A, lower at site 1B, and lowest at site 2B.

Table 1. Water chemistry values for sites on each sampling date (mean ± SD; n=2 for all events).

Site	Water Temp(°C)	Spec Cond (µS cm^{-1})	pH	NO_2-N + NO_3-N (ppb)	NH_4-N (ppb)	DIN (ppb)	SRP (ppb)	DIN:SRP
May								
1A	25 ± 2	736 ± 59	7.8 ± 0.0	194 ± 6	22 ± 1	217 ± 5	4 ± 3	84 ± 69
1B	25 ± 3	715 ± 51	7.9 ± 0.2	44 ± 29	19 ± 6	63 ± 23	6 ± 4	14 ± 12
2B	26 ± 3	642 ± 65	7.8 ± 0.2	6 ± 2	14 ± 11	20 ± 10	5 ± 4	5 ± 2
July								
1A	30 ± 1	708 ± 344	8.0 ± 0.3	227 ± 136	69 ± 4	296 ± 132	8 ± 4	38 ± 4
1B	27 ± 0	665 ± 344	8.0 ± 0.3	42 ± 8	44 ± 27	87 ± 19	11 ± 8	12 ± 10
2B	29 ± 0	592 ± 399	8.0 ± 0.7	5 ± 3	15 ± 3	21 ± 1	4 ± 3	7 ± 5
September								
1A	26 ± 0	490 ± 12	8.1 ± 0.3	210 ± 89	74 ± 20	284 ± 69	3 ± 0	30 ± 115
1B	23 ± 1	501 ± 83	7.8 ± 0.6	100 ± 112	14 ± 13	115 ± 125	8 ± 5	12 ± 10
2B	24 ± 1	507 ± 83	7.8 ± 1.1	6 ± 3	8 ± 7	15 ± 4	1 ± 0	11 ± 4

However, this trend disappeared in July when highest rates were observed at site 1B, followed by 1A then 2B. Site 1B remained the most productive site in September, but site 2B displayed higher primary production than site 1A during this month. N_2 fixation measured using acetylene reduction (AR) was not detected at site 1A on any sampling event, but was always measurable at sites 1B and 2B (Table 2). N_2 fixation measured by AR was always light-dependent (Figure 2). Furthermore, the N_2 fixation rate was negatively correlated with average DIN concentration in the water column (Figure 3A) which resulted in a consistent spatial pattern of decreasing DIN and increasing periphyton N_2 fixation along the flow path of water. Phosphatase activity was always greatest at site 2B followed by site 1A then site 1B, except in September when phosphatase activity at site 1A exceeded that observed at site 2B (Table 2). In general, phosphatase activity was negatively correlated with SRP concentration in the water column (Figure 3B).

Periphyton Elemental and Isotopic Composition

The elemental composition of periphyton mats exhibited both spatial and temporal heterogeneity (Table 2). Carbon content at all sites was relatively low in May but generally increased through July and September. The only exception was at site 1A where C content appeared to slightly decrease from July to September. Nitrogen content followed a temporal pattern almost identical to C. Nitrogen content increased throughout the summer at all sites except 1A where N content was greatest in July but slightly decreased by September. Insufficient sample was collected for the determination of P content in the May samples. Data from the remainder of the summer show that periphyton P content was greater in July than in September for all sample sites. Elemental composition of periphyton did not appear to follow a spatial pattern similar to the distribution of dissolved inorganic nutrients except in September when periphyton C content was negatively correlated with mean DIN and periphyton P content was positively correlated with mean SRP (Tables 1 and 2). The carbon to nitrogen ratio (C:N) of periphyton was consistently between 12 and 15 except at sites 1A and 1B in May where values ranged between 18 and 21 (Figure 4). The ratio of carbon to phosphorus (C:P) and nitrogen to phosphorus (N:P) tended to exhibit more heterogeneity. In July, C:P and N:P were similar at sites 1A and 1B but higher at site 2B (Figure 5). This difference was due to diminished

Table 2. Primary production, enzyme activities, elemental composition, and isotopic composition of periphyton community for sites on each sampling date. All values are mean ± SD. For all values, n=8 except where indicated parenthetically.

Mont h Site	Primary Production (mg C g DW^{-1} day^{-1})	Acetylene Reduction[1] (µg N g DW^{-1} day^{-1})	Phosphatase Activity (nmol P_{ase} g DW^{-1} min^{-1})	Carbon (wt. %)	Nitrogen (wt. %)	Phospho (wt. %)
May						
1A	39.0 ± 12.0 (7)	BDL[2]	60.5 ± 16.6	20.9 ± 3.3	1.21 ± 0.31	IS[3]
1B	22.0 ± 11.7	42.6 ± 33.6	41.6 ± 21.2 (7)	22.0 ± 3.2	1.08 ± 0.20	IS[3]
2B	10.6 ± 3.2	221.7 ± 38.1	104.4 ± 24.3 (4)	21.0 ± 1.7	1.41 ± 0.12	IS[3]
July						
1A	65.0 ± 23.8	BDL[2]	23.9 ± 12.6 (7)	23.3 ± 3.9	1.86 ± 0.45	0.26 ± 0
1B	82.3 ± 36.2 (7)	67.8 ± 106.3 (7)	14.2 ± 5.1 (7)	26.4 ± 2.6 (7)	1.93 ± 0.51 (7)	0.27 ± 0 (7)
2B	41.4 ± 16.3	384.9 ± 284.8	76.4 ± 33.8	24.3 ± 1.3	1.80 ± 0.15	0.18 ± 0
September						
1A	27.1 ± 10.5 (7)	BDL[2]	95.7 ± 50.8	19.9 ± 2.1	1.49 ± 0.20	0.10 ± 0
1B	107.3 ± 46.5	6.1 ± 6.3	31.9 ± 15.1	27.6 ± 4.1	2.28 ± 0.53	0.21 ± 0
2B	42.2 ± 6.7	60.7 ± 32.6	77.2 ± 25.0	32.1 ± 1.8	2.02 ± 0.27	0.16 ± 0

[1] N_2 fixation determined from acetylene reduction assays with intact periphyton.
[2] BDL – below detection level (1 ppm ethylene).
[3] IS – Insufficient sample for phosphorus analysis.

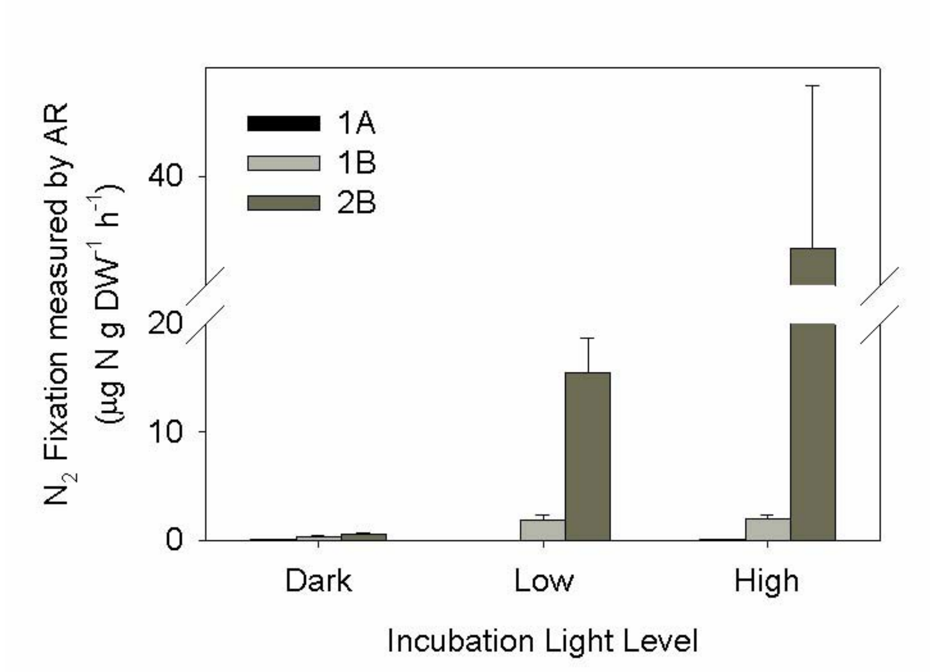

Figure 2. N_2 fixation measured by acetylene reduction (expressed in hourly units) at each incubation light level for the entire study. Bars indicate mean rate determined at each site for the entire summer (± SE).

periphyton P content at site 2B in July (Table 2). In September, C:P and N:P were greatest at site 1A, followed by site 2B then site 1B (Figure 5). Again, these differences were primarily the result of the relatively large difference in periphyton P content observed between sites (Table 2). The N:P ratio in periphyton was not strongly related to the ratio of DIN:SRP in July but appeared to be more positively correlated in September (Figure 4 and Table 1).

Contribution of N_2 fixation to total N uptake
Estimates of the contribution of N_2 fixation to total N uptake determined by AR assays and $\delta^{15}N$ composition of periphyton are shown in Figure 5. In general, $\delta^{15}N$ derived values tended to overestimate the percent contribution of N_2 fixation as measured via AR. Although a strong correlation between estimates existed in May ($r^2 = 0.88$; Figure 5), $\delta^{15}N$ derived values were 1.4 times greater than estimates derived from AR. Furthermore, the correlation between these estimates was greatly reduced in July and September. The poor correlation was the result of greatly reduced estimates of the percent contribution of N_2 fixation determined via AR (0 – 30%) but relatively high estimates from the $\delta^{15}N$ derivation, particularly from site 2B (Figure 5).

Interestingly, both AR and $\delta^{15}N$ derived estimates demonstrated unique relationships with periphyton N content (Figure 6). Periphyton N content and AR derived estimates appeared to correlate on a temporal scale. In particular, AR derived estimates and periphyton N content were positively correlated in May, but negatively correlated in July and September (Figure 6A). Percent contribution of N_2 fixation derived from $\delta^{15}N$ appeared to correlate with periphyton N content on a temporal and spatial scale. At site 1B in May, the relationship between periphyton N content and percent contribution of N_2 fixation derived from $\delta^{15}N$ was positive and could be modeled on the same regression line with observations from all months at site 2B (Figure 6B).

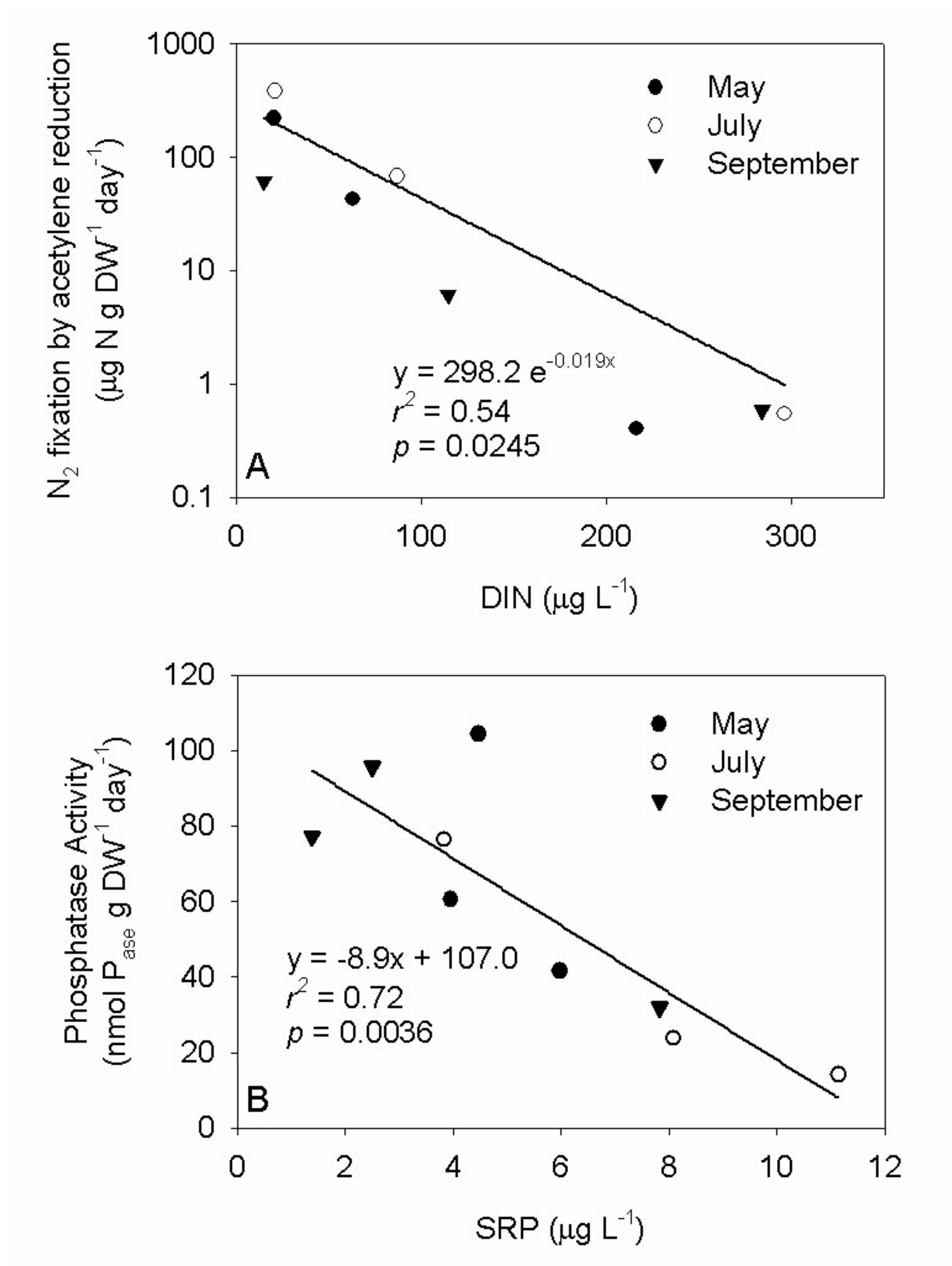

Figure 3. Enzymatic activity versus nutrient concentrations for each sampling event. A) Daily N_2 fixation, measured by acetylene reduction, versus mean DIN concentration in the water column. B) Phosphatase activity versus mean SRP concentration in the water column.

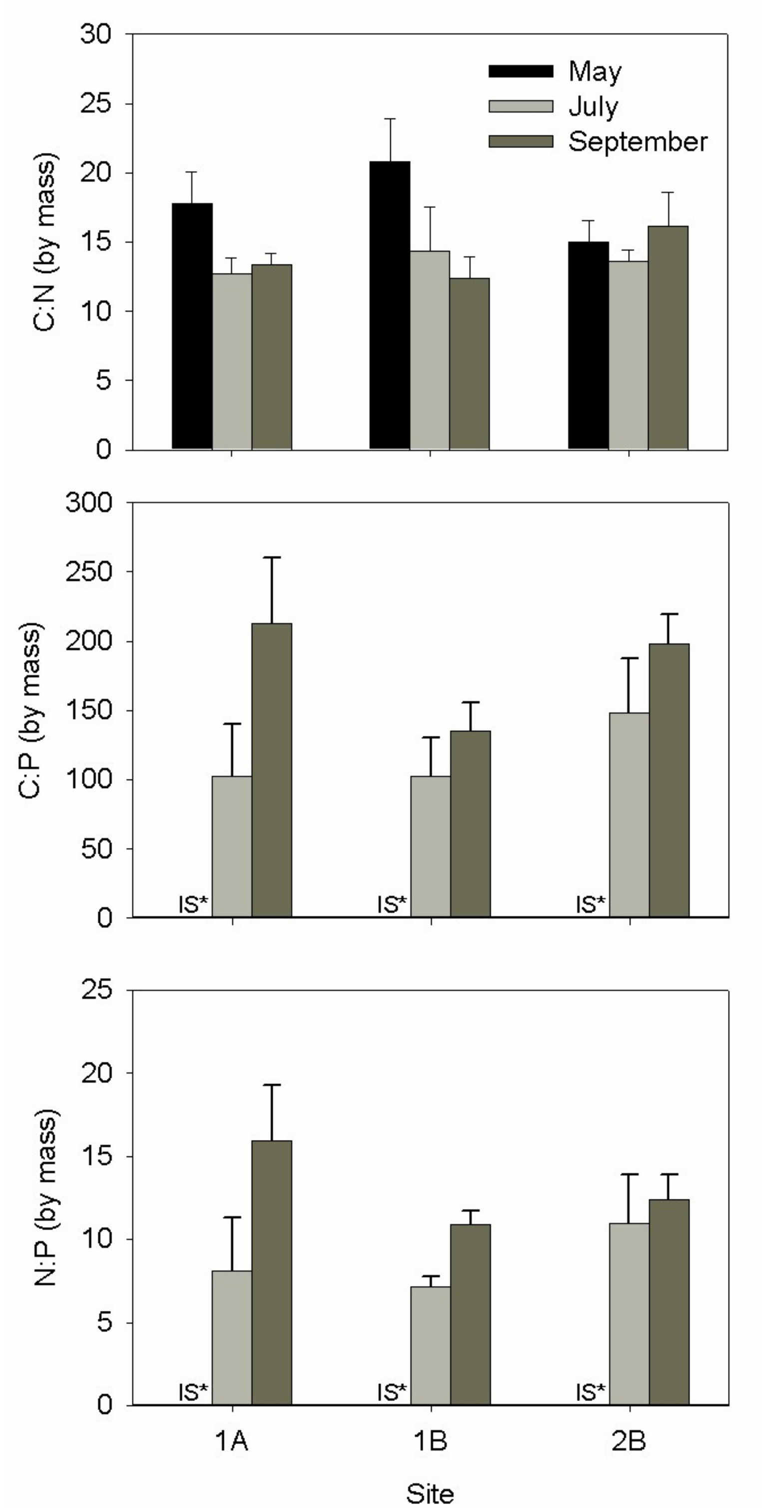

Figure 4. Elemental ratios of periphyton for each sampling event (mean ± SD; n = 7-8, see Table 2 for details on number of samples). Black bars represent samples collected in May 2004, light gray bars represent samples collected in July 2004, and medium gray represent samples collected in September 2004. Insufficient sample was collected during May 2004 for phosphorus determination (IS*), therefore, C:P and N:P values are not available for that sampling event.

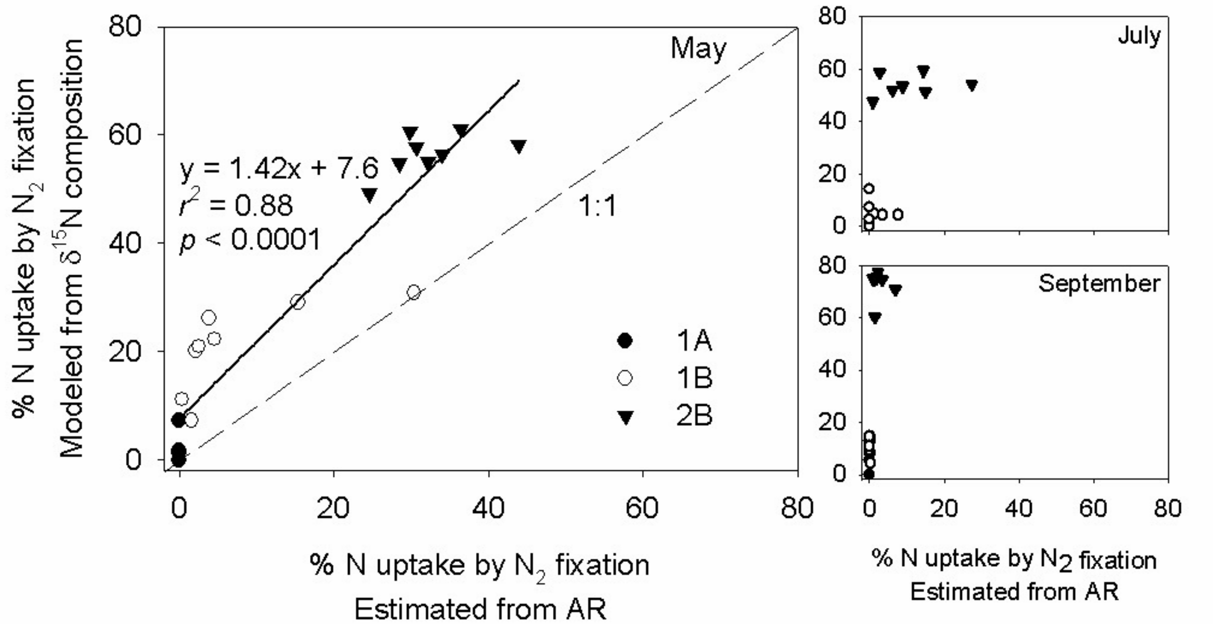

Figure 5. Measured versus modeled percentage of N uptake derived from N_2 fixation. Measured values determined by dividing acetylene reduction estimates of N_2 fixation by estimates of gross N uptake. Modeled values determined from isotope mixing model. Black circles represent samples from area 1A, white circles represent samples from area 1B, and black triangles represent samples from 2B. The mixing model estimates generally agreed with empirical estimates from acetylene reduction in May only. In July and September, modeling with $\delta^{15}N$ tended to overestimate the instantaneous contribution of N_2 fixation to total N uptake.

The correlation between these variables was less pronounced at site 1B in July and September and at site 1A during all sampling events (Figure 6B).

Correlates of Periphyton Primary Production

In May, periphyton primary production appeared to correlate with water column DIN concentrations (Tables 1 and 2). However, this relationship did not exist in July or September. In these months, periphyton primary production was more generally correlated (inversely) with phosphatase activity, and also periphyton P content in September (Table 2). When normalized to periphyton N content and considered over the entire summer, periphyton primary production was strongly inversely correlated with phosphatase activity (Figure 7).

Discussion

Results of this study demonstrate the seasonal evolution of P-limitation in a lentic periphyton community. Periphyton primary production appeared to be N-limited during spring but became P-limited, and remained so, throughout the summer. This was indicated by several relationships between primary production and indicators of nutrient stress. For instance, average primary production was inversely correlated with average DIN in May but became more generally correlated with phosphatase activity in July and September (Tables 1 and 2). This switch between DIN correlation and phosphatase correlation with primary production

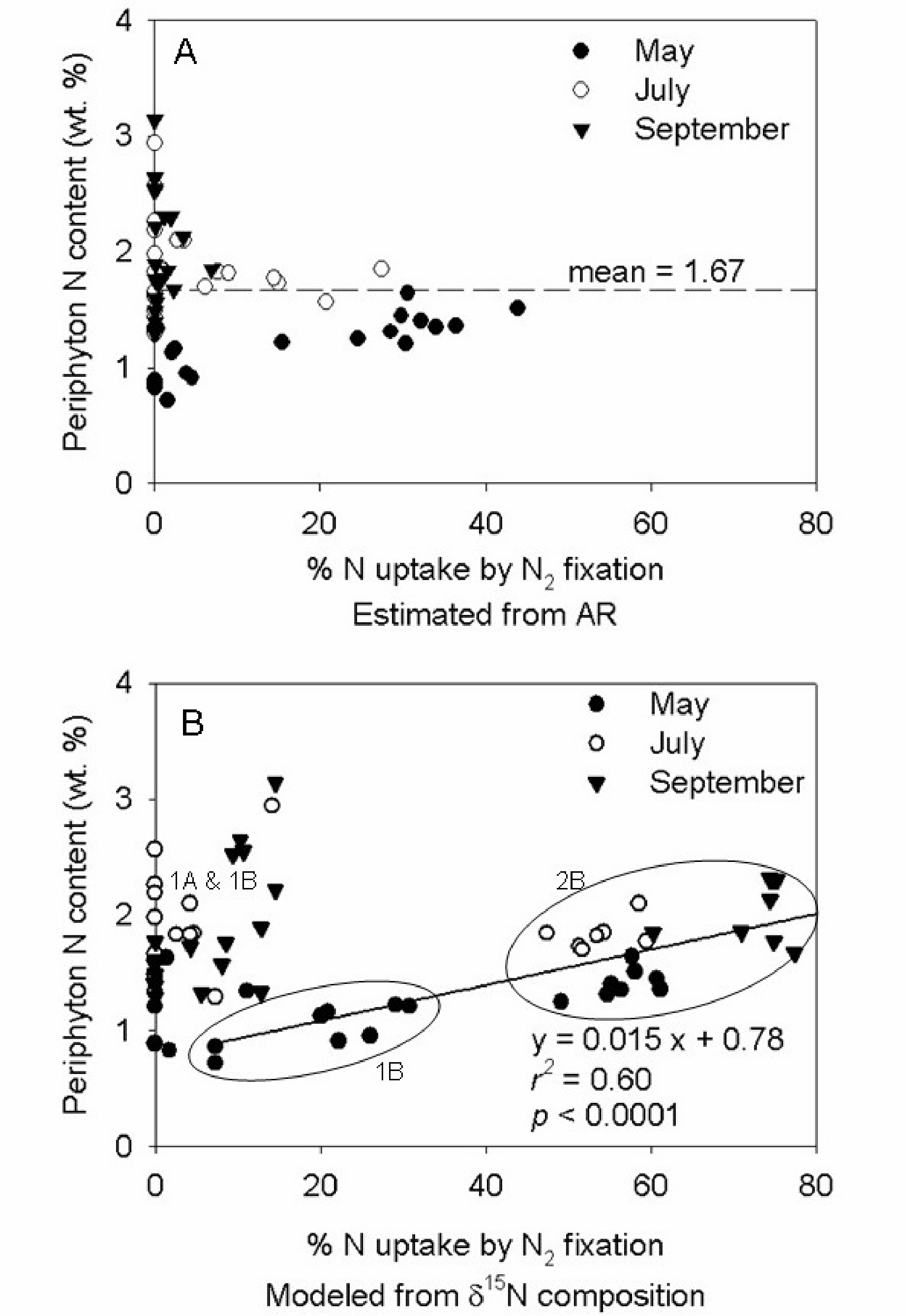

Figure 6. Relationship between N_2 fixation and periphyton nitrogen content. In both plots, black circles represent samples collected in May 2004, white circles represent samples from July 2004, and black triangles represent samples from September 2004. A) Relationship between N_2 fixation measured using acetylene reduction and periphyton nitrogen content in sampling areas 1B and 2B. B) Relationship between N_2 fixation as indicated by $\delta^{15}N$ natural abundance and periphyton nitrogen content in sampling areas 1B and 2B. Decreasing $\delta^{15}N$ corresponds to increasing N_2 fixation. Regression lines were derived for two data subsets: 1) all samples

collected in area 2B and samples collected in area 1B in May 2004, and 2) samples collected in area 1B in July 2004 and September 2004. See discussion for details of these groupings.

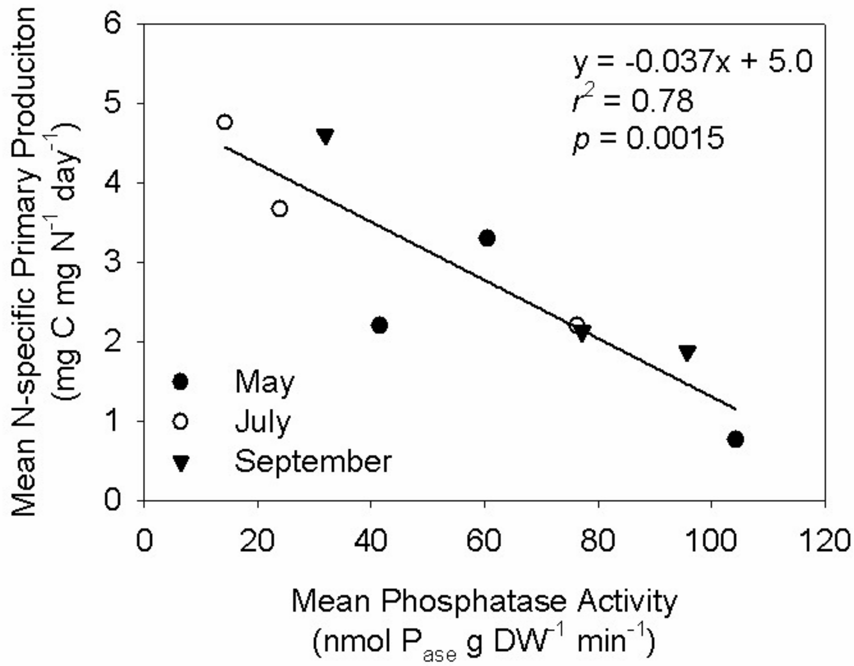

Figure 7. Relationship between mean phosphatase activity and mean nitrogen-specific primary production from all sampling events.

corresponded to a 1.5 to 1.6 fold increase in average periphyton N content from May to July and September, respectively (Table 2). Furthermore, the percent contribution of N_2 fixation to total N uptake, estimated via AR, was generally highest in May and decreased iteratively in July and September. This suggests that periphytic cyanobacteria may have down regulated N_2 fixation in response to accumulating N. In fact, this trend is supported by the N isotopic signature of the periphyton mat. Periphyton $\delta^{15}N$ composition retained the atmospheric signature (approaching 0 ‰) at site 2B even when N_2 fixation measured by AR had diminished (Table 2). However, lighter isotopic values, and subsequently larger isotopic estimates of the percent contribution of N_2 fixation to total N uptake (> 20 %), were generally correlated with higher periphyton N content (Figure 6B). We submit that the accumulation and retention of N in the periphyton mats eventually resulted in P-limited primary production. Interestingly, when primary production was normalized to N content, a strong inverse correlation with phosphatase activity was apparent across all sampling events (Figure 7). Therefore, short-term correlates of nutrient limitation (instantaneous from each month) indicate a springtime period of N-limitation followed by an extended period of P-limitation. However, over a seasonal time scale (all months), N-specific primary production appeared limited by P availability (Figure 7).

Elemental balance within the periphyton mats may also indicate nutrient limitation status. Periphyton C:N was only elevated at sites 1A and 1B in May, and appeared relatively balanced during the remainder of the growing season (Figure 4). Because stoichiometric theory tells us that nutrient limitation of photoautotrophs is generally coupled with an increase in the C:nutrient ratio (Sterner and Elser 2002), periphyton C:N indicate that N may only have been limiting in May. Furthermore, C:P appears to have increased at all sites from July to September. Unfortunately, it remains unknown whether C:P would have been lowest in May because insufficient sample was available for the determination of P content.

The accumulation and retention of N appears to be a critical factor in controlling primary production and inducing P-limitation. Nitrogen availability was primarily driven by DIN supply and secondarily driven by N_2 fixation. For instance, N_2 fixation was never observed nearest inflowing waters (site 1A) where DIN was relatively high. However, N_2 fixation appeared increasingly important at downstream sites where DIN concentrations were greatly reduced (Tables 1 and 2; Figure 3A). Furthermore, N_2 fixation appeared to balance periphyton N content on the scale of weeks in the downstream, most N poor, areas.

Estimates of the percent contribution of N_2 fixation to total N uptake can be derived using both AR (coupled with estimated of gross N assimilation) and periphyton $\delta^{15}N$ composition. Recent studies have attempted to characterize the importance of lentic periphyton N_2 fixation using the N isotopic method with somewhat mixed results. Inglett et al. (2004) found that average AR rates correlated well with average $\delta^{15}N$ composition in an Everglades periphyton community. However, measurements in that study were limited to one location over a two-year period and potential differences between individual measurements (AR versus $\delta^{15}N$) were not considered. Rejmánková et al. (2004) did use individual measurements in an attempt to predict N_2 fixation rates (derived using AR) from $\delta^{15}N$ signatures in a number of tropical wetland periphyton communities. Although their correlation showed some promise, the dataset had poor resolution when N_2 fixation rates were low. The authors ultimately found that a simple threshold in periphyton $\delta^{15}N$ was the most robust indicator of either high or low N_2 fixation.

In this study, we used a mechanistic N isotope approach (*i.e.* a two-end member mixing model) to develop estimates of the percent contribution of N_2 fixation to total N uptake. When compared with empirical estimates of the percent contribution of N_2 fixation (from AR), $\delta^{15}N$ estimates tended to overestimate the importance of N_2 fixation. Although a good correlation between estimates was observed in May samples, the isotope model overestimated the percent contribution of N_2 fixation to total N uptake by almost 1.5 fold (Figure 5). Furthermore, isotope model values for site 2B were grossly overestimated in July and September (Figure 5). We propose that this overestimation was caused by the accumulation of atmospherically derived N in the periphyton mat through time. This accumulation violated the model assumption of negligible N recycling and therefore caused overestimates of the percent contribution of N_2 fixation. Although not explicitly measured in this study, periphyton communities are known to retain and recycle nutrients with great efficiency (Borchardt 1996). Because instantaneous N_2 fixation (AR) appeared to contribute a large amount of N to periphyton at site 2B in spring and early summer (Figure 6A), accumulation and recycling of this fixed N may have caused periphyton $\delta^{15}N$ to continually reflect a high contribution of N_2 fixation throughout the summer even though instantaneous N_2 fixation rates (AR) had diminished (Figure 5). Therefore, periphyton $\delta^{15}N$ comprises a time-integrated estimate of the relative contributions of DIN and N_2 fixation to the N content of the community. Although this inherent characteristic was suggested in early comparisons between N_2 fixation measured by AR and estimates from $\delta^{15}N$ composition (Gu and Alexander 1993; France et al. 1998), recent studies have not considered this potential inconsistency and subsequently have generated mixed results on the usefulness of the technique (Rejmánková et al. 2004; Inglett et al. 2004).

Interestingly, relatively low $\delta^{15}N$ (*i.e.* relatively high percent contribution of N_2 fixation total N uptake) was always correlated with periphyton N content when instantaneous N_2 fixation (measured by AR) was contributing to N content. For example, periphyton N at site 2B during all months and at site 1B in May increased by 0.015 % for every 1 % increase in the contribution of N_2 fixation to total N uptake (see regression in Figure 6B). This trend was not apparent at site 1B in July and September and never apparent at site 1A. This evidence in particular, along with reduced N_2 fixation (AR) observed with increasing periphyton N content, suggest the importance of accumulating atmospherically derived N to alleviate N deficiency in this floating periphyton mat. Although a N rich lifestyle could be expected when N_2 fixers are present (Gu and Alexander 1993), our results indicate that fixed N may be efficiently retained by a periphyton community long after instantaneous N_2 fixation ceases.

Conclusions

Results of this study suggest that periphyton communities can rapidly fix and accumulate significant amounts of atmospheric N_2, thereby driving the community toward P-limitation. It appears that the buildup and retention of N to a critical threshold can occur within a matter of weeks during the early growing season, at least within the warm-temperate zone similar to this study. When N content exceeds a critical threshold, instantaneous N_2 fixation rates fall rapidly but isotopic composition continues to reflect an atmospheric N source. We hypothesize that sustained $\delta^{15}N$ in the range of atmospheric N_2 was caused by the efficient retention and recycling of fixed N_2. Efficient retention brought periphyton N content into stoichiometric balance causing N-specific primary production to be limited by P availability. This study confirms the importance of fixed N_2 as a N source to periphyton community production and provides an example of seasonally-evolving P-limitation in a shallow aquatic ecosystem.

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Carbon Aerogel Electrodes: Adsorption-Desorption and Regeneration Study for Purification of Water

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Carbon Aerogel Electrodes: Adsorption-Desorption and Regeneration Study for Purification of Water

Sanjay Tewari

Abstract

Carbon has been used traditionally in many forms, to name a few charcoal; powder; activated pellets; carbon cloth; for water treatment but there have been various problems associated with their use. Carbon aerogel (CA) is comparatively new form. It has large surface area because of its ultra-micro-porous structure; it also has high conductivity which is suitable for capacitive de-ionization (CDI) technology. CA electrodes were used in CDI for metal ions, bacteria, and some organic pollutants removal. The problem is once these electrodes are used and saturated they lose their capacity for removing ions and they need to be replaced. CA is expensive and replacement of CA electrodes increases the cost of water treatment for this reason they needs to be regenerated. Regeneration studies by various researchers so far involves equal or more amount of clean water than the amount of water treated by it. In addition to this cost estimation for this process has not been done extensive. This study investigates various methods to regenerate CA electrodes to reduce the amount of water involved. To predict desorption behavior in a better manner a model is to be prepared.

1.0 Introduction & Background

Carbon Aerogels

Carbon has been used in different forms to treat water electrochemically. Some carbon forms used are high area carbon-cloth[1] or carbon-felt electrodes[2-4] and recently carbon aerogels (CAs).[5-12] "Under most conditions, pollutant impurities are present at low concentrations so that the electrochemical processes are diffusion-controlled".[2] This diffusion limited mass-transport can be enhanced by using high-area, porous electrodes at which 2-dimensional electrochemistry start acting like "quasi-3-dimensional behavior" due to the large distributed area.[2]

Ayranci and Conway (2001)[3] successfully used high surface area carbon-felt electrodes for water purification. They studied inorganic, sulfur-containing anions and concluded that adsorptive effectiveness was related to factors such as charge, size and shape of ions that play important role in their hydration behavior. They also observed that polarization of carbon-felt surfaces caused an increase in the rate of adsorption of the ions. It was also found that reversing the polarization for sufficiently long periods of time caused an initial desorption of ions due to discharging of the electrode, followed by the re-adsorption of oppositely charged ions.

A successful attempt was made, showing that electro-adsorbing carbon electrodes may be multi-staged in a column of two porous electrodes that can desalinate water to a concentration ratio greater than 100 between product and waste.[13] The process was based on *electrochemical parametric pumping*, a method developed in conjunction with multi-staging electro-adsorption.[9] This concept of electro-sorption of charged species was generalized to include particulate matter such as colloids and bacteria. It was thus shown that *E. coli* bacteria[14], which carry a negative charge; such that porous carbon electrodes can partially retain the organisms (alive) upon potential reversal.

Recent research has shown that carbon aero-gels can be used effectively for the demineralization of wastewater of low-to-moderate ionic strength. Electro-sorption has been used for different kinds of water purification processes like heavy metal ion removal and desalination of dilute solutions.

CA Preparation and Properties

CAs represent a new class of nanoporous materials. They have utrafine cell/pore size (<100 nm), high surface area (> 400 m^2/g), and a solid matrix composed of interconnected colloidal-like particles, platelets, or fibers, synthesized from resorcinol-formaldehyde (RF), phenol-resorcinol-formaldehyde, phenolic-furfural, melamine-formal dehyde, polyurethanes and polyureas.[15-20] These organic aerogels can be transformed in the forms of monoliths, powders, micro spheres, or thin film composites, if pyrolyzed in an inert atmosphere.[5, 21, 22]

Fricke and Tillotson (1997)[23] discussed production, characterization, and applications of carbon aero-gels in detail. Li and Guo (2000)[24] carried out some experiments for the preparation of low-density carbon aero-gels from cresol/formaldehyde mixtures and in their experiments, a cresol mixture is first used to poly-condense with formaldehyde (F) catalyzed by NaOH for the preparation of the organic aero-gels. Li and Guo (2000)[24] concluded that a cresol mixture could be used as a raw material to prepare low-density monolithic, crack-free aero-gels and carbon aero-gels. Density is an important index to judge aero-gel quality. The lower the carbon aero-gel density, the lower the electrical resistivity, hence the preparation of super-low-density aero-gel is important in understanding the physical transport mechanism within these materials. Li *et al.* (2002)[25] attempted to make lower cost aero-gels by using cresol. A mixture of cresol (C_m), resorcinol and formaldehyde has been used as an alternative economic route to the classical resorcinol-formaldehyde synthesis. The porous structure of the mixed carbon aero-gels (C_mRF) is similar to that of RF carbon aero-gels.

The idea behind electro-sorption is to force ions or ionic species towards oppositely charged electrodes with the help of an electric field. Under this kind of environment charged ions are held in the strong field on the electrodes, and once the electric field is removed the ions are quickly released. Obviously in these systems electrodes of high electrical conductivity and high surface area form electrical double layers near their surfaces is required. Electrical double layer is formed in the solutions when a charged surfaces comes in contact to liquid solutions having charged ions in it and ions of opposite charge get attracted to this charged surface and they make a layer at the surface of contact. Granular activated carbon (GAC) has been used for electrodes[26-28] however there were some problems associated with GAC used as an electrode in electro-sorption such as applying GAC as a uniform coating where some kind of glue is needed. This glue reduces the efficiency and is not able to hold GAC to the surface adequately. Carbon aero-gel monolithic, high-surface area and high-electrical conductivity material[10] has been found to have excellent characteristics for electro-sorption.[5-11]

The thermal properties of carbon aero-gels do not play much of a role in water treatment processes but heat/temperature treatment during their formation plays an important role in determining the structure of the carbon aero-gels. It is known that the porosity of the carbon, measured by adsorptive methods, decreases with increasing heat treatment temperature (Marsh and Wynne-Jones).[29] Much work has been carried out to understand the thermal properties of carbon aero-gels. Bock *et al.* (1995)[30], Gross and Fricke (1995)[31], and Hanzawa *et al.* (2002)[32] discussed the thermal behavior of carbon aero-gels during its preparation.

Reichenauer *et al.* (1998)[33] and Saliger *et al.* (2000)[34] conducted investigations concerning the micro-porosity of carbon aero-gels. Reichenauer *et al.* (1998)[33] concluded that higher pyrolysis temperatures trigger formation and growth of 'encapsulated' micro-pores like those present in glassy carbon. Saliger *et al.* (2000)[34] observed in their experiments that a large amount of micro-porosity that is hidden in carbon aero-gels could be made accessible by activation methods without loss of monolithicity. Tamon *et al.* (1998)[35] studied the meso-porous structure of organic and carbon aero-gels and concluded that meso-pore radius of the RF can be controlled in the range of 2.5-9.2 nm by changing the mole ratio of resorcinol to Na_2CO_3 used as catalyst and the ratio of the of resorcinol to distilled water used as dilutent. Shrinkage also plays a role in the control of the meso-pore radius. The pyrolysis temperature is also significant, as it increases, the meso-pore volume becomes small but the peak radius of pore size distribution is maintained. It was also noticed that with the increase in the pyrolysis temperature, ethane adsorption becomes larger than ethylene adsorption on the aero-gels. The carbon aero-gels prepared by pyrolysis at 1000 °C have the same adsorption characteristics of ethane and ethylene as activated carbons do.

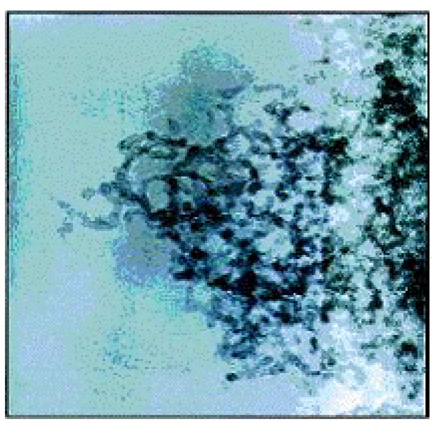

Fig. 1 Carbon aero-gel microstructure: transmission electron micrograph at 500, 000 X magnification.[11]

CA and electrochemical applications

Carbon aerogels were the first electrically conductive aerogels. Their high electrical conductivity, high surface area and ultra-fine (nanometer) pore size make them an ideal choice for electrodes in super-capacitors and capacitive de-ionization (CDI) processes[23]. Wang *et al.* (2001)[36] studied the morphological effects on the electrical and electrochemical properties of carbon aero-gels. Suitability of carbon aero-gels for super-capacitors was explored by Fisher *et al.* (1997)[37], Saliger *et al.* (1998)[38], and Pekala *et al.* (1998)[9]. A super-capacitor is used for energy storage using voltage-induced separation of charge at the electrolyte/solid interface. CDI uses a similar principal as super-capacitors where a voltage is applied to the carbon electrodes acting as cathode and anode, which removes ionic impurities from a flowing aqueous stream. Jayson *et al.* (1987)[4] investigated electro-sorption of mercury (II) acetate onto activated charcoal cloth from aqueous solutions using shaking and flow through techniques. The flow-through method gave lower adsorption results due to a decrease in concentration gradient and the limitation of film diffusion. Jayson *et al.* applied the electrical potential to activated carbon cloth and demonstrated an increase in the uptake of the mercury (II). Total capacity of electro-sorption depends mainly upon two factors; the first is the electrical double layer capacity due to the electrostatic attraction force between the ions and electrode. This is affected chiefly by the concentration of the ions in solution and the applied voltage. The other factor is the pseudo-capacity due to faradic reactions, which depend on the chemical characteristics of the solute and the functional groups on the electrode surface[12]. Yang *et al.* (2001)[10] proposed a model to understand the electro-sorption mechanisms on the carbon aero-gels from a microscopic view in order to describe total ion capacity. This model predicts electro-sorption of ions from aqueous solutions by carbon aero-gel electrodes. Because of the porous nature of the electrodes, the total capacity of the systems was obtained by summing the contributions of the individual pores. When a pore has a width smaller than a specific value (cutoff pore width), it does not contribute to the total capacity because of the electrical double-layer overlapping effect and this effect greatly reduces the electro-sorption capacity for electrodes with significant numbers of micro-pores. The cutoff pore width was found to decrease with increasing ion solution concentration and applied voltage. Traditional approaches consider that the total surface area of the material is available for the electro-sorption, while Ying *et al.* (2001)[10] showed that pore size distribution of the material should also be considered. Therefore, integrating the capacity in each pore over the pore size distribution rather than using the total surface area should calculate total capacity.

Flow through electrode model: From past research[39-43] it has been shown that flow-through porous electrodes can remove heavy metals from dilute streams, and direct comparison with other electrode systems (fluidized bed electrodes and parallel plate electrodes) show that flow-through porous electrodes can perform better. Trainham and Newman (1977)[44] emphasized that more sophisticated models are required to help design better flow-through porous electrodes so that they can compete with other processes (e.g., foam fractionation, ion exchange, precipitation, and cementation). Trainham and Newman developed a one-dimensional model for flow-through porous electrodes operating above and below the limiting current of a metal deposition reaction. The model assumes that there is one primary reactant species in an excess of supporting electrolyte, and that a simultaneous side reaction may occur. Ohmic mass-transfer and heterogeneous kinetic limitations were considered to predict a non-uniform reaction rate. According to Trainham and Newman (1977)[44], the metal-ion removal from dilute streams using a flow-through porous electrode with parallel current and fluid can be described with the following restrictions:

- (i) The model is one dimensional;
- (ii) The porous cathode is of length L and has an isotropic porosity ε and specific surface area 'a' which remains constant in time;
- (iii) The hydrodynamics are characterized by superficial velocity ν and an average mass-transfer coefficient k_m, where axial diffusion and dispersion account for deviations from plug flow;
- (iv) There is one reactant species in excess supportive electrolyte;
- (v) A simultaneous side reaction may occur which is characterized by its rate at half-wave potential of the primary reaction. Also if the side reaction involves generation of a gas, it is assumed that the gas will remain in the solution so that the velocity profile will not be disturbed;
- (vi) The conductivity of the matrix and pore solution phases is uniform.

Assumptions i-iii simplify the calculation procedure, and are necessary due to the lack of a better description of the complex porous geometry. The validity of the assumptions iv-vi rests on a small reactant concentration. As a consequence of assumptions iv and v, the current efficiency should be high, which further simplifies the model by removing the need to follow any reactant species concentration, which participates in the side reaction. This approach emphasizes the salient features of the interaction between an unwanted side reaction and metal deposition reaction." Analysis and numerical solutions have been carried out in related publications. Trainham and Newman observed satisfactory agreement between model predictions and experimental data on over-all reactor performance and deposit distributions.

Capacitive de-ionization technology

CDI is the process of removing ions using capacitive adsorption. Ions are adsorbed onto the surface of the porous electrodes by applying electric field, producing de-ionized water as discussed before. However, the efficiency of CDI strongly depends upon the surface properties of the electrodes such as surface area and surface chemistry[45,9]. A number of publications and patents have appeared showing the use of porous electrodes for recovery of heavy metals from aqueous solutions[27, 43, 44, 46-48]. In these studies electro-sorption of metallic ions were observed on cathodes with relatively low surface areas.

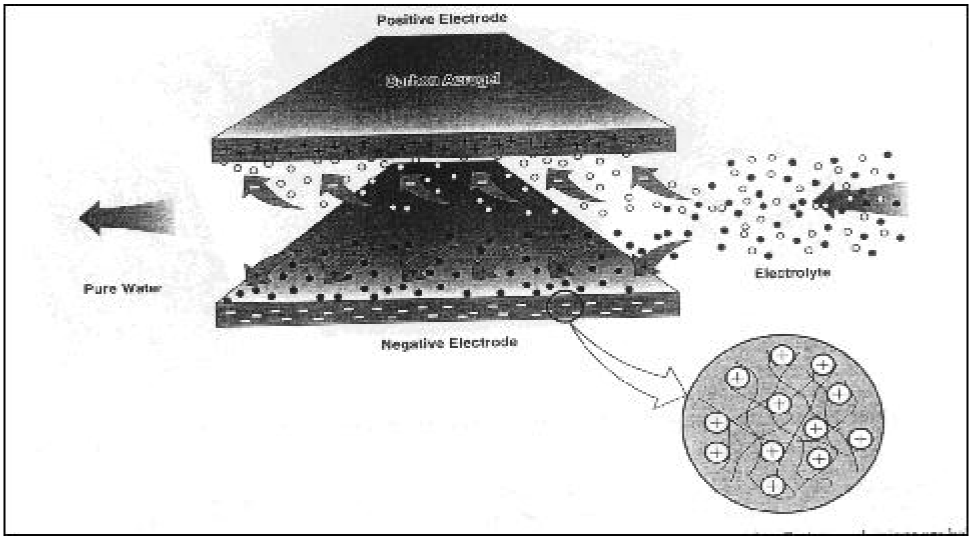

Fig. 2 Schematic diagram illustrating the principle of capacitive deionization with carbon aero-gel electrodes. Cations and anions are held in the electric double layers formed at the cathode and anode, respectively. The high specific surface area of carbon aero-gel enables the process to remove a significant amount of dissolved ions from the water passing between the electrodes.[6]

The earliest studies on CDI were conducted at the University of Oklahoma in the early 1960's[26]. Johnson and Newman (1971)[49] conceived upon a comprehensive theoretical model for the capacitive charging of porous carbon electrodes, this analysis is still generally applicable to all CDI systems. Activated carbon was difficult to hold and form into thin conductive sheets for use as electrodes. Inert polymeric binders were used to hold the GAC particles together in thin sheets and this inert material was not helpful in the electro-sorption process. Durability of the electrodes was the main problem found in the research of Johnson and Newman. Between 1978 and 1983 CDI studies were conducted using carbon aerogels[50, 13]. Two separated electrodes were used in the form of a column and were able to reduce the concentration of NaCl and $NaNO_3$ by a factor of (1/100). Carbon aero-gels have been used successfully and efficiently for capacitive de-ionization of NaCl and $NaNO_3$ solutions[5], NH_4ClO_4 solutions[6], electro-sorption of chromium ions as a means of treating ground water[7], electro-sorption of inorganic salts from aqueous solution[51] and treating low-level radioactive waste and remediating contaminated ground water[8]. The basic principle of the capacitive de-ionization is illustrated in Fig. 2. A voltage is applied to the carbon aero-gel electrodes, acting as cathode and anode, removing ionic impurities from a flowing aqueous stream, as the ions tend to move to oppositely charged electrodes.

Farmer *et al.* (1996)[5] carried out experiments on NaCl and $NaNO_3$ solutions. The solutions were passed through stacks of carbon, high specific surface area (400 to 1100 m^2/g), aero-gel electrodes as shown in Fig. 3. After electrode polarization, non-reducible and non-oxidizable ions were removed from the electrolyte by the imposed electric fields and held in the electric double layers formed at the surfaces of the electrodes. Experiments were conducted over a broad range of solution conductivity and cell voltage.

Conductivities ranged from 10 to 1000 μS/cm, and voltage levels were 0.0, 0.4, 0.6, 0.7, 0.8, 1.0, and 1.2 V. Four liters of electrolyte was recycled continuously in batch mode experiments at a flow rate of 1.0 liter/min. Single-pass experiments were conducted pumping 20 liters of electrolyte through the electrode stack at a flow of 25 ml/min and there was no recycle of electrolyte. The ability of the electrodes to remove ions from water had a strong dependence on cell voltage. 1.2 V gave best results and at 0.4 V performance was relatively poor. 95% of the salt in a 100 μS/cm feed stream was removed until saturation of the carbon aero-gel electrodes was reached. After operating for months a loss of 6 to 8 % of electrode capacity was observed. Rejuvenation of aged electrodes was done by voltage reversal. It was concluded that voltage reversal drives chemically bound ions from the surface of the carbon aero-gel by imposing significant repulsive electrostatic force. Rejuvenation was used to increase the electro-sorption capacity of aged electrodes back to initial levels (approximately 80% to above 95%).

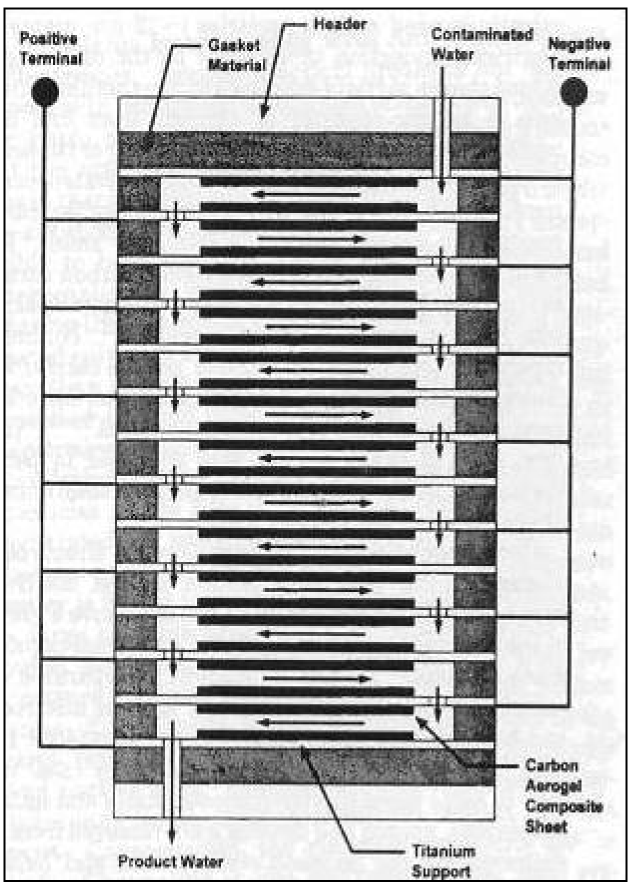

Fig. 3 Schematic representation of an electrochemical cell similar to that used for experiments with 12 double-sided electrodes[7]

Farmer *et al.* (1996)[6] treated NH_4ClO_4 solutions following same procedure as described above in their NaCl and $NaNO_3$ experiments. The best salt removal voltage was found to be 1.2 V. For the single-pass experiments, 384 electrodes pairs were used in the system. 95% of the salt in a 100 μS/cm feed stream was removed until saturation of the carbon aero-gel electrodes was reached. The capacity of the carbon aero-gel anode to electro-sorb (ClO_4^-) was found to be small, compared to the capacity of these electrodes to electro-sorb Cl^- ions. This was also true in case of NO_3^- ions. This would indicate some preference for smaller size ions in the aero-gel system.

Framer *et al.* (1997)[7] examined the treatment of groundwater, contaminated with Cr (VI). During a feasibility study, it was observed that the level of hexavalent chromium in the groundwater could be lowered from 35 to 2 ppb, which is well below the acceptable level of 11 ppb. A field test was also carried out successfully, in which three stacks of 48 double-sided carbon aero-gel electrodes were polarized at 1.2 V and used to continuously remove Cr (VI) and Cr (III) from raw untreated ground water. It was seen that electro-sorption of chromium was favored over other anions at the part per million level. The selectivity of chromium ions over these other ions was great; chromium was removed in the presence of 530 ppm of TDS.

Gabelich *et al.* (2002)[11] carried out extensive studies on the removal of various cations and anions by carbon aero-gels. Gabelich *et al.* determined that the effects of ion charge, ion size, and ion mass on electro-sorption capacity were the main variables from several series of experiments containing one or more representative ions of the varying properties. Ca^{2+}, Na^+, Mg^{2+}, and Rb^+ cations and Cl^-, Br^-, NO_3^-, and SO_4^{2-} anions were selected as they can be found in natural water and are readily available as reagents. Experiments were carried out with 0.005 M solutions in a single-pass manner using CDI stacks as discussed before. The run time for these tests was 10 min at 1.4 V. No poisoning, scaling, or electrode degradation under these operating conditions was observed, even after 36 experiments. Percent removal for sodium and potassium were high as compared to calcium and magnesium, and a similar pattern was observed in the case of anions also. Percent removal of chloride was highest and removal of nitrates and SiO_2 was very low, while removal of sulfate was satisfactory.

Regeneration of CA electrodes

As stated elsewhere in this proposal, the regeneration process of saturated CA electrodes can occur via several methods. The basic technique is to simply back wash the cell with clean water. However backwashing normally requires equal or more water for regeneration than the clean water produced, so additional techniques in combination of backwash are required.

Gabelich *et al.* (2000)[11] applied short circuiting of the electrodes while recycling back the original test water. The regeneration was carried out for approximately 20 min. After each experiment the CDI unit was flushed with deionized water. Information about the amount of water required for regeneration was not given.

Farmer *et al.* (1996)[5] also short circuited the electrodes so that accumulated charge can be discharged and so can attracted ions and thus regeneration process but the regeneration period was 32 min. However they failed to mention the water required for this step. Farmer *et al.* carried out another experiment[6], this time with NH_4ClO_4 solutions where regeneration was complete after 30 min. However they again did not mention the quantity of water used in the regeneration process.

Ryoo and Seo (2003)[1] improved capacitive deionization function of activated carbon cloth (ACC) by titania modification. Ryoo and Seo (2003)[1], in their experiments with ACC electrodes, noticed decrease in concentration of electrolyte (NaCl) due to adsorption either physically or electrically. ACC is composed of activated carbon fiber thus has large surface area and many charging sites, ions are adsorbed on it, this is physical adsorption, apply electrical field to ACC and more ions are adsorbed, it is now electric potential adsorption. Ions adsorbed during electric potential adsorption are easily desorbed when either electric field is taken off or electrodes are discharged. Ryoo and Seo (2003)[1] found that a large electric potential is effective for regeneration step while large physical adsorption reduces the efficiency of regeneration process.

Ayranci and Conway (2001)[3] did system evaluation for water purification using adsorption and electrosorption at high-area carbon-felt electrodes and discovered that partial desorption was achieved by discharging the electrodes. They suggested flushing the system by hot water, as desorption is expected to increase with temperature.

Natrajan and Wankat (2003)[52] carried out experiments for concentrating dilute solutions using adsorption on activated carbon followed by partial thermal regeneration. After studying existing processes (as shown in the figure 4) for adsorption and desorption; they proposed a new process “Hot-Feed Addition” (HFA), a combination of the principles of co-current Thermal-Swing Adsorption (TSA) and Cycling Zone Adsorption (CZA). HFA is a co-current process, which cycles between cold feed, hot solvent and hot feed. TSA, CZA and HFA are illustrated in the figure below. The possibility of the successful use of HFA is to be explored in the regeneration of the CA electrodes.

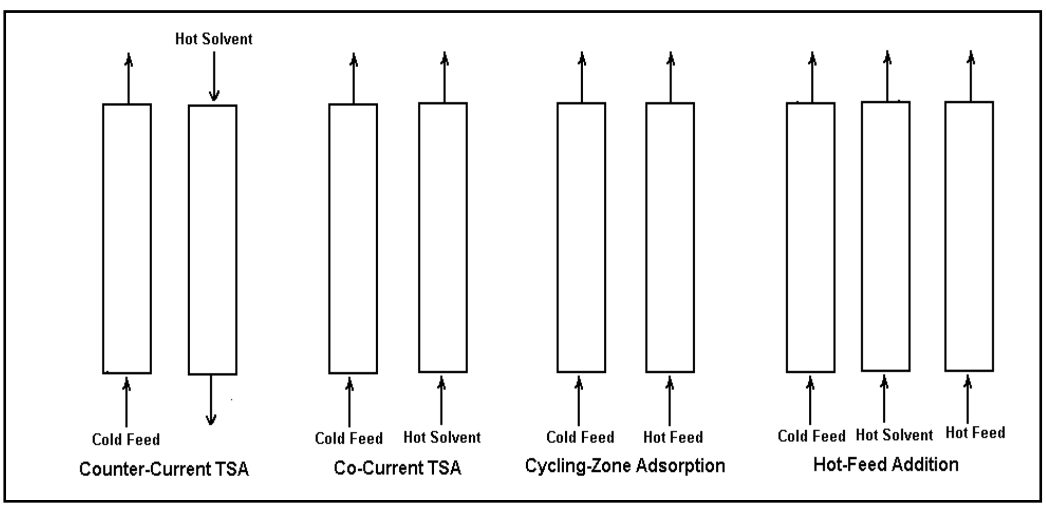

Fig. 4 Adsorption processes as discussed by Natrajan and Wankat (2003)[52]

Koresh and Soffer(1977)[28] studied double layer capacitance of ultramicroporous carbon electrodes and concluded that the "mobility of ions into ultra-micro-pores of carbon electrodes is several orders of magnitude smaller than in the free solution outside the pores".

Kramer *et al.* (2005)[53] conducted an evaluation of carbon aerogel aquacell of Capacitive Deionization Technology Systems, Inc., for desalination using capacitive deionization and concluded that successful regeneration can be carried out for low TDS values but the amount of water used for regeneration was more than the amount of clean water produced. Deterioration of CA was also noticed during experiments in the cells prepared by CDT, Inc. It was also concluded that due to short circuiting of water flow utilization of total CA was not achieved.

Carbon aero-gels can be very useful in the purification of water, as there is very little loss of the aero-gel material during regeneration. There is no large power requirement for operating CDI units. Carbon aero-gels are better candidates for electrodes when compared to loosely bound activated carbons.

Basic information for studying electro-sorption of metals and other impurities are available and can be used in experiments for complex systems and to explore the possibility of using this system for wastewater of higher strength. Systems should have ionic selectivity, depending upon the size, charge, and complexation of the ions being separated. Initial parametric studies have not provided sufficient data to establish the performance of the electrodes over extended periods of times.

However, it must be noted that very little work, if any, has been documented on the regeneration of the aero-gels and the proper methods of operation in order to maximize the quantity of clean water produced. Model of regeneration behavior of carbon aero-gel electrodes is not available and is one of the objectives of this proposal. Further, none of the literature mentioned any cost estimates for the CDI technology. The focus of this study is going to be regeneration of saturated carbon aero-gel electrodes with minimal use of water. This study also focuses on modeling of this regeneration behavior.

2.0 Research Objectives

The goal of this study is to obtain fundamental information about the desorption behavior of adsorbed metal ions on CA electrodes and determine suitable conditions for efficient regeneration of CA electrodes.

Objective 1 - Establish effect of concentration gradient on desorption

Concentration gradient is to be increased by increasing flow velocity of flush water and by sonication under flow and non flow conditions. This will favor diffusion from CA surface and thus desorption. Effect of flow rate of water on desorption will help determine optimal flow rate conditions for efficient regeneration. This will also be studied in combination of some other test conditions such as HFA, shorting of electrodes and by reversing polarity of the electrodes to explore the cumulative effects on desorption.

Objective 2 - Study effect of physical size of ions on desorption

As explained earlier if ions are to get out of pores their individual size becomes important. Small ions will be desorbed from these micro pores easily as compared to larger ions. Results from this study would establish desorption behavior of CA as a function of physical ion size. This will help understand the suitability of CDT in the treatment of water with various ions.

Objective 3 - Examine the effect of multivalent and monovalent ions on desorption

Effect of individual charge of ions will be examined during regeneration of CA electrodes.

Objective 4 - Study effect of pore size of CA electrodes on desorption

Since ions get adsorbed on numerous charging sites on the surface and in micropores of CA, during regeneration process these trapped ions are needed to be freed. Small pore size and greater large surface area means pores have small opening while having comparatively large surface area and this would create problem during desorption as ions will not be able to get out that easily. The larger the pore size will favor more desorption. How variation in ion size and type affect desorption process will be studied and this will help to elucidate desorption as a diffusion limited process.

Objective 5 – Effect of CA thickness on adsorption and desorption

CA thickness is to be varied and effect of variation of thickness would be studied on desorption process.

Objective 6 - Examine the thermal effect on desorption of ion from CA electrodes

General thermal properties of desorption indicate rise in temperature increases desorption and this property would be used here to enhance the regeneration of CA electrodes. Behavior of CA is to be examined in HFA process. Effect of temperature of feed water on desorption would be the outcome of this phase.

Objective 7 - Modeling the desorption behavior of CA

Based on results of all experiments for desorption of CA, modeling of desorption will be the final step. In this step existing models will be unified and/or modified to represent this study as a surface-pore-diffusion model.

3.0 Materials/Methodology

Chemicals

All chemicals will be analytical grade and used without further purification. Solutions will be prepared with deionized (17.8 MΩ-cm) water. Plastic volumetric flasks and vessels will be cleaned with 1 % HNO_3 or 1 % HCl and rinsed several times with deionized (DI) water before use. All tubing and pumps will be cleaned with DI water. Gabelich *et al.*[11] carried out their studies using certified ACS-grade potassium chloride, potassium bromide, rubidium chloride, rubidium bromide magnesium sulfate, magnesium bromide, sodium nitrate and potassium nitrate, this study will use the same chemicals for the desorption studies. In addition to these chemicals, sodium chloride will also be used.

Adsorption on CA

CA sheets will be immersed in water with varying TDS for saturation at different periods of time so that ions are adsorbed on CA surface this is physical adsorption and then adsorption would be carried out applying some potential across electrodes, this will help in electrical field adsorption as explained by Ryoo and Seo (2003)[1]. Effect of structural properties of CA and chemical properties of the ions will not be studied as it is well documented[5-9, 12-14], desorption process would be the next step and is the focus of this study.

Desorption Process

The desorption process will be studied for the effect of charge, effect of mass and effect of radius of ions along with flow rate across electrodes and voltage applied to CA electrodes. CA pyrolyzed at two different temperatures and of two different densities would be used for the evaluation of the effect of CA structural properties on disorption process. Effect of structural properties on desorption process will be evaluated. A combination of the different thickness and density will be used for this purpose. This will give an opportunity to evaluate the effect of variation of pore size of CA on the desorption process.

Analytical Methods

The main parameter would be conductivity of the water and it would be monitored constantly using a Corning conductivity meter coupled to a computer using serial port connection and data acquisition software (TAL technologies Inc.). Samples would be taken at regular time intervals and would be analyzed for ion content. Atomic adsorption spectroscopy (method 3500) would be used for cations and ion chromatography (method 4500) would be used for anions.

4.0 Results and Conclusions

Experiments are still being carried out and once the study is completed, results will be shared with Texas A&M University and Texas Water Research Institute.

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A Decision Support system to Develop Sustainable Groundwater Management Policies for a Multi-county Single Aquifer System

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A Decision Support System to Develop Sustainable Groundwater Management Policies for a Multi-county Single Aquifer System

Muthukumar Kuchanur

Abstract

In arid and semiarid regions, groundwater is one of the critical natural resource constraints. Groundwater, who owns it, and how a regulatory authority governs it remain issues of importance to all Texans and particularly for citizens in parts of the state that receive little rainfall and experiencing rapid population growth. The importance of sustainable groundwater management that incorporates ecological demands is being widely recognized in Texas. Groundwater conservation districts (GCD) are authorized by state law (Texas Water Code, Chapter 36) and are empowered to regulate groundwater resources within their boundaries. Many of these GCDs are striving to formulate sustainable groundwater policies that reconcile both the economical growth and the ecological demands of the region. Typically GCD's jurisdiction confines with the county boundaries and as such does not span the entire aquifer. In other words, the same aquifer is governed by different GCDs. In such instances, the policies formulated by one county will greatly influence the groundwater dynamics in the other counties because of the interconnected nature of the geological formations in this region.

Therefore, ad hoc groundwater management policies adopted by a single county (GCD) without systematic integration of science, management and cooperation among adjoining counties may act as a serious impediment for regional-scale sustainable growth. Hence the development of a strategic decision support framework to formulate and assess these sovereign yet highly interactive groundwater management policies is essential. In this research work a game theory based decision support framework is developed and the application of this framework is illustrated using case studies in South Texas.

Introduction

The major aquifers in Texas span over multiple counties but typically the jurisdiction of a GCD is confined within the county boundaries. In other words, the same aquifer is shared and governed by different GCDs. In such instances, the policies formulated by one county (GCD) will greatly influence the groundwater dynamics in the neighboring counties because of the interconnected nature of the geological formations of the aquifers. Consequently, the subjective preferences in the policy formulation of one GCD can persuade the policy decisions of the other neighboring GCDs in the region. Therefore, ad hoc groundwater management policies adopted by a single county (GCD) without systematic integration of science, management and cooperation among adjoining counties may act as a serious impediment for regional-scale sustainable growth. However, the uncertainty in management decisions resulting from disagreements between the GCDs needs to be effectively characterized to move towards sustainable groundwater management. Thus, the development of a strategic decision support framework that can guide the decision makers to assess these sovereign yet highly interactive groundwater management policies is essential.

Groundwater is a multi-dimensional resource and often is shared by stakeholders with competing objectives. When aquifers are shared and managed by different GCDs these competing objectives may become conflicts that are more difficult to resolve because of the inherent emotional nature of the problem coupled with administrative obstacles. The overall goal of this research is to develop a strategic framework that reconciles the impacts of externalities in policy decisions and in particular, to evaluate the effect of the groundwater management policies formulated by one county towards the other. Game theoretic approaches are illustrated in this research as suitable tools to evaluate policy options and guide negotiations between decision makers towards adopting sustainable groundwater management policies.

Research objectives

This research is aimed at the formulation of a decision support framework for developing sustainable groundwater management policies. A common management goal for the GCDs is to fully analyze water resources for economic and social benefit. However, sustainable management of groundwater aquifers is a complex issue that requires a delicate balance between the abstractions and recharges. Particularly in semiarid coastal regions critical issues like baseflows to the bays, saltwater intrusions craft the management of groundwater into a more exigent framework.

In light of the discussion above, the objectives of this research include (1) To develop a transparent and pragmatic methodology that helps the GCDs and decision makers to evaluate sustainable regional groundwater management policies;(2)To develop and demonstrate game theoretic framework that reconciles the environmentally conservative options vs. economically beneficial pay offs and their interactions between different counties; (3) To use game theoretic approach coupled with simulation-optimization to develop payoff matrices and thus making it a transparent tool that facilitates stakeholder participation; (4) To incorporate subjective preferences, uncertainties in the utilities function, and risk behaviors of various players.

Methodology

Game theoretic framework

Game theory is a formal way to analyze strategic interaction among a group of rational players (or agents) who behave strategically. Game theory has been widely used in the areas of economics, social sciences, industrial management, logistics, military and political sciences and the literature is replete with the application of game theory in these areas (Thomas 1984; Wolters and Schuller, 1997; Burns and Gomolinska 2001; Bell and Cassir, 2002; Li et al., 2002; Tchangani, 2005). The bestowal of the Nobel price for John Nash in 1994 and in 2005 to Robert J. Aumann and Thomas C. Schelling for their works in game theory underscores the important role of game theory in resolving conflicts. Despite its applicability to characterize conflicts, game theory has not been widely used in groundwater management. Recently Loaiciga (2004) had implemented an analytical game theoretic formulation to explore the roles of cooperation and non-cooperation on the sustainable exploitation of groundwater. However, game theory has not been applied to analyze the policy interactions between groundwater management institutions and this study is an effort to illustrate the application of game theory in this arena.

The object of study in game theory is the game, which is a formal model of an interactive situation. Typically, a game can be defined as consisting of three elements:
(i) Players denoted as i, and can vary from (2, 3….N),
(ii) Strategies chosen by a player (i) from a set of strategies Si and
(iii)Payoff to a player Pi (Ai,Oi), where Pi is the payoff to player i when the player chooses a strategy Ai and the other players choose a strategy Oi

The players are assumed to be rational and choose strategies that maximize their expected pay offs. However, in situations involving resources that are shared by multiple decision makers/entities the payoff to a player's strategy (action) cannot be determined without taking into account the strategies chosen by other players. Thus, game theory acts as a tool to model the interaction between the players (decision makers) and helps the decision makers to analyze policy choices anticipating the strategies of the other players. Games are broadly classified as being (a) dual or plural, (b) finite or infinite, and (c) cooperative or non-cooperative (Owen, 1982). Briefly, if the number of players is two, it is a dual game or if the players are more than two it is a plural game (multi-player game). Depending on the possible number of strategies and moves the game can be classified as a finite or infinite game. In non-zero-sum games, the two players' payoffs are not directly opposed. In such cases, the games can be classified as co-operative (where communication, binding contracts and correlated strategies are allowed) and non-cooperative games (where no possibilities of commitment are allowed).

In the context of groundwater availability estimation, an aquifer can be considered a common resource that is shared by multiple GCDs. The GCDs can be construed as players. The GCDs consider and analyze various policy strategies that may include a gamut of choices. Some of the policy choices are: (i) A GCD may decide on a policy level either to develop or not to develop groundwater within their jurisdiction. (ii) In both of the above cases, the GCD may opt to have a conservative or a liberal policy. The extent and the nature of liberal or conservative behavior of a GCD largely hinges on the risk preferences and other geologic factors of their county. (iii) The GCDs may also decide either to honor or not to honor their neighbor's policies and the degree of this policy behavior may vary from honoring all or some of the neighbor's policies to not considering any of their policies/concerns at all. A schematic of the policy choices that are deliberated by GCDs at various stages of policy formulation is shown in Figure1. If the neighboring county does not have a GCD (which is the case of some counties in the coastal bend region like Calhoun, Kleberg Counties) it can be broadly grouped into the category of a county not honoring their neighbor's policy. But in this particular case the reason for not honoring the neighbor's policy is that they do not have a GCD and consequently no management policy as such.

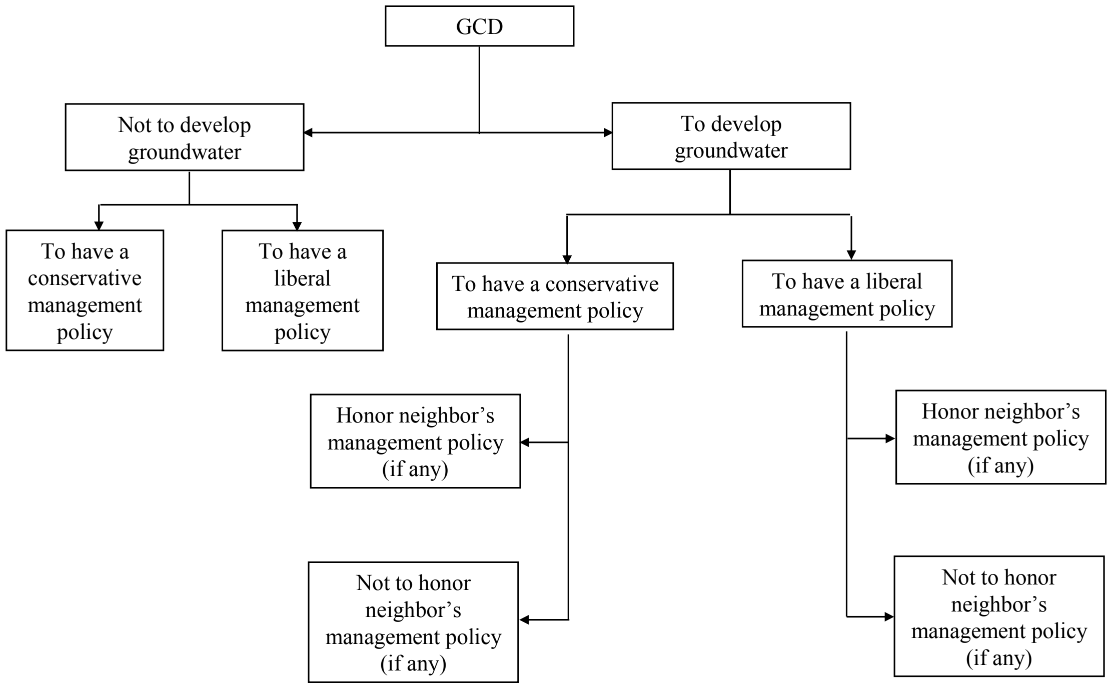

Figure 1: Overview of policy choices for a GCD

Groundwater is a shared resource and various stakeholders may have different payoffs or utilities that are dependent directly or indirectly on groundwater. The utility function reflects the interests and orientation of the GCDs. The utility function may be as simple as the amount of groundwater pumped from the aquifer to as complex as the ecosystem productivity in the bays and estuaries. GCDs are deemed to reconcile the environmentally conservative options vs. economically beneficial pay offs. Therefore, in this research a ratio of the amount of groundwater pumped (Q in ac-ft/year) over drawdown inducted by pumpage this Q (h in ft) is used as the payoff function. The amount of groundwater (Q) that can be pumped from the aquifer is an indicator of the economic benefits that can be derived and the drawdown induced can be used as a surrogate measure of the environmental impacts and other negative externalities that include: (i) decreased water availability, (ii) decreased environmental flows, (iii) negative economic externalities linked with the drying of shallow wells, (iv) associated increase in the cost of pumpage with increased drawdowns (v) impacts potential saltwater intrusion and (vi) impacts of subsidence. Thus a ratio between Q and h acts as an adequate payoff function that reconciles both the positive and negative impacts associated with any policy formulation made by a GCD and is used in this research as such. Hence a higher value of this ratio indicates a higher payoff to the player.

Simulation – Optimization approaches can be used to calculate the payoff function as they have been demonstrated to be capable of incorporating the preferences of the stakeholders within a GCD (Uddameri et al., 2006; Uddameri and Kuchanur, 2006). The ratio of Q/h can be calculated using this approach. The payoffs need to be calculated for all the identified policy interactions within GCDs and then can be summarized in a payoff matrix. A typical two player payoff matrix is shown in figure 2.

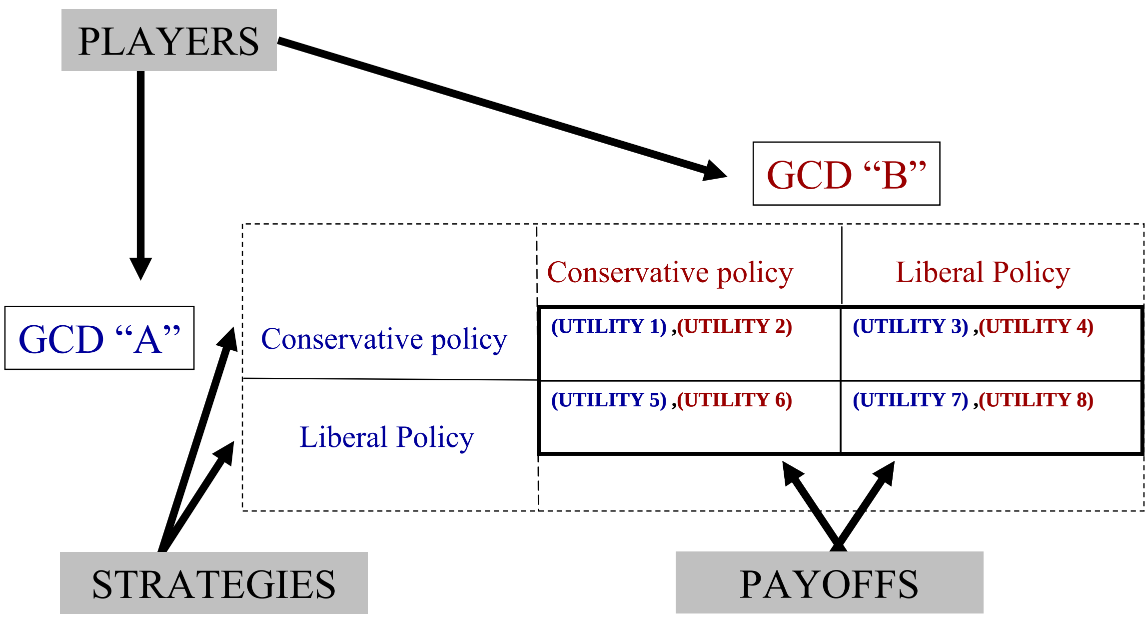

Figure 2: Schematic of a two player payoff matrix

It is important to note that this payoff can be easily modified to reflect the orientation and the risk preferences of a GCD by adequately incorporating weights for Q and h in the identified payoff ratio. In some cases the payoff function can also be an aggregate of sub-payoff functions.

Game-theory provides a simple yet effective tool that can model the interaction between various GCDs. It is concerned with identifying the impacts triggered by the actions of the neighboring GCDs while a GCD is formulating its own policy. This framework enables the GCDs to choose the best possible strategies (dominant and closer to optimality) given the potential policy choices by the neighboring GCDs. A strategy is dominant if it outperforms all other choices no matter what opposing players do. This approach helps the GCDs to identify the dominant strategies (both strict and weak) of theirs as well as their neighbors and provides the insight that both the GCD and their neighbors will try to adopt their dominant strategies. From a policy standpoint, this approach also emphasizes the fact that optimality can be relative and is generally difficult to define the best possible outcome for a GCD without considering the impacts of the externalities caused by their neighbors. The value of game-theoretic approaches lies in its ability to provide insights that are easy to discern by the decision makers. Based on the above discussion, a broad overview of the steps needed in the development of a game-theoretic tool is depicted in Figure 3.

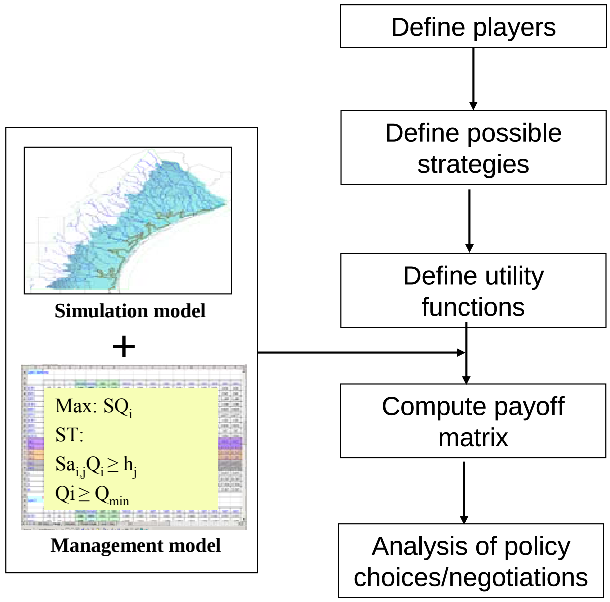

Figure 3: Overview of the development of a game theory based groundwater management tool

Three case studies illustrating the application of game theory based tools for groundwater management in the Gulf Coast aquifer of Texas are presented next.

Illustrative Case Studies:
Background:
The game-theoretic will be demonstrated in the coastal bend region of south-Texas particularly focusing on the three-county area of Bee, Goliad and Refugio. The groundwater flow gradient is typically from north-west to south-east towards the Gulf of Mexico (Chowdhury et al., 2004; Uddameri and Kuchanur 2006). The Mission river flows across all the three counties and is depicted in Figure 4

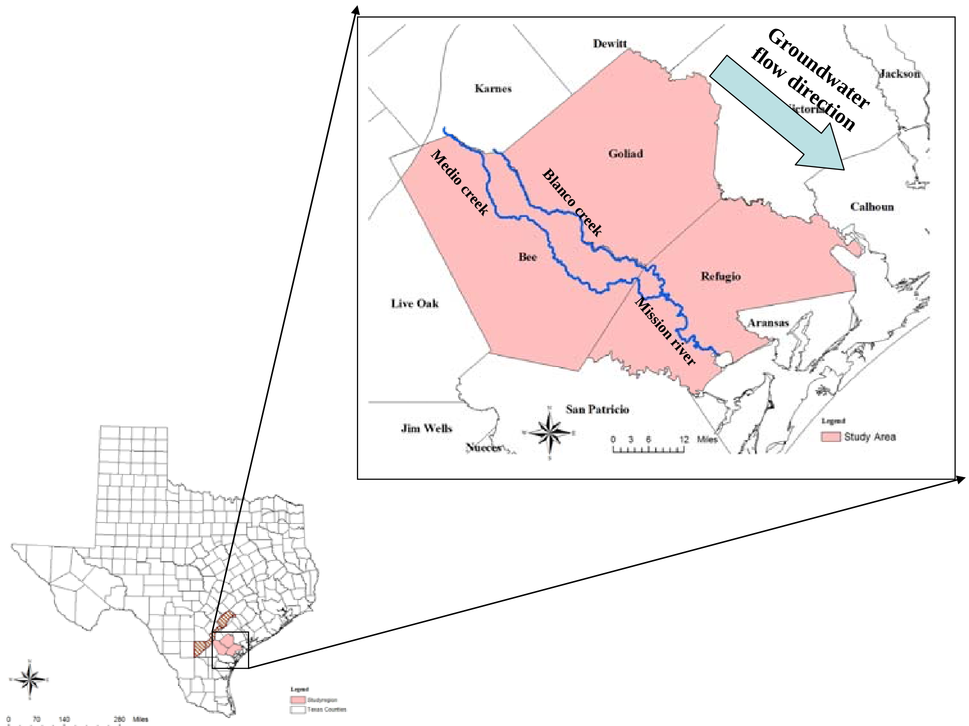

Figure 4: Three-County study region

The water demand in all the three counties almost remains constant for the next 50 years (TWDB, 2002). Municipal, irrigation and livestock are the major water demand categories. The sandy Evangeline aquifer outcrops in the Bee and Goliad Counties (Figure 3.4) and also acts as a major source of recharge for the deeper Evangeline aquifer underlying Refugio County. Refugio County consists of the outcrops of Chicot formation which is mainly the Beaumont and the upper Lissie sand deposits. The interconnected nature of the aquifer formation with all the relevant hydrologic processes in the region is depicted in Figure 5.

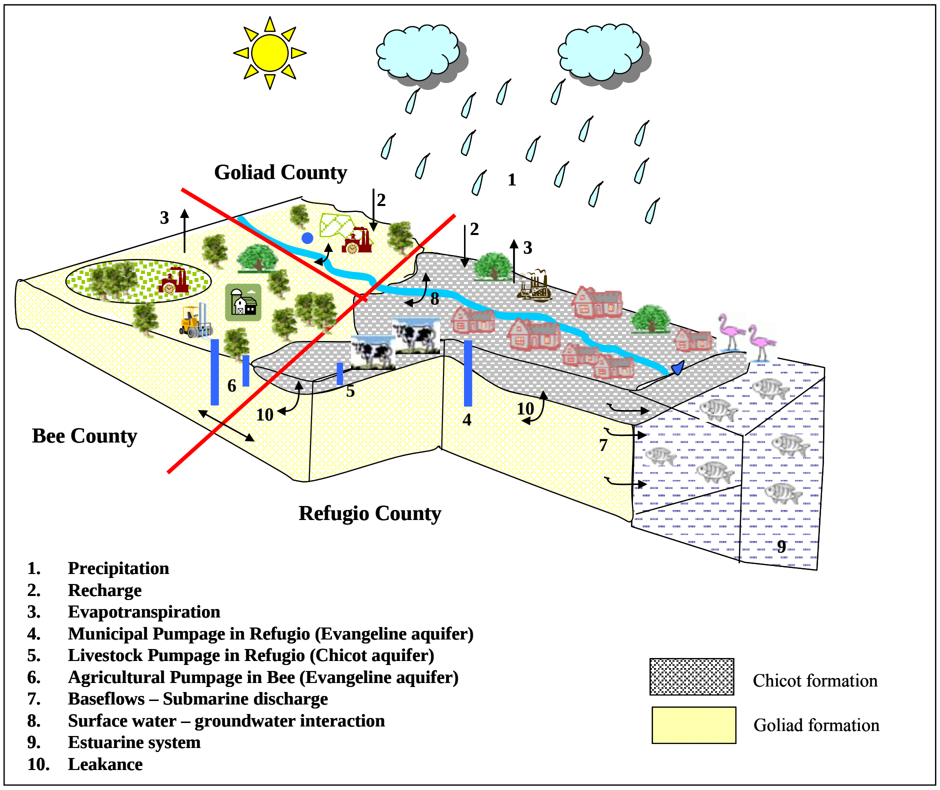

Figure 5: Depiction of aquifer formations and key hydrologic processes

Considering the hydrogeologic studies carried out by Mason (1963), the Evangeline aquifer is found to be more prolific and any future groundwater development projects may be located in the Evangeline formation. However, any such development in a larger scale even in any of one of these counties will affect the groundwater dynamics in the other two counties. For example, a proposed large scale development in the deeper Evangeline aquifer in Refugio County may affect the drawdowns at the wells located in the shallow Evangeline aquifer in Bee and Goliad Counties. Also, if the proposed groundwater development is carried out improperly it may affect the regional flow gradients and consequently the baseflows to the Mission river which flows through all the three counties. Though the aquifer is shared by all the three counties, the concerns and views of the stakeholders towards future large-scale need not be the same. For example, due to the proximity of Refugio to the coast, the foremost concerns for this GCD may be potential saltwater intrusion, reduction in baseflows to Copano and Aransas bays. These concerns may or may not be shared by Bee and Goliad GCD depending on their risk as well subjective preferences. But, understanding these interactions are crucial for regional-scale sustainable growth. The potential policy choices for these counties and the associated payoffs and interactions among them using game theory are presented next.

Players:

In this case study the defined players are (1) Bee GCD, (2) Goliad GCD and (3) Refugio GCD. The individual GCDs assumed to be rational and seek to play in a manner which maximizes their own payoffs. There are three illustrative two-player case studies presented in this research study. The players in these case studies are presented in Table 1

Table 1: Players in the case studies

Case Study	Players (GCDs) involved
Case study: I	Refugio and Goliad
Case study: II	Bee and Refugio
Case study: III	Bee and Goliad

Strategies:

A strategy is a complete plan of choices, one for each decision point of the player. Considering the infrastructure costs involved and administrative challenges in changing an implemented groundwater management the case studies assume that there is only one decision point for each player. Some of the strategies deliberated by a GCD are depicted in Figure 1. Based on these possible choices five games were designed for each of the case studies to obtain relevant insights on the interactive impacts of these potential management policies. For illustrative purposes, the GCDs are assumed to have 6 policy choices

(i) To allow the development of groundwater within the jurisdiction of a GCD
(ii) Not to allow the development of groundwater within the jurisdiction of a GCD
(iii) Adopt a conservative management policy; where the allowed drawdown should not be greater than 5 ft.
(iv) Adopt a liberal management policy; where the allowed drawdown should not be greater than 25 ft.
(v) To honor the management of the neighbor(s).
(vi) Not to honor the management of the neighbor(s).

A total of 15 games were designed incorporating a variety of combinations of the above strategies and is listed in Table 2.

Table 2: List of illustrative games

Game	Strategy
	Case study : I **Players: Refugio and Goliad**
1	Groundwater development is only in Refugio and Refugio decides not to honor Goliad's management policies
2	Groundwater development is only in Goliad and Goliad decides not to honor Goliad's management policies
3	Groundwater development is only in Refugio and Refugio decides to honor Goliad's management policies
4	Groundwater development is only in Goliad and Goliad decides to honor Goliad's management policies
5	Groundwater development is in both Refugio and Goliad. Both the counties decide to honor their neighbor's policies.
	Case study : II **Players: Bee and Refugio**
6	Groundwater development is only in Bee and Bee decides not to honor Refugio's management policies
7	Groundwater development is only in Refugio and Refugio decides not to honor Bee's management policies
8	Groundwater development is only in Bee and Bee decides to honor Refugio's management policies
9	Groundwater development is only in Refugio and Refugio decides to honor Bee's management policies
10	Groundwater development is in both Bee and Refugio. Both the counties decide to honor their neighbor's policies.
	Case study : II **Players: Bee and Goliad**
11	Groundwater development is only in Bee and Bee decides not to honor Goliad's management policies
12	Groundwater development is only in Goliad and Goliad decides not to honor Bee's management policies
13	Groundwater development is only in Bee and Bee decides to honor Goliad's management policies
14	Groundwater development is only in Goliad and Refugio decides to honor Bee's management policies
15	Groundwater development is in both Bee and Goliad. Both the counties decide to honor their neighbor's policies

Payoff matrix:
The ratio between the amount of groundwater pumped (Q in ac-ft/year) to the levels of average drawdown (h in ft) induced by this pumpage is defined in this case study as the payoff for the GCDs.

$$Payoff = \frac{\textit{Total amount groundwater pumped from a GCD}(Q \text{ in ac - ft/year})}{\text{Average drawdown induced by Q in the GCD (h in ft)}}$$

The simulation optimization approach as illustrated in Uddameri and Kuchanur 2006; and Uddameri et al., 2006 is used to calculate the amount of groundwater pumped and the average drawdowns in the monitoring locations.

The steady-state Central Gulf Coast aquifer Groundwater Availability Model developed by the TWDB (Chowdhury et al., 2004) was used as the simulation model. In order to calculate the payoff matrices and to model the strategic interactions between the three GCDs a management schematic was developed as depicted in Figures 6 and 7. A total of 51 well fields were selected with 17 in each county. Nine well fields (3 in each county) were located in the Chicot aquifer. The remaining 42 well fields (14 in each county) were located in the Evangeline formation. Monitoring locations were also identified to be uniformly located near the county boundaries in such a way to monitor the drawdowns near the boundaries. Ten monitoring wells were located in Chicot formation and 18 monitoring wells were located in Evangeline aquifer. The identified well fields are hypothetical and these are used only for the illustrative purposes of this dissertation.

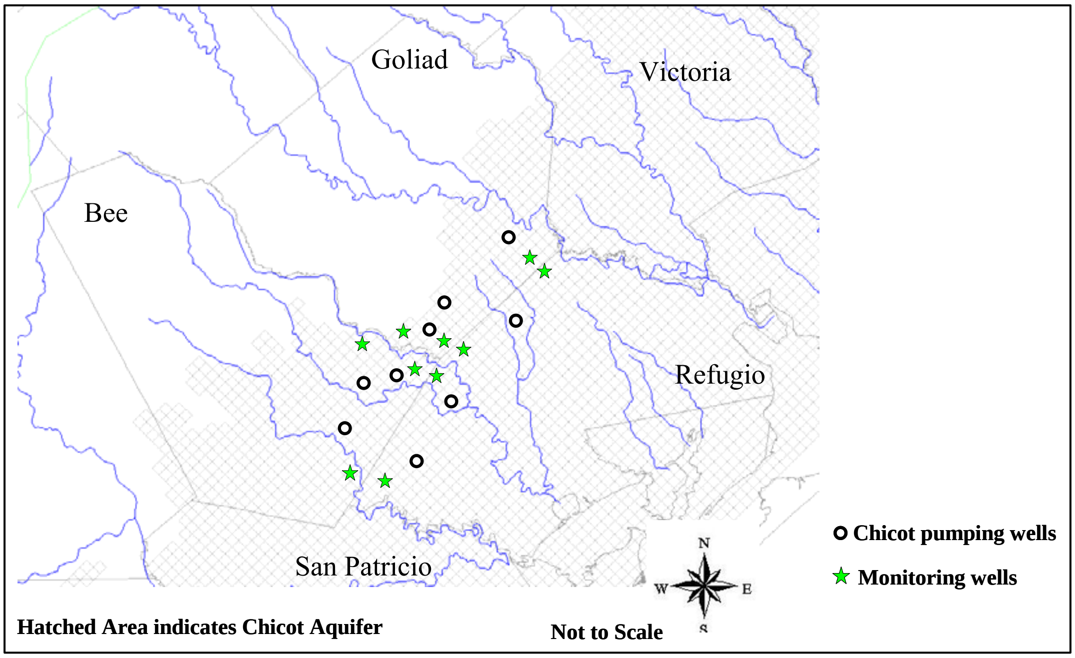

Figure 6: Location of pumping and monitoring wells in Chicot aquifer

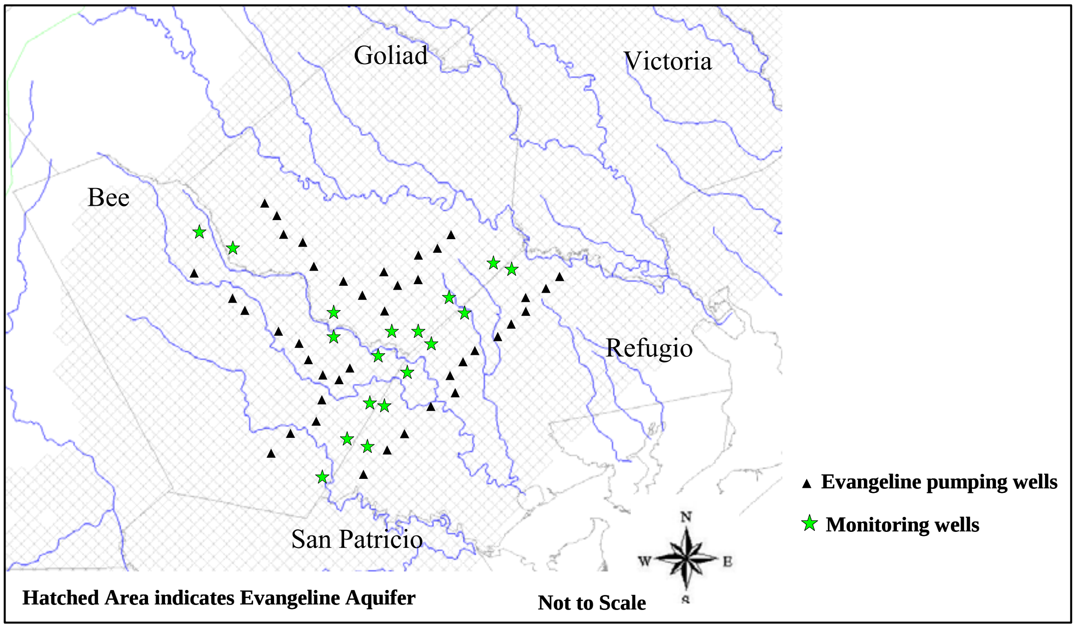

Figure 7: Location of pumping and monitoring wells in Evangeline aquifer

The optimization model used in the case studies is mathematically represented as:

$$Max\ :\ \sum_{i=1}^{i=17} Q_{i,GCD} \quad \text{...} (1)$$

Where,

i is the number of pumping wells
GCD represents the pumping wells in Refugio for games 1,3,7,9
GCD represents the pumping wells in Goliad for games 2, 4, 12, 14
GCD represents the pumping wells in Bee for games 6, 8, 11, 13
GCD represents the pumping wells in Refugio and Goliad for game 5
GCD represents the pumping wells in Bee and Refugio for game 10
GCD represents the pumping wells in Bee and Goliad for game 15

Subject to:
Constraints:

$$DD_{AP,1,k,GCD} \leq \Delta \ \forall \ and \ k = 1,2,3; \{GCD = Player1, Player2\} \quad \text{.........................} (2)$$

$$DD_{AP,2,k,GCD} \leq \Delta \ \forall \ and \ k = 1,,...,6; \{GCD = Player1, Player2\} \quad \text{.........................} (3)$$

$$Q_{i,GCD} \geq Q_{\min,i,GCD} \quad \forall \ i = 1,...,34; \{GCD = Player1, Player2\} \quad \text{.........................} (4)$$

Equation (1) represents the objective of maximizing the amount of groundwater that can be safely pumped (Q) from the aquifer. The objective function includes only the pumpage from wells in a GCD where groundwater development is allowed. The drawdowns in the monitoring locations in Chicot and Evangeline formations are captured by equations 2 and 3 respectively. The value of Δ is 5 ft if the policy of the player is conservative or 25 ft in the case of a liberal management policy and Δ can also be changed to any value depending on the preferences of a GCD. If a player (GCD) decides to honor their neighbor's policy then the constraints set by both the players (player 1 and player 2) should be met. If the chosen strategy of a GCD is not to honor their neighbor's policy then, only the constraints set by the GCD need to be met. The players and the constraints to be included for each game are tabulated in Table 3. Equation 4 indicates the minimum total amount of pumpage from a county in order to render the calculation of payoff ratio as a non-zero numerical value.

Table 3: Objective functions and drawdown constraints

Game	Player 1	Player 2	Objective function (Equation 1) includes the pumping wells in:	Drawdown constraints (Equations 2 and 3) to be met for:
1	Refugio	Goliad	Refugio	Refugio
2	Refugio	Goliad	Goliad	Goliad
3	Refugio	Goliad	Refugio	Refugio and Goliad
4	Refugio	Goliad	Goliad	Refugio and Goliad
5	Refugio	Goliad	Refugio and Goliad	Refugio and Goliad
6	Bee	Refugio	Bee	Bee
7	Bee	Refugio	Refugio	Refugio
8	Bee	Refugio	Bee	Bee and Refugio
9	Bee	Refugio	Refugio	Bee and Refugio
10	Bee	Refugio	Bee and Refugio	Bee and Refugio
11	Bee	Goliad	Bee	Bee
12	Bee	Goliad	Goliad	Goliad
13	Bee	Goliad	Bee	Bee and Goliad
14	Bee	Goliad	Goliad	Bee and Goliad
15	Bee	Goliad	Bee and Goliad	Bee and Goliad

Finally, the payoff ratios are calculated using the simulation-optimization approach and are tabulated in a matrix format. The results from the illustrative case studies will be presented next.

Results:

Case study: I – Refugio Vs Goliad

The payoff matrices for case study I (Games 1 to 5) are represented in figure 8. Game 1 considers the scenario where the strategy of Refugio GCD is to allow the development of groundwater and the strategy of Goliad GCD is not to allow the development of groundwater. In this game Refugio GCD does not honor the policy preferences of Goliad. The payoff matrix for game 1 in figure 8 indicates the payoffs for Refugio and Goliad under both conservative (5 ft average drawdown) and liberal (25 ft average drawdown) management choices set by Refugio GCD. The payoffs for Refugio in this game are more than Goliad; however the payoff decreases when Refugio opts for a liberal management strategy. Further analysis indicated that though the amount of groundwater pumped increases, the ratio of this increase over the drawdown values make the payoff to decrease to a lower value than the payoff under the conservative management scenario. Similarly payoff matrices were also calculated for Games 2, 3, 4 and 5 and are summarized in figure 8.

Game	Payoff matrix

1

		Goliad: No Pumping/No Policy	
Refugio Pumping	Conservative policy	1675,63	
	Liberal Policy	1579,13	

2

	Goliad Pumping: Conservative policy	Goliad Pumping: Liberal Policy
Refugio No Pumping/No Policy	174,8353	39,8698

3

		Goliad No Pumping: Conservative policy	Goliad No Pumping: Liberal Policy
Refugio Pumping	Conservative policy	1675,62	1675,62
	Liberal Policy	1426,47	1579,13

4

		Goliad Pumping: Conservative policy	Goliad Pumping: Liberal Policy
Refugio No Pumping	Conservative policy	174,8353	40,8853
	Liberal Policy	174,8353	39,8698

5

		Goliad Pumping: Conservative policy	Goliad Pumping: Liberal Policy
Refugio Pumping	Conservative policy	1531,6938	50,8854
	Liberal Policy	1471,6121	1449,7149

Figure 8: Payoff matrices for case study I

Games 1 to 4 are designed with an assumption that groundwater development is carried in only in one of the counties. The GCD that allowed the development of groundwater ended up with a higher payoff in all these cases. In reality this may not be the case, however these games will help the decision makers to identify the minimum-most and the maximum possible payoff that can be obtained for their GCD. Game 5 is a more realistic scenario where the groundwater development is in both the counties and the GCDs honor their neighbor's policies. From the payoff matrix, it can be noted that the payoffs for Refugio are lower than Goliad irrespective of their strategies; which is a reflection of the hydro-geologic conditions in this region. This is an example of a lop-sided game where the payoffs of one player completely outplay the other under all strategies considered.

Typically, the preferred strategy of a player is to choose a point of equilibrium. This point is called as Nash equilibrium or strategic equilibrium (Owen 1982, Nash, 1950). Nash equilibrium is a pair of strategies with the property that none of the players would be able to increase their payoffs by switching strategies unless others did. Nash equilibrium can be calculated by either a simple cell by cell inspection or using the iterated elimination of strictly dominated strategies. A strategy is dominated if there is some other strategy which always does better. For example in game 5, the conservative strategy of Goliad always yields a lesser payoff to Goliad irrespective of the strategies of Refugio. Therefore, the conservative strategy of Goliad is strictly dominated by the liberal strategy and it is eliminated. Then, the comparison of payoffs for Refugio's strategies indicate that the conservative strategy of Refugio is dominated by their liberal strategy. The eliminations carried out indicate that the pair of liberal policy of Goliad and liberal policy of Refugio turns out to be the equilibrium point in this game under the given conditions (Figure 9). In other words, this pair of strategies has the property that no player can unilaterally change their strategy and get a better payoff.

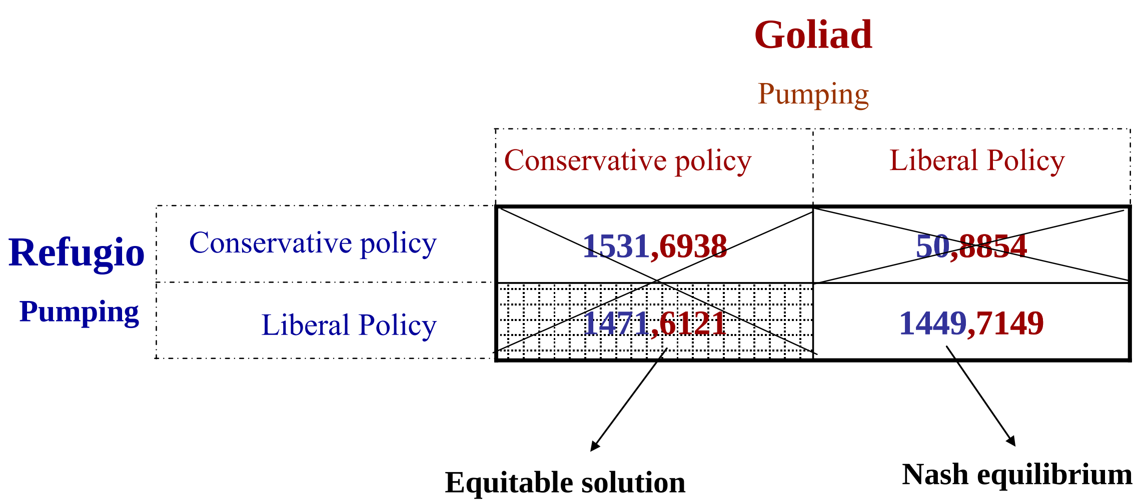

Figure 9: Nash equilibrium and equitable solution for game 5

Social/economic equity is an impact aspect of sustainable solutions. The equity of a solution can be computed by taking into account the difference in payoffs between the players for a particular strategy. A minimal difference in the payoffs between the players indicates a more equitable solution. An equitable payoff may also result in consensus and will reduce standoffs and possible legal disputes between the players. From figure 9, it can be noted that the difference in payoffs (surrogate for equity) is found to be minimal when Refugio adopts a liberal policy and Goliad a conservative policy. Thus, it can also be noted that equitable solution may be different from the equilibrium solution.

As can be seen from figure 9, the players do not achieve their maximum payoffs by adopting equilibrium or equitable solutions. There is a reduction in the payoff (also referred as regret) by not adopting the strategy that can yield the maximum most payoff. In this game, Goliad has a regret of 1705 (8854-7149) for adopting the equilibrium solution and a regret of 2733 (8854-6121) for adopting the equitable solution. Similarly, Refugio has regret of 82 (1531-1449) for adopting the equilibrium solution and a regret of 60 (1531-1471) for adopting the equitable solution. Thus, in the case of Goliad adopting an equitable solution generates a higher regret than adopting the equilibrium solution but in the case of Refugio agreeing to an equilibrium solution has a higher regret. This is also an indicator of the existing hydro-geologic conditions in these counties. As Goliad is located in the recharge region, adopting an equilibrium stance yields a higher payoff. However, the scenario of Refugio following a liberal strategy when Goliad adopting a conservative management strategy increases the payoffs of Refugio (as drawdown impacts in Refugio caused by Goliad are reduced) and thus yielding a more equitable solution. While moving from equilibrium to an equitable solution the net regret for Goliad is -1028 but the payoffs of Refugio increase by 22.

Case study: II – Bee Vs Refugio

The results of this case study are also observed to be similar to case study I and the results are depicted in figure 10. In games 6, 7, 8 and 9 the groundwater development is assumed to be only either in Bee or Refugio. The results from these games indicate the payoffs are always higher in the county where development is allowed under the given conditions. Game 10 is a more realistic scenario in which groundwater development is allowed in both the counties and the counties also decide to honor their neighbor's policies. From the payoff matrix of game 10, it can be inferred that this game is also a lop-sided game and the payoff of Bee always out-perform the payoff of Refugio GCD. A comparison between the payoffs of Refugio between games 5 and 10 indicates that Goliad's policy preferences have a higher impact on Refugio, when Refugio has a conservative strategy. But, When Refugio has a liberal management policy; the policy preferences of Bee GCD have a higher impact on the payoffs of Refugio.

Game	Payoff matrix

Game 6

		Refugio	
		No Pumping/No Policy	
Bee Pumping	Conservative policy	(6273,74)	
	Liberal Policy	(6236,15)	

Game 7

	Refugio Pumping: Conservative policy	Refugio Pumping: Liberal Policy
Bee No Pumping/No Policy	(75 , 1675)	(15, 1579)

Game 8

		Refugio No Pumping: Conservative policy	Refugio No Pumping: Liberal Policy
Bee	Conservative policy	6273,74	6273,74
	Liberal Policy	10738,55	6236,15

Game 9

		Refugio Pumping: Conservative policy	Refugio Pumping: Liberal Policy
Bee No Pumping	Conservative policy	75,1675	55,1843
	Liberal Policy	75,1675	15,1579

Game 10

		Refugio Pumping: Conservative policy	Refugio Pumping: Liberal Policy
Bee Pumping	Conservative policy	6162,1087	6042,2013
	Liberal Policy	10466,853	6140,962

Figure 10: Payoff matrices for case study II

The Nash equilibrium for game 10 is calculated using the iterated elimination of strictly dominated strategies and is denoted in Figure 11. The conservative policy of Refugio is strictly dominated by its liberal policy. Therefore, the conservative strategy of Refugio is eliminated. Then, the payoffs of Bee were compared and the conservative policy choice is also eliminated. Thus, the Nash equilibrium in game 10 is also similar to game 5 and the both the GCDs are expected to choose a liberal management strategy to achieve equilibrium.

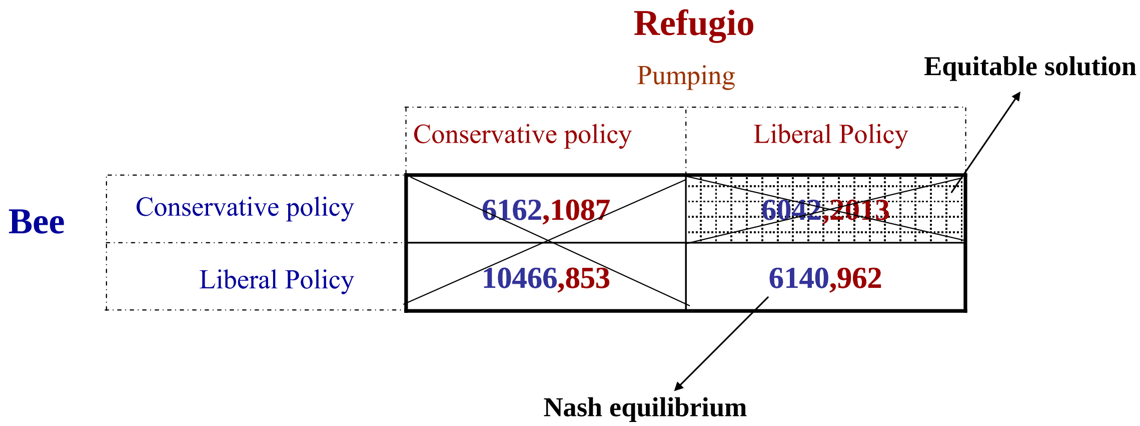

Figure 11: Nash equilibrium and equitable solution for game 10

From figure 11, it can be noted that the difference in payoffs is found to be minimal when Refugio adopts a liberal policy and Bee a conservative policy. As can be seen from figure11, Bee has a regret of 4326 (10466-6140) for adopting the equilibrium solution and a regret of 4424 (10466- 6042) for adopting the equitable solution. Similarly, Refugio has regret of 1051 (2013-962) for adopting the equilibrium solution. However, in this game the maximum payoff is incidentally associated with the equitable solution. Therefore, Refugio has zero regret for adopting the equitable solution.

In the case of Bee adopting an equitable solution generates a higher regret than adopting the equilibrium solution but in the case of Refugio agreeing to an equilibrium solution has a higher regret. While moving from equilibrium to an equitable solution the net regret for Goliad is -98 but the payoffs of Refugio increase more than twice the equilibrium payoff.

Case study: II – Bee Vs Goliad

This illustrative case is also designed with 5 games (games 11 to 15) and the payoff matrices are shown in figure 12. In games 11 and 13 the development of groundwater is only in Bee and the payoff matrices indicate that irrespective of Bee GCD's policy behaviors towards Goliad, the payoffs of Bee tend to remain higher. Similarly, in games 12 and 14 the payoffs of Goliad are always higher. Game 15 which is a more realistic case, the payoff matrix indicate that the payoff of a GCD is higher if it has a liberal management policy and the neighboring GCD has a conservative policy. However the calculation of Nash equilibrium indicates that both the GCDs will tend to adopt liberal strategies under the given conditions.

Game	Payoff matrix
11	see below
12	see below
13	see below
14	see below
15	see below

Game 11

Bee: Pumping	Goliad: No Pumping/No Policy	
Conservative policy	(6273,102)	
Liberal Policy	(6236 ,23)	

Game 12

Bee	Goliad: Pumping – Conservative policy	Goliad: Pumping – Liberal Policy
No Pumping/No Policy	(198 , 8353)	(40, 8698)

Game 13

Bee: Pumping	Goliad: No Pumping – Conservative policy	Goliad: No Pumping – Liberal Policy
Conservative policy	6273,102	6273,102
Liberal Policy	7298,61	6326,23

Game 14

Bee	Goliad: Pumping – Conservative policy	Goliad: Pumping – Liberal Policy
Conservative policy	198,8353	49,8741
Liberal Policy	198,8353	40,8698

Game 15

Bee: Pumping	Goliad: Pumping – Conservative policy	Goliad: Pumping – Liberal Policy
Conservative policy	5551,5951	1841,8467
Liberal Policy	7190,3285	5517,6208

Figure 12: Payoff matrices for case study III

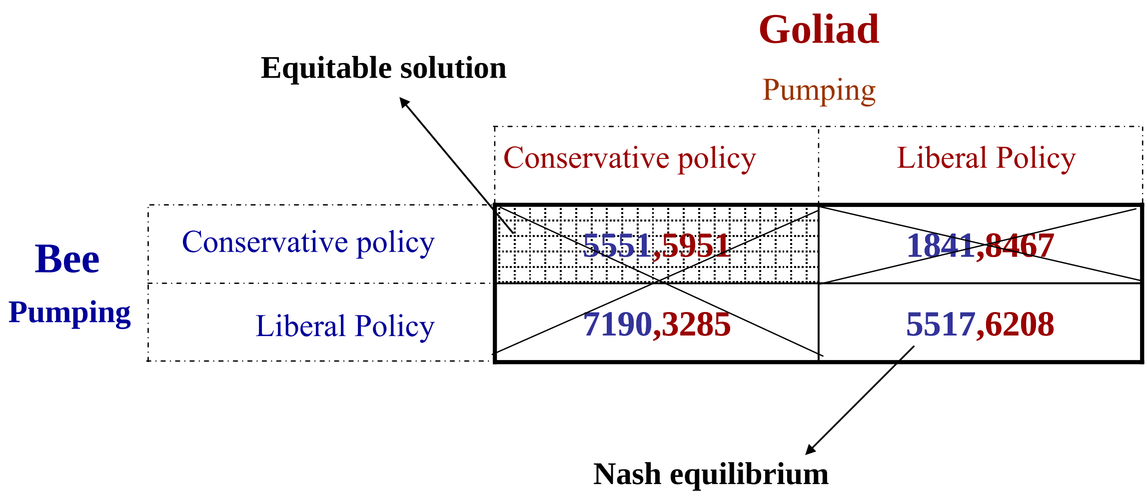

Figure 13: Nash equilibrium for game 15

The result from the Nash equilibrium (figure 13) indicates that for the calculated equilibrium the payoff of Goliad is higher than Bee. Further analysis on the differences between various choices in game 15 indicates that when both the counties have conservative policies, the difference in payoffs between them is less and thus an equitable solution can be realized. When Bee and Goliad decide to move from the equilibrium solution to a more equitable solution, the regret of Goliad is -257 but the payoffs of Bee increase by 34.

Discussion

In this study, a steady-state regional groundwater model (CGC – GAM) as the basis for development. As such, large-scale groundwater extractions at the management wells were assumed to occur at a continuous rate and the investments for the development of groundwater tend to be fairly large. Hence a change in policy of a GCD in time may face stiff resistance from the investors. Moreover, for long-term policy planning endeavors decision makers must work under the assumption that the groundwater users will utilize all of their permitted withdrawals within the allotted time. However, the same game theoretic approach can be extended to multi-stage games. Multi-stage incorporates the option for the GCDs to review and change their strategies if needed after the stipulated planning period (say 10 years). The locations of the identified pumping and monitoring well locations in this study are hypothetical and depending on the real world proposed pumpage projects and mutually agreed monitoring well locations, the results will vary for the GCDs.

The games illustrated in this study are two-player games and can be easily converted to multi-player games as warranted by the hydro-geologic condition. On the other hand, it is important to be borne in mind that the increase in the number of players also increases the complexity and hence affects the understanding and insights that can be obtained by decision makers. Similarly, the strategies of the players are limited to liberal and conservative choices in this study and they can even be varied with a range of choices as indicated by the decision makers (like most conservative, most liberal... etc).

The defined payoff (Q/h) in this study is a simple yet effective surrogate to account for both the economic benefits and the associated environmental impacts. However, in real world scenarios the defined payoff may or may not be the same for all the GCDs. Therefore, different payoff calculations can be used to indicate the different management inclinations of the involved GCDs. The results from this study (figures 9, 11 and 13) indicate that the Nash equilibrium of all these case studies occurs when both the players adopt liberal management policies. This can be attributed to the defined payoff (Q/h) in this study, a different payoff say Q/(2h) or decrease in baseflows may shift the equilibrium to some other policy choice. The highly sensitive nature of game-theoretic approaches with respect to this definition of payoffs should be adequately conveyed to the decision makers. This in-turn will help the GCDs to identify as well refine and quantify their management goals. It is also to be noted that when the players involved do not have the same defined payoffs; then the comparison of the payoffs between players have to be carried with adequate caution in considering the differences in the definitions of the computed payoffs.

Summary and conclusions

The objective of this research was to develop and illustrate a decision support framework to guide the decision makers to assess the sovereign yet highly interactive groundwater management policies. Game theoretic approaches were identified to adequately capture the strategic interactions between the policies of neighboring GCDs. As part of this endeavor three illustrative case studies were developed and 15 games were designed to demonstrate and asses the impacts of policy choices made by one county over the other. The first two case studies (Refugio Vs Goliad and Bee Vs Refugio) were found to be lop-sided and Refugio ended up with lower payoffs irrespective of the management policies of Goliad and Bee GCDs. This was also found to be a reflector of the hydro-geologic conditions, where Bee and Goliad are located in the recharge and Refugio in the discharge area. Refugio outplayed Goliad and Bee GCDs only in the games (1, 3, 7 and 9) where the development was assumed to occur only in Refugio and not in Bee or Goliad. The third case study (Bee Vs Goliad) was found to be an equal strength game where the chances to achieve an optimal or equitable payoff between the GCDs are possible.

The calculations of regret for each GCD indicate that Goliad always incurs regret (decrease in payoff) and Refugio always increases its payoffs when moving from equilibrium to an equitable solution. However, Bee incurs a regret in game 10 (Bee vs. Refugio) but also experiences some minimal gains in game 15 (Bee vs. Goliad) while adopting an equitable strategy instead of equilibrium. Thus, this analysis indicates that the equitable strategy cannot be achieved without some loss in payoffs for Goliad and Bee. As there is an associated reduction in payoffs for Bee and Goliad counties for adopting an equitable solution, it can be inferred from these case studies that Bee and Goliad may prefer to adopt equilibrium strategies and may neglect Refugio's preferences in formulating their management policies. However, it is vital for Refugio to negotiate with both Bee and Goliad to protect its interests. The results also provide an important insight that the gain in payoffs associated with a change in the policy of a GCD does not exactly balance the loss in the payoffs of the neighbor. Thus regional groundwater management is not an exact zero sum game as the gain of one GCD does not translate into an equal loss for the neighboring GCD. Thus the results highlight the importance of joint planning and help the decision makers prioritize their negotiations and tradeoffs.

Game theoretic approaches when used in-tandem with reliable simulation models provides transparent easy-to-use decision support platform to analyze policy interactions. The application of this approach in an interactive mode can help the GCDs to initiate dialogues and move towards groundwater management strategies focused on regional-scale sustainability. Game theoretic tools provide valuable insights as well quantify the increase or decrease in the defined payoffs of a GCD while negotiating with their neighbors on policy tradeoffs.

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Evaluation of Spatial Heterogeneity of Watershed through HRU Concept Using SWAT

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Evaluation of spatial heterogeneity of watershed through HRU concept using SWAT

Xuesong Zhang

Abstract

The accurate simulation of SWAT can assist the government in making correct decisions about water management practices, which are important for human health, agricultural management, industry development, environmental quality, flood risk assessment, and recreation. In this project, the PIs were trying to improve the simulation accuracy of the SWAT model through developing new algorithm to obtain accurate rainfall input. The PIs developed a GIS based automatic rainfall interpolation program which incorporates six interpolation methods to estimate rainfall field for the distributed hydrologic model – SWAT (Soil and Water Assessment Tool). The simulated results show that the areal mean rainfall depths estimated by different methods are similar to each other, while the spatial distribution of a rainfall field could exhibit great differences. The stream flow simulated by the SWAT model is sensitive to rainfall fields estimated by different methods, especially for the daily temporal scale, both hydrograph shape and flow volume could show big differences. The accuracy of rainfall field information is essential for distributed hydrologic modeling, and the tool developed in this study will be useful for accurately estimating rainfall fields. The tools developed in these studies are expected to be used in the HAWQS (Hydrologic and Water Quality System) project supported by the USEPA.

Developing a GIS tool for Accurately Estimating rainfall field for the SWAT model

1. Introduction

Numerous field experiments have revealed that hydrological processes and parameters can show considerable spatial variability (Merz and Bárdossy, 1998). Distributed hydrologic models offer the ability to simulate hydrologic processes using spatially distributed input data, which makes them preferable tools to predict water availability, sediments delivery and nutrients transport at a regional scale for sustainable water resource management, food security, human health and natural ecosystems (Chaplot et al. 2005). As rainfall is one of the primary hydrologic model inputs, it is essential to accurately represent rainfall in time and space for distributed rainfall-runoff modeling. Previous studies have shown that the spatial variability of rainfall fields can have a large influence on simulated runoff volume, time shift of hydrographs, sediment delivery and nutrient yield (Dawdy and Bergman, 1969; Wilson et al., 1979; Troutman, 1983; Duncan et al., 1993; Faurès et al., 1995; Shah et al., 1996a; Shah et al., 1996b; Lopes, 1996; Koren et al., 1999; Chaubey et al., 1999; Arnaud et al., 2002; Merz and Bárdossy, 1998; Smith et al., 2004; Chaplot et al. 2005). Generally, the methods used to study the sensitivity of hydrologic models to spatial rainfall variability are rain gauge network density and rainstorm displacement (Arnaud, et al., 2002). What needs to be noted is that in order to input spatially distributed rainfall into a distributed hydrologic model, the rainfall values at rain gauge points need to be interpolated to estimate rainfall value at the point without observed data. There are many interpolation methods that could be used for rainfall field estimation, and these methods will provide different rainfall fields. The tasks are to find how different the estimated rainfall fields will be and how much impact these differences could exert on distributed hydrologic modeling.

The general methods used by distributed hydrological models to estimate rainfall fields include Thiessen polygon and IDW (Inverse Distance Weighted). For example, SWAT and MIKE SHE use Thiessen Polygon, and VIC uses IDW. The theory of Thiessen polygon and IDW are simple and easy to be realized programmatically, but Goovaerts' (2000) work showed that the accuracy of these two methods is not as good as several other methods, including Linear Regression, Ordinary Kriging, and Simple Kriging with varying local means. Lloyd (2004) also showed that different interpolation methods could vary in accuracy of estimated rainfall distribution. In this work, six different interpolation methods were used: Thiessen polygon and IDW, which are widely used in distributed hydrologic modeling; Spline and Ordinary Kriging, which are widely used to interpolate spatially distributed environmental variables; and Linear Regression and Simple Kriging with varying local means, which incorporate elevation into spatial interpolation. Areal mean, coefficient of variability, and accuracy of rainfall fields predicted by different methods will be calculated and compared. The distributed rainfall fields interpreted by the various methods will be input into a physically based distributed hydrologic model – SWAT (Soil and Water Assessment Tool), and the simulation results will be compared and discussed at the annual, monthly, and daily temporal scales.

2. Materials and Methods

2.1 Study Area Description

The study site was selected at the downstream area of the Luohe River, which is the largest tributary of the downstream Yellow River (YR), whose area is about 5239 km^2. The study area covers the land of 12 cities and counties: Yiyang, Shanxian, Luoning, Ruyang, Yinchuan, Mianchi, Yima, Xinan, Luanchuan, Mengjin, Yanshi and Luoyang, which are characterized by flat alluvial and foothill plains. The average elevation of the Luohe basin is about 520 m. The Luohe River Basin belongs to the warm temperate climate zone with average annual rainfall depth 600 mm. Forty-one rain gauges, located within or around the study area, with daily rainfall records will be used in this study. As shown in Figure 1, the 31 solid circles denote the rain gauges will be used to interpolate rainfall spatial distribution, and the 10 solid triangles on the left denote the rain gauges used to test the accuracy of estimated rainfall field.

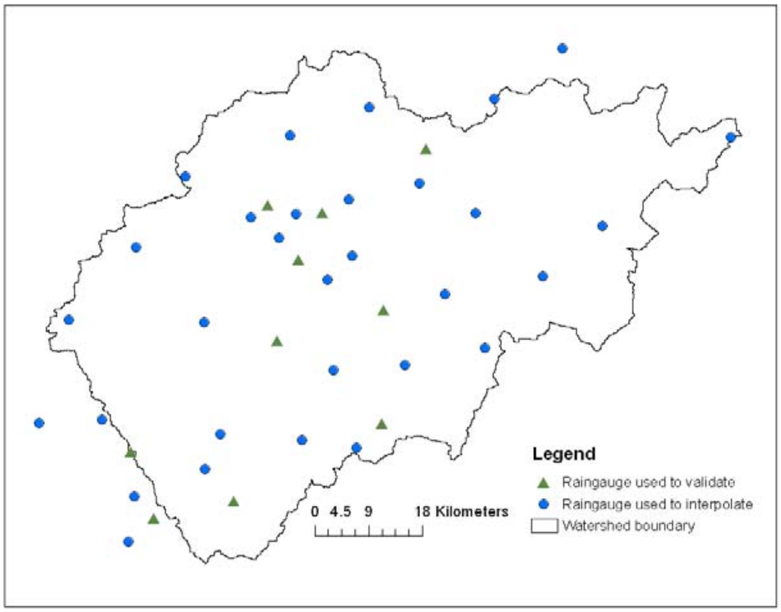

Figure 1. The rain gauges used for rainfall field interpolation and validation.

2.2 Interpolation Methods

2.2.1 *Thiessen Polygon*

Thiessen polygons, also referred to as Voronoi Diagrams, are polygons whose boundaries define the area that is closer to that polygon's centroid point than all other points. Then the point without observed rainfall value will be assigned the closest rain gauge's record (Thiessen, 1911). Let (Z_i, i = 1, … , n) be the set of rainfall data measured at n rain gauges, and here $n = 31$. The rainfall depth Z at an unsampled location *u* is estimated using function below:

$$Z_u = Z_i \quad h_{ui} < h_{uj} \forall i \neq j . \tag{1}$$

where Z_u is the interpolated value, Z_i is the data value of ith sampled location, h_{ui} denotes the distance between unsampled location u and the sampled location i, h_{uj} denotes the distance between unsampled location u and the sampled location j.

2.2.2 Spline

The Spline method uses a basic minimum-curvature technique to interpolate a spatial surface, which 1) passes exactly through the data points, 2) has minimal curvature (ESRI, 2005). The Spline function uses the following formula for the surface interpolation:

$$Z_u = T_u + \sum_{i=1}^{n} \lambda_{ui} R(h_{ui}) \tag{2}$$

Where, Z_u is the interpolated value, n is the number sampled location points, λ_{ui} are coefficients found by the solution of a system of linear equations, h_{ui} is the distance between the unsampled point *u* to the sampled location i. Trend function T_u and generating function $R(h_{ui})$ are determined by the REGULARIZED or TENSION option of Spline. In this work, we use REGULARIZED Spline, which incorporate third derivatives into the smooth seminorm (Mitas and Mitasova, 1988). For detailed introduction to Spline method, please reference to Franke (1982), and Mitas and Mitasova (1988).

2.2.3 IDW

The IDW interpolation method explicitly implements the assumption that things that are close to one another are more alike than those that are farther apart. It weights the points closer to the prediction location greater than those farther away. With inverse distance weighting, data points are weighted during interpolation so that the influence of one data point relative to another declines with distance from the interpolation point:

$$Z_u = \frac{1}{\sum_{i=1}^{n} \lambda_{ui}} \sum_{i=1}^{n} \lambda_{ui} Z_i \qquad \lambda_{ui} = \frac{1}{h_{ui}} \tag{3}$$

where Z_u is the interpolated value, n represents the total number of sample data values around the unsampled location that will be used in interpolation, Z_i is the i th rain gauge value, h_{ui} denotes the separation distance between unsampled location u and the measured data value location i, and λ_{ui} denotes the weight of the i th measured data value.

2.2.4 Kriging

Kriging is an advanced geostatistical procedure that provides a best linear unbiased estimation model. The unknown rainfall depth Z at the unsampled location u is estimated by a linear combination of observed neighboring rain gauge values:

$$Z_u = \sum_{i=1}^{n} \lambda_{ui} Z_i \tag{4}$$

where Z_u and Z_i have the same meaning as described above. Instead of weighting nearby data points by some power of their inverted distance, the Ordinary Kriging relies on the spatial correlation structure of the data to determine the weighting values. Ordinary Kriging determines the weights λ_{ui} under two assumptions: 1) ensuring the unbiased nature of the estimator, $E\{Z_u - Z_u^*\} = 0$; 2) minimizing the estimation variance, $Var\{Z_u - Z_u^*\}$, where Z_u^* denotes the measurement value. Kriging uses semi-variogram to identify the weights of the points that surround the predicted points through solving a series of linear function known as the “Ordinary Kriging system” (Goovaerts, 2000):

$$\sum_{j=1}^{n} \lambda_{uj} \gamma(h_{ij}) - \mu(u) = \gamma(h_{ui}) \quad i = 1,\dots,n \tag{5}$$

$$\sum_{j=1}^{n} \lambda_{uj} = 1 \tag{6}$$

where $\mu(u)$ is the Lagrange parameter accounting for the constraint on the weights. h_{ui} denotes the separation distance between unsampled location u and sampled location i, h_{ij} denotes the separation distance between sampled location i and j. The semi-variogram $\gamma(h)$ is computed using the equation below:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i}^{N(h)} (z_i - z_{i+h})^2 \qquad (7)$$

where h is the difference between two point location, $N(h)$ is the number of pairs of points separated by h, $z_i - z_{i+h}$ is the value difference between point i and another point separated by distance h. For more information on Kriging, please refer to Edward and Srivastava (1989).

2.2.5 Linear Regression

With the orographic effect, rainfall tends to increase with increasing elevation. Hevesi et al. (1992) and Goovaerts (2000) both reported a significant correlation between average annual precipitation and elevation in Nevada and southeastern California, and Aogarve (the most southern region of Portugal) respectively. Goovaerts (2000) also reported average monthly rainfall has close correlation with elevation for most months except for July and August. A simple method to incorporate elevation into rainfall distribution estimation is to develope the linear regression function:

$$Z_u = f(y_u) = a0 + a1 \times y_u \qquad (8)$$

where y_u is the elevation at prediction point u, the $a0$ and $a1$ are regression coefficients estimated with a set of collocated rainfall and elevation data $\{(Z_i, y_i),\ i = 1, \cdots, n)\}$.

2.2.6 Simple Kriging with varying local means

Goovaerts (2000) presented the basic form of Simple Kriging with varying local means (SKlm), which replaces the known stationary mean in the simple Kriging estimate by known varying means m_u derived from the secondary information:

$$Z_u - m_u = \sum_{i=1}^{n} \lambda_{ui}(R_i) \qquad (9)$$

where $R_i = Z_i - m_i$. In this work the local means are derived using linear regression function (8). Then the estimated rainfall at unsampled point u can be expressed as:

$$Z_u = f(y_u) + \sum_{i=1}^{n} \lambda_{ui}(R_i) \qquad (10)$$

where the weights λ_{ui} are obtained by solving the simple Kriging system:

$$\sum_{j=1}^{n} \lambda_{uj} C_R(h_{ji}) = C_R(h_{ui}) \quad i = 1, \cdots, n \qquad (11)$$

where $C_R(h)$ is the covariance function of the residual R_i, not that of Z_i itself (Goovaerts, 2000). And other variables denote the same meaning as stated above. For more detailed information on SKlm, please refer to Goovaerts (1997).

2.3 Distributed hydrologic model

SWAT is a continuous-time, long-term, distributed-parameter model (Arnold et al., 1998). SWAT subdivides a watershed into sub-basins, and further delineates Hyrologic Response Unit

(HRU) consisting of unique combinations of land cover and soils in each sub-basin. HRU delineation can minimize computational costs of simulations by lumping similar soil and land use areas into a single unit (Neitsch et al., 2000). The hydrologic routines within SWAT account for snow fall and snow melt, vadose zone processes (*i.e.*, infiltration, evaporation, plant uptake, lateral flows and percolation), and ground water flows. Surface runoff volume is estimated using a modified version of the SCS CN method (USDA-SCS, 1972). A kinematic storage model (Sloan et al., 1983) is used to predict lateral flow. And return flow is simulated by creating a shallow aquifer (Arnold et al. 1993; Arnold et al., 1998). Channel flood routing uses the Muskingum method. Outflow from a channel is also adjusted for transmission losses, evaporation, diversions, and return flow.

As a physically based distributed model, SWAT needs many input data:

1. Topography: the 1:250,000 DEM obtained from National Geomatics Center of China will be used to provide terrain characteristics of Luohe basin.
2. Soil: the soil map at 1:4,000,000 scale obtained from Institute of Soil Science, Chinese Academy of Sciences (CAS), provides the soil spatial distribution and physical properties like bulk density, texture, saturated conductivity, etc.
3. Land use: Land-use classifications such as cropland, pasture, forest, etc were obtained from Institute of Geographical Sciences and Natural Resources Research, CAS at 1: 1,000,000 scale.
4. Weather: Water Resources Conservancy Committee of the YR basin provided precipitation, air temperature, relative humidity, solar radiation and wind speed, etc.

2.4 GIS based rainfall field interpolation program

GIS is a very powerful tool to facilitate geospatial related research, including spatially interpolated climate data and analysis of storm kinematics (Jeffrey et al., 2001; Tsanis and Gad, 2001). In this work, we wanted to interpolate the daily rainfall in 1991 and output the spatially distributed rainfall into the distributed hydrologic model, which required much manual work. An automatic interpolation program developed as an extension of ArcGIS 9.0 was used to facilitate rainfall field estimation and output job. The function of this GIS based program includes: automaticaly and continuously estimating rainfall distribution using the six interpolation methods described above; calculating each day's areal mean rainfall depth and coefficient of variability (CV) of estimated rainfall fields; validating the accuracy of estimated rainfall fields using Mean Absolute Error (MAE); calculating each hydrologic unit's mean rainfall, which will be input into distributed hydrologic model. Since ArcObject doesn't provide the Simple Kriging estimator, in order to use the SKlm method, the user still has to manually perform the Simple Kriging interpolation procedure using the Geostatistical Analyst extension of ArcGIS. This shortcoming of the program is expected to be overcome when ArcObject provides the Simple Kriging estimator. The general work flow chart of this program is shown in Figure 2. The equations for calculating CV and MAE are:

$$MAE = \frac{1}{n}\sum_{l-1}^{n}\left|Z_i^{\,o} - Z_i^{\,p}\right| \qquad (11)$$

$$CV = \frac{\partial}{z_{ave}} \qquad (12)$$

where Z_i^o is the true rainfall depth value, Z_i^p is estimated value, n is the number of rain gauges used to validate the accuracy of estimated rainfall fields, ∂ is standard deviation of rainfall field and z_{ave} is areal mean rainfall.

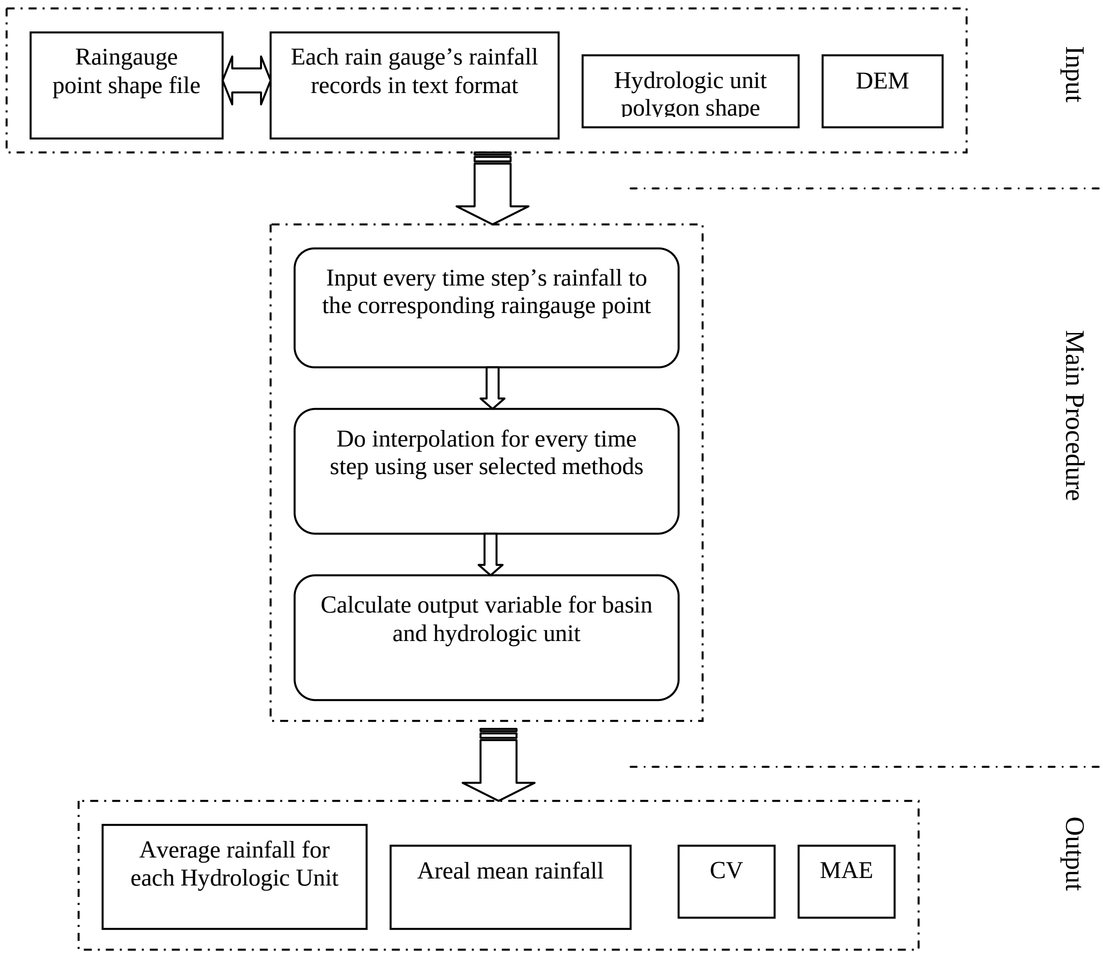

Figure 2. Work flowchart of GIS based interpolation program.

3. Results and Discussion

3.1 Difference between rainfall fields estimated by different methods

The daily rainfall data from the 31 rain gauges in 1991 were used to test the differences between rainfall fields estimated by different methods discussed in section 2.1. The parameters of different methods are listed in Table 1. There were 52 total storms whose rainfall depth was larger than 2 mm, and the accuracy, areal mean and spatial variability of these 52 storms will be compared and discussed.

Table 1. Parameters used by different methods for rainfall field estimation.

Parameters / Methods	Search radius setting (Number of points)	Out put cell size (m)	Others
Thiessen polygon	-	100	-
IDW	12	100	Distance Porwer: 2
Spline	12	100	Spline type: Regularized Weight: 0.1
Linear regression	-	100	-
Kriging	12	100	Semi-variogram model: Spherical
SKlm	12	100	Covariance model: Spherical

3.1.1 Accuracy comparison of different methods

Figure 3 shows the accuracy for rainfall fields estimated by six different interpolation methods. There is no one method that can always predict better results than the other methods. For example, for storm No. 4 Spline gives the worst result, while for storm No.35 it is the best predictor. It's hard to say which method is the best, and different methods may be applicable to predict different types of storms. In order to give a general idea about which method is more reliable, the average MAE for the 52 storms was used to assess performance of different methods. SKlm predicted the smallest average MAE (2.65). Kriging and IDW give similar results (2.77 and 2.80 respectively). Thiessen polygon gives the largest average MAE (3.80). Linear regression and Spline predict 3.23 and 3.75 respectively. This result is similar to Goovaerts' (2000), but the complex geostatistical method SKlm doesn't show much advantage over other methods. The reason maybe that the topography of the study area is not complex, elevation does not change much and has no great impact on rainfall distribution. Since we can't get the actual rainfall field, in the following analysis, we will choose the rainfall field estimated by SKlm as a standard for comparison purposes.

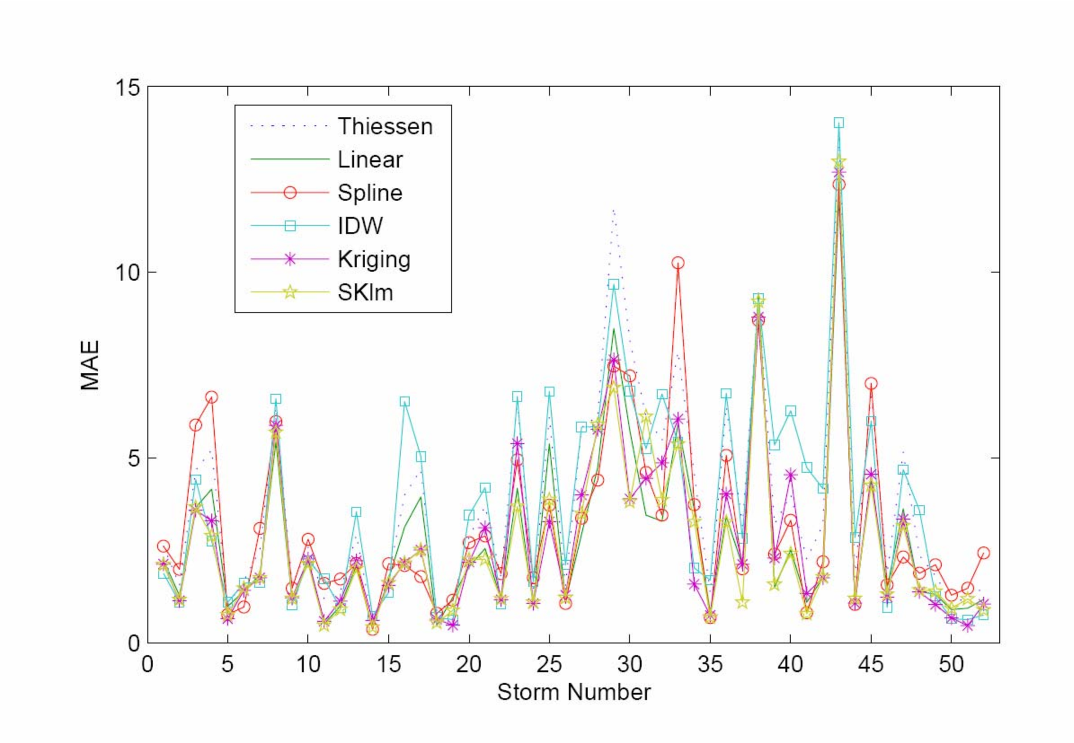

Figure 3. Accuracy of rainfall estimated using different methods for 52 storm events.

3.1.2 Areal mean rainfall

Figure 4 reveals that the areal mean rainfall depths interpreted by different methods are closely related, except for storm No. 31, 32 and 34. Using the areal mean estimated by SKlm as a standard, the relative error of areal mean rainfall for the other five methods was calculated. The absolute relative error for IDW and Kriging is no more than 20%, and for most cases was within 10%. For the Thiessen polygon, Spline and Linear methods, the absolute relative error was always with 25%, and for most cases was within 15%. Generally, there was little variation among areal mean rainfall depths for the different interpolation methods.

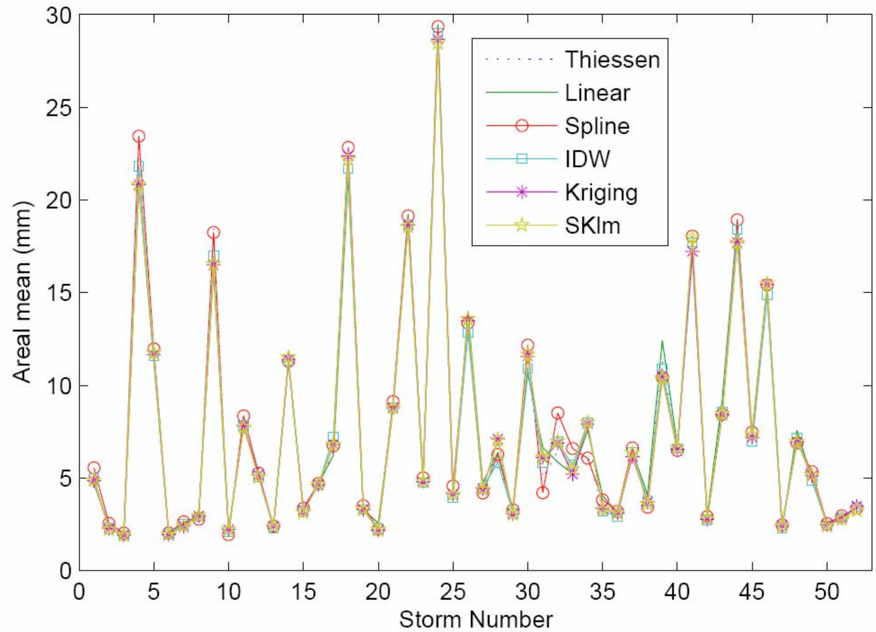

Figure 4. Areal mean rainfall estimated using different methods for 52 storm events.

3.1.3 Spatial distribution of rainfall

The coefficient of variability of the rainfall fields estimated by different methods in Figure 5 shows that different methods can predict different rainfall distribution. Spline predicted the largest rainfall distribution variability for almost all the 52 storms (average CV for 52 storms is 0.93), while Linear regression predicted the lowest average CV value 0.25. Thiessen polygon, IDW, Kriging and SKlm predicted similar CV, 0.71, 0.63, 0.55 and 0.59 respectively. The No. 1 storm event was used as an example to visually show the difference among six interpolated rainfall fields by different methods in Figure 6, and the statistical characteristics of different rainfall fields are listed in Table 2. It's obvious that there is big visual and statistical differences among the rainfall fields estimated by the various methods. Spline even predicted negative value input into hydrologic model, which is set to zero to avoid negative rainfall when input into the SWAT model. And as rainfall has no significant relationship with elevation ($R^2 = 0.06$) for this storm, the spatial pattern predicted by SKlm is different than that of Linear regression. The big difference in spatial patterns of rainfall fields will exert impact on the processes that route a rain drop through the basin.

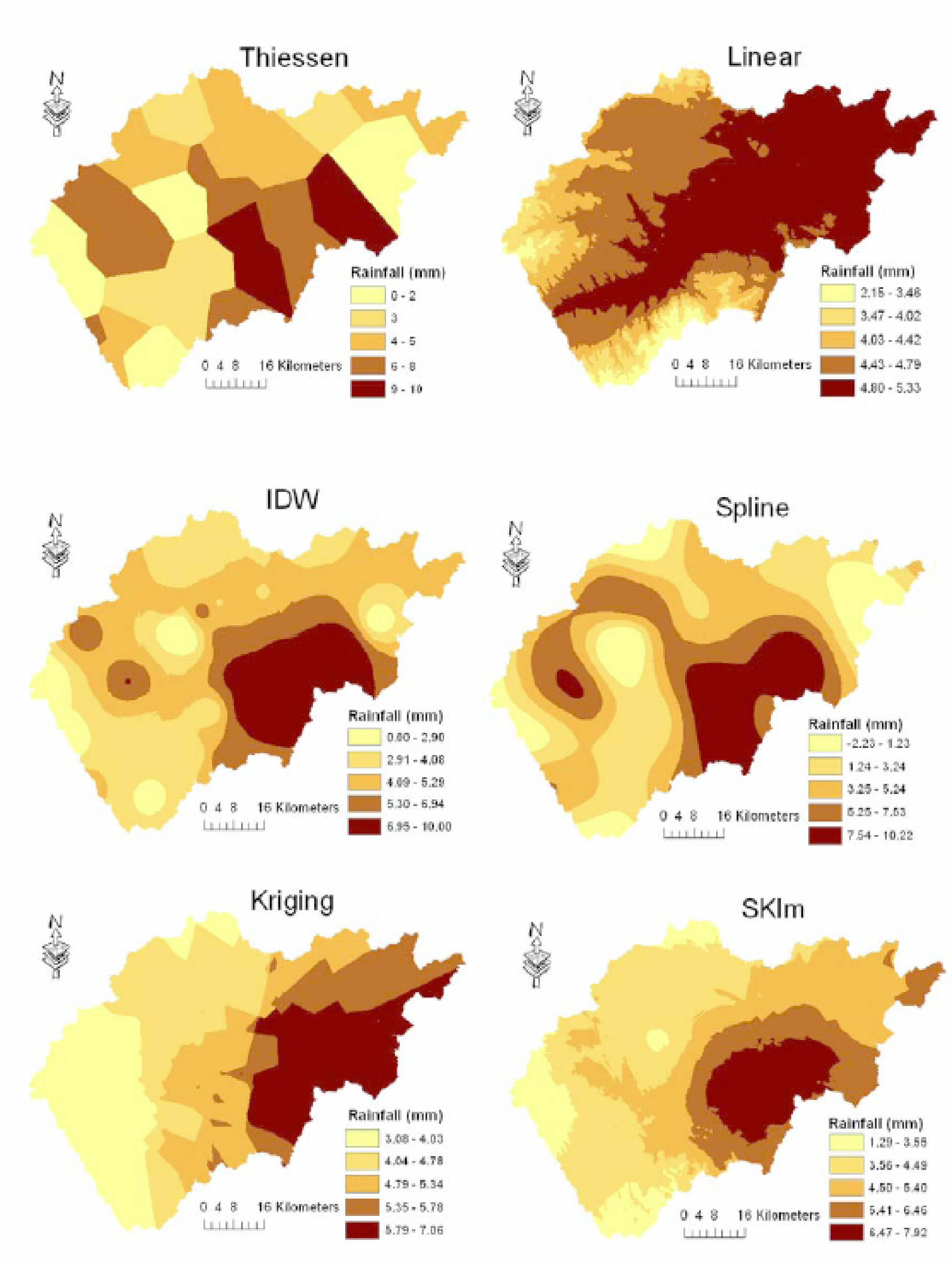

Figure 6. Rainfall fields estimated using different methods.

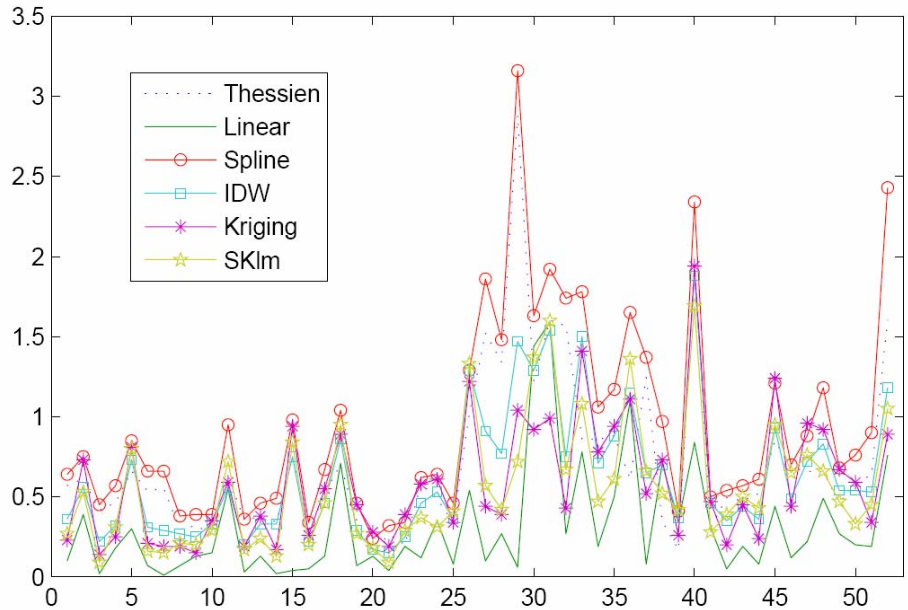

Figure 5. Spatial variability of rainfall filed estimated using different methods for 52 storm events.

Table 2. Statistical characteristic of rainfall field estimated by different methods.

Variable / Methods	Areal mean	CV	Highest value	Lowest value
Thiessen polygon	4.77	0.57	10	0
IDW	4.99	0.36	9.99	0.001
Spline	5.54	0.64	10.2	-2.23
Linear regression	4.63	0.10	5.33	2.15
Kriging	4.85	0.23	7.06	3.08
SKlm	4.87	0.27	7.92	1.28

3.2 Impact of estimated rainfall fields on distributed hydrologic modeling

The outputs from the GIS based interpolation program were input into the SWAT model. Hydrologic modeling of flow at the outlet of the Luohe River was conducted at a daily time scale using daily rainfall data in 1991. In order to reflect differences of estimated rainfall fields on the water yield in the study area, the upstream inflow was not input into model. The parameters used here were the default values in SWAT. The differences of simulated flow were discussed at the annual, monthly and daily temporal scale, and we took the simulated flow with rainfall input interpreted by SKlm as the standard for comparison purpose.

Figure 7 shows the annual flow simulated according to different interpolation methods. The Spline method predicted highest flow volume with relative difference of 25% compared to SKlm. The Thiesen polygon predicted a relative difference of 16%. Linear regression, IDW and Kriging predicted a relative difference within 10%. At the annual temporal scale, the simulated flow volume difference is small.

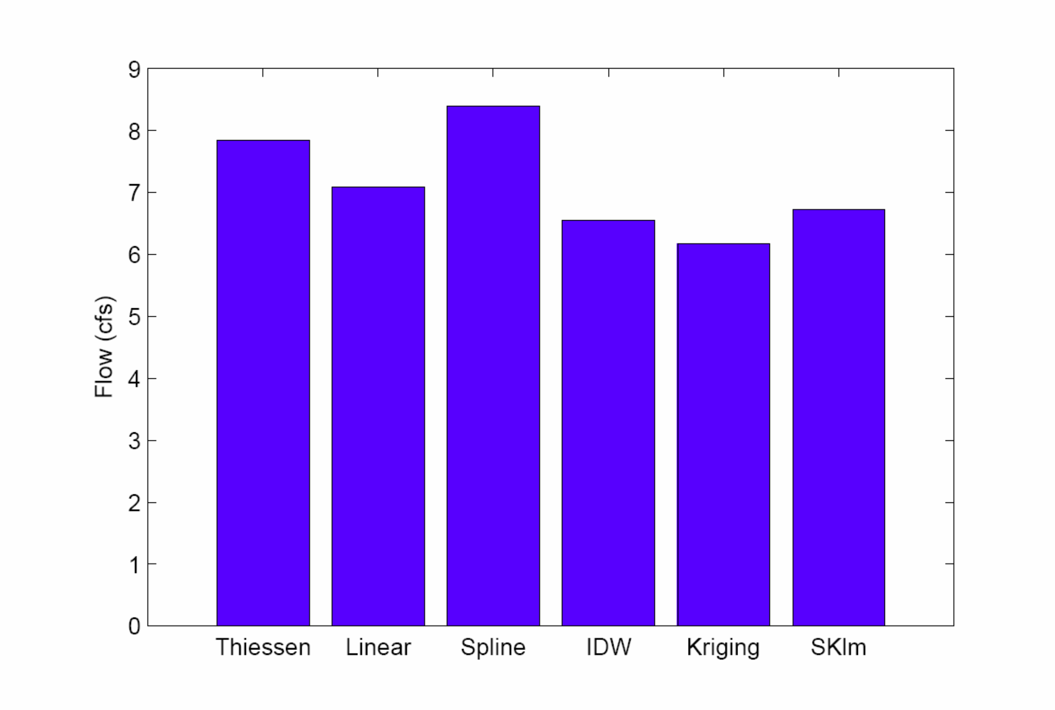

Figure 7. Simulated annual flow volume in 1991 using different interpolation methods.

The simulate monthly flows are shown in Figure 8. The general hydrograph shape simulated according to different rainfall field estimation methods is similar, and the peaks appear at the same month (September). But for each individual month, the simulated flow volume shows obvious differences. For example, in April, the relative difference is 116% for Thiessen polygon, 65% for IDW, 85% for Spline, 33% for Linear regression and -3% for Kriging. The highest flow interpreted by Thiessen polygon reached 4.28m^3/s, while the lowest flow interpreted by Kriging is only 1.9m^3/s in April. And in July, the relative difference is 31% for Thiessen polygon, 7.6% for IDW, 46% for Spline, -7.7% for Linear regression and -15% for Kriging. The difference between Spline and Kriging is 4 m^3/s, which accounts for 50% of the flow volume simulated by Kriging. At the monthly temporal scale, the difference between simulated flows interpreted by different methods is much more appreciable than at annual scale.

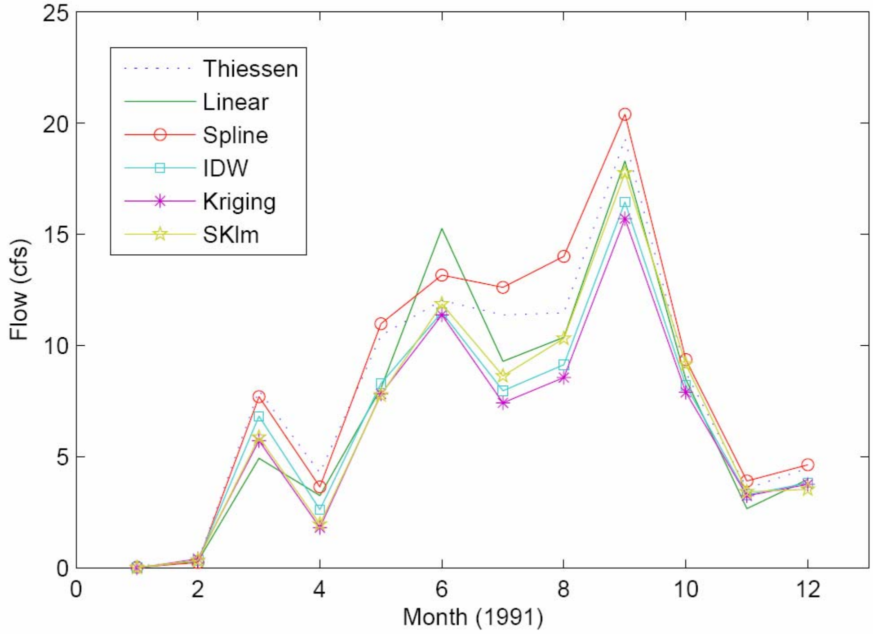

Figure 8. Simulated monthly flow volume in 1991 using different interpolation methods.

Finally, we wanted to examine the simulated daily flow difference. Figure 9 shows the daily flow discharge hydrograph simulated by the SWAT model based on rainfall fields estimated by the different methods. Generally, the hydrographs have similar shape during low flow period, while predicted peak flows show big difference during a flood event. Here we selected daily flows during July as an example to analyze, Figure10. This figure shows that the hydrograph shape estimated by the different methods doesn't correlate well. The peak flow simulated by Thiessen polygon appears on July 23, Linear regression on July 24, Spline on July 19, IDW on July 24, Kriging on July 24, and SKlm on July 23. The flow volume simulated by different methods also shows dramatic differences. For example, on July 19 the Thiessen polygon predicted 32.4 m^3/s, Linear regression 10.7 m^3/s, Spline 46.1 m^3/s, IDW 19.9 m^3/s, Kriging 8.9 m^3/s, and SKlm 10.8 m^3/s. Also significant is that the hydrographs during the flood recession period (July 1 to 14) generally have a similar trend and flow volume, but for the period with a large rainfall storm (July 15 to 20 and July 23 to 28), the hydrographs' shapes and flow volumes have obvious differences. To some extent, we can infer that the hydrograph shape and flow volume difference is mainly caused by surface flow routing during a storm event, while the ground water flow simulated based on different methods doesn't show dramatic differences. In addition, although the accuracy, areal mean rainfall and CV for rainfall field estimated by IDW, Kriging, SKlm are close, we can still see differences in the hydrographs during July 15 to 20 and July 22 to 26.

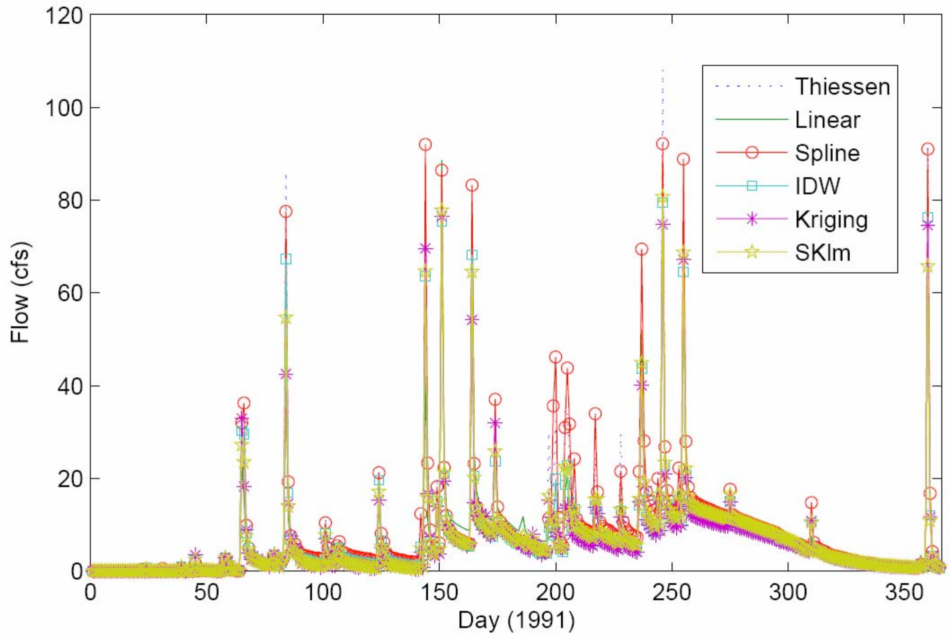

Figure 9. Simulated daily flow volume in 1991 using different interpolation methods.

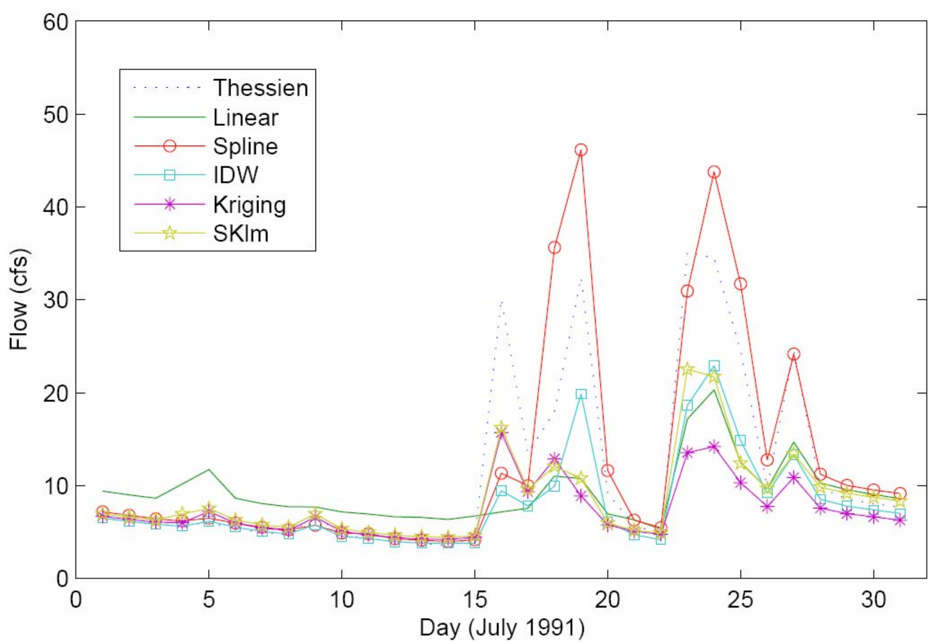

Figure 10. Simulated daily flow volume in July, 1991 using different interpolation methods.

3.3 Discussion

Intuitively, the results described above show that different interpolation method will predict obviously different rainfall field. Based on previous reported results that the spatial variability of rainfall could exert great impact on rainfall-runoff simulation, and combined with the obvious difference of spatial variability of rainfall fields and little difference of areal mean rainfall depth estimated by different interpolation methods (Figure5), it seems that spatial distribution is the major reason explaining the difference of simulated flow. But at same time we should note that distributed hydrologic model describing the basin's dynamic behavior is a nonlinear system, small difference in input data may cause dramatic output change. So according to the results got in this work, we can't exclude the possibility that the small difference of areal mean rainfall may generate greatly different flow. More detailed process based analysis of soil water, evapotranspiration, plant growth, flood routing (overland and channel), and interaction between surface and subsurface water may provide us deeper insight into the mechanism how rainfall depth and spatial distribution impact rainfall-runoff process. Also we should not extrapolate the results got in this work directly to other watershed and distributed hydrologic model. Different types of rainfall-runoff conversion models, characteristic of basin and storm, density of rain gauge network (Arnaud, 2002; Koren, 1999; Smith, 2004) are also the factors need to be considered for explaining hydrologic response.

As we can't get the accurate rainfall field, it's impossible to assess the exact difference between interpolated rainfall field and actual rainfall field. But the average MAE for 52 selected storms show that the difference between the estimated rainfall field and actual one is relatively large, the reason maybe the sparse rain gauge network (31 rain gauges though a 5239 km^2 watershed) used to interpolated rainfall fields. The difference between the highest and lowest average MAE of all interpolation methods is 1.15 mm, which is less than half of the lowest average MAE 2.65 mm. And given the significant difference between flow simulated using different interpolation methods, the difference between the flow simulated using interpolated rainfall field and the flow simulated using actual rainfall field may be more significant.

Since rainfall is a driving force behind many kinds of pollutant release and subsequent transport and spread mechanisms, ignoring this property of rainfall in the application of distributed hydrologic modeling limits the accuracy of the model results (Chaubey et al., 1999). O'Cornell and Todini (1996) suggested using radar and dense network of rain gauge data to gain better capturing of rainfall filed, which seems necessary for model developers and users to reduce rainfall inputs error. As radar and dense network of rain gauge data are difficult to collect, choosing the best interpolation method according to accuracy evaluation maybe an acceptable compromise.

4. Conclusions

In this work, the authors reported the difference of rainfall field estimated by different interpolation methods and to how extent this difference could impact distributed hydrologic simulation in a meso-scale watershed. The objective of this work was realized by combining a GIS based automatic rainfall field interpolation program and distributed hydrologic model – SWAT. The results got in this paper were generalized below.

The estimated 52 storms' rainfall field by six different interpolation methods reveal: 1) The accuracy of rainfall fields estimated by different interpolation could show big difference. Complex geo-statistical methods can provide more accurate results. 2) Areal mean rainfall depth doesn't show big difference between different methods. Compared with the value predicted by SKlm, the relative differences of areal mean rainfall for the other methods are all within 25%. 3) Spatial distribution of rainfall field estimated by different interpolation methods show obvious difference. The highest average CV for 52 storms is 0.93 for Spline method while lowest CV is 0.25 for Linear regression method.

Daily flow simulation using distributed rainfall input estimated by the six interpolation methods were conducted, and the results were analyzed at annual, monthly and daily temporal scale. With the temporal scale decrease from annual to monthly and daily, the variation between simulated flow volumes became more and more obvious, and hydrograph shape simulated at daily time step could show dramatic difference for different methods.

Generally, different interpolation methods could yield obviously different rainfall field, and distributed hydrologic model could be very sensitive to the methods used to interpolate rainfall field. Also it should be noted, the results got in this paper are sensitive to many factors, such as types of distributed hydrologic models, state or parameters of hydrologic model, characteristic of basin, storm property and density of rain gauge network and so on. Much care should be taken when conclusions generalized here be used to different situations.

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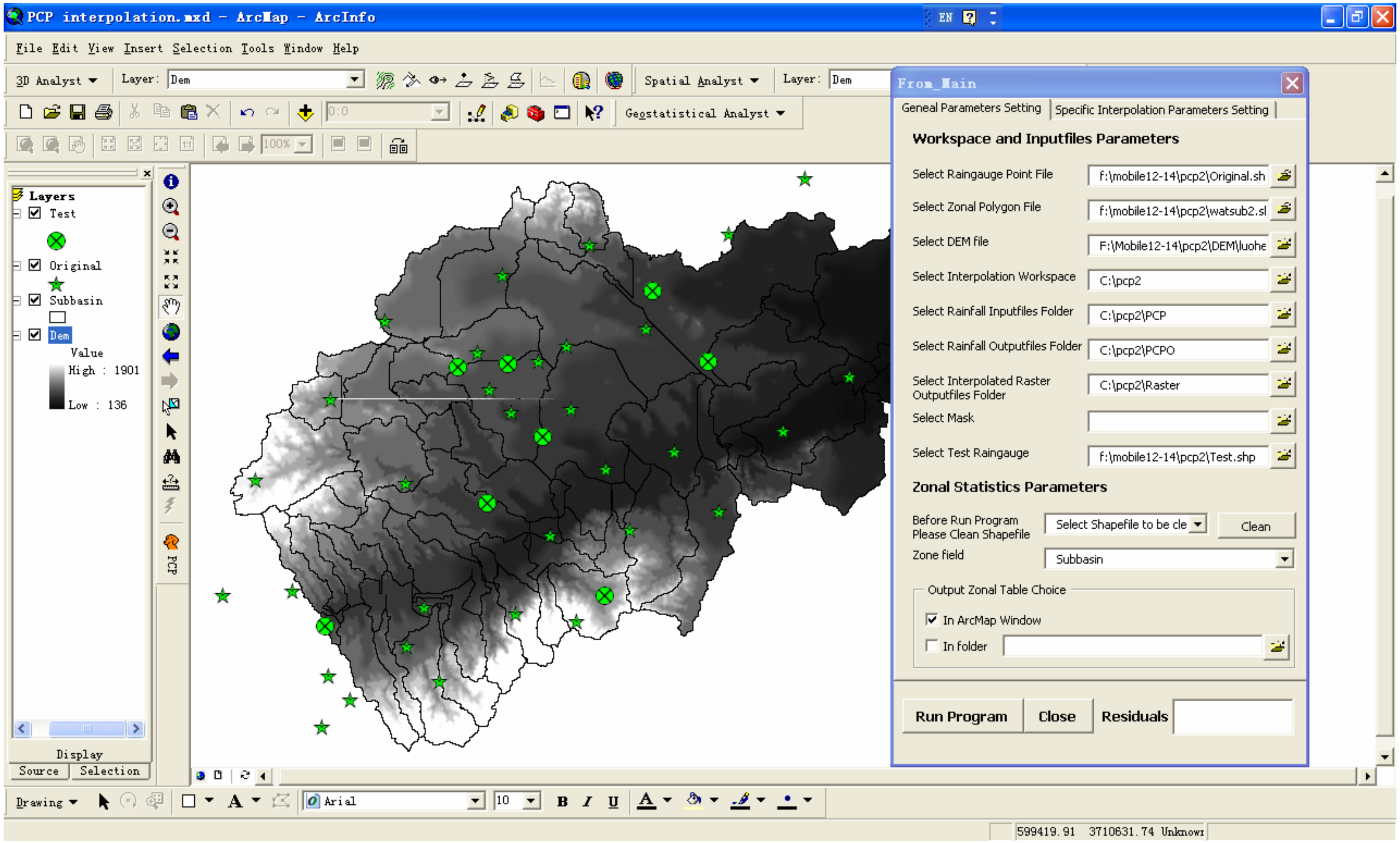
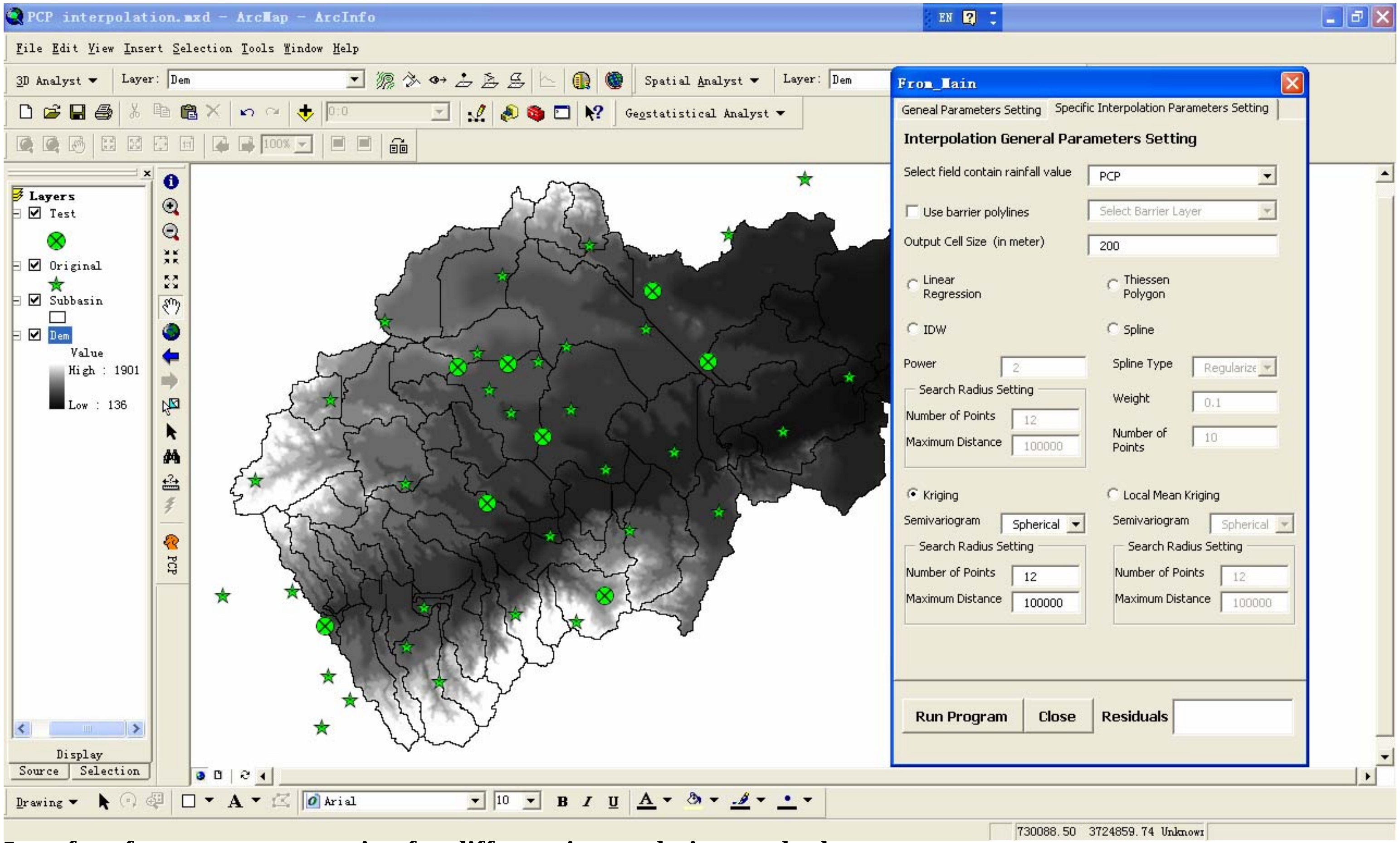
APPENDIX I – GIS INTERFACE FOR AUTOMATIC RAINFALL FIELD ESTIMATION PROGRAM



Interface for workspace and input data setting



Interface for parameters setting for different interpolation methods

Information Transfer Program

In 2005, the Texas Water Resources Institute increased its efforts to communicate university-based water resources research and education outreach programs in Texas.

The Institutes communications team revamped its publications vehicles and is now publishing 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.

tx H2O, 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.

Working to get the news out the various publics, the Institute worked with Texas A&M Universitys Agricultural Communications to produce news releases about projects as well as beginning a policy of generating its own written releases. The Institute also sent press packets to 12 targeted news media. The Institute, its projects or researchers had at least 64 mentions in the media.

The Institute developed 14 water education fact sheets to increase the publics understanding of topics such as watersheds, agricultural water use, non-point source pollution, urban pollution, and water conservation. For each of the Institutes project, the institute published one-page fact sheets that explained the purpose, background and objects of the projects. The communications team initiated development of topic or issues fact sheets; drought and golden alga were the first two.

The Institute continues to enhance its Web presence by increasing its Web sites to 16 and continually updating the information contained within the Web sites. The Web site administrator added RSS feed capability to the Institutes site and posted Institute-related news article to the Web site.

Information Transfer

Basic Information

Title:	Information Transfer
Project Number:	2005TX214B
Start Date:	3/1/2005
End Date:	2/28/2006
Funding Source:	104B
Congressional District:	17th
Research Category:	Not Applicable
Focus Category:	Law, Institutions, and Policy, Management and Planning, Water Use
Descriptors:	None
Principal Investigators:	Bill L. Harris, Clint D. Wolfe

Publication

Texas Water Resources Institute
Information Transfer Activities
March 2005 – February 2006

<u>Technical Publications</u>:

TR-290 An Overview of the Operational Characteristics of Selected Irrigation Districts in the Texas Lower Rio Grande Valley: Delta Lake Irrigation District
Clint D. Wolfe, Megan J. Stubbs, M. Edward Rister, Allen W. Sturdivant, Ronald D. Lacewell

TR-288 Economic and Conservation Evaluation of Capital Renovation Projects: United Irrigation District of Hidalgo County (United) - Rehabilitation of Main Canal, Laterals, and Diversion Pump Station - Final
M. Edward Rister, Ronald D. Lacewell, Allen W. Sturdivant

TR-287 Diagnosis and Management of Salinity Problems in Irrigated Pecan Productions
S. Miyamoto

TR-286 Economic and Conservation Evaluation of Capital Renovation Projects; United Irrigation District of Hidalgo County (United): Rehabilitation of Main Canal, Laterals and Diversion Pump Station, Preliminary
M. Edward Rister, Ronald D. Lacewell, Allen W. Sturdivant

TR-285 Management Tools for Aquatic Systems: The Role of Periodic Hydraulic Disturbances on Planktonic Communities
Yesim Buyukates and Daniel Roelke

TR-284 Manual on Conditional Reliability, Daily Time Step, Flood Control, and Salinity Features of WRAP
Ralph A. Wurbs

TR-283 Fundamentals of Water Availability Modeling with WRAP
Ralph A. Wurbs

TR-282 Comparative Evaluation of Generalized Reservoir/River System Models
Ralph A. Wurbs

TR-280 Estimating the Required Investment to Attain Region M Water Savings Through Rehabilitation of Water-Delivery Infrastructure - 2005 Perspectives
Ronald D. Lacewell, M. Edward Rister and Allen W. Sturdivant

TR-279 An Overview of Operational Characteristics of Selected Irrigation Districts in the Texas Lower Rio Grande Valley: Hidalgo County Irrigation District No. 2 (San Juan)
Megan J. Stubbs, M. Edward Rister, Allen W. Sturdivant, Ronald D. Lacewell

TR-278 Resources for Stormwater Managers throughout the Texas Gulf Coast: An Annotated Bibliography
John Jacob, Ric Jensen

TR-270 An Overview of the Operational Characteristics of Selected Irrigation districts in the Texas Lower Rio Grande Valley: Harlingen Irrigation District Cameron County No. 1
Clint D. Wolfe, Megan J. Stubbs, M. Edward Rister, Allen W. Sturdivant, Ronald D. Lacewell

TR-256 The Water Rights Analysis Package Users Manual, Version 2.0
Ralph A. Wurbs

TR-255 The Water Rights Analysis Package Reference Manual, Version 2.0
Ralph A. Wurbs

SR 2005-03 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

SR 2005-02 Validating the Estimated Cost of Saving Water Through Infrastructure Rehabilitation in the Texas Lower Rio Grande Valley (Hidalgo County Irrigation District No. 2)
Ronald D. Lacewell, M. Edward Rister, Allen W. Sturdivant

SR 2005-01 Validating the Estimated Cost of Saving Water Through Infrastructure Rehabilitation in the Texas Lower Rio Grande Valley (Hidalgo County Irrigation District No. 1)
Ronald D. Lacewell, M. Edward Rister, Allen W. Sturdivant

Extension/Education Publications:

B-182 (Ext.) Know Your Grasses
Barron S. Rector

B-6160 (Ext.) Basics of Microirrigation
Juan Enciso, Dana Porter

B-6156 (Ext.) Irrigation of Sugarcane in Texas
Juan Enciso, Bob Wiedenfeld, Guy Fipps

E-351 (Ext.) Shock Chlorination of Stored Water Supplies
Monty Dozier, Mark McFarland

L-5468 (Ext.) Drinking Water Problems: Perchlorate
M. Dozier, R. Melton, M. Hare, D. Porter, B. Lesikar

L-5467 (Ext.) Drinking Water Problems: Arsenic
B. Lesikar, R. Melton, M. Hare, J. Hopkins, M. Dozier

B-6077 (Ext.) On-site Wastewater Treatment Systems: Selecting and Permitting
Bruce Lesikar

B-6175 (Ext.) On-site Wastewater Treatment Systems: Soil Particle Analysis Procedure
B. Lesikar, C. Hallmark, R. Melton, B. Harris

B-6171 (Ext.) On-site Wastewater Treatment Systems: Homeowner's Guide to Evaluating Service Contracts
B. Lesikar, C. O'Neill, N. Deal, G. Loomis, D. Gustafson, D. Lindbo

B-6180 (Ext.) Views from the River Front
Valeen Silvy, Ronald Kaiser, Bruce Lesikar

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/
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/

Newsletters

tx H20, Volume 1, number 1. March 2005
tx H20, Volume 2, number 1. September 2005
tx H20, Volume 2, number 2. January 2006

New Waves, October 2005.
New Waves, November 2005
New Waves, December 2005
New Waves, January 2006
New Waves, February 2006

Rio Grande Basin Initiatives Outcomes, Volume 4, number 2. May 2005.
Rio Grande Basin Initiatives Outcomes, Volume 4, number 3. August 2005.
Rio Grande Basin Initiatives Outcomes, Volume 4, number 4. November 2005.
Rio Grande Basin Initiatives Outcomes, Volume 5, number 1. February 2006.

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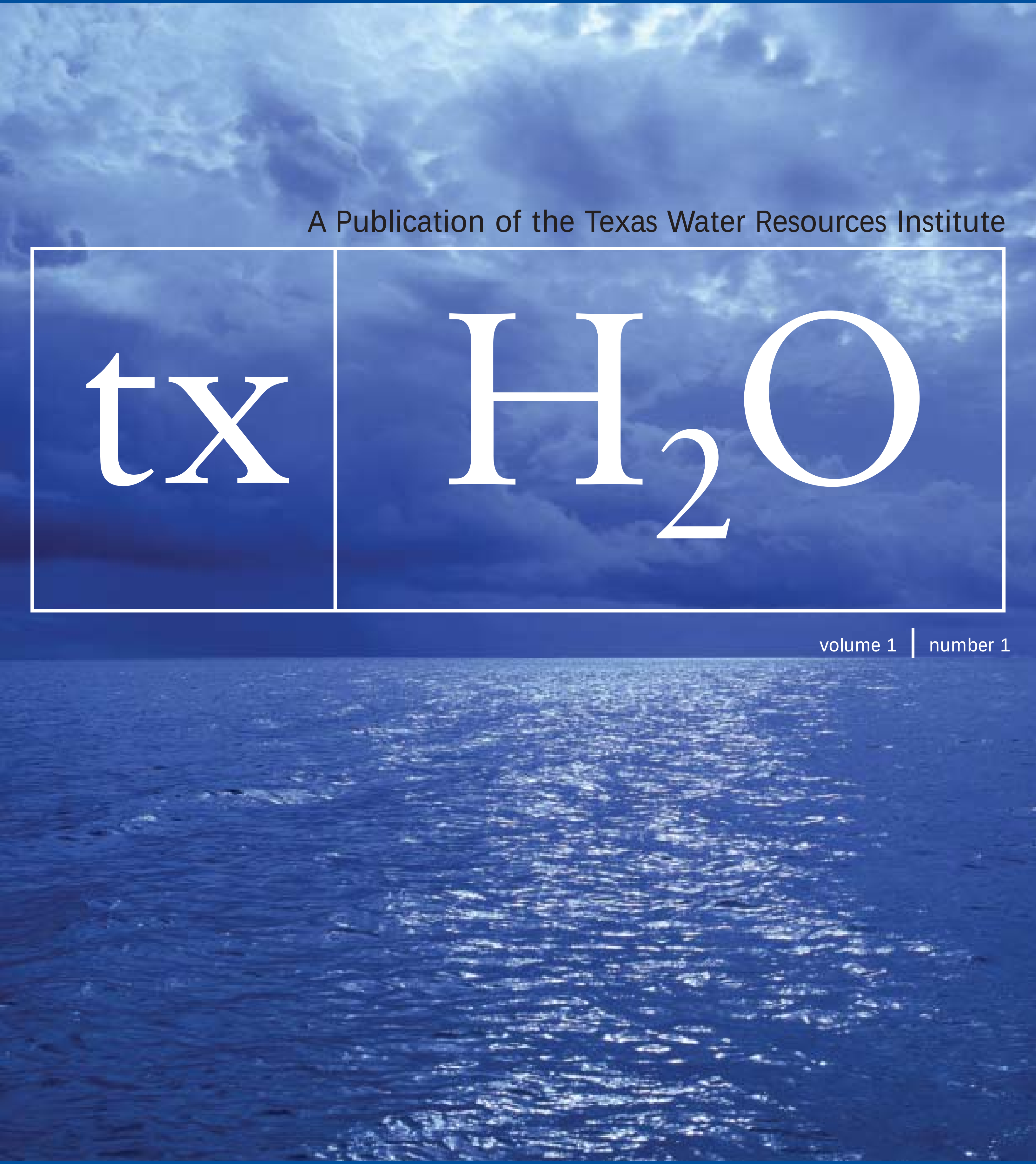

A Publication of the Texas Water Resources Institute

tx H_2O

volume 1 | number 1

In This Issue:

- MEXICO'S WATER DEBT • THE FUTURE OF DESALINATION • SEDIMENT SETBACK • PHOSPHORUS LOSS
- CLOUD SEEDING • RAINWATER HARVESTING • AND MUCH MORE!

Building on the Past, Looking to the Future

Drs. Elsa Murano and Ed Smith have made it clear—water resources issues continue to be a high priority for TAES, TCE and the College of Agriculture and Life Sciences. They also strongly support our cooperation with other TAMU colleges, state and federal agencies, and other universities. TWRI looks forward to providing continued leadership for water resources programs through grant administration, project management, and communication and outreach programs.

Notable accomplishments:

- Increased total funding obtained, administered and/or facilitated by the Institute from roughly $500,000 in FY00 to more than $8 million in FY05

- Developed close-working relationships with water scientists throughout Texas and with other states, other water centers and institutes, and diverse agencies and organizations

- Strengthened Extension education and communication abilities related to water resources and developed capabilities for project management

- Initiated a competitive grants program for graduate students with USGS funds to promote graduate student involvement in water resources-related fields of study. Since FY01 the Institute has supported 53 students with over $269,000 in funding

- Helped more than 100 faculty members obtain funding for research and/or Extension education projects

- Developed strong working relationships with The Texas A&M University System's Washington D.C office and with key Texas Congressional offices, as well as with more than 25 local, regional, state and federal agencies, and universities

- Recognized by USGS and National Institutes of Water Resources as a "Top Five" water institute in the review of all U.S. water institutes over the past five years

tx H_2O

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Texas Water Resources Institute

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Mexico Transfers Water to U.S.

New issues arise after partial water debt is paid

Mexico released 210,785 acre-feet of water to Texas into Amistad International Reservoir on Saturday, March 19, 2005, to alleviate its sizable water debt to the U.S. arising from international treaty requirements. This delivery is an addition to the 56,750 acre-feet of water Mexico transferred to Texas on March 12 in Falcon Reservoir. Mexico's recent water debt is now cut by more than 50 percent.

Mexico released the water soon after signing a settlement with the U.S. calling for the whole debt to be paid by September 2005. Now farmers and other water users in the Rio Grande Valley are effectively utilizing this extra water.

“Impacts on this year's crop mix would be hard to determine exactly because planting intentions were made before the water became U.S. property,” said Allen Sturdivant, Extension Associate for Texas Cooperative Extension. “Annual crop mixes fluctuate for a number reasons including weather, comparative and market-window advantages, pricing expectations, and the expected profitability of alternative crop enterprises.”

Mexico's water transfer allows for this year's planting patterns and crop estimates to go as planned and for future patterns or extra crop production to be possible.

“The current situation favors an increase in overall irrigated acreage since there is more available water, or a loosening of resource constraints,” Sturdivant said. “Whether the water will be used to increase [the production of] vegetables, sugarcane, or other field crops is still unknown.”

New regulations pertaining to the extra water, such as adopting water-saving technologies, have not yet been imposed.

Sturdivant said the water transfer does not pose much of a storage problem since some of the debt delivery was a paper transfer of water already in the reservoirs. Also, Falcon and Amistad Reservoirs still aren't completely full.

“The added water that will actually hit the farm gates will be less than the accumulated debt,” Sturdivant said. Under the 1944 Water

Treaty, 41 percent of the water is for conveyance loss credits.

Since the Rio Grande is over-appropriated and its water shared between the U.S. and Mexico, water issues in this region have been and continue to be complex. Water availability issues in this region have been controversial, especially since Mexico acquired a total debt of 1.5 million acre-feet of water from 1992-2002. As of October 2004, Mexico owed 717,000 acre-feet of water.

In 1992, the effects of Mexico's water debt were not immediately felt in the Rio Grande Valley because reservoir water remained and was still being consumed. Water supply and irrigation deficiencies started in 1995 when water demands surpassed the amount of accessible water.

Over the past 12 years, South Texas communities have endured many economic losses during times of drought because of Mexico's delay in repaying their water debt. Without Mexico's water inflows, the Falcon and Amistad Reservoir's essential roles to provide resources for crops and growers, tourism, and jobs for South Texas' economy are diminished.

With Mexico's currently scheduled repayment plans, water resources and crops in the Rio Grande Valley can withstand the effects of drought conditions, and water levels maintained. The two lakes located at Falcon and Amistad Reservoirs are extremely vital to crop growth and the irrigation systems since these reservoirs are the primary sources of water for the valley.

The additional water will guarantee Valley farmers the water they need for the planting season. South Texas growers, ranchers, and stakeholders have a sense of assurance that they can depend on Mexico for future water transfers in the coming months.

Photo by Jim Lyle

Story by Amanda Crawford

The Future of Desalination in Texas

Brine can transform water supplies in Texas communities

As Texas' population grows, the ever-present threat of water shortages looms. However, technology is also advancing, providing possible solutions for water deficiencies. One such solution is desalination–a cost-effective method of producing potable and useable water from existing saltwater resources.

While desalination use has advanced along the Texas Gulf Coast after Governor Rick Perry's 2002 desalination initiative announcement, water treatment opportunities in other areas still exist. The Texas Water Development Board (TWDB) published a report identifying the location and amount of brackish and saline groundwater in Texas available for desalination.

Oil production brings contaminated or produced water (also called brackish water) to the surface. There are more than 200,000 producing wells in Texas, and most of them produce about seven times more water than oil. Handling this water is expensive because it must be transported for storage and injection into another well.

However, if produced water is desalinated on site, the pollutants can be reinjected into the formation without an Environmental Protection Agency (EPA) Class I hazardous injection permit; salts from the brackish water came from the original formation. Presently, several research efforts are underway to find beneficial uses for waters produced from oil and gas exploration in Texas.

Even with its obstacles, desalination of produced water is a more cost-efficient method of dealing with brine. For example, produced water management and disposal costs can amount to $2,000 a day for every 1,000 barrels of oil (bbl) produced. Using on-site desalination could save half of this cost, producing an annual net profit of more than a quarter million dollars. If only 10 percent of operators take advantage of desalination, they can save $3.5 million annually, dramatically demonstrating the profitability of brine desalination.

To better understand desalination, here are terms used to describe water and groundwater.

- Freshwater contains less than 1,000 milligrams per liter (mg/L) of total dissolved solids (TDS).
- Brackish groundwater includes slightly-saline (between 1,000 to 3,000 mg/L TDS) and moderately-saline (3,000 to 10,000 mg/L TDS) levels.
- Saline water has more than 10,000 mg/L TDS and seawater has about 35,000 mg/L TDS.

Both water produced from oil wells and some groundwater contain brackish and saline water. In terms of desalination, brackish water is the best treatment candidate, and approximately one-third of the produced water in Texas falls into this category.

Desalinating produced brackish water comes with its drawbacks. Produced water can be up to four times saltier than seawater, making it difficult to work with. In addition, it contains crude petroleum which can be somewhat soluble in water and metal salts leached from rock formations. Furthermore, because of the oil in this produced water, it requires more pre-treatment than seawater does.

Even with the additional cost of pre-treatment, the total operating costs during 7-hour days average less than $10 for 23,000 gallons of brackish water processed. For an average $1 bottle of water (16.9 fl. oz.), the cost of producing this water would be approximately $.000057 per bottle, for a profit of nearly 100 percent. To be fair, standards for drinking water are high, and such treatment would receive intense examination by the state before approval.

If drinking water is not the ideal use for this water, there are several other alternatives. Because minimal regulations exist for livestock drinking water, ranchers can use desalinated water for their purposes. More than 133 million gallons of treatable water are produced each day, which is a sufficient irrigation amount for farmers as well, even if no other sources for irrigation existed.

Besides the economic benefits, on-site treatment is less hazardous than transporting large qualities of brine on public roads. As researchers assess the environmental efficiency of desalination, it is clear that desalination will play an integral part in the future of water production and conservation.

Many universities, state agencies and other organizations have been key players in desalination studies. By 2020, the U.S. Bureau of Reclamation, EPA, Department of Energy, Bureau of Land Management and Sandia National Laboratories are anticipating that desalination and water purification technologies will contribute significantly to ensuring a safe, sustainable, affordable, and adequate water supply for the United States. These organizations address both the potential for groundwater purification and the challenges that lie ahead.

Researchers from Texas A&M University, University of Texas at Austin, Rice University, University of Houston, Lamar University, Texas Tech University, University of Texas at El Paso and Texas A&M University-Kingsville are also making key advances in desalination research.

Texas A&M University

- Modeling and designing pretreatment processes and strategies that influence performance of desalination processes
- Evaluating patented capacitive deionization technology
- Finding methods to desalinate brackish and saline groundwater, and treat oilfield-produced water
- Evaluating operational issues related to proposed desalination plants
- Modeling how salinity constraints affect usable water yield in river and reservoir systems

University of Texas at Austin

- Differentiating traits of ideal membranes to develop a total recycle membrane system
- Modifying polymers to improve membrane performance through a unique stretching process
- Assessing desalination byproducts
- Evaluating effects of brine reject waters discharged with bays and estuaries and on dissolved oxygen levels
- Assessing how plant operations might affect temperature and salinity regimens in Lavaca Bay
- Examining public attitudes toward desalination projects

Rice University

- Evaluating parameters that optimize pretreatment processes
- Assessing use of certain membranes to treat waters with high levels of dissolved organic matter and suspended solids
- Developing data about water quality parameters associated with oilfield-produced water
- Assessing whether additional water via desalination may improve long-term peace between Israel and the Gaza Strip

Lamar University

- Comparing performance of conventional pretreatment methods used in desalination with the use of membranes and deoxygenation methods
- Developing membranes resistant to inorganic scaling and characterizing how desalination processes affect the stability of the membranes

Texas Tech University

- Developing closed loop pretreatment systems for space travel
- Creating methods to reuse desalination byproducts

University of Houston

- Evaluating and testing effects of pretreatment and operating conditions on membrane performance
- Monitoring and predicting membrane performance with other technologies
- Developing integrated portable membrane systems for use in remote locations

University of Texas at El Paso

- Evaluating use of desalination technologies to treat impaired and saline waters
- Incorporating thermal energy to power membrane distillation

Photo by: Jerrold Summerlin

Pond Scum

Researchers prepare a plan to use Riverside Campus ponds

Eight years ago, 10 ponds were built on the Texas A&M University Riverside Campus. But the agricultural program for which these ponds were intended moved away from that campus and the ponds were neither used nor maintained. Thomas DeWitt, assistant professor of ecological genetics with the Department of Wildlife and Fisheries Sciences, and his colleagues recently discovered these ponds and set out to make educational and experimental use of them through the creation of mesocosms, or culture systems for fish larvae.

According to Dewitt's report, the existing aquatic projects were conducted in Dewitt's 180-gallon aquaria at the Riverside Campus indoor facility. Using the ponds reduces many problems these indoor aquaria produce, such as conflict among faculty research and teaching programs. For this reason, the Texas Water Resources Institute (TWRI) chose to award a Water Resources Research Grant for the restoration and operation of these ponds.

Because of their neglected state, the ponds required a few improvements. Two ponds needed work removing cattails, one had to be deepened to match the others, and two more ponds were added.

Despite the necessary improvements, the ponds have major potential. Because they were dug in a natural clay area, they can hold water without requiring liners. The pond site was also equipped with water and electricity, making on-site research potentially more productive. In addition, there are security fences and regular police patrols of the area to protect research.

DeWitt recommended that the ponds be used for at least eight undergraduate courses in the Department of Wildlife and Fisheries Sciences to evaluate and measure natural selection factors, predator behavior and morphology, experimental foodweb manipulations, habitat structure and use, ecology, and several additional proposed research studies.

These ponds also offer the ability to perform nutrient and chemical studies, behavioral and functional ecology experiments, and community ecological and evolutional studies of algae, aquatic vascular plants, invertebrate grazers and predators (snails, insects, crustacean), larval amphibians, fish, and turtles.

“The ponds not only provide a new research area, but also encourage cooperation among faculty,” DeWitt said. “These ponds have the potential to provide priceless training and learning expansion into the future.”

Story by Amanda Crawford

Photo by: Dennis Hoffman

Sediment Setback

Fort Hood's sediment and erosion cause problems for the base

Since 1942, Fort Hood has been home to the U.S. Army's III Mobile Armored Corps. It is the only U.S. military post able to station and train two armored divisions at once. At this base, troops execute weapons qualification tasks and tank gunnery training to equip them to become some of the best soldiers in the country.

The heavy artillery traffic that operates on the 335-square-mile terrain greatly disturbs and deteriorates the soil and vegetation, causing serious topsoil loss and sediment problems. Direct raindrop impact on the pulverized bare soil leads to erosion and sediment-filled runoff, which deteriorates the land and contaminates local water sources. For this reason, the Texas Water Resources Institute (TWRI) and Blackland Research and Extension Center (BREC) are working with the military and USDA Natural Resource Conservation Service in attempting to conserve and protect the soils on the base, reduce sedimentation problems, and enhance training opportunities for future soldiers.

Sediment's Dangers

Sediment-filled runoff ends up in Lake Belton, the water source for Fort Hood and local communities. Ultraviolet light, or sunlight, naturally kills bacteria; therefore, suspended sediment in the area's water is particularly problematic because of its ability to diminish the water's light absorption. Sediment can also spread absorbed hazardous chemicals or compounds such as pesticides through the water.

In addition, the trampling of plants deteriorates the vegetation, changing from taller plants to shorter grasses. In extreme cases, the soil is exposed. Erosion at Fort Hood strips the land of essential nutrients that plants need to grow, and destroys any chance that the vegetation will redevelop on its own. Further trampling and erosion exposes the rocks beneath the soil and produces large gullies, or ditches. This has negative effects on military maneuvering and watershed ecology, permanently destroying surrounding habitats, and diminishing the quality of the training grounds.

Hope in Sight

Restoration at an early stage provides hope for success because some of the nutrients are still available in the soil. It also saves money because restoration can be expensive if starting over from scratch.

Proper use of vegetation, the most important element in land rehabilitation, can improve the sediment problem. Vegetation protects the soil from damage, and vegetation and soil work together to maintain a nutrient balance. It also acts as a filter to remove sediment from run-off, preventing the sediment from entering lakes and rivers. Plants also reduce the speed of water flow over the soil, slowing erosion.

The future looks more optimistic for Fort Hood thanks to TWRI, BREC, and NRCS's introduction of new ways to protect the area's land and water. One of the new practices being introduced is the use of compost to more rapidly establish protective regetative cover. Another effective solution is installing small check-dams, also called "gully-plugs," across eroding channels, which prevents further erosion by blocking the flow of water and reducing sediment loads in runoff. Another solution is soil ripping, which rejuvenates the soil and provides opportunities for growth and plant stability improvement. Water flows into the soil, rather than turning off and eroding trenches.

Because of the nature of Fort Hood's training, erosion and sediment will always be a problem. The efforts of TWRI and BREC on this project minimize the problems and provide hope for safety and excellence at this base.

Supporting Student Research

The Texas Water Resources Institute (TWRI) will fund 10 graduate student research projects for 2005-06 conducted by graduate students and researchers at Texas A&M University, Rice University, Texas A&M University Kingsville, Baylor, and the University of Texas at Austin.

Funded by TWRI through 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 these studies.

Grants began March 1, 2005, and will run through February 28, 2006. Awarded up to $5,000 to begin, expand, or extend research projects, each applicant had to also provide evidence of $10,000 in matching funds. TWRI received over 70 submissions in response to this year's request for proposals.

The following projects were funded:

- "Evaluation of Standards for Compost Blankets in Stormwater Control," Lindsay Birt, Department of Biological and Agricultural Engineering at Texas A&M University; Russell Persyn, research advisor.
- "Evolution of Irrigation Scheduling Using the Biotic Model," Josh Bynum, Department of Soil and Crop Sciences at Texas A&M University; J. Tom Cothren, research advisor.
- "Enhancing a Distributed Hydrologic Model for Storm Water Analysis within GIS Framework in an Urban Area," Zheng Fang, Department of Civil and Environmental Engineering at Rice University; Philip Bedient, research advisor.
- "Assessing the Potential of Zerovalent Iron to Reduce Nitrate Mobility," Omar Harvey, Department of Soil and Crop Sciences at Texas A&M University; Cristine Morgan, research advisor.
- "Determining the Efficacy of Biological Control of Saltcedar on the Colorado River of Texas," Jeremy Hudgeons, Department of Entomology at Texas A&M University; Allen Knutson, research advisor.
- "A Decision Support System to Develop Sustainable Groundwater Management Policies for a Multi-County Single Aquifer System," Muthukumar Kuchanur, Department of Environmental and Civil Engineering at Texas A&M University - Kingsville; Venkatesh Uddameri, research advisor.
- "Watershed Development and Climate Change Effects on Environmental Flows and Estuarine Function," Marc Russell, Department of Natural Sciences at the University of Texas at Austin; Paul Montagna, research advisor.
- "Spatial Patterns in Wetland Nutrient Biogeochemistry: Implications for Ecosystem Functions," Thad Scott, Department of Biology at Baylor University; Robert Doyle, research advisor.
- "Carbon Aerogel Electrodes: Absorption-Desorption and Regeneration Study for Purification of Water," Sanjay Tewari, Department of Civil Engineering at Texas A&M University; Timothy Kramer, research advisor.
- "Evaluation of Spatial Hetergeneity of Watershed through HRU Concept Using SWAT," Xueson Zhang, Department of Forest Science; Raghavan Srinivasan, research advisor.

For more information on these research projects visit our Web site at http://twri.tamu.edu/usgs.php.

Assessing Phosphorus Loss to Protect Surface Water

The Texas State Soil and Water Conservation Board (TSSWCB) in collaboration with the Department of Soil and Crop Sciences at Texas A&M University, Texas Cooperative Extension (TCE), Texas Water Resources Institute (TWRI), and the U.S. Department of Agriculture's Natural Resource Conservation Service (NRCS), have developed a field validation of the Texas Phosphorus Index.

This project, located near Bosque and Leon Rivers, began June 1, 2002, and ended June 30, 2004. The main objectives were to determine how soil properties in the Bosque and Leon River watersheds affect phosphorus levels, and to modify the Texas Phosphorus Index to improve its ability to predict the concentration of phosphorus in precipitation runoff. The Texas Phosphorus Index, a tool designed to assess the potential for phosphorus to move from agricultural fields to surface water, is a promising resource management method that better formulates and implements such regulation programs. It is an integrated approach that considers soil and landscape features in order to find appropriate phosphorus management practices by estimating phosphorus delivery to surface water.

Other goals were to compare soil tests and extractable soil solution phosphorus levels in runoff, and to evaluate the Texas Phosphorus Index in better classifying field sites relative to phosphorus loss potential, which can be used to prioritize fields for phosphorus management. Agriculturalists are developing and operating programs that minimize phosphorus losses, thereby reducing the amount that enters regional waters.

Phosphorous is a necessary element in the growth and nutrition of plants and animals. Since there is a need for it in crop production, many fertilizers are used to enhance the supply of existing phosphorus in soils.

Environmental concerns arise when too much phosphorus, along with other nutrients, becomes runoff and reaches surface waters. When phosphorus is lost from fields or other sources and comes in contact with surface waters, eutrophication occurs. Eutrophication is an increase in the fertility status of natural waters that causes faster growth of algae and other aquatic plants. Phosphorus levels are directly related to excessive algae growth in most fresh waters. It is one of the principal causes of impaired surface water quality in Texas, as well as the United States.

Minimizing phosphorus pollution of surface water from agricultural fields involves management practices that control both the source and transportation factors of soil. Influences that affect the source and the amount of phosphorus transported include the type of phosphorus applied and the content in the soil itself. Transportation factors include rainfall, irrigation, erosion, and runoff.

The overall aim of environmentally sound practices is to keep soil fertility levels of phosphorus to a range that is best for crop growth, while decreasing the loss of soluble phosphorus by runoff, drainage, or erosion.

Researchers studied 40 sites (20 the first year and 20 in the second year) in the Bosque and Leon River watersheds. Site selection was based on fixed features designed to evaluate data and related variables including soil testing rates, timing and methods of fertilizer application, and whether phosphorus was used near streams or other bodies of water. These factors better assessed the sources of phosphorus and the potential for runoff or erosion.

Runoff factors for a field are used in a mathematical equation, outlined in an 8 x 5 matrix, to determine whether the phosphorus movement risk is very low, low, medium, high, or very high. Weighted values, based on condition classes and relative importance, enable researchers to calculate a numeric point value. Total index points for a certain field are then compared to a standard index to find the overall phosphorus runoff risk for that site.

A rainfall simulator, called a Tlaloc 3000, measured phosphorus levels, and estimated other nutrient levels in runoff. A series of three simulations were conducted at each location on 1.5 m x 2 m plots. The application rate was 7.5 cm per hour, which is the standard rate used across the nation. Runoff samples (1,000 mL) gathered at two intervals were then analyzed for pH, element content, soluble phosphorus, and suspended phosphorus by the Texas A&M Soil, Water and Forage Testing Laboratory.

Public education and outreach was another purpose of this study. Through the efforts of county Extension agents and multi-county meetings, resource managers and landowners learned about the hazard of phosphorus runoff and how to use the Texas Phosphorus Index as a management tool. Efforts to provide news and training about the Phosphorus Index for the Texas Commission on Environmental Quality (TCEQ), TSSWCB, NRCS and other groups was also important.

Results of this field study will help confirm the Texas Phosphorus Index by proposing modifications to improve accuracy. Quantitative evaluations involving the measurement and estimation of phosphorus in runoff, and runoff analysis dealing with the type of phosphorus, can determine necessary best management practices (BMPs) to decrease the magnitude of phosphorus losses from agricultural fields.

Ultimately, the Texas Phosphorus Index helps determine the main factors that lead to phosphorus risks. Management of phosphorus can be very site specific and requires a well-coordinated effort between landowners, agriculturalists and soil conservationists.

The major challenge is to create a plan that effectively uses all nutrient sources and reduces phosphorus losses in bodies of water while maintaining or improving crop profitability and environmental quality.

The Sky is Falling

Using cloud-seeding technology to produce rain

Because drought and water shortages are ever-present threats, many Texas Water Districts have constructed alternate methods of preserving, and now producing water. Cloud-seeding is one such solution.

Cloud-seeding introduces foreign particles into an unproductive cloud, enhancing the formation of water droplets. In simpler terms, it is a way to produce rain by increasing the size of water droplets in a cloud that otherwise aren't heavy enough to fall on their own.

Silver iodide is a favored seeding agent because its crystalline composition is almost equal to the structure of ice crystals contained in convective clouds. Seeding with silver iodide can supply up to ten trillion artificial ice crystals.

Seeding takes place either below or above a cloud. In the first method, an aircraft's wings are mounted with flares burning silver iodide, which is then released beneath the cloud. The cloud's updraft carries the particles into the core of the cloud where tiny water droplets, which can create rain, are abundant. Wing-tipped generators containing acetone and seeding material can also outfit the aircraft.

From above the cloud, an aircraft drops the silver iodide flares into the upper region of seedable convective clouds. The crystals develop rapidly by tapping the vast field of moisture as the cloud grows, attracting water droplets in the cloud. The ice crystals quickly transform into a raindrop heavy enough to fall to the ground.

Texas has a rather extensive weather modification program.

- The first statewide program, the Colorado River Municipal Water District, is one of the oldest weather modification programs in the world. Established in 1971 to generate runoff into Lake Thomas and E.V. Spence Reservoir on the Colorado River, this program covers 2.6 million acres between Lubbock and Midland.

- The West Texas Weather Modification Association, based in San Angelo, covers 6.4 million acres in west central Texas.

- The South Texas Weather Modification Association is based just south of San Antonio and runs on a year-round basis, covering 6.6 million acres.

- The Southern Ogallala Aquifer Rain Program embraces territory in Texas and New Mexico. It covers 5.8 million acres.

- The West Central Texas Weather Modification Association, established in 2001, covers 4.9 million acres and bases its radar and aircraft in Abilene.

- The Trans Pecos Weather Modification Association is the newest rain enhancement program. Begun in May 2003, it covers 5.1 million acres between El Paso and Midland and operates its own equipment.

Cloud-seeding is a long-term commitment that requires much planning and constant work. It must be done consistently to provide definite results. Weather modification programs must survive for years in order to be useful because of the great variations in weather.

Additionally, cloud-seeding can be counterproductive if performed too late in the cloud formation-dissipation cycle. Since not all clouds have the potential to create rain, there are certain guidelines. Convective clouds are best for cloud-seeding because they are unstable in the atmosphere, making them better alteration candidates. The cloud must also have a temperature below 23 degrees Fahrenheit and have sufficient moisture, or seeding will not be effective. Seeding at the wrong time or place can actually decrease rainfall.

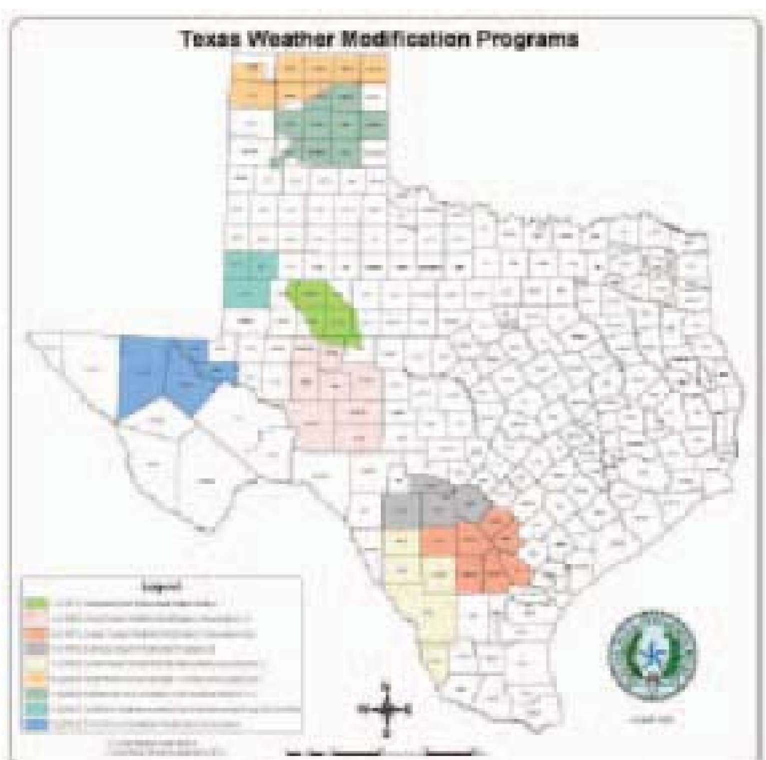
Another concern regarding cloud-seeding is the downwind effect–the theory that increased rainfall produced by weather modification in one area is offset by decreased rainfall in another area. However, the Texas Department of Licensing and Regulation (TDLR), claims that cloud-seeding can actually increase rainfall up to 100 miles downwind from the intended area.

The TDLR works to promote the growth and use of cloud-seeding technology through research, contributing $0.045 per acre of the total cost (about $0.08 per acre) of cloud-seeding. The TDLR was also responsible for administrating the Texas Weather Modification Act of 1967. This act requires agencies to regulate cloud-seeding through a licensing process in order to control it in the state of Texas, forcing responsible use of this weather modification technique.

The most obvious advantage of cloud-seeding is increased rainfall compared with unseeded clouds of the same height.

"Cloud-seeding can increase rain levels by 200 percent, cloud area by 43 percent and precipitation time by 39 percent," said George Bomar, state meteorologist. "Weather modification can also reduce the size of hail, another beneficial result."

Seeded clouds also have more longevity and ground area coverage. The resulting rains are more gentle, widespread, and longer-lasting.



Communicating Outcomes

Collaboration leads to water conservation

Sunny skies and cool weather greeted project participants as they arrived at the fourth annual Rio Grande Basin Initiatives (RGBI) Conference, April 12-14, 2005, in Alpine. It was a productive week that provided numerous discussions on local water issues, agency reports, and Task Group breakout sessions and concurrent Task Group reports.

The RGBI is a federally funded effort involving Experiment Station researchers and Extension educators from both Texas and New Mexico. The project partners with a number of other state and federal agencies to enhance water conservation programs. The purpose for the initiative is to develop and adapt water conservation practices through research, and then through Extension education, to implement water-saving practices. Primarily, the project focuses on irrigation efficiency in both agricultural and urban areas.

RGBI project participants from New Mexico State University (NMSU) and Texas Agricultural Experiment Station and Texas Cooperative Extension attended the meeting as well as participants of new 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.

"A wealth of information is being developed, not only by ourselves, but collaboratively with a number of others involved," said B. L. Harris, Project Manager of the Rio Grande Basin

Initiative and associate director of the Texas Water Resources Institute.

The purpose of this conference was to put all three of the separately funded projects together to discuss methods and ways to collaborate and cooperate, and to prevent unnecessary duplication, Harris said. The conference brought together several RGBI Task Groups for annual reporting of significant accomplishments and joint planning for future efforts. Peer and merit reviews evaluated on-going activities, and participants discussed partnership opportunities with federal and state agencies for both Texas and New Mexico.

“Obviously one of the principal themes over the past few days and life of the project has been collaboration, collaboration, collaboration,” said Craig Runyan, Water Quality and RGBI Program Coordinator for NMSU, during closing remarks. “It's meaningful and it's helped a lot. It's certainly helped our water program at NMSU. Collaboration isn't something new to us. Institutionally, professionally, career-wise, that's what we do—we collaborate.”

The cooperation between the universities and the interaction with those universities, stakeholders, and other agencies has given us an institutional capacity to keep this project relevant, Runyan said.

The RGBI is in its fourth year and continues to work toward the common goal, conserving the water in the Rio Grande Basin.

For conference presentations and reports, go to: http://riogrande.tamu.edu.

Live, Learn and Thrive

RGBI team award presented at NMSU ceremony

by Danielle Supercinski

Rio Grande Basin Initiative (RGBI) participants received the Team Award from New Mexico State University (NMSU) on April 21, 2005, during the NMSU Live, Learn and Thrive awards convocation.

New Mexico efforts are led by Craig Runyan, coordinator for NMSU project efforts, and assisted by Leeann DeMouche. Runyan, DeMouche and 40 other members of the RGBI received this award for demonstrating the power of team action in achieving significant water savings in agricultural irrigation and in addressing community water needs. Other partners who also received this award were B. L. Harris, Sterling Grogan, Gary Esslinger, and Subas Shah.

The RGBI is a joint project involving NMSU and The Texas A&M University System agencies, Texas Cooperative Extension and Texas Agricultural Experiment Station. It is a federally funded effort through the Cooperative Research, Education and Extension Services. The project partners with a number of other state and federal agencies, including Elephant Butte Irrigation District and the Middle Rio Grande Conservancy District in New Mexico.

(From left to right) Leeann DeMouche, Bill Harris, Craig Runyan, and Gary Esslinger were all present to receive the RGBI Team Award for their collaborative efforts in water conservation and efficiency.

Story by Amanda Crawford

Rainwater Harvesting

An Underutilized Conservation Project

Rainwater harvesting, a water collection practice used throughout the world for over 4,000 years, gives consumers access to an additional water source on their property. The collected rainwater is often used for landscape irrigation, but, with proper treatment, it can be used for drinking water.

Most people do not take advantage of this sensible opportunity. While rainwater-harvesting systems do involve costs, in the long run, they have the potential to conserve both money and water.

There are two general approaches to harvesting rainwater: a simple system and a complex system.

Simple System:

In a simple rainwater harvesting system, runoff from rainfall is collected and used on-site. Distribution systems channel the captured rainwater to holding areas.

The roof of a building or home is one commonly used catchment. The bigger the roof, the larger the volume of water collected. Gravity then naturally directs the water to collection vessels at the edge of the roof which store it for direct landscape use.

Roofing made from iron, aluminum, or cement is preferable because it absorbs little or no water.

Complex System:

A complex rainwater harvesting system also includes catchments, but the water is directed by a conveyance system to closed storage containers. Roof catchment systems use canals or gutters and downspouts as conveyance systems.

Filtration removes debris from the water before it is stored. The amount of filtration needed depends on the size of the distribution tubing and emission devices. Larger tubing requires more filtration due to increased debris amounts. In-line filters and leaf screens are effective filtration methods.

Storage containers can be under or above ground. Underground containers, while having the advantage of gravity's natural pull, are more expensive.

When it is time to use the water, the distribution system uses garden hoses, constructed channels, pipes, or drip systems (with or without pumps) to direct water from the storage containers to landscape plants or other outdoor or in-home uses.

Why install a rainwater harvesting system?

Texas is particularly suitable for rainwater harvesting because of its unique rainfall pattern. Peak rainfall occurs in April and May, followed by a dry period from June to August, with more rain from September to October. Using an adequate rainwater harvesting system, Texans can easily get through the dry periods of the year without the need for additional water.

Each year, irrigation accounts for 30 percent to 50 percent of Texas urban water use, averaging 20 gallons of water per square foot per year (871,200 gallons per acre). Using a rainwater harvesting system, a 1,000 square foot roof area can collect 600 gallons of water from only an inch of rain. Clearly, harvested rainwater can help reduce the demands on surface and groundwater for urban landscape irrigation, save municipal water supplies, and lower homeowner water bills.

Rainwater quality is another benefit when compared to treated water sources. For example, naturally occurring rainwater is sodium-free, which can force salts away from the root zone, an important consideration in areas with waters with moderate to high salinity.

“Sodium-free rainwater can also prevent the buildup of sodium in the soil profile,” said Dr. Monty Dozier, Texas A&M University water resources Extension specialist. “Use of irrigation water with moderate to high sodium content can impact soil quality and interfere with plants' water uptake.”

Plants respond much better to natural rainwater because it lacks the chemicals that are added to processed water, and its natural softness makes it better for household uses. Because of its low salinity, purified rainwater is also much healthier for those on a low-sodium diet.

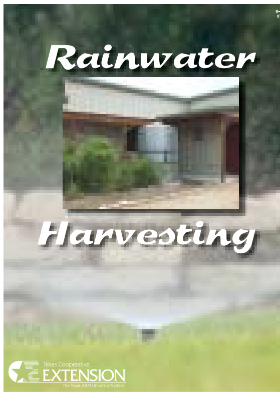
Rainwater harvesting can also reduce flooding, erosion, and contamination of surface water by better controlling hydrologic processes on an individual piece of property.

The cost of implementing a home rainwater harvesting system ranges from $5,000 to $8,000. Many Texas cities have offered rebates and tax exemptions for those willing to install them.

In 2001, Senate Bill 2 was passed to exempt tax on items purchased for rainwater harvesting. The City of Austin offers a rebate of half the cost of a system installation to industrial, commercial, and institutional customers at existing facilities—a value of up to $40,000. Hays County provides a property tax and application fee rebate for those with rainwater harvesting systems.

These incentives are definitely encouraging people to build rainwater harvesting systems. The number of people with harvesting systems increases every year, but there is still more room for growth. Rural landowners and homeowners may find use of a complete rainwater harvesting system an attractive alternative to the expense of drilling and maintaining a private water well. In fact, in some areas of Texas, groundwater may not be available, making rainwater harvesting the only viable way to secure a water supply.

Rainwater harvesting systems are a practical alternative for Texans, especially related to water costs and conservation. If you are interested in learning more about rainwater harvesting, download or purchase a copy of the latest Texas Cooperative Extension publication B-6153 available at http://tcebookstore.org/.



Improving Stormwater Quality

The City of Houston, Harris County, the Harris County Flood Control District and the Texas Department of Transportation have teamed up through a Joint Task Force (JTF) to address Houston's stormwater pollution prevention efforts and requirements of the National Pollutant Discharge Elimination System (NPDES) stormwater permit program.

Background:

In 1998, the Environmental Protection Agency (EPA) Region 6 in Dallas issued an NPDES permit to the JTF. The JTF has been recognized as being consistent, economical, and efficient by the EPA and they have commended the JTF for their unity and cooperation involved in the environmental efforts of each of the four entities. The Houston/Harris County community will be moving toward the Texas Pollutant Discharge Elimination System (TPDES) that has now completed its fifth year with the NPDES permit.

Problem:

Stormwater is an increasingly serious concern because it impairs the quality of water resources. Stormwater, when produced by rain or snowmelt flowing over the land, captures debris, chemicals, hazardous wastes, and/or sediment. These contaminants then make their way to drainage systems that flow directly into rivers, lakes, wetlands, or bays. The polluted stormwater runoff can affect the health of plants, fish, animals, and people, as well as reduce the recreational value of water resources.

Urbanization also has a major impact on the quality of local streams because it alters what and how stormwater flows in each watershed. Construction activities inherent to urbanization replace natural groundcover with impervious surfaces such as buildings, roads, and parking lots that do not allow rainfall to penetrate the soil.

Without the presence of vegetation, stormwater is rapidly converted into runoff, meaning that a greater volume of water reaches drainage systems faster, resulting in increased flooding. Moreover, most stormwater is contaminated with pesticides, fertilizers, pet waste, automotive by-products, floatable debris, and other toxic materials that pour directly into downstream waters.

Dr. John Jacob, director of the Texas Coastal Watershed Program, said urban planning is very important because as cities expand, so do impervious surfaces.

“By making communities denser, cities will better control their growth, drastically improving water quality,” Jacob said. “The pattern of development is the single most important part of preserving our natural environment.”

Jacob also said that as polluted stormwater becomes a key contributor to the declining quality of water bodies, strong enforcement of stormwater regulations and compliance with these regulations has become essential.

The Clean Water Act (CWA) was enacted to decrease or eliminate pollution sources from industrial sites that are exposed to stormwater runoff. The CWA, along with the EPA, has authorized the NPDES permit program and requires industrial locations to implement a Stormwater Pollution Prevention Plan.

In order to implement a Stormwater Pollution Prevention Plan, nine sections must be fulfilled. These sections include a project description, best management practices (BMPs), structural control practices, permanent stormwater controls, other water controls, approved state and local proposals, maintenance and inspections of controls, and pollution deterrence measures for non-stormwater discharges.

Best management practices are the primary method to regulate stormwater. These practices aim at decreasing the quantity of contaminants polluting water resources. BMPs consist of sediment, erosion, and stormwater management controls. Most BMPs focus on managing pollution from agricultural regions, automotive facilities, construction and industrial sites, forestry locations, and residential areas. These BMPs provide standard procedures to better manage stormwater runoff and maintain or improve water quality.

"The Texas Coastal Watershed Program is involved in city landscaping projects in which fertilizers and pesticides are restricted," Jacob said. "This program also works with Houston area cities and the Harris County Flood Control District to develop wetlands in order to route and cleanse stormwater."

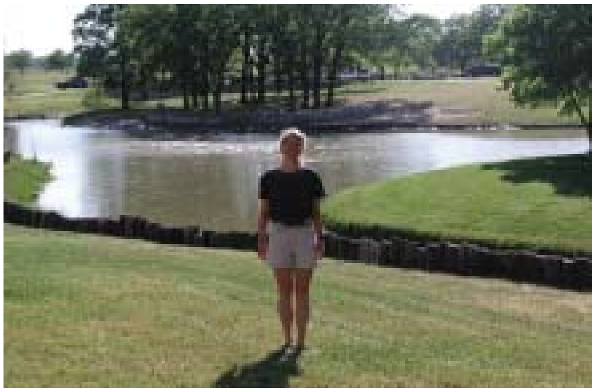
Public education is needed to support the implementation of stormwater programs and to communicate the significance of pollution prevention. Educational and outreach programs are initiated by the Texas Coastal Watershed Program, such as Marissa Sipocz's Wetland Restoration Team and Chris LaChance's Water Smart Landscaping Program. The Wetland Restoration Team actively works with urban children to teach them the importance of water quality.

Other programs and organizations in the Houston area were also created to enhance stormwater quality. The Galveston Bay Estuary Program is a program of the Texas Commission on Environmental Quality (TCEQ) that intends to restore, preserve, and safeguard estuaries that are in danger of being polluted by eliminating the number of floatables that pass through streams into the bay.

Managing stormwater is key in maintaining the security and quality of our water resources. Controlling stormwater by both its quality and quantity entails minimizing interferences with its natural flow. By proper design and regulation, the impact of urbanization and pollution on local watersheds can be considerably reduced.

Radon Concern in the Hickory Aquifer

Graduate student assesses radionuclide problem



As the primary water source for Mason, Concho, McCulloch, San Saba, Menard, Kimble, and Gillespie counties in Central Texas, the threat of elevated radionuclide concentrations in the Hickory Aquifer's groundwater poses health risks for residents in the area.

Radon is a natural, radioactive gas that may be found indoors in air or drinking water. Radon is the decay product of radium, so radon indirectly reflects the presence of radium. Radon in groundwater occurs from the decay of radium both within the aquifer host rock and in the groundwater itself. It does not react chemically with either, however, because it is a noble or inert gas. About 1 percent to 2 percent of potentially harmful radon originates in drinking water.

Studies have shown that people exposed to large quantities of radon in the air may have increased lung cancer risk. Although the health effects related to drinking water with high radon are unclear, household use of water containing high radon concentrations can release potentially dangerous levels of radon into the air.

Leslie Randolph, a graduate student at Texas A&M University's Department of Geology, is using her U.S. Geological Survey (USGS) Research Grant administered through the Texas Water Resources Institute (TWRI) to assess the spatial and temporal distribution of radon in Hickory groundwater.

Randolph conducts her research at a small field site in the Katemcy Creek watershed in northern Mason and southern McCulloch counties. She hopes to gather enough data to achieve the first step in a long-term assessment of radionuclides in the Hickory aquifer system's groundwater.

Previously, no systematic study has been done to assess the degree of the radionuclide problem, but Randolph will explore the relationships between observed radon distributions, aquifer stratigraphy and mineralogy, and groundwater dynamics.

A primary goal of the research is to evaluate the function of major stratigraphic variations on radon concentrations. Randolph hopes to "provide new insights regarding the occurrence and distribution of radon and radium in the world's aquifers that are geologically and hydrologically similar to the Hickory aquifer," she said, anticipating her research leading to further investigations of relationships between radon gas and its parent nuclides, aquifer mineralogy, and aquifer geochemistry.

Another goal, which she admits may be idealistic, is to determine if one or more stratigraphic zones in the aquifer contain radionuclide concentrations within adequately safe levels in terms of human risk.

"Water wells could be designed to draw from only those zones, rather than from across the entire aquifer as typically is done," Randolph said.

Groundwater samples are collected during both the summer irrigation season and periods of static flow in the aquifer. This allows Randolph to better assess effects of differing groundwater flow rates on radon activity. At the field site, Randolph prepares the samples for radon and radium analysis, and she analyzes them for anion concentrations. Additional samples are sent to the TAMU Trace Element Research Lab for cation and trace element analysis.

Randolph designed a groundwater sampling scheme based on the stratigraphic variations in the Hickory sandstone aquifer at the field site. Her preliminary measurements show that radon activities vary between approximately 100 picoCuries per liter (pCi/L) and 1000 pCi/L, with the lowest activities in water collected from within a fault zone, and the higher activities found generally in the lower parts of the aquifer. Activities overall are generally higher when nearby irrigation wells are pumping.

These numbers may sound high, but they actually are of questionable concern in terms of human health risk. The EPA has not yet set a maximum contaminant level (MCL) for radon in drinking water, but recommends a limit of 4000 pCi/L for untreated water and 300 pCi/L for treated water.

However, radon's radioactive parent radium has been detected in groundwater from many Hickory Aquifer water wells at levels that exceed the MCL of 5 pCi/L. Randolph uses stratigraphy to assess the variations in radium concentrations at her field site.

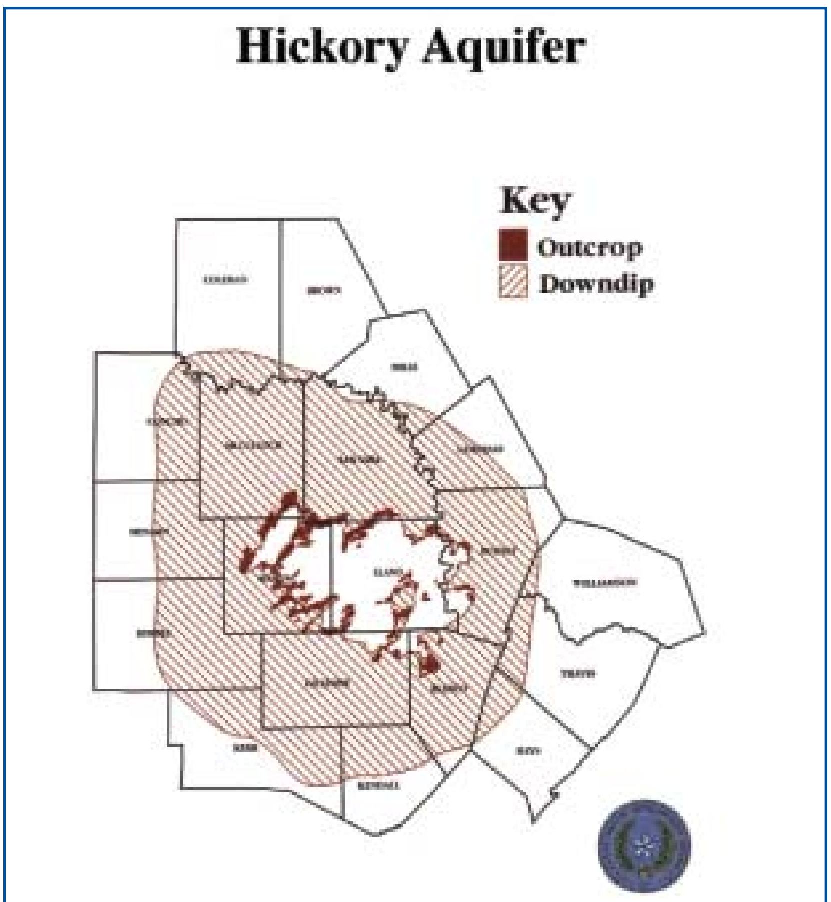
Through this preliminary effort, Randolph has discovered that not only has the expenditure been surprisingly high, but she has run into some other difficulties as well.

"The financial cost of doing the research is higher than I anticipated," Randolph said. "Coordinating groundwater collection opportunities with the researcher who installed the wells, the local farmers, and Mother Nature has proven more difficult than I anticipated."

She said that she appreciates the TWRI grant because it has helped her pay for necessary analytical instruments and field and laboratory supplies.

"This research could not have been done without TWRI's help," Randolph said.

Because most people are not aware of the risks associated with radionuclides in drinking water, Randolph hopes her research will inform the average person about their existence and give them the knowledge to be on the lookout for these natural contaminants.



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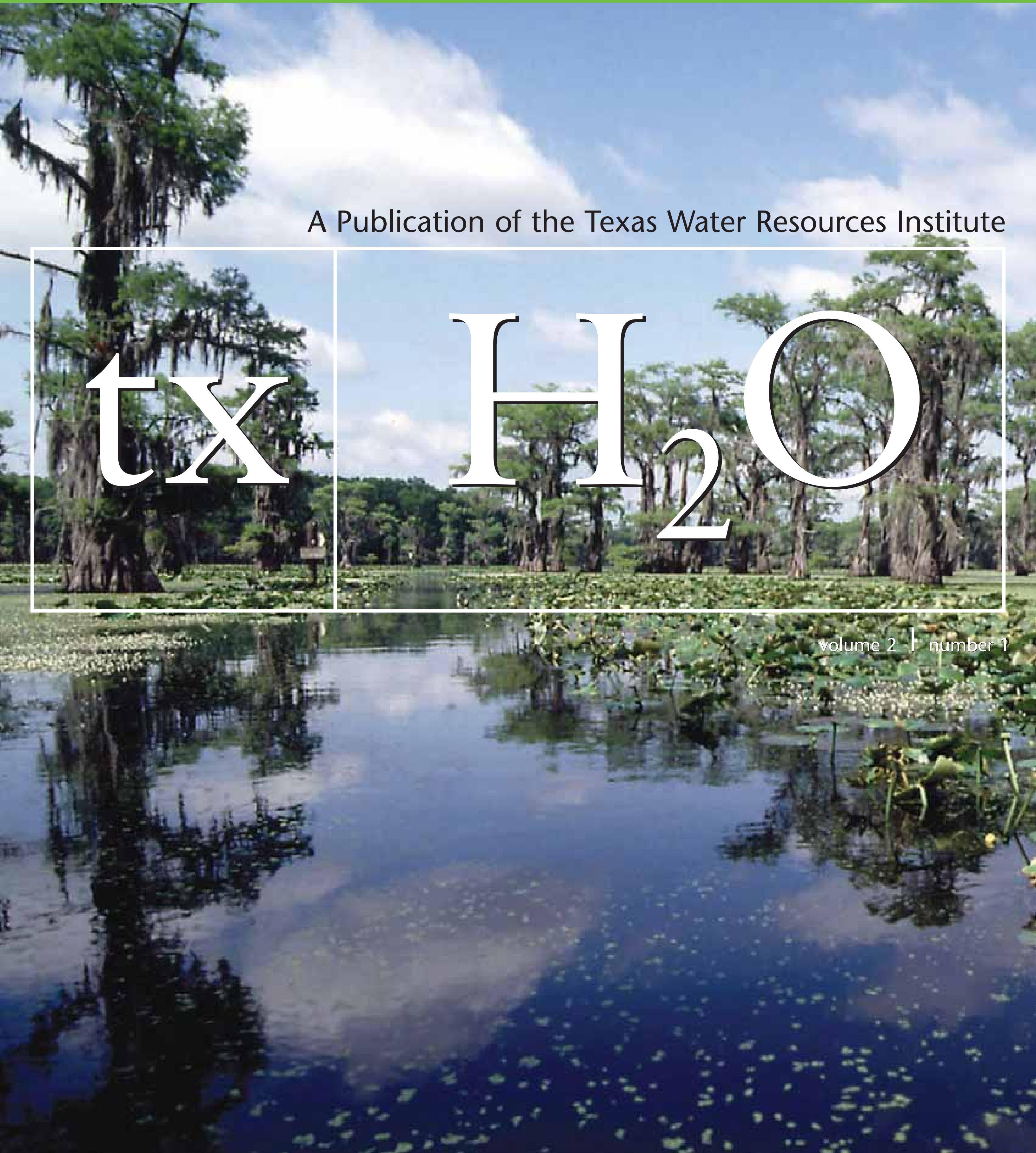

In This Issue:

- TEXAS' NATURAL LAKE • PANHANDLE AGRIPARTNERS • COMPUTERIZED WATERS • WEST TEXAS RAIN
- WHAT'S THE PLAN? • PREPARING FOR THE FUTURE • AND MORE

Working Together for Texas Water

As you can see from the diverse story topics in this issue, the Texas Water Resources Institute works with many Experiment Station and university researchers and Extension specialists across the state to develop and promote water conservation and water quality research and outreach programs. We have also established positive working relations with most state and federal agencies in our role as the designated Water Resources Research Institute for the state of Texas.

It is our mission to continue these partnerships and collaborations through proposal development, grant management and multi-agency collaboration with university faculty, agency researchers and Extension personnel throughout the state.

We currently manage more than 50 projects involving some 150 faculty members with more than $8 million in research or outreach funds. We partner with more than 100 public and private institutions in Texas, the United States and internationally. The projects cover a broad spectrum of water issues—from seeking alternative sources of water to reducing the water needs of cities and farms to ensuring the quality of the water we have. Looking to the future, we administer scholarship programs for undergraduate and graduate students at Texas A&M and other Texas universities.

Because water resources issues are often complex, TWRI is committed to expanding and strengthening these partnerships and collaborations to ensure that our state, our nation and our world have needed water now and in the future.

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Texas Water Resources Institute

Clint Wolfe
Managing Editor
Texas Water Resources Institute

Kathy Wythe
Editor
Texas Water Resources Institute

Steven Keating
Art Director
Agricultural Communications

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for more information.

On the cover:
Caddo Lake
Photo courtesy of Texas Parks
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Texas Water
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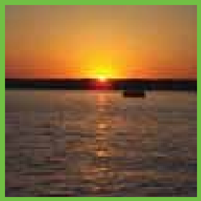
Inside



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Story by Kathy Wythe

Texas' Natural Lake

Research to help restore environmental flows to Caddo Lake

Unique—a word frequently used to describe Caddo Lake on the border of Texas and Louisiana. Unique because it is the only natural lake in Texas, believed to have originally formed from a logjam on the Red River. Unique because it is one of only 19 wetlands "of unique importance" in the United States. Unique because of its bald cypress and tupelo trees that are Caddo's Lake signature.

This unique lake and its ecosystem, however, are being threatened.

Although the lake has developed several problems over time, the overriding concern, according to people involved in preserving the lake, is the amount of freshwater flowing from the Lake O' the Pines Reservoir to Caddo Lake. After the U.S. Army Corps of Engineers built Lake O' the Pines on Big Cypress Creek upstream of Caddo, the area no longer flooded as much. The regulated water flows from the dam stabilized lake levels, reducing regeneration of bald cypress forests. The cypress trees must have floods to distribute their seeds and dry spells that lower lake levels and allow seeds to germinate.

Flooding in the past also helped sweep sediment from the lake and inhibited plant growth. Invasive aquatic plants, introduced by man, are choking off water bodies; and heavy metals, including mercury found in the lignite coal used to power electricity-generating plants, are accumulating in fish tissues.

Scientists are developing plans to restore environmental flows to Caddo Lake, Texas' only natural lake.

But, efforts are under way to help the lake remain the diverse and economically important wetland that establishes its uniqueness.

Texas Agricultural Experiment Station (TAES) scientists along with the Caddo Lake Institute, The Nature Conservancy, the U.S. Army Corps of Engineers, Northeast Texas Municipal Water District, other federal and state agencies, and local citizens are working together to find solutions to the lake's problems.

The Caddo Lake Institute has worked on water quality and water flow research for the last 15 years, said Dwight Shellman, Caddo Lake Institute's former director. One question that needs to be answered, Shellman said, is "Would restoring the natural pattern of water flow help the ecosystem to respond better?

"The existence of the dam and reservoir gives us the opportunity of restoring the natural variability patterns even if we don't restore all of the water."

The Nature Conservancy's Sustainable Waters program, designed to protect river ecosystems downstream of dams, has sponsored two workshops within the last year to determine the research needed to develop ecologically based environmental flow recommendations for Caddo Lake. Environmental flows is the amount of water that needs to flow down the river to maintain the ecological system in the lake, river and flood plain.

Dan Weber, the Conservancy's northwest Louisiana program manager, said, "We recognize several problems downstream associated with both water quality and quantity. The effort under way is a science-based approach to determine exactly how much water is really required and under what conditions for the downstream environment to persist over time, while continuing to provide quality habitat for associated flora and fauna."

These flow recommendations, when implemented by the Corps, will enhance the ecological structure and function of Big Cypress Creek, its floodplain and

Caddo Lake's signature bald cypress trees need the high and low flow of waters for distribution and germination of their seeds.

greater Caddo Lake, according to a summary report presented at the second workshop by TAES researchers involved in the project.

Although other issues affect the lake, including nutrient and contaminant loading, logging, and agricultural and residential development, the consensus of the workshop participants was that some restoration of the timing, magnitude and duration of flows in Big Cypress Creek is critical to the sustainability of the lake's ecosystem.

Kirk Winemiller, a professor in Texas A&M's Department of Wildlife and Fisheries Sciences, said the summary report synthesizes the "state of knowledge" about the geography, hydrology, ecology and environmental impacts affecting Caddo Lake and Big Cypress Creek. At the second workshop, the group reviewed all the information and developed "building blocks," describing the expected ecological responses or conditions associated with specific river flows or lake level fluctuations for Big Cypress Bayou and Caddo Lake. Winemiller said the group came up with preliminary recommendations for researching environmental flows as well as research to fill information gaps and to improve estimates. (See sidebar for top research needs.)

A critically important next step toward implementing the building blocks identified for the creek and lake is to develop a plan for conducting necessary baseline monitoring of ecological conditions in Big Cypress Bayou in 2005 and implementing Big Cypress Bayou low-flow and high-flow management strategies beginning in 2006. In addition, the plan will examine the feasibility of modifying the Lake O' the Pines outlet to improve control of lake levels, nutrient flows and cypress regeneration.

Analyzing long-term changes in the lake's ecosystem will provide a scientific baseline for current and future studies. The TAES scientists involved in the workshops are Brad Wilcox, associate professor of rangeland ecology and management, studying the hydrology; Anne Chin, associate professor of geography, studying the fluvial geomorphology; and Dan Roelke, associate professor of wildlife and fisheries sciences and oceanography, concerned with nutrients, productivity and aquatic plants. Steve Davis, assistant professor of wildlife and fisheries sciences, is studying the riparian and floodplain vegetation, and Winemiller is studying the aquatic and terrestrial fauna.

"Hopefully the process will continue," Winemiller said. "We're limited in what we can learn in water responses in two years."

Shellman has organized a research coordination network for the Caddo Lake watershed. The network will regularly call for, and coordinate, needed field research by key agencies, scientists and stakeholders to establish a permanent process known as adaptive management.

"Research and adjustment, and then more research and adjustment" is what is needed, he said.

Once additional research is accomplished, Winemiller said, subsequent workshops will make recommendations for a watershed management plan that will advise agencies involved with water planning for Caddo Lake.

Scientists identify Caddo Lake's top research needs

Hydrology:

- Develop correlation between Jefferson flow gauging sites or re-establish gauge at old Jefferson site
- Determine gain/loss of water between Lake O' the Pines and Caddo Lake
- Assess floodwater accumulation and backwater hydraulics below confluence of Little Cypress and Black Cypress

Fluvial Geomorphology:

- Estimate sediment budget and develop better characterization of sediment composition along entire creek
- Collect baseline geomorphological data to better assess the responses during and following flow

Aquatic Ecology:

- Determine how much of the floodplain is inundated and how much fish access is available at various flow levels in different reaches of the creek
- Examine paddlefish and bluehead shiner ecology

Terrestrial ecology:

- Examine flood inundation-vegetation relationships

Story by Kathy Wythe

Panhandle AgriPartners

Program helps farmers manage farms, water more efficiently

After 33 years in agribusiness, Dennis Beilue found he wasn't ready to hang up his agricultural hat when he retired in 2000. Three years later he was back in the business as a Texas Cooperative Extension farm demonstration assistant with the Panhandle AgriPartners Program.

AgriPartners is a collaborative program between Extension, the Texas Agricultural Experiment Station, farmers, farm commodity groups, industry, water districts and other entities. The program, with its farm demonstration assistants, provides technical support to Texas A&M researchers and Extension specialists and agents while giving Panhandle farmers up-to-date information on their crops' growth, water use, and pest and disease control to help farmers make good farming decisions.

(Top) Dennis Beilue, a Panhandle AgriPartner farm demonstration assistant, checks on cotton grown by subsurface drip irrigation (left hand) and center point irrigation (right hand). The demonstrations are in a field near Etter in Moore County.

(Center) Dennis Beilue reads the water meter for Doug May's subsurface drip irrigation system. Drip irrigation systems, although more costly to install, are proving to be efficient irrigation systems.

(Bottom) Cotton, which takes less water than other crops, is becoming more popular as a profitable crop in the Texas Panhandle. The AgriPartners Program helps farmers make management decisions such as replacing other crops with cotton.

The AgriPartners demonstrations are tied to the Texas High Plains Evapotranspiration program, which provides daily information on irrigation schedules. Center pivot irrigation systems have become more efficient using the TXHPET.

Beilue, from Dumas, became one of five assistants who work part-time under the supervision of Texas Cooperative Extension agents in five Panhandle offices. The assistants visit participating farms twice a week to monitor the farms' water use, crop development and growth, and pest status. They calculate water use by measuring the moisture in the soil at 1, 2 and 3 feet depths, and use rain gauges to determine rainfall and water meters for irrigation water use.

"At the end of each growing season, we can account for all water use," said O. R. (Reggie) Jones, technical coordinator of the program.

The assistants also help with demonstrations of new or improved farming and irrigation practices, crop genetics and technologies on participating farms.

Doug May of Dumas is one farmer who has new irrigation practices being tested on his farm. In its first year as a demonstration farm, half of May's cotton crop is being irrigated by the traditional pivot sprinkler system while the other half is irrigated by a new subsurface drip irrigation method.

Dr. Bob Robinson, Extension regional agriculture program director and one of the founders of AgriPartners, said Extension and research programs had never had the capability to monitor the crops so closely and integrate applied research so quickly before the start of this program.

"Our agents are so busy," Robinson said. "They couldn't visit the same farm at the same time twice a week for the entire growing season."

Since its inception in 1998, the program members have conducted 498 demonstrations on about 54,835 acres with more than 389 farmers.

In 2005, the Panhandle AgriPartners program conducted 40 cropping and irrigation demonstrations with cotton, wheat, corn, sorghum, silage, soybean and peanuts, involving more than 4,000 acres and 32 farmers in 14 counties.

Likewise, in 2004 the program conducted 44 on-farm crop and irrigation demonstrations involving seven crops, 4,716 acres of cropland and 29 cooperating producers in 17 Panhandle counties.

All demonstrations are tied to the Texas High Plains Evapotranspiration (TXHPET) research program, aimed at providing daily information on the water needs of the crops so farmers can adjust their irrigation schedules for efficient irrigation water use. The TXHPET network is a series of weather stations that measure daily evaporation and rainfall and it predicts the transpiration of a well-watered plant throughout its typical growing season.

Information gathered by the assistants is put in databases for developing and calibrating crop, pest and economic models used in PET and other production agriculture modeling and prediction efforts.

With this increased monitoring and more rapid application of research and technology, Panhandle farmers have seen increases in the efficiency of irrigation, improved yields of their crops and better economics of their production systems.

"Water is precious," Robinson said. "By using our monitoring system and the PET, farmers are able to strategically apply the correct amount of water to maximize yields, but also conserve water."

Farmer and AgriPartner demonstration assistant Dan Krienke agreed. Before he started participating in the program in 1998, Krienke said he was "shooting from the hip" to determine how much to irrigate his wheat crops.

"Now I have a plan," he said. "I've learned that I can water at 70 percent of PET and get 70 bushels of wheat per acre."

The program has also helped Krienke time the watering of his crops.

"I can start and stop watering a little earlier now because I have confidence that the moisture sensors will tell me the amount of water in the soil," Krienke said. "I can definitely say I've saved water. The groundwater district says we can use no more than 24 inches per acre each growing season and I use about 13 inches by better managing my water use."

Leon New, Extension irrigation specialist at the Texas Agricultural Research and Extension Center in Amarillo, said production of crops per inch of irrigation has increased over time through better management of irrigation water and adopting better irrigation techniques.

New, who compiles all data gathered by the AgriPartners program each year, said over the years the numbers have shown that center pivot irrigation is more efficient than furrow irrigation. In 2004, for corn production, center pivot used 7.5 inches per acre less water than row water and produced 349 pounds of corn per acre inch of rainfall, irrigation and soil water compared to 252 pounds using row water.

He said he has documented similar results for cotton with subsurface drip irrigation proving to be another efficient irrigation system.

"For 2004, a cooperating grower produced 148 pounds of cotton per inch of irrigation using subsurface systems and 53 pounds per inch of rain, irrigation and soil water. Another grower using center pivot irrigation produced 115 pounds of cotton per inch of irrigation and 56 pounds per inch of total water," New said, interpreting his research data collected each year. Average cotton production for 71 field tests is 86 pounds from each inch of irrigation and 41 pounds per inch of rainfall, soil water and irrigation measured.

AgriPartners Demonstration Assistant Dan Krienke and Extension agent for agriculture Scott Strawn examine maturing cotton on an irrigated demonstration farm near Perryton in the upper Texas Panhandle.

"The AgriPartner program uses leader growers who show the way. Some growers are doing a better job of managing their irrigation water," New said. "And it must continue due to the price of irrigation, fuel, and declining available water. Growers here are aware they must continue to produce more with less to survive."

Information gathered from demonstration farms is shared with other farmers in the area. New said farmers not participating directly in the program are more likely to accept the irrigation and crop management information collected from their neighbors than from other research results.

Seito Mellano, a Dalhart farmer, said this local information is the best part of the program because it helps farmers make better management decisions that result in greater profitability.

"What works in Corpus Christi doesn't work in Dalhart," Mellano said.

Dumas farmer Keith Watson agreed. "A lot of very important information comes out of that (the water monitoring)," he said.

Watson is working with AgriPartners to determine which varieties of cotton work best in the Panhandle because the area is "new cotton country." AgriPartners provides the computer programs, equipment, technology and knowledge to supply comprehensive research to the farmers, he said.

The PET program is especially important to new cotton farmers, Watson said, because the tendency might be to overwater since cotton takes about one-third less water than other crops like corn.

The AgriPartners information is also valuable for state water planning, New said. When Region A's water planning group wrote the state-mandated water plan, the AgriPartner data provided accurate irrigation demand data, he said. The program has soil water information for each grower demonstration that no other area in the state has collected as well as irrigation and rainfall measurements.

"No other state water planning region has this quality of data to use in their planning process," he said.

Texas Cooperative Extension and the Texas Agricultural Experiment Station have funded the AgriPartners program along with major agricultural industry partners and Texas farm commodity groups. Major commodity groups include the Texas Wheat Producers Board, Texas Corn Producers Board, Texas Grain Sorghum Board, Texas Soybean Board, Texas State Support Committee of Cotton, Inc. and the Texas Peanut Producers Board.

In the big picture, Robinson said, the farm-based projects serve as building blocks to advance The Texas A&M University System's initiatives in water conservation and improved production agriculture.

"AgriPartners is working to build partnerships that strongly support and benefit Panhandle agriculture," Robinson said. "We have just scratched the surface with this unique and productive partnership program, and so much remains to be done."

Beilue is glad he is involved in AgriPartners.

"It allows me to help, in some small way, the local farmers cope with a difficult, changing agriculture environment," Beilue said. "The AgriPartners program has been a win-win for me, the area's farmers and Texas Cooperative Extension."

Story by Kathy Wythe

Computerized Waters

Model changes management of Texas surface waters

In an office on the second floor of a Texas A&M University building, on a desktop computer operating with the popular Microsoft Windows, Dr. Ralph Wurbs has designed a computer modeling system that has changed the way Texas manages its rivers, streams and reservoirs.

The modeling system called Water Rights Availability Package, or WRAP for short, is a set of computer programs developed by Wurbs, a professor of civil engineering, and his graduate students that simulates management of the water resources of river basins. The model helps determine how much and at what level of reliability water will be available for environmental and human needs.

The Texas Commission on Environmental Quality (TCEQ) uses WRAP in its Texas Water Availability Modeling (WAM) system to evaluate and approve surface water right permits in Texas. Any water resources development project or water use action involving the streams and lakes of the state requires either a new permit or modification of an existing permit. The WRAP/WAM modeling system determines whether sufficient water is available for a proposed new or expanded water use and assesses the impacts on all the other water uses in the river basin.

Dr. Ralph Wurbs, professor of civil engineering, examines the Texas river basin maps with Richard Hoffpauir, graduate student. These maps were developed, using the WAM/WRAP modeling system. Hoffpauir traveled to Armenia to help that country work on water modeling and availability.

Dr. Ralph Wurbs of the Department of Civil Engineering has published five technical reports on the WRAP modeling system with the Texas Water Resources Institute.

Currently, the state has about 8,000 active water right permits.

TCEQ requires that permit applicants and their consultants use the WRAP/WAM system in preparing their applications.

“Discussion of pertinent issues is significantly enhanced by both the water right permit applicant and regulatory agency staff using the same modeling system,” Wurbs said.

TCEQ and its partner agencies—Texas Water Development Board and Texas Parks and Wildlife Department—and consulting firms developed the WAM system after the Texas Legislature enacted Senate Bill 1 in 1997, following the drought of 1996.

In addition to the generalized WRAP simulation model, the WAM system has specific information (or datasets) for all 23 river basins in the state.

Ten consulting engineering firms, under contract with TCEQ during 1997–2003, developed the individual datasets and simulated a set of alternative water-use scenarios. The Center for Research in Water Resources at the University of Texas provided geographic information system (GIS) support for developing the datasets. During the same time Wurbs and his graduate students, working under a contract between the commission and the Texas Water Resources Institute, expanded WRAP methodologies and software from earlier versions.

The state currently has active permits for about 3,500 reservoirs, thousands of water supply diversions, several hydroelectric plants and numerous environmental instream flow requirements. Each of these active permits is included in the datasets.

Besides the commission using the WAM/WRAP modeling system in water rights permiting, the Texas Water Development Board and its 16 regional planning groups use the modeling system for developing its water plans, which were also mandated by Senate bill 1. TCEQ’s approval of water right permit applications requires that proposed actions be consistent with relevant regional plans.

River authorities, water districts and other water management organizations are beginning to use the WRAP model in operational planning studies to optimize operations of their facilities and available water resources, Wurbs said.

“The Texas experience has also generated interest in similar applications of WRAP in other states and countries,” he said, including a project in Armenia by one of his graduate students.

Twenty years of refining

The WRAP modeling program and its widespread use did not get where it is overnight. Dr. Ralph Wurbs and his stream of graduate students have tweaked and fine-tuned WRAP for 20 years.

The original WRAP, initially called TAMUWRAP, stemmed from a 1986–1988 research project at Texas A&M University titled, *Optimizing Reservoir Operations in Texas,* sponsored by the federal/state Cooperative Research Program administered by the U.S. Geological Survey and Texas Water Resources Institute. The Brazos River Authority served as the nonfederal sponsor.

Some of the newest changes to WRAP, developed during 2002–2005 and documented in TWRI's Technical Report 284 released in January 2006, include:

- Capabilities for short-term reliability analyses based on current storage conditions (Or what is the likelihood of meeting water needs in the near future knowing storage conditions today?)
- Flood control operations
- Salinity tracking motivated primarily by natural salt pollution problems in several Texas river basins
- Daily or other sub-monthly time steps
- Disaggregation of monthly naturalized flows to daily flows
- Flow forecasting
- Flow routing
- Calibration of routing parameters

Other recent updates to WRAP with significant enhancements can be found in the following publications:

- *Water Rights Analysis Package Modeling System Reference Manual.* TWRI Technical Report 255, Second Edition, April 2005.
- *Water Rights Analysis Package Modeling System Users Manual.* TWRI Technical Report 256, Second Edition, April 2005.
- *Fundamentals of Water Availability Modeling with WRAP.* TWRI Technical Report 283, April 2005. This report serves as an introductory tutorial to help new users apply the model quickly for basic water availability modeling applications.
- *Comparative Evaluation of Generalized Reservoir/River System Models.* TWRI Technical Report 282, April 2005. This report combines a broad coverage of reservoir/river system modeling in general with a focus on the SUPER, RiverWare, MODSIM, HEC-ResSim, and WRAP modeling systems.

These technical reports are available at http://twri.tamu.edu/reports.php.

The software and documentation are also available at http://ceprofs.tamu.edu/rwurbs/wrap.htm. The public domain WRAP software and documentation, along with input datasets for all the river basins of Texas and other WAM information, are available under the heading *Water Availability Modeling* at the TCEQ Web site: http://www.tceq.org.

Development and expansion of WRAP has been sponsored by:

- Texas Commission on Environmental Quality
- U.S. Army Corps of Engineers Fort Worth District.
- Texas Water Resources Institute
- U.S. Department of the Interior
- Texas Advanced Technology Program administered by the Higher Education Coordinating Board

Story by Kathy Wythe

Preparing for the Future

University establishes water management degree program

Texas A&M University launched an interdisciplinary water management degree program during the fall 2005 semester with 12 students seeking either master's or doctorate degrees in water management and hydrologic sciences.

The degree program, the first in Texas, includes 42 faculty members in 12 departments from four different colleges, said Ron Kaiser, program chairman.

"Our program is unique because it is not housed in one department. It's not department-specific, but degree-specific," Kaiser said.

Kaiser, a professor in the Department of Recreation, Park and Tourism Sciences, said the degree program will prepare high-quality graduate students for careers in the critically important areas of water management and hydrology, and will serve as the cornerstone of the university's new water program.

Kaiser said the interdisciplinary character and practical orientation of this degree program reflects the growing complexity of water issues.

"In an increasingly complex world, seeking solutions to water problems requires crossing traditional departmental and disciplinary boundaries," Kaiser said. "This program achieves that goal by bringing together faculty from across the university community to guide students."

Kaiser and John Giardino, dean of graduate studies and a professor in the Department of Geology and Geophysics, worked with a team from the Colleges of Agriculture and Life Sciences, Engineering, and Geosciences to develop the curriculum and program. Using information from a National Science Foundation report that recommended an integrative approach, they developed the multi-college, multi-department water program.

"There will be tremendous job opportunities for A&M graduates of this program," Giardino said.

(Left) Water Management and hydrologic sciences graduate student Alyson McDonald downloads data from a data logger. McDonald is studying groundwater and surface water hydrology at Texas A&M to compliment her background in soils and plant ecology.

(Right) Master's degree candidate Nick Russo works with the Harris County Storm Water Quality program and oversees the construction enforcement and post-construction storm water controls for new developments or significant redevelopments.

"We're preparing students for being water leaders for tomorrow."

One of the master's degree graduate students, Nick Russo, already works in water management for the Harris County Storm Water Quality program. When searching for a graduate program to pursue, Russo said he examined A&M's new program. "I felt that this (program) was my shot at completing a master's degree in this growing field."

Russo agreed with Giardino about the job opportunities for water managers.

"I believe that water quality and quantity needs will be in the forefront in the coming years," Russo said. "Demand is obviously going to be high for those willing to attempt solving our water needs."

Doctoral student Alyson McDonald, who works as an Extension assistant in hydrology for Texas Cooperative Extension in Ft. Stockton, said the degree program was "a perfect fit with my degree plan."

After receiving her doctoral degree, McDonald plans to continue hydrologic research in arid environments in southwestern United States and northern Mexico.

Kaiser said this master's degree will prepare students to manage public water systems and water resources in cities, counties, river authorities and other entities.

The doctoral degree is designed to give students a thorough and comprehensive knowledge of water science and hydrology and training in methods of research.

"Over the past 25 years, population shifts, industrial developments, changes in water law and advances in technology have intensified competition for water resources and place new burdens on planners, policy makers and managers," he said.

In addition to the graduate degrees, the water program consists of integrative water research and outreach programs, Kaiser said.

Objectives of the program are:

- To foster faculty collaboration in developing a state, national and internationally recognized program in water management and hydrology,
- To prepare students for professional and academic careers in the water management and hydrological sciences in Texas and at the national and international levels,
- To create and sustain a teaching and research environment that brings together a variety of professions and disciplines for an exchange of knowledge about the unique attributes of managing water,
- To provide a teaching and research base for an ongoing series of research collaborations, lectures, seminars and workshops that will improve communication and exchange of knowledge between Texas A&M University students, faculty and professionals around Texas and the nation, and
- To assist in protecting homeland security of public water supplies.

The Texas A&M University System Board of Regents approved the degree program in December 2004 with a $2.5 million, five-year budget and the Texas Higher Education Coordinating Board approved the program in March 2005.

For more information, go to **http://waterprogram.tamu.edu** or contact Dr. Val Silvy, **vsilvy@tamu.edu**.

Water Program Faculty

Robin Autenrieth, Associate Professor,
TAMU School of Rural and Public Health

Sherry Bame, Associate Professor,
Landscape Architecture and Urban Planning

Bill Batchelor, Professor,
Civil Engineering

Kelly Brumbelow, Assistant Professor,
Civil Engineering

Anthony Cahill, Assistant Professor,
Civil Engineering

Anne Chin, Associate Professor,
Geography

Yavuz Corapcioglu, Professor,
Civil Engineering

Stephen Davis, III, Assistant Professor,
Wildlife and Fisheries Sciences

Delbert Gatlin, III, Professor and Associate
Department Head, Wildlife and Fisheries Sciences

John R. Giardino, Professor and Dean of Graduate
Studies, Geology and Geophysics

James R. Gilley, Professor,
Biological and Agricultural Engineering

Ron Griffin, Professor,
Agricultural Economics

Patricia Haan, Assistant Professor,
Biological and Agricultural Engineering

Bruce Herbert, Associate Professor,
Geology and Geophysics

Ronald Kaiser, Professor,
Recreation, Park and Tourism Sciences

Ann Lee Kenimer, Professor,
Biological and Agricultural Engineering

Robert Knight, Associate Professor and Associate
Department Head, Rangeland Ecology and Management

Ronald Lacewell, Professor,
Agricultural Economics

Bruce Lesikar, Professor and Extension Specialist
and Associate Department Head, Biological and
Agricultural Engineering

Ming-Han Li, Assistant Professor,
Landscape Architecture and Urban Planning

Bruce McCarl, Professor,
Agricultural Economics

Kevin J. McInnes, Professor,
Soil and Crop Sciences

Jim Mjelde, Professor,
Agricultural Economics

Binayak P. Mohanty, Professor,
Biological and Agricultural Engineering

Georgianne W. Moore, Assistant Professor,
Rangeland Ecology and Management

Cristine S. Morgan, Assistant Professor,
Soil and Crop Sciences

Clyde Munster, Associate Professor,
Biological and Agricultural Engineering

William H. Neill, Professor,
Wildlife and Fisheries Sciences

Gerald North, Professor,
Atmospheric Sciences, Oceanography

Francisco Olivera, Assistant Professor,
Civil Engineering

David Prior, Professor and Executive VP and Provost,
Geology and Geophysics, Oceanography

Daniel Roelke, Associate Professor,
Wildlife and Fisheries Sciences

Douglass Shaw, Professor,
Agricultural Economics

Raghavan Srinivasan, Associate Professor and Director,
Spatial Sciences Laboratory, Forest Science

John T. Vitek, Assistant Dean,
Office of Graduate Studies

Richard Weaver, Professor,
Soil and Crop Sciences

Bradford Wilcox, Professor,
Rangeland Ecology and Management

Richard Woodward, Associate Professor,
Agricultural Economics

Ralph Wurbs, Professor,
Civil Engineering

Hongbin Zhan, Associate Professor,
Geology and Geophysics

Story by Kathy Wythe

Putting Dollars to Work

319(h) projects help control nonpoint source pollution in Texas

Protection of our water resources is one of the most significant environmental challenges of the new millennium. Nonpoint source (NPS) pollution (pollution from rain or snowmelt runoff containing natural and man-made pollutants) from urban and agricultural activities represents a major pollution source.

Congress enacted Section 319(h) of the Clean Water Act in 1987, establishing a national program to control nonpoint sources of water pollution. Through Section 319(h), the Environmental Protection Agency provides federal funds to states for the development and implementation of the state's Nonpoint Source Management Program. The 319(h) funding in Texas is divided between the Texas Commission on Environmental Quality (TCEQ) and Texas State Soil and Water Conservation Board (TSSWCB).

Kevin Wagner, project manager for Texas Water Resources Institute's 319(h) projects, said the long-term goal of the state's NPS pollution program is to protect and restore water quality from NPS pollution through assessment of pollution sources, implementation of improved management practices and education.

(Above) The Pecos River in West Texas is the focus of one of TWRI's nonpoint source pollution projects.

TWRI, in collaboration with TCEQ, TSSWCB and other groups and agencies, manages several projects designed to reduce pollution in priority areas.

Current TWRI-led 319(h) projects

Evaluation of Best Management Practices in the Arroyo Colorado Watershed
This project helps restore the Arroyo Colorado, the most important stream draining the delta formed by the Rio Grande in South Texas. The program will educate farmers on how to produce crops while managing their land to reduce the potential for NPS pollution. The project also supports and promotes associated programs that implement best management practices (BMPs) related to water quality protection.

Seymour Aquifer Water Quality Improvement Project
This project provides water quality education to increase farmers' awareness and use of irrigation and nutrient BMPs to help reduce the nitrate levels in the aquifer. This project also estimates the reductions

in nitrate concentrations resulting from ongoing BMP efforts and provides an analysis of additional measures needed to achieve water quality standards in the aquifer.

The Impact of Proper Organic Fertilizer Management in Production of Agriculture
The Leon River Basin is adjacent to the Bosque River Basin, where excess nutrients have impaired water quality. Because the Leon River Basin contains similar nutrient sources, stakeholders in the Leon River watershed are paying careful attention to emerging water quality issues. Agriculture has the potential to contribute to the problems of excessive nutrients and bacteria in surface water, especially if recommended management practices are not used. This project assesses the effectiveness of BMPs then educates farmers to facilitate BMP implementation.

Buck Creek Watershed Water Quality Sampling/Assessment Project
This project monitors 12 different sites on Buck Creek to determine the extent to which bacteria are present. If these data demonstrate the need for an assessment of total maximum daily loads, experts in bacterial source tracking will help plan and implement appropriate follow-up.

Dairy Compost Utilization
This project addresses the elevated concentrations of ammonia, nitrogen, phosphorus and fecal bacteria found in parts of the North Bosque River, Upper North Bosque River and Leon River. Texas A&M agricultural scientists are working with composters and the dairy industry in Central Texas to expand the marketing of dairy compost in this area. TCEQ is providing incentive payments to state agencies, local governments and other public entities to expand purchases of their dairy compost. The project is also providing research data and education demonstrations on dairy compost usage, emphasizing cost-effectiveness, product safety and environmental sustainability.

Improving Water Quality by Developing, Implementing and Field Testing Innovative Methods
In this project researchers identify, evaluate, and field-test new technologies for reducing high levels of phosphorus in runoff from dairies. Once these assessments are completed, project members will communicate the results to dairy managers and other stakeholders, who can implement the proven technologies to reduce water pollution by dairy wastes.

Watershed Protection Plan Development for the Pecos River
Flows of the Pecos River have dwindled due to man-induced causes. This project evaluates the physical features of the Pecos River Basin, educates rural and urban stakeholders on water quality and quantity issues and develops a watershed protection plan for part of the river basin.

Texas Phosphorus Index
The Texas Phosphorus Index relies on a number of factors including soil testing, fertilizer application rates, and whether phosphorus is applied near streams to provide a basic assessment of the sources of phosphorus in water bodies. The index also helps predict phosphorus and nutrient runoff. The Texas Phosphorus Index 319(h) projects evaluate the ability of the index to estimate phosphorus losses in different field conditions. Researchers then develop recommendations to improve the index.

Other TAMU water-related 319(h) projects

Texas Watershed Steward Program
This pilot project will develop a community-based water quality curriculum to increase local stakeholder involvement in watershed protection programs. The curriculum will increase local understanding of the forces that can adversely impact water resources and the tools to prevent them, including effective watershed plans.

Texas Stewards of Ag-land Resources: T-STAR
This project develops and tests the education component of the T-STAR program in a pilot watershed. The T-STAR program provides agricultural producers and related industry with a combination of production and environmental training to better manage and protect their land and water resources.

Story by Kathy Wythe

Got Manure?

Technologies reducing phosphorus in dairy wastes

By the end of 2007, dairy farmers in Central Texas may have several new technologies to help them reduce phosphorus in dairy manure wastewater. Too much phosphorus runoff from the over 165 dairies in the area contributes to poor water quality in the North Bosque River, Leon River and Lake Waco.

Dr. Saqib Mukhtar, a Texas Cooperative Extension specialist in animal waste management, and his team are providing third-party evaluation of the six technologies. Although results are very preliminary, Mukhtar said some of the results are encouraging.

Currently, many dairy farmers flush the manure and its wastewater into lagoons or man-made ponds where it is stored. This wastewater, called effluent, is used for irrigating pastures or crops not consumed by humans and supplies essential plant nutrients including phosphorus to the soils. If the wastewater contains more phosphorus than the crops can use, however, excess phosphorus may eventually end up in the areas' streams and rivers. Too much phosphorus in water can cause algal growth and toxicity in surface waters, killing fish. The EPA has mandated that phosphorus levels in the North Bosque and Leon River watersheds be reduced by 50 percent.

Mukhtar and his Extension team are currently working with two companies—Envirotech, Inc. and Envirolink—to evaluate and demonstrate their technologies. The Envirotech technology uses Bauxsol, a soil-like material, in a filtration system to pull out the phosphorus. Envirolink is using bacteria to reduce phosphorus in the wastewater.

(Top) In the first stage of the electrocoagulation process, dairy effluent enters the mixing tank and lime, coagulants and an emulsion polymer are added and agitated.

(Center) After going through the electrocoagulation process, the effluent passes through the dissolved air flotation clarifier, sludge is removed, and treated water is discharged.

(Bottom) Dairy farmers and other stakeholders observe the Geotube demonstration at the Triple X Dairy in the Leon River watershed.

The first year's technologies—electrocoagulation, developed by Ecoloclean Industries, and geotextile solids separation systems (Geotube™), developed by Miratech Division both appear to reduce phosphorus levels in the processed water, Mukhtar said.

With electrocoagulation technology, dairy wastewater is processed, separating the solids from the liquid. Aluminum and/or iron electrodes are placed in the wastewater stream to attract and coagulate the negatively charged ions of phosphorus. The system then removes the coagulated phosphorus-containing particles, leaving treated water ready to irrigate forage and pasture land.

The Geotextile solids separation system uses large, porous tubes (up to 45 feet in circumference and up to 400 feet long) made from a heavy-duty fabric. The lagoon effluent is pumped into these "large socks" after adding alum or other chemicals to bind and precipitate the phosphorus. As the liquid leaves the porous tubes, solids larger than the pore size of the tube are trapped. Once the tubes are full, the solid waste is hauled off and used as compost or fertilizer in fields with low soil phosphorus and the liquid out of the tube with reduced amount of phosphorus is routed back to the lagoon or to a waste application field.

Dairy producers are positive about learning about the technologies.

"Nearly 100 dairy producers attended a Geotube technology demonstration in the spring and producers were very interested in learning more about the performance and economics of this technology," Mukhtar said.

Mukhtar said each technology company selected for the project will prepare reports, including costs, of its technology. Extension and Texas Water Resources Institute staffers will develop fact sheets on each technology for producers, regulators and agricultural businesspeople so they can make their own decisions about the performance and cost effectiveness of each technology.

Mukhtar sees the technology advisory committee established to review and select technologies for this project as perhaps serving as a clearinghouse for technology providers and producers on future technologies developed.

"The committee could continue to look at new technologies and select the most suitable technologies that have the potential to decrease phosphorus from dairy effluent," he said.

John Cowan, executive director of the Texas Association of Dairymen, agreed.

"Dairymen need good science-based evaluations for any technology they use," Cowan said. A clearinghouse for different technologies, Cowan said, would provide "the farmer some sense and confidence the technology is beneficial and doable."

Before the project, Ned Meister of the Texas Farm Bureau said the bureau was constantly being contacted by vendors who said they had products or processes to help with the dairy wastewater,

"We did not have the capability to validate any of their claims and therefore could not and would not refer the vendors to anyone in the dairy business," Meister said. "Now, when we are contacted by the vendors, we refer them to the program, thus providing them the opportunity to demonstrate their product or process."

The U.S. Environmental Protection Agency, Texas State Soil and Water Conservation Board, Texas Commission on Environmental Quality, Brazos River Authority, Texas Farm Bureau and USDA's National Resources Conservation Service are represented on the technical advisory committee in addition to TWRI, Extension and Texas Agricultural Experiment Station scientists.

Story by Danielle Supercinski

West Texas Rain

Rainwater harvesting demonstration sites save water and money

Rainwater, one of the purest sources of water available, is scarce in West Texas. Residents in this arid land must use all available methods of saving water. Rainwater harvesting, a common water resource used in the early 1900s, is becoming one such option.

The Texas Water Resources Institute (TWRI) and Texas Cooperative Extension, working with several partners, are planning and constructing rainwater harvesting demonstrations in West Texas to educate the public about its potential as an alternative and inexpensive source of high-quality water.

Most rainwater harvesting systems in the past were for personal use, but some businesses, industries and public institutions are beginning to use these practices as well.

The Culberson County Courthouse in Van Horn, the Ward County 4-H Center in Monahans, and the Hudspeth County Extension Office in Sierra Blanca have or will soon have rainwater harvesting demonstrations, some of the first in this area.

These West Texas demonstrations help promote the systems in the area, said Mike Mecke, Extension water program specialist with TWRI in Far West Texas.

"Rainwater harvesting is of special interest in the drier half of Texas and is being promoted through the *Water for West Texans* program, headquartered at the Fort Stockton Extension Center," Mecke said.

In Culberson County, Extension partnered with the Rio Grande Basin Initiative through TWRI, the International Boundary and Water Commission, Culberson County Underground Water District and county officials to install a 2,500-gallon rainwater harvesting tank at the Culberson County Courthouse.

(Above Left) One of the three rainwater harvesting demonstrations is located at the Culberson County Courthouse in Van Horn. This 2,500-gallon tank has been installed to catch and store the rainwater.

(Above Right) Landscape irrigation using the harvested rainwater can help maintain nice looking landscape plants, as well as conserve water.

A 2,000-gallon tank and 3,000-gallon tank at the Ward County 4-H Center is planned. The Hudspeth County Extension Office is planning a 1,000-gallon tank for inside drinking water and a 3,000-gallon tank for outside landscape irrigation.

Although harvesting rainwater for drinking water complicates installation and raises the cost of treatment, Mecke said the Extension agent for Hudspeth County, Cathy Klein, wants the demonstration to show its viability to residents who currently must haul water or buy bottled water.

Mecke said more demonstrations are tentatively planned for the West Texas region including the Alpine Library, McDonald Observatory in Fort Davis, several locations in Fort Stockton, Sanderson, San Angelo, Alpine, Ozona, Midland and El Paso.

The largest planned project is for Baptist Memorials Center, a nursing home in San Angelo. A team is developing a long range plan to install a rainwater harvesting system, drip irrigation system, in-home water conservation and low water-use landscapes at that site.

Mecke said the nursing home rainwater harvesting project will be a three- to five-year project, working with staff from Baptist Memorials, the City of San Angelo, Extension, and Texas A&M University System scientists and engineers from College Station and San Angelo. Billy Kniffen, Extension agent for agriculture in Menard County, and John Begnaud, an Extension agent for Tom Green County, are also working on the project with Mecke.

Begnaud is guiding the planning and installation of water-efficient drip irrigation and landscape plantings. Janie Harris, Extension housing and environment specialist, is working with Kathlene Aycock, Extension agent for family and consumer sciences in Tom Green County, to set up an in-home water conservation demonstration to complement the other efforts and to monitor effectiveness.

Other rainwater harvesting demonstrations throughout other parts of Texas include the Lady Bird Johnson Wildflower Center in Austin, Wells Branch Municipal Utility District in North Austin, Advanced Micro Devices fabrication plant in Austin, and Reynolds Metals in Ingleside.

More information on designing and constructing rainwater harvesting systems is available. A new *Rainwater Harvesting* Extension publication by Russell Persyn, Dana Porter and Valeen Silvy can be found at http://tcebookstore.org/pubinfo.cfm?pubid=1979.

The Texas Water Development Board has recently produced the *Texas Guide to Rainwater Harvesting Third Edition.* This publication can be downloaded free of charge from either the TWDB Web site, www.twdb.state.tx.us, or from the American Rainwater Catchment Systems Association Web site, www.arcsa-usa.org.

Extension agent for agriculture Billy Kniffen has constructed a rainwater harvesting system for his own home. These catchment tanks are used to hold up to 16,500 gallons of rainwater, providing enough water for his indoor and outdoor uses all year.

Story by Kathy Wythe

Investing in the Future

TWRI awards Mills Scholarships to graduate students

The Texas Water Resources Institute recently awarded Mills Scholarships to 11 Texas A&M University graduate students and four Texas A&M University–Galveston graduate students for the 2005-06 academic year to pursue water-related research.

TWRI's Mills Scholars Program, an endowed fund that supports research in water conservation and management, provided the $1,500 scholarships to each student to use for education-related expenses. The scholarship program supports graduate students in diverse water research programs at Texas A&M University and Texas A&M University-Galveston.

Students receiving the scholarships include: Omar Amawi, Scott Beech, Larry R. Demich and Aarin Teague, Department of Biological and Agricultural Engineering; Elizabeth Bristow, Department of Civil Engineering; Regan M. Errera and Danielle M. Rutka, Department of Wildlife and Fisheries Sciences; David Hansen, Stephen Lichlyter and Douglas S. Sassen, Department of Geology and Geophysics; and Shelli L. Meyer, Department of Oceanography.

Graduates students from Texas A&M–Galveston are Charlotte Hieke, Joe Mikulas, Kimberly A. Roberts, all of the Department of Marine Geology; and Linda R. Roehrborn, Phytoplankton Dynamics Laboratory.

Mills Cox, a former chairman of the Texas Water Development Board, endowed the Mills Scholarships. For more information on the Mills Scholarship program or to learn more about the projects, visit our Web site at http://twri.tamu.edu/mills.php.

Story by Kathy Wythe

(Above Left) Lake Granbury and the communities around it have flourished since the lake was completed in 1969. The population on or near Lake Granbury is increasing 16 percent every year.

(Above Right) Lake Granbury serves as the critical water supply in North Central Texas, providing water for more than 250,000 people in more than 15 cities.

What's the Plan?

Groups tackling water quality problems on Lake Granbury

The lake glistens, fish jump, and people swim. But not if the water quality of Lake Granbury—a popular tourist attraction and critical water supply to some 250,000 people in 15 cities—continues to decline.

In recent years, toxic blooms of golden algae have caused fish kills, and *Escherichia coli* bacteria have invaded some of the lake's coves, limiting their recreational use.

After meeting with the area's stakeholders, State Sen. Kip Averitt and U.S. Rep. Chet Edwards both solicited federal funds to help correct the problems. Now federal, state and local entities are working together on two projects to ensure the lake retains its water quality and its recreational appeal.

For one project Sen. Averitt obtained $1.4 million from the U.S. Environmental Protection Agency for Brazos River Authority (BRA) and Texas Commission on Environmental Quality(TCEQ) to develop the watershed protection plan, focusing on the *E. coli* found in the lake.

Monitoring studies conducted by the BRA have shown that some of Lake Granbury's coves—shallow bodies of water with little interaction with the main lake—are contaminated with *E. coli.*

"A possible source (of the *E. coli* contamination) is the large population of septic systems," said Tiffany Morgan with the BRA. Unincorporated subdivisions that rely on septic systems make up a large part of the developed area around the lake. Some contamination, Morgan said, may also be coming from wildlife in the area. Research is needed to positively determine the source, she said.

Morgan, manager for BRA's project, said the first step is identifying the sources of the *E. coli* contamination and then identifying solutions to the problem.

BRA's project will estimate the decrease in bacteria concentrations expected through identified best management strategies and will develop criteria that can be used to determine if progress is being made.

Morgan said the river authority will seek public input through stakeholder participation meetings to help develop the watershed protection plan. Stakeholder participation is key to the success of the implementation of the plan, she said.

Edwards obtained $500,000 in the 2006 federal budget for a consortium to develop water quality education for local stakeholders and conduct research on control of golden algae. The Texas Water Resources Institute is teaming with Texas Agricultural Experiment Station, Texas Cooperative Extension, BRA, TCEQ and local stakeholders to work on this project.

Extension, led by Dr. Bruce Lesikar, Extension specialist in the Department of Biological and Agricultural Engineering, will conduct water quality education programs for adults and schoolchildren to help minimize the impacts on water quality of bacteria, golden algae, nutrients, pesticides and stormwater.

The golden algae study is led by Dr. Daniel Roelke from Texas A&M University, and team members include scientists from Baylor University, University of Texas-Arlington and U.S. Geological Survey. The research will determine how golden algae blooms are affected by inorganic nutrients, dissolved organic matter and microbes, including *E. coli*. Scientists will use high-resolution spatial mapping and water sampling to identify sources of inorganic nutrients and dissolved organic matter, and to predict the impacts of best management practices on golden algae blooms.

Both Edwards and Averitt are pleased these two projects will help solve the lake's problems.

"Lake Granbury is a tremendous asset for the city of Granbury and for all of Hood County, and I believe protecting the quality of water in the lake is an important investment in the future of the area," said Rep. Edwards. "I am gratified that we now have significant funding for the Texas Water Resources Institute and other state agencies to work with local officials in planning how to best protect Lake Granbury for years to come."

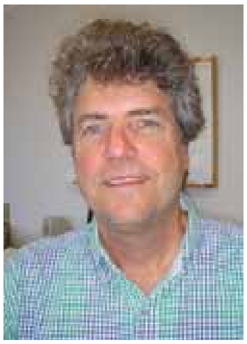
Sen. Averitt agreed. "Lake Granbury is crucial to Hood County and its citizens," said Averitt. "Our area relies on the lake for its drinking water, industry and recreation. I look forward to working with stakeholders to protect and improve the quality of this valuable resource."

(Below Left) In recent years, *Escherichia coli* bacteria have been found in the coves and canals of the lake. Faulty septic systems, found in unincorporated subdivisions around the lake, are a potential source of the *E. coli*.

(Below Right) Lake Granbury and the town of Granbury with its historic buildings including the town's courthouse have grown into a popular tour destination.

New Faculty Expand Water Resources Expertise

Agricultural Economics and Recreation, Park and Tourism Sciences


Shaw

W. Douglass Shaw, professor, joined the Departments of Agricultural Economics and Recreation, Park and Tourism Sciences in 2004.

Dr. Shaw received his doctorate in economics from the University of Colorado in December 1985.

His expertise is the area of valuation of water quality and quantity changes, with an emphasis on health risks and uncertainty, value of health risk reductions associated with arsenic in drinking water and value of increased water supply at recreation areas.

Specific research includes arsenic in drinking water. A competitive grant from the U. S. Environmental Protection Agency will assess perceived risks that households have relating to arsenic exposure. The focus is on children's health risks.

Another research project involves the economics of perceived risks, which is an investigation into economic risk models that incorporate the idea that individuals often have difficulty expressing and processing information relating to risks and uncertainty.

Two of his recent papers involving research on arsenic in drinking water are published in the *Journal of Water and Health* (September 2005), and *Risk Analysis* (December 2005).

Biological and Agricultural Engineering

Dr. R. Karthikeyan joined the Department of Biological and Agricultural Engineering in 2005 as an assistant professor.


Karthikeyan

Dr. Karthikeyan received his bachelor's degree in agricultural engineering from Tamil Nadu Agricultural University in 1993 and his master's degree in 1997 from the University of Georgia. His doctoral degree in engineering is from Kansas State University in 2001.

His research involves application of spatial science tools (GIS and remote sensing) in agriculture, biological and homeland security, disease (human and animal) tracking and control, disaster management and response, natural resources management and water quality. He is also involved in research in the fate, transport, and removal of contaminant's in terrestrial and aquatic environments.

Rangeland Ecology and Management


Moore

Dr. Georgianne Moore, an assistant professor with expertise in ecohydrology and woody vegetation management, joined the Department of Rangeland Ecology and Management in February 2005.

She received her bachelor's degree in applied biology from Georgia Institute of Technology in 1995 with emphases in ecology and environmental science; and her doctorate in interdisciplinary environmental sciences in 2003 with an emphasis in small watershed hydrology and forest ecology.

Her particular interest is the role of vegetation in the water cycle and how vegetation management/change affects water resources. Dr. Moore is conducting research in Texas and New Mexico comparing water use by native and invasive woody species in riparian ecosystems under different management regimes. She is also investigating the effects of brush clearing on spring flow and surface runoff from small watersheds and initial and long-term effects of root plowing mesquite on groundwater dynamics and aquifer recharge.

Wildlife and Fisheries Sciences

Peterson

Dr. Tarla Rai Peterson joined the Department of Wildlife and Fisheries Sciences as the Boone and Crockett Wildlife and Conservation Policy Chair at Texas A&M University in January 2006.

The chair was established with a $500,000 gift from the Boone and Crockett Club and a matching $500,000 from the Texas A&M Development Foundation. The purpose of the chair is to help to close the gap between the knowledge of wildlife science and the implementation of wildlife policy, according to Dr. Robert Brown, department head for the Department of Wildlife and Fisheries Sciences.

Dr. Peterson was chosen for the Texas A&M position because of her academic background; her successes in teaching, grantsmanship, publication and graduate student mentorship; and her enthusiasm and dedication to sustainable conservation and sound wildlife policy on private lands, Brown said.

Peterson received a bachelor's degree in history from the University of Idaho in 1976. She earned a master's degree in speech communication in 1980 and a doctorate through the interdisciplinary program in environmental conflict in 1986, both from Washington State University.

TWRI Welcomes New Faces

Kevin Wagner joined the Texas Water Resources Institute in July 2005 as a project manager in charge of 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 oversees the development of project research and educational programs and is responsible for project reporting.

Kathy Wythe began at Texas Water Resources Institute in July 2005 as the communications coordinator. Wythe will provide leadership for TWRI communications, including newsletters, brochures, presentations, media relations and special projects.

As a business coordinator, Sarah Erwin handles all payroll and human resources processing at Texas Water Resources Institute. She maintains accounts for travel and purchasing and assists with handling other TWRI accounts.

Erwin joined TWRI in December of 2005 and was previously employed as a benefits assistant by the TAMU System Human Resources office.

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Panhandle AgriPartners

The Panhandle AgriPartners program uses farm demonstration agents to provide up-to-date information on water use, crop development and growth, and pest status to participating farmers. Since AgriPartners' inception in 1998, the program has conducted around 500 demonstrations of improved farming and irrigation practices, helping farmers increase their irrigation efficiency and improve crop yields (see story on page 5).

Texas Water Resources Institute | Texas Agricultural Experiment Station | Texas Cooperative Extension

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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

Published by
Texas Water Resources Institute

Clint Wolfe
Managing Editor
Texas Water Resources Institute

Kathy Wythe
Editor
Texas Water Resources Institute

Courtney Swyden
Assistant Editor
Texas Water Resources Institute

Steven Keating
Art Director
Agricultural Communications

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

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Inside

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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."

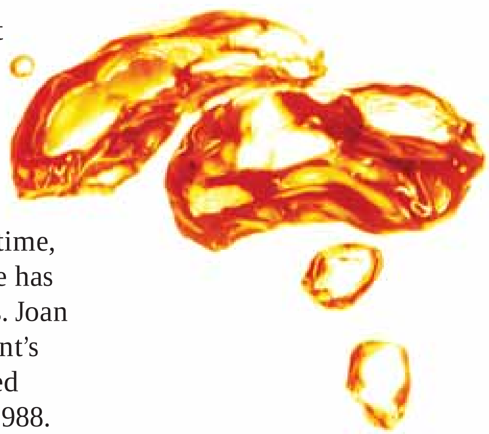
U.S. Rep. John Carter gave his congratulations for the award. "I applaud all of the partners in this project and am proud to support practices that will benefit not only Fort Hood's training capabilities, but also the environment," he said.

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.

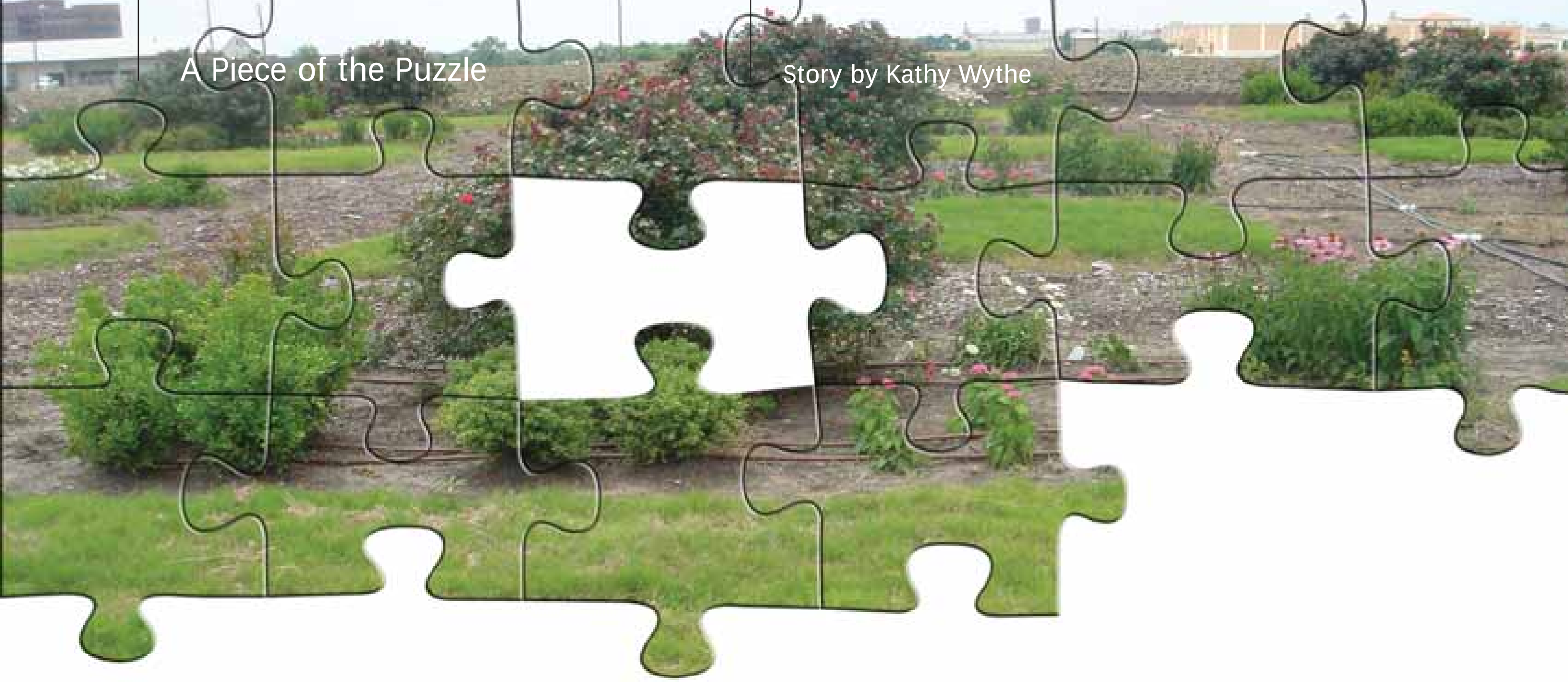
Since Texas presently reclaims about 5 percent of its wastewater with the potential to reclaim greater quantities, further research is being focused on salty groundwater, graywater and concentrate as alternative water sources for irrigation in rural and urban areas. The research strategy is to remove 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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OUTCOMES

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Students Try on New “Hat”

Water well screening program provides efficient water for urban consumers and irrigation

by
Jenna Smith

Experts in the water science field are getting younger and younger. Nearly 200 high school and middle school students in El Paso County screened water samples for private well owners in the area.

Monty Dozier, water resources specialist with Texas Cooperative Extension, working with local County Extension Agents Ray Bader, Orlando Flores and Jimmy Rodgers, conducted the private water well screenings as a component of the El Paso Youth Water Leadership Institute at three El Paso County schools—Clint High School, Fabens Middle School and Canutillo High School.

Dozier said students benefited from the hands-on aspect of the program and enjoyed learning how to analyze water. The methods they used were similar to those used in the real world.

Dozier works with students to screen water.

In addition, land owners received water quality information for free.

El Paso County Extension agents solicited teachers to participate in the screening program. Teachers then chose which students would take part in the water sampling opportunity. Water sample kits and bags were distributed to county landowners who wanted to have their water tested on a volunteer basis.

Monty Dozier explains the process of screening water to students at the El Paso Water Screening Camp.

> ***“The program helps private well owners make informed decisions on how to use their water to reduce health impacts on themselves, their families, livestock, pets and plants.”***

Clint High School students participating in the screening began by attending a watershed protection seminar at the school. Similar, condensed versions of the presentation were also presented at Fabens and Canutillo high schools. Dozier said the seminar introduced students to how water behaves in the environment, potential sources of contamination, water use trends and how our everyday activities impact the world around us.

"The seminar was a lead-in to why we screen or test water for various contaminants," Dozier said. "Students learned how to make a determination of water quality based on available data."

During the two-day program, students were trained in lab analysis and reporting using mobile lab techniques. More than 56 water samples were screened for the presence of contaminants, especially fecal coliform bacteria. Both animal and human sources contribute to fecal coliform contamination.

"Students learn how their individual activities and those of others impact the quality of water in the watershed where they live."

Dozier said that many times, water quality problems associated with fecal coliform is a local issue around an individual well.

"The program helps private well owners make informed decisions on how to use their water to

Students test their water for fecal coliform.

reduce health impacts on themselves, their families, livestock, pets and plants," Dozier said. "Students learn how their individual activities and those of others impact the quality of water in the watershed where they live."

The screening program is offered to counties across Texas as a means to educate private well owners on knowing the water quality of their well and how to better manage and protect their well from contamination.

"Our main message that we try to drive home for the students is that everyone lives in a watershed, and everyone impacts the quality of water in that watershed."

The water well screening program began in 1999 and has grown each year to include additional counties in various parts of the state.

"We have been asked back to several of the same counties year after year," Dozier said. "Our main message that we try to drive home for the students is that everyone lives in a watershed, and everyone impacts the quality of water in that watershed."

Students nitrate testing their water samples.

Photos courtesy of Monty Dozier

CroPMan Programs Aid Growers

Computer models help growers irrigate crops efficiently

by
Danielle Supercinski

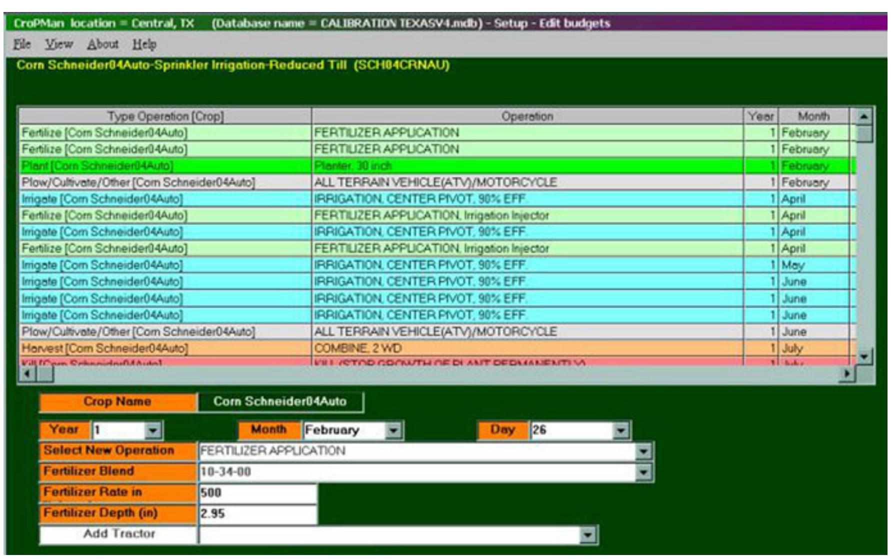
Crop simulation models have been developed and used by the research community to simulate the impact that cropping practices have on yield and natural resources—soil, water and air.

Many models are only designed to simulate the growth of specific crops, but the EPIC model is capable of simulating a wide variety of crops and cropping practices. In recent years, two Windows-based decision aids, CroPMan and WinEPIC, were developed by Drs. Tom Gerik, Wyatte Harman, Jimmy Williams and others at the Blackland Agricultural Research and Extension Center. They wanted to harness the capability of the EPIC model so Texas growers and Cooperative Extension could readily identify the most effective cropping practices that conserve water for irrigation and improve production and profitability.

"CroPMan and WinEPIC are being field tested with growers, Texas Cooperative Extension and Texas Agricultural Experiment Station researchers in South Texas to identify cropping practices and monitoring technologies that most effectively conserve water applied through irrigation with minimal adverse impact on crop yield and profitability," said Tom Gerik, Experiment Station Researcher at Blackland Agricultural Research and Extension Center in Temple.

"CroPMan and WinEPIC identify cropping practices and monitoring technologies that most effectively conserve water applied through irrigation."

"The project entails monitoring and assessment of current cropping practices on grower's fields in the Rio Grande Valley, Coastal Bend, Upper Gulf Coast and Texas Winter Garden (near Uvalde)."

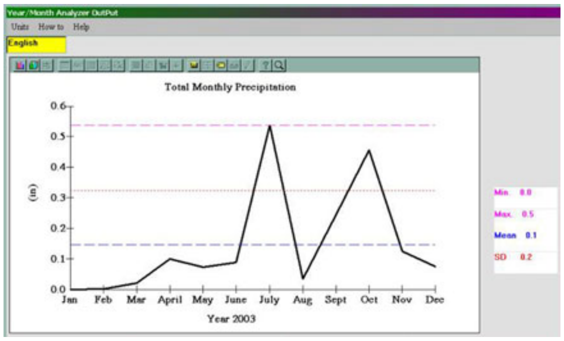


The screen image shows one of many CroPMan interfaces. Users can choose which operation they would like to select, for how many years, which month and even which day.

CroPMan is used to assess "real-time" situations in the field—estimating crop and soil-water-fertility status, and to project implications of additional irrigation and fertilization (i.e., timing and amount) on crop productivity, Gerik said.

"CroPMan is designed to be used by Extension specialists and agricultural consultants," he said. "Many of EPIC's features are hard-wired and streamlined for Texas."

CroPMan contains a feature known as "Projected Run," which enables the user to assess the "real-time" status of a crop by stopping the model on any date of interest. The user can then update the soil or crop status, or alter subsequent management operations. They can estimate crop yield using 30



CroPMan provides numerous graphical outputs, including total monthly precipitation for any given year(s).

to 100 location specific weather scenarios through the end of the growing season. This feature assists growers with decisions on replanting, late planting, irrigation timing management and estimates of yield. CroPMan provides graphical outputs of numerous growth characteristics, crop stresses, economical variables and pesticide fate variables.

"WinEPIC was designed to provide researchers with all the features, power and flexibility as EPIC," Gerik said.

"The databases are constructed for the five distinct agricultural regions in Texas - West, South, Central, East and the Lower Rio Grande Valley."

WinEPIC is used to determine long-term implications of new irrigation practices, such as conversion of furrow irrigation to sub-surface drip and/or low energy spray application (LESA)/low energy precision application (LEPA) sprinklers, and comparisons of single cropping (monocrop) and double cropping systems.

"In WinEPIC the user can manipulate EPIC's control files to simulate the full range of cropping scenarios," he said. "The user can compare results of hundreds of scenarios (runs) through the batch mode."

WinEPIC does not contain the 'Projected Runs' feature or graphical output of results found in CroPMan. However, all data are stored in Microsoft Access tables where the user can view and export the data for further manipulation, and both programs use the Microsoft Access structure to operate.

"The databases are constructed for the five distinct agricultural regions of Texas – West, South, Central, East and the Lower Rio Grande Valley," Gerik said.

Each database contains tables with actual soil data, historical weather data, field operations, common crops and cropping systems, crop parameters, machinery/equipment, and numerous control type files. The field operation budgets include information on the type and timing of cultural practices such as tillage operations, irrigation, fertilization, planting date and harvest date.

"All operation budgets can be edited to produce the desired cropping practices of the user."

"All operation budgets can be edited to produce the desired cropping practices of the user," Gerik said. "Daily weather files and weather stations can be updated and created through a complementary software utility named the Crop Weather Analyzer."

CroPMan, WinEPIC and the Crop Weather Analyzer are available on CD-ROM or can be downloaded from the CroPMan website at http://cropman.brc.tamus.edu or by contacting Tom Gerik at gerik@brc.tamus.edu.

Photos courtesy of Tom Gerik

Communicating Outcomes

Collaboration leads to water conservation

By
Danielle Supercinski

Sunny skies and cool weather greeted project participants as they arrived at the fourth annual Rio Grande Basin Initiatives (RGBI) Conference, April 12-14, 2005, in Alpine, Texas. It was a productive week that provided numerous discussions on local water issues, agency reports, Task Group breakout sessions and concurrent Task Group reports.

The RGBI is a federally funded effort involving Experiment Station researchers and Extension educators from both Texas and New Mexico. The project partners with a number of other state and federal agencies to enhance water conservation programs. The purpose for the Initiative is to develop and adapt water conservation practices through research and then through Extension education implement water saving practices. Primarily, the project focuses on irrigation efficiency in both agricultural and urban areas.

Some participants stayed for the 02 Ranch Field Tour on Thursday, April 14. Here we are looking at Terlingua Creek, the largest tributary to the Rio Grande in Brewster County. Tour guide Bonnie Warnock shows the slow regeneration of the flood plain after the Terlingua Creek dam failed. Photo courtesy of Charlie Hart.

RGBI project participants from Texas and New Mexico Agricultural Experiment Stations and Cooperative Extension attended the meeting as well as participants of new 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 from various offices, irrigation district managers, Extension agents and specialists, and Experiment Station researchers.

Conference participants are listening to the wide variety of speakers scheduled for each session. From here they can collaborate with other Task Group members and formulate their future goals. Photo courtesy of Zhuping Sheng.

"A wealth of information is being developed, not only by ourselves, but collaboratively with a number of others involved," said B. L. Harris, Project Manager of the Rio Grande Basin Initiative and associate director of the Texas Water Resources Institute. "It's our goal to minimize duplication and encourage collaboration."

The purpose of this conference was to put all three of the separately funded projects together to discuss methods and ways to collaborate and cooperate, and to prevent unnecessary duplication, Harris said. The conference was also planned to bring the several RGBI Task Groups together for annual reporting of significant accomplishments and joint planning for future efforts. Peer and merit reviews were facilitated for on-going activities and participants were able to discuss partnership opportunities with federal and state agencies for both Texas and New Mexico.

"Obviously one of the principal themes over the past few days and life of the project has been collaboration, collaboration, collaboration," said Craig Runyan, Water Quality and RGBI Program Coordinator for New Mexico State University (NMSU), during closing remarks. "It's meaningful and it's helped a lot. It's certainly helped our water program at NMSU. Collaboration isn't something new to us. Institutionally, professionally, career-wise, that's what we do – we collaborate."

Runyan said the collaboration between the universities and the interaction with those universities, stakeholders and other agencies has given us an institutional capacity to keep this project relevant.

The RGBI is in its fourth year and continues to go forward, collaborating and working towards the common goal – to conserve the water in the Rio Grande Basin. Without the collaboration of all of the groups involved, this would not be possible, but together it can be done.

For conference presentations and reports, go to: http://riogrande.tamu.edu.

Live, Learn and Thrive

RGBI Team Award presented at NMSU ceremony

By
Danielle Supercinski

Rio Grande Basin Initiative (RGBI) participants received the Team Award from New Mexico State University (NMSU) on April 21, 2005, during the NMSU *Live, Learn and Thrive* awards convocation.

New Mexico efforts are led by Craig Runyan, RGBI Program coordinator for NMSU, and assisted by Leeann DeMouche. Runyan, DeMouche and almost 40 other members of the RGBI received this award for demonstrating the power of team action in achieving significant water savings in agricultural irrigation and in addressing community water needs. In addition, other partners who also received this award were: B. L. Harris, Sterling Grogan, Gary Esslinger and Subas Shah.

The RGBI is a joint project involving NMSU and Texas A&M University Systems Cooperative Extension and Agricultural Experiment Stations. It is a federally funded effort through the Cooperative Research, Education and Extension Services. The project partners with a number of other state and federal agencies, including the Elephant Butte Irrigation District and the Middle Rio Grande Conservancy District in New Mexico. Once again collaboration has paid off.

(From left to right) Leeann DeMouche, Bill Harris, Craig Runyan and Gary Esslinger were all present to receive the RGBI Team Award for their collaborative efforts in water conservation and efficiency.

Increasing Irrigation Efficiency in the Rio Grande Basin through Research and Education

Through Extension and research efforts, the Texas A&M University System Agriculture Program and the New Mexico State University College of Agriculture and Home Economics are implementing strategies for meeting present and future water demand 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 2005, Vol 4. No. 2

B.L. Harris, Project Director,
Associate Director,
Texas Water Resources Institute

Craig Runyan, Project Director,
Water Quality Coordinator,
New Mexico State University Plant Sciences

Danielle Supercinski, Editor

Send comments or subscription requests to *Outcomes* Editor, Texas Water Resources Institute, 2118 TAMU, College Station, Texas, 77843-2118. Call (979) 845-1851 or e-mail riogrande@tamu.edu.

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Texas Water Resources Institute
1500 Research Parkway, Suite A240
2118 TAMU
College Station, Texas 77843-2118

Rio Grande Basin Initiative

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For these and other stories, please visit:
http://riogrande.tamu.edu

Polypipe Conserves Water

Tests in Mexico demonstrate up to 50 percent water savings

by
Danielle Supercinski

Texas Agricultural Experiment Station and Texas Cooperative Extension scientists and engineers, through the Rio Grande Basin Initiative, are helping farmers in Mexico test polypipe to conserve water, and thereby provide an expanded water source to help meet future water demands, maintain flows to the river system, and retain better levels in Falcon and Amistad Reservoirs to enhance wildlife and natural resources in the area.

"Polypipe is like a garden hose 15 inches in diameter made out of 10 ply pieces of plastic," said Gordon Hill, former General Manager for Bayview Irrigation District. "You make holes where your turnout is – where you want to water the plants. There are no losses and the water pours out right onto the plant."

Three polypipe test blocks have been installed in Tamaulipas, Mexico by Hill, Winzen Film & Fiber Inc., and Mexican farmers. Research personnel Drs. Juan Enciso and Guy Fipps will collect and certify the data to determine effectiveness and water savings. Tony Hinojosa from Texas A&M Kingsville and four student interns from Monterey Tech are also involved with this project.

Field days and demonstrations were held to teach Mexican farmers how to properly install polypipe so it irrigates their crops efficiently.

"If we can reduce demands on the supply by 50 percent and apply it to their water supply, along with rainfall and a stable economy, it will significantly benefit the area."

Three test blocks were installed April 1, April 6, and April 11, respectively, while another field beside them is using conventional irrigation methods common to the area.

The three metered, irrigated fields are using polypipe and will be compared to the conventional irrigation field. The fields will be watered and tested for six months. After the testing period, the data will be compiled to determine how much water was saved.

"To determine the savings due to the use of polypipe we are conducting these three tests, then we will multiply (the data) by 700,000, which is the number of irrigated acreage in the area, to predict how much water polypipe potentially could save," Hill said.

"Using polypipe is the easiest way to conserve water for the least amount of money, and it gets the biggest bang for the buck."

Currently the overall irrigated acreage in the Rio Grande Valley of Mexico is twice as much as the irrigated acreage along the Lower Rio Grande in Texas, he said.

Two 50 acre blocks are being measured for volume of water lost off the field. Open ditch irrigation, volume, crop yields and other data are also being collected.

"Twenty to 25 percent of water was saved from seepage in the Bayview Irrigation District by using polypipe, and Mexico could save up to 50 percent,"

BEFORE:
Typical dirt-lined canals and ditches are leaky, and water is wasted as it "slips through the cracks."

AFTER:
Polypipe prevents canal leakage losses by keeping the water contained in this garden hose-like pipe.

Hill said. "So presume we save 50 percent. That means Mexico will have an additional 700,000 to 800,000 acre-feet of water each year. If we can reduce demands on the supply by 50 percent and apply it to their water supply, along with rainfall and a stable economy, it will significantly benefit the area."

"It keeps the river charged constantly because water is available and there is still enough to water crops. It has enhanced the ecosystem and the environment in the area."

Tom Wilson, representative for Winzen Film & Fiber Inc. in Sulphur Springs, Texas, donated seven rolls of polypipe for these tests. The Lower Rio Grande Authority, which consists of all Irrigation Districts in the Valley, donated the money to purchase six meters. The meters were then given to Texas Cooperative Extension to meter and evaluate the research and certify this project. This work is also supported by the U.S. State Department, Senator Kay Bailey Hutchinson, Senator John Cornyn and Governor Perry's office. Hill said they all see the big picture and understand how the project affects all of us, and they are interested in what it will do for both Texas and Tamaulipas.

The Comisión Nacional del Agua (CNA), Mexico's governmental research agency, is interested in the data and has been involved step-by-step along the way. Costa Ricans and United Nations personnel are also interested in the data.

"The CNA wants to take (the data) and make a Mexican government policy to subsidize use of polypipe," Hill said. "Now they are subsidizing use of gated pipe, but it is expensive, isn't used much, and a lot of water pressure builds up in it. Polypipe can be used by all farms for irrigation. Using polypipe is the easiest way to conserve water for the least amount of money, and it gets the biggest bang for the buck."

Use of polypipe causes a chain reaction of events to take place that leads to conserving water and farmers' money in the Tamaulipas area.

"With university assistance with this technology through the Texas Agricultural Experiment Station and Texas Cooperative Extension, we use less water, so there is more water left in Falcon and Amistad Reservoirs, and therefore, more water available for other uses," Hill said. "It helps keep the river charged constantly because water is available and there is still enough to water crops. It also has enhanced the ecosystem and environment in the area."

The overall global picture is that this technology is helping the environment throughout the Rio Grande Basin by maintaining higher water levels in both reservoirs, creating steady flows, maintaining adequate supplies for irrigators, increasing the quality of life with water savings and crop differences, and

*See **Polypipe** page 5*

NMSU Turf Research

Tray system serves up big water savings

by
Norman Martin

New Mexico State University scientists studying turf irrigation have discovered how a series of 5-by-5 foot trays buried a foot below ground can cut water use in half. The work sheds new light on a puzzle that has long intrigued New Mexicans: How can desert dwellers have a lush lawn or golf course?

An international research group headed by Bernhard Leinauer, an NMSU turfgrass specialist, has found that a subirrigation technique, Evaporative Control Systems, used the least amount of water while providing the highest quality turf. The two-year study examined three water application methods here on the arid southern New Mexico campus.

J. Victor Espinoza

Bernhard Leinauer, New Mexico State University turfgrass specialist, examines a subirrigation tray. Experimental studies suggest that the 5-by-5 foot trays buried a foot below ground can cut turf water use in half.

"Over a year's time, this system used 50 percent less water than our traditional sprinkler system."

"Hands down, it was the winner," Leinauer said. "Over a year's time, this system used 50 percent less water than our traditional sprinkler system. On top of that, during the hottest part of the summer, it used about 80 percent less water."

Two years ago Leinauer and his colleagues built what they call a rolling green, a 41,000-square-foot series of subsurface drip and sprinkler irrigated plots. One of the turf trial's critical elements is its alternating series of south-facing 5 percent slopes followed by flat areas.

"We're trying to match real-world conditions such as you would find on a golf course or in your own yard."

The project is funded by NMSU's Experiment Station, The U.S. Golf Association, Toro Co., and the Rio Grande Basin Initiative.

"The information from these sloping areas is very important because not all turf areas are flat," Leinauer said. "We're trying to match real-world conditions such as you would find on a golf course or in your own yard."

Creeping bentgrass, used on many of the state's golf greens, was selected for the experiment because it is one of the most intensively maintained grasses in New Mexico. From a bird's eye view, Leinauer's rolling green looks like a huge, manicured or well-maintained golf green. But underneath the green

This golf course plot shows the three major irrigation treatments: Sprinkler (far back), tray system (middle) and drip (front). If you look closely, the Evaporative Control System plot is the greenest.

carpet is a complex array of irrigation systems, including traditional pop-up sprinklers, subsurface drip irrigation and subirrigation.

Sprinklers, which apply water to the surface, are commonly used in many parts of the state. In subsurface drip irrigation, water is applied directly to plant roots through a grid of black plastic liners or drip tape buried more than a foot deep.

Subirrigation uses a combination of flood irrigation and 5-by-5 foot drain tiles or trays. The three-inch-deep tiles are buried a foot below the surface, and water is injected through a patented distribution system at very low pressure into the trays. The water then wicks to the surface from the base of the trays. Installation is about double the cost of a conventional sprinkler system.

Evaporative Control Systems, invented by Jonas Sipaila in Reno, Nev., are specifically targeted for newly constructed golf and housing developments. “This isn’t something that can be easily retrofitted,” Leinauer said. “You really have to start from scratch.”

Because of the cost and scope of installing subirrigation, Leinauer doesn’t foresee its application over entire golf courses. But the method could be applied to high-profile areas like greens and specific fairways.

Leinauer admitted that subirrigation is “a little far out there, but part of our job is to look at where we can be.” With the population continuing to grow in the Southwest, water conservation will remain a high priority for the foreseeable future, he said.

Scientists know that more than 90 percent of the water used by grass goes to transpirational cooling. In other words, the water evaporates from the leaves to keep the plant cool.

Leinauer’s rolling green experiment is scheduled to run at least another 10 years to determine the long-term viability of irrigation systems. “Root intrusion and plugging are always a concern,” he said. “The performance of the systems needs to be monitored.”

Polypipe

continued from page 3

impacting the economy on both sides of the River, he said.

“I think we’re going to do well,” Hill said. “The only way I was able to do all of this is with the approval of the Bayview Irrigation District Board of Directors and through what the Texas Agricultural Experiment Station and Texas Cooperative Extension does as part of the Rio Grande Basin Initiative project to help provide the information, find where the water losses are occurring, and where water savings can be made. We could not have done this without the funding and technical support from the university through the Rio Grande Basin Initiative.”

Modern Marvel Guarantees Water

New pumping plant saves energy and operating costs, controls water pumping

by
Jenna Smith

Old traditions are hard to break, yet a new tradition has begun in the Lower Rio Grande Valley. Cameron County, once the site of a worn, 100-year-old water pumping plant, has been given a facelift—a modern pumping facility that will more efficiently deliver water to agricultural, municipal and industrial customers serviced by Cameron County Irrigation District No. 2 (CCID#2), headquartered in San Benito and managed by Sonia Kaniger.

This 100-year-old water pumping plant in Cameron County was in need of modernizations to more efficiently conserve water.

Allen Sturdivant, Extension Associate at the Texas A&M Agricultural Research and Extension Center in Weslaco, and a team of Extension economists have analyzed the economics of water and energy savings that the modern CCID#2 will bring to South Texas. The analysis was funded as part of the Rio Grande Basin Initiative, which promotes efficient irrigation for water conservation.

Sturdivant said a computer model consistent with a program entitled Capital Budgeting was used to determine the economic efficiency of saving water with the new pumping plant. With infrastructure rehabilitation, water savings measures typically include any activity that can add to a region's water supply, such as reduced seepage and/or evaporation.

"The new pumping plant does not save water in a traditional sense," Sturdivant said. "Rather, it adds to the regional supply by allowing the diversion of additional 'no-charge' water from the Rio Grande. Otherwise, the excess flow would go into the Gulf."

"The modern facility has the flexibility to pump water at a slower rate, which lowers the volume of water being pushed through the facility."

"No-charge" refers to a temporary situation of excess water flow in the Rio Grande at "no charge" to the district's Watermaster-controlled allocation.

Using historical data and engineering calculations of the old pumping plant, the new plant will produce an annual energy savings of 791,386 kilowatt-hour (kwh), approximately $48,554, or 37,986,544 kwh over its expected 48-year life span.

Sturdivant said the energy efficiency of the new plant is due to its eight new, highly-efficient pumps, which consist of four different sizes that pump water at various rates.

"Since the new plant's existence, canals have been lined, leaky reservoirs have been repaired and pumping has been better metered."

"The modern facility has the flexibility to pump water at a slower rate, which lowers the volume of water being pushed through the facility," Sturdivant said. "Greater pumping control allows the management team to more efficiently regulate the water supply."

Bill Norris, president of NRS Consulting Engineers, oversaw the bidding and construction phases of the project.

"The new pumping plant was designed to help manage the canal rehabilitation and interconnect project," Norris said. "Since the new plant's existence, canals have been lined, leaky reservoirs

This new pumping plant is equipped with eight highly-efficient pumps, which consist of four different sizes that pump water at various rates.

have been repaired and pumping has been better metered."

Norris said Cameron County Irrigation District No. 6 has plans to build a new pumping plant as well.

The new plant is now the third largest pumping facility in the Valley and provides water to over 57,000 acres of farmland and to the cities of San Benito and Rio Hondo.

Prior to the plant's opening in February, Sturdivant and his team determined the cost of saving water from the plant to be $119.41 per acre-foot of water. Key factors used in arriving at this value included the initial construction cost, the reduced energy and operations and maintenance costs, and the expected useful life. The new plant will also save $431,195 each year in anticipated operations and maintenance costs, and $48,554 in energy costs.

"One thing is for sure—the new pumping plant guarantees its customer base a consistent and dependable water supply for years to come," Sturdivant said. "Kudos to Sonia Kaniger, Bill Norris and others for making the new plant a reality for the rapidly expanding Lower Rio Grande Valley."

Faces of RGBI

Right-hand to the RGBI project

by

B.L. Harris

Most of you have probably heard of or been in contact with Danielle Supercinski, but now you can put a face with the name. Danielle began working for the Texas Water Resources Institute this past February, specifically on the Rio Grande Basin Initiative project.

Danielle is continuing in her relatively new role as our "right hand" on the RGBI project. She is directly involved in collecting information about programs, progress, outcomes and pictures. Her goal is to maintain visibility for efforts of scientists, Extension personnel, and the cooperation and collaboration of the RGBI as a whole.

If you have any big events coming up, newsworthy information regarding your project, or anything else related to the RGBI (think **Outcomes**), Danielle is the one to contact about it.

Increasing Irrigation Efficiency in the Rio Grande Basin through Research and Education

Through Extension and research efforts, the Texas A&M University System Agriculture Program and the New Mexico State University College of Agriculture and Home Economics are implementing strategies for meeting present and future water demand 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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B.L. Harris, Project Director,
Associate Director,
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Danielle Supercinski, Editor

Send comments or subscription requests to *Outcomes* Editor, Texas Water Resources Institute, 2118 TAMU, College Station, Texas, 77843-2118. Call (979) 845-1851 or e-mail riogrande@tamu.edu.

http://riogrande.tamu.edu

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Texas Water Resources Institute
1500 Research Parkway, Suite A240
2118 TAMU
College Station, Texas 77843-2118

Rio Grande Basin Initiative

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New Mexico State University
College of Agriculture and Home Economics

For these and other stories, please visit:
http://riogrande.tamu.edu

Mapping the Rio Grande Basin

New management tool aids irrigation districts

by
Danielle Supercinski

GIS-based maps of 30 Rio Grande Basin irrigation districts in Texas completed during the spring 2005 will serve as an indispensable tool for planning future projects and managing districts' day-to-day operations.

Quality paper maps are just one of the byproducts of the GIS efforts.

"We began the (GIS-based) mapping effort as part of a regional water planning study to determine potential water savings that result from district modernization and rehabilitation," said Guy Fipps, Extension agricultural engineer and director of the Irrigation Technology Center. "These maps allowed us to extrapolate water savings test results from a small number of canals to the entire region, and to produce reasonable estimates of water savings."

"These maps allowed us to extrapolate water savings test results from a small number of canals to the entire region, and to produce reasonable estimates of water savings."

It took years to assemble the basic attribute data (canal sizes and conditions, for example) on the water distribution networks needed to produce these maps. This information is currently helping districts to decide which canal segments need rehabilitation or have high water loss, and which are suitable for replacement with a combination of synthetic liners and pipelines.

"These maps are indispensable for this purpose," Fipps said. "The districts estimate that to date these projects have saved about 50,000 acre-feet per year of water that otherwise would have been lost, with many more rehabilitation projects to be done."

Features displayed on these maps include: district boundaries, lined and unlined canals, pipelines, siphons, reservoirs, resacas, river pumping stations, district to district diversion points, roads, and aerial photographs. Some maps also include the Rio Grande River and Arroyo Colorado systems.

Irrigation districts also use these maps to determine exact "water account" of field boundaries and areas, and for the formal process of excluding land from the district as it urbanizes.

"The districts estimate that to date these projects have saved about 50,000 acre-feet per year of water that otherwise would have been lost."

"In recent years, more districts have been using the GIS and maps for day-to-day management decisions, maintenance scheduling, on-farm water delivery strategies and optimization, and for rehabilitation planning," Fipps said. "We have also implemented a technical training and assistance program for districts to develop their own 'in-house' capabilities to update the maps in the future."

The general public may even have an interest in these maps to determine exact locations of district facilities and to see how these facilities may impact their property. Many organizations, including environmental and wildlife interests, use these maps as part of their conservation and public education programs.

Many steps were involved in creating such useful maps.

The first step required assistance from the irrigation districts to locate old paper maps that could be used as a beginning guide. Aerial photographs of districts became the basis of all maps produced. These aerial photographs were developed by the U.S. Geological Survey and have resolutions of about one meter and exact locations of canals and other features are clearly visible, Fipps said. Then, in many cases, field inspections and explorations were conducted using GPS surveying equipment to verify the locations.

"Since the GIS mapping began, it has allowed us to study districts in ways that would have been impossible without the GIS," said Eric Leigh, Extension associate in biological and agricultural engineering. "The GIS maps are not only lines on a sheet of paper, but a wealth of information, storing any and all attributes for each section in a database."

Two specific GIS components are useful for this purpose.

"One allows you to actually draw the map," Fipps said. "The difference between GIS and other drawing software, such as AutoCAD, is that each point on the GIS corresponds to the exact location expressed in latitude and longitudinal coordinates. Thus, this map or 'layer' can be combined with any other layers."

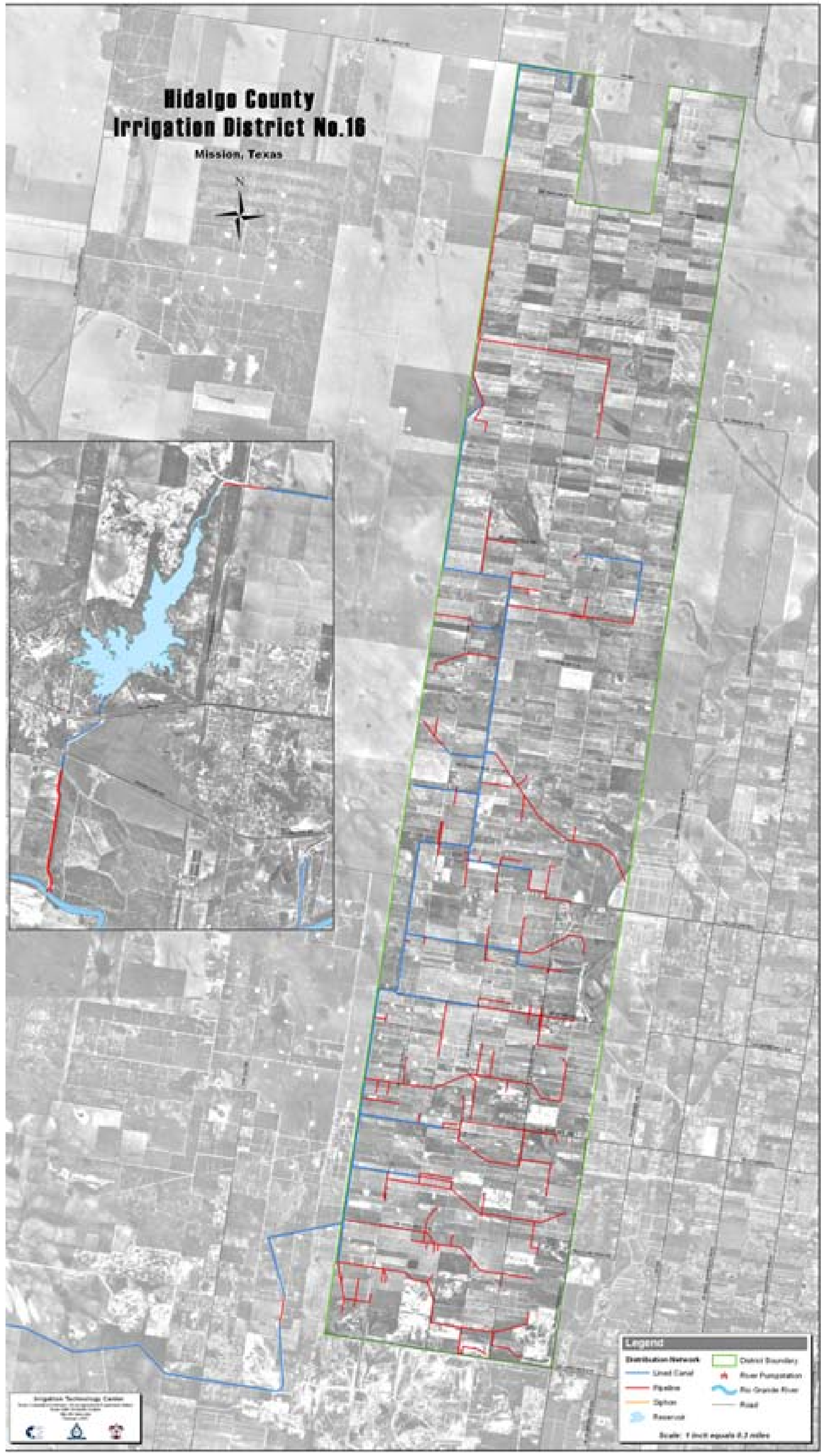
For example, roads in Texas are available in GIS, which can then be combined with these district maps.

"The second feature of GIS that is useful is being able to link 'attribute' data with other map features and display these when printing out the map or making a map image," Fipps said.

The mapping of irrigation districts began in 1996 as part of the GIS development program. This is the fourth major map release completed since 1998.

These irrigation district maps can be ordered online using the order form posted on the IDEA Web site at http://idea.tamu.edu/gismaps.php. There are several options to choose from, including the district, type of paper and

*See **Maps** page 5*



Irrigation district maps, such as this Hidalgo County map, can be obtained for 30 Rio Grande counties displaying district boundaries, lined and unlined canals, pipelines, reservoirs, and resacas, to name a few.

NMSU Specialist Saves Water

Dickerson teaches gardeners to harvest rainfall

by
Kevin Robinson-Avila

Horticulture specialist George Dickerson practices what he preaches when it comes to water conservation.

In his home garden in Albuquerque's Southeast Heights, Dickerson has arranged his landscape entirely around the concept of harvesting rainwater for irrigation.

"Water is precious in New Mexico, so when it rains, we want to get as much use from it as possible," said Dickerson, a veteran horticulturist with New Mexico State University's Cooperative Extension Service. "In my garden, I use about 90 percent of rainwater for irrigation through simple techniques that allow me to capture rain for future use or direct it to trees and shrubs in my landscape."

In August, Dickerson shared his personal and professional experience in water harvesting with gardeners during a series of free workshops, sponsored by the Rio Grande Basin Initiative, in Albuquerque, Santa Fe, Los Alamos, Taos and Las Cruces.

"Most rainfall is lost to runoff," Dickerson said. "But by harvesting rainwater, gardeners can reduce the amount of tap water needed to irrigate gardens and landscapes. It's also better for plant health because rainwater is salt-free. "

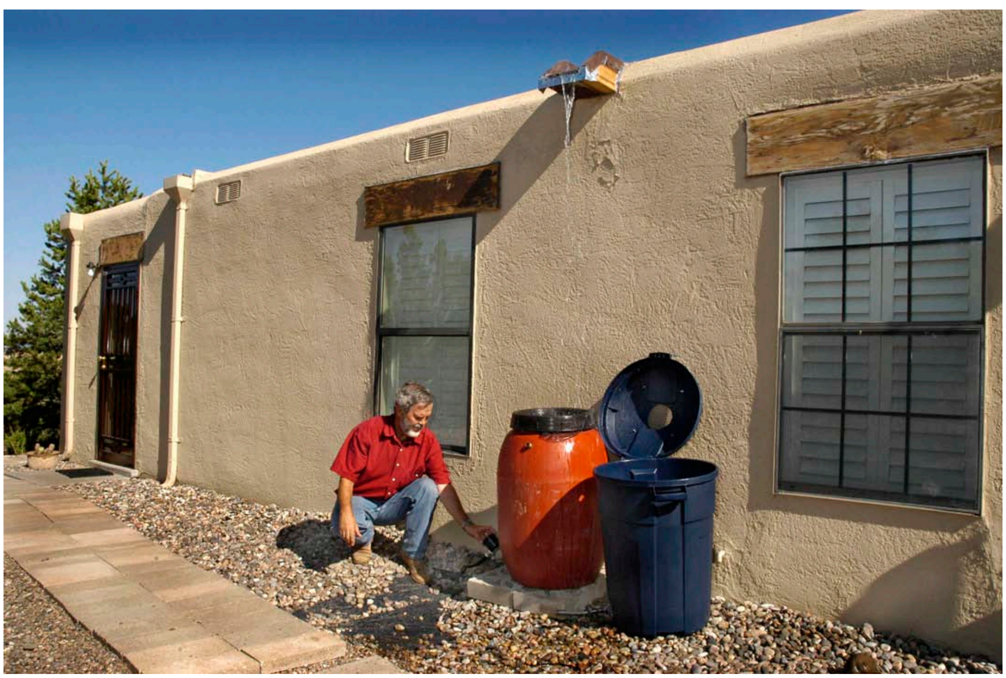
"By harvesting rainwater, gardeners can reduce the amount of tap water needed to irrigate gardens and landscapes."

Dickerson's garden is an exemplary model of water-harvesting creativity.

The property slopes away from his house on all sides, allowing rainwater to drain toward trees and shrubs. Sloped brick walkways hug the home's perimeter, all of which are lined underneath with nonporous heavy plastic. That reduces evaporation, controls weeds and forces rainwater to flow toward the garden instead of seeping through cracks.

"The idea is to channel rainwater with slopes, canals and swales toward the vegetation," Dickerson said. "A tremendous amount of water rolls off roofs and down driveways and sidewalks when it rains, so the landscape design needs to capture and transport that water."

Dickerson grows water-thrifty plants like cactus and desert shrubs farthest from the house because less runoff



George Dickerson, horticulture specialist with NMSU's Cooperative Extension Service, demonstrates how roof water flows to rain barrels below to catch runoff for irrigation. The factory-made orange barrel cost Dickerson $60, but the black barrel is a trash bin he converted to a rain barrel for less than $20.

reaches them. Thirstier trees like aspens are located closer to the home to catch more rainwater from the roof and walkways.

"Rain barrels can cost $50 to $100 or more at stores, but I converted the plastic trash bins for less than $20 each."

Dickerson lives on hilly land. To avoid soil erosion and trap more water, the steepest slopes are terraced with railroad ties. He also laid woven plastic mulch and compost around most trees and shrubs.

"The plastic is porous to allow water through while controlling weeds," Dickerson said. "The compost acts like a big sponge to grab and save water."

Dickerson uses rain barrels to capture water from his roof. Wooden canals and aluminum drainpipes channel water to barrels, which have plastic spouts near the bottom and top. The lower spigot is to irrigate the garden between storms, while the upper spout allows overflowing rainwater to drain from the barrel when it gets full. Canals and plastic tubing guide water from barrels to the garden.

"With a 1,500 square-foot roof, a homeowner could potentially collect 930 gallons for every inch of rainfall."

Factory-made rain barrels are often expensive, so Dickerson converted cheap plastic garbage bins into rain barrels by cutting holes at the bottom and top and gluing plastic spouts to them. He cut holes in the lids and placed netting on top to capture roof runoff and filter debris from water.

"Rain barrels can cost $50 to $100 or more at stores, but I converted the plastic trash bins for less than $20 each," Dickerson said.

Dickerson's roof is flat. To drain puddles, he places barrels on the ground beneath problem areas, runs a plastic hose from the barrel to the roof and sucks the water at the bottom end to create capillary action.

Under ideal circumstances, Dickerson said an inch of rainfall could produce about 0.62 gallons of water per square foot of roof. "With a 1,500 square-foot roof, a homeowner could potentially collect 930 gallons for every inch of rainfall," he said.

Dickerson's landscape is built to harvest rainwater for irrigation. The property slopes away from the house to direct runoff to the garden. Water-thrifty plants like cactus are planted farthest from the house where less water reaches and thirstier trees like aspens and pines are closer to the home to catch more water. An underground drain canal in the driveway directs runoff to more garden areas on the right side of the house.

Photos courtesy of J. Victor Espinoza

Maps

continued from page 3

size. Custom maps are another option. Districts with GIS capabilities can receive a copy of the shape files at no charge. A pdf version is also available.

Three sets of additional maps have been published and can be found on the IDEA Web site as well. These maps include U.S. Congressional District Maps, Municipal Water Supply Network of districts and regional scale maps.

Current project staff includes Guy Fipps, Eric Leigh, David Flahive and Askar Karimov. Funding for the mapping has been provided through the *Efficient Irrigation for Water Conservation in the Rio Grande Basin* project for the past 5 years.

Photos courtesy of Guy Fipps, Eric Leigh and Askar Karimov

NMSU Studies Cover Crops

Evaluating which crops are most appropriate for winter kill mulch

by
Jennifer Gipson

Lablab beans, cow peas and sudex were chosen as cover crops to evaluate the soil moisture and conservation benefits.

Dr. Erin Silva, assistant professor at New Mexico State University in the Agronomy and Horticulture Department, along with Co-PI, Dr. Constance Falk, professor in the Agricultural Business and Agricultural Economics Department, are currently working on the Rio Grande Basin Initiative project *Killed Mulch Cover Crop Systems and Water Management in Southern New Mexico.* The objective of their project is to determine which cover crops are most appropriate for use in a winter kill mulch system in both conventional and organic vegetable production.

They are evaluating the emergence and ground coverage of selected warm-season annual cover crops while also determining optimal planting dates for selected warm-season annual cover crops. The water usage, biomass production, soil water moisture retention and weed suppression of these crops are also assessed to determine the effect of cover crops on the subsequent yields of vegetable crops planted into mulch.

The study is evaluating the soil moisture conservation benefits of three different cover crops planted in late summer and early autumn. The cover crops that were chosen are lablab beans, cow peas and sudex. Currently, the crops are monitored for the amount of water they are using. Once they die, the percentage of groundcover will be monitored, along with weed suppression capabilities.

The ultimate outcome will provide recommendations for potential cover crop varieties and planting dates for use in killed-mulch systems that would provide soil moisture conservation, weed suppression, and wind protection on the subsequent crops. At the conclusion of the project, actual amounts of water saved through the adoption of the system will be calculated. Economic analyses and cost and return estimates regarding the use of a killed-mulch system will be reported and made available to growers.

A presentation on this project is planned for the 2006 Southwest Vegetable Conference in Las Cruces, to describe the work to growers. In addition, a presentation of this experiment will be included at the 2006 Chili Field Day with the intention of distributing the information to growers who may be interested in this production technique. Results will also be presented at the Rio Grande Basin Initiative Annual Conference.

Photo courtesy of Erin Silva

Every Drop Counts...

2006 RGBI Conference Plans in the Works

The 5th Annual Rio Grande Basin Initiative Conference will be held March 27-30, 2006, in Ruidoso, NM at the Ruidoso Convention Center. Conference information can be found at http://spectre.nmsu.edu/riogrande/welcome.html and http://riogrande.tamu.edu/conference2006.

Registration and more information will be posted as it becomes available.

2006 USDA-CSREES National Water Conference

The 2006 USDA-CSREES National Water Conference will be held in San Antonio, Texas, Feb. 5-9, 2006, at the Marriott Rivercenter.

The conference will provide opportunities for water quality professionals engaged in research, extension and education to share knowledge and ideas, to identify and update emerging issues, and to network with the CSREES National Water Quality Program and partner organizations. For more information go to http://www.soil.ncsu.edu/swetc/waterconf/2006/main.htm.

El Paso Ordinance Promotes Conservation

El Paso residents are doing their part to help conserve water, mostly due to a Water Conservation Ordinance in place by El Paso Water Utilities. The Ordinance applies to any person who uses water from the EPWU supply system. It contains mandatory, year-round restrictions on certain water use activities and prohibits water waste.

There is no residential watering allowed on Mondays; however customers of EPWU can water their landscapes three days a week, year-round.

Residential car washing is allowed only if a bucket and/or hand-held hose equipped with a positive shut-off nozzle is used. However, during times of a water emergency, drought restrictions or fundraising car wash events, washing is only permitted at a commercial car wash.

Rio Grande Basin Initiative personnel with Extension are providing educational programs in support of EPWU programs to help El Pasoans conserve water in their homes and landscapes. Experiment Station scientists are researching the use of wastewater for irrigation and more efficient systems for water usage.

Side Note from the Editor

In an attempt to update our newsletter mailing list, please report address changes or subscriber name changes to Danielle Supercinski at DMSupercinski@ag.tamu.edu.

Faces of RGBI

Administrative support for the project

by

Danielle Supercinski

Ellen Weichert has been a part of Texas Water Resources Institute since September 2001 and has worked with the Rio Grande Basin Initiative since the original proposal. She works with all the project personnel regarding budgeting, purchasing and staff issues. Ellen also helps coordinate meetings and conferences, and prepares related materials. In addition, she provides administrative support to Dr. B.L. Harris, Texas Water Resources Institute associate director and Rio Grande Basin Initiative project director, which may be the hardest part of all.

Ellen is definitely a benefit to the Rio Grande Basin Initiative and its participants. We thank Ellen for all of her work in keeping the Rio Grande Basin Initiative budgets flowing.

Increasing Irrigation Efficiency in the Rio Grande Basin through Research and Education

Through Extension and research efforts, the Texas A&M University System Agriculture Program and the New Mexico State University College of Agriculture and Home Economics are implementing strategies for meeting present and future water demand 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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Send comments or subscription requests to *Outcomes* Editor, Texas Water Resources Institute, 2118 TAMU, College Station, Texas, 77843-2118. Call (979) 845-1851 or e-mail riogrande@tamu.edu.

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Texas Water Resources Institute
1500 Research Parkway, Suite A240
2118 TAMU
College Station, Texas 77843-2118

Rio Grande Basin Initiative

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For these and other stories, please visit:
http://riogrande.tamu.edu

Joint Conference Set for March 27-30

Experiment Stations, Extension meet with other Rio Grande Initiatives

by
Jennifer Gipson

The Joint Rio Grande Basin Initiatives Annual Conference will take place in Ruidoso, NM from March 27 through 30, 2006 at the Ruidoso Convention Center. This conference draws together three Rio Grande Basin Initiative Projects, which are the Efficient Irrigation For Water Conservation in the Rio Grande Basin (Texas and New Mexico Agricultural Experiment Stations and Cooperative Extension), Physical Assessment Project (University of Texas) and the Sustainable Agricultural Water Conservation in the Rio Grande Basin (Texas State University System) to share ideas, information and program impacts related to water research and Extension. Conference information, as well as the registration form, can be found on the joint conference Web site at http://riogrande-conference.tamu.edu.

The conference fee for early registration postmarked prior to February 24, 2006, is $115.00, and $135.00 for registration received on or after February 24, 2006. Hotel reservations can be made at the Hawthorn Suites (505-258-5500 or 1-866-211-7727), Comfort Inn (505-257-2770 or 1-866-859-5146) and Holiday Inn Express (505-257-3736 or 1-800-257-5477). Mention the RGBI/Rio Grande Conference to receive the conference rate for your hotel room.

For those who like to golf, the "6th best course in New Mexico" ranked by "Golf Digest Magazine" is right next door to the Hawthorn Suites and Ruidoso Convention Center.

Registration is under way, and the form and mailing address can be found on the joint conference Web site.

Efficient Irrigation for Water Conservation in the Rio Grande Basin

Texas and New Mexico Agricultural Experiment Stations and Cooperative Extension

Texas A&M University System
http://riogrande.tamu.edu

New Mexico State University
http://spectre.nmsu.edu/riogrande/welcome.html

Sustainable Agricultural Water Conservation in the Rio Grande Basin

Texas State University System

http://www.sulross.edu/pages/4624.asp

Physical Assessment Project

University of Texas - Austin

http://www.crwr.utexas.edu/riogrande.shtml
http://www.riogrande-riobravo.org/

Photos courtesy of Danielle Supercinski

RGBI Team Receives Partnership Award

by
Danielle Supercinski

Photo courtesy of Mark Beal

The Rio Grande Basin Initiative (RGBI) team received the Vice Chancellor's Award in Excellence for Industry-Agency-University-Association Partnership Jan. 10, at the 2006 Texas A&M Agriculture's Awards Convocation.

Dr. Elsa Murano, Texas A&M University System vice chancellor and dean of agriculture and life sciences, presented the partnership award to the RGBI team for working with numerous individuals, groups, organizations and agencies to reach the goals and objectives originally set forth for the project.

Primary partners chosen to represent this team include: Edmund Archuleta, El Paso Water Utilities; Dr. B.L. Harris, Texas Water Resources Institute associate director in College Station; Sonny Hinojosa, Hildalgo County Irrigation District No. 2 general manager; Michael Irlbeck, U.S. Bureau of Reclamation special projects director in Austin; Dr. Allan Jones, Texas Water Resources Institute director in College Station; and Craig Runyan, New Mexico State Cooperative Extension.

These team members were selected as primary representatives from the numerous partners and approximately 160 participants of the Rio Grande Basin Initiative as a whole.

Together all of these groups and participants work towards the common goal of efficient irrigation for water conservation in the Rio Grande Basin.

Symposium to be held Feb. 23-24

NMSU conference on efficient water use in urban landscapes

by
Jennifer Gipson

The Rio Grande Basin Initiative, in partnership with New Mexico State University, will be co-sponsoring the first annual "Symposium on Efficient Water Use in the Urban Landscape" in Las Cruces. The symposium will be held February 23 and 24, 2006, on the New Mexico State University campus. Rolston St. Hilaire is the conference chairman and is working along side Jeanine Castillo on coordinating the event.

The goal of the symposium is to provide opportunities for water and landscape professionals to share their knowledge and scientific methods. A focus of the conference will be to update and identify methods by which to increase the efficiency of water use in the urban landscape. Another goal of the symposium is to compile and publish a proceedings publication. More information on the "Call for Papers" can be found on the conference Web site at http://spectre.nmsu.edu/water.

The keynote speaker for the conference will be David Zoldoske, who works for the Center for Irrigation Technology at California State University in Fresno. The topic of his presentation will be 'smart irrigation.' Other invited speakers will address landscape irrigation and technologies, ornamental plants for moisture limited landscapes, sociohorticulture issues in the urban landscape, and policy and ordinances affecting the urban landscape.

Registration will be $75 before February 3, 2006, and $100 after February 3. Please visit the conference Web site for additional information or contact Jeanine Castillo at (505) 649-0501 or rjeanine@nmsu.edu.

Canal Operation Automation

New measures taken in irrigation district to maximize efficiency

by
Danielle Supercinski

This pump house is located southeast from the split section of the main canal and water is received through the gate structure. There are two pumps that pump the flow into the pipelines.

Today's irrigation and water districts face increasing challenges in their daily operations. Challenges include increased demands for flexible and efficient operation, rising costs of energy, limited water supplies and expensive labor.

The Irrigation District Engineering & Assistance (IDEA) team of Texas Cooperative Extension is assisting districts on addressing these problems by focusing their efforts on water conservation projects in the Mexican border region of Texas to produce water savings and improve conveyance efficiency through optimal irrigation canal and pipeline management.

"For more precise water management of a large and complex irrigation system, rapid processing of the large amounts of data is required," said Azim Nazarov, Extension associate at Weslaco Agricultural Research and Extension Center, Texas A&M University System. "Canal automation is a rapidly improving technology that will open up new possibilities for processing data and perform the complex adjustments of gates for water control.

"In addition, automation will result in more efficient water management with benefits from improved crop yield, reduced operation and maintenance costs, and water conservation through reduced spillage and seepage," Nazarov said.

A new project to install automation equipment has been initiated through the Rio Grande Basin Initiative (RGBI) to demonstrate the benefits of canal automation. The project will include system design, mechanical and electrical refurbishment, automation equipment procurement, installation services, programming (software), field-testing and training. Delta Lake Irrigation District (DLID) is the first district where a canal automation system will be implemented through RGBI.

Currently, manual operation of water control structures is predominant in the region, but district personnel lack sufficient experience and technical knowledge to manage those complex systems. There is also a lack of modern, reliable water flow information and communication systems which force district administrators to make management and operational decisions based on insufficient information. The automatic control systems planned for the district will overcome the weaknesses of these manually controlled systems.

"Canal automation is a rapidly improving technology that will open up new possibilities for processing data."

The IDEA Team will demonstrate a type of control system called Supervisory Control and Data Acquisition (SCADA) in DLID. Delayed delivery of scheduled flows has been a problem in the district, but with implementation of the SCADA system, scheduled flows can be delivered on time. Implementation will also result in more efficient water management with benefits from improved crop yield, reduced operation and maintenance costs, and water conservation through reduced spillage and seepage.

"The unique feature of this project is that the automatically controlled gates will be coupled with optimal water delivery at the farm turnouts in order to maximize on-farm efficiencies and reduce conveyance losses," said Guy Fipps, Extension agricultural engineer and director of the Irrigation Technology Center.

Water control structures, such as the gates, can be controlled by a unit located either at the site (local automatic control) or by a unit at the monitoring station away from the site (remote automatic control).

"Delta Lake Irrigation District's canal automation project will serve as a model for replication of similar projects around the Lower Rio Grande Valley."

"Remote control of the automatic control structures can be more efficient because all of the data and information is displayed at the console in the monitoring station," Fipps said. "Positions of all water control structures can be changed simultaneously to desired levels by pushing one button."

The IDEA Team is working to develop an equipment list and associated costs to help the districts choose the appropriate items needed for this demonstration. Districts will be required to cover the costs of equipment items such as motors and actuators. Extension will be covering the costs of the automation equipment, including the communication equipment, software, Programmable Logic Controllers (PLC) and water level sensors.

"Increasing the efficiency of water used in agriculture is essential to support rural livelihoods, sufficient food production for the growing population, and continued social and economic development," Fipps said. "With current development of SCADA technology it is now possible to think of developing and implementing centralized and automated canal control approaches that would allow the simultaneous operation of multiple control structures."

These approaches would be more effective than current manual operations and would lead to optimization of canal water management procedures, he said.

According to the 2003 DLID Water Conservation Project Report, the estimated quantity of water lost due to system spills is approximately 7.5 percent of the annual irrigation water diversted or 5,678 acre-feet per year. Aproximately 3 to 5 percent, or 2,271 to 3,785 acre-feet per year, of the annual irrigation water diverted is estimated to be saved by implementation of canal automation.

"As the district gains more control of their irrigation system you will see more timely on-farm irrigation, which will increase the on-farm efficiency and decrease operating costs of the district," said Eric Leigh, Extension associate in biological and agricultural engineering.

The IDEA Team on this project expects the DLID SCADA system to improve water use efficiency, facilitate the scheduling of water delivery, and planning for ongoing maintenance and future rehabilitation programs.

"Delta Lake Irrigation District's canal automation project will serve as a model for replication of similar projects around the Lower Rio Grande Valley," Fipps said.

The Irrigation District Engineering & Assistance (IDEA) team plans to implement two additional demonstrations at United Irrigation District and in El Paso.

This project is made possible with funding from the Rio Grande Basin Initiative, administered through Texas Water Resources Institute.

This very old head gate will be equipped with SCADA equipment and will be controlled from the Delta Lake Irrigation District Office.

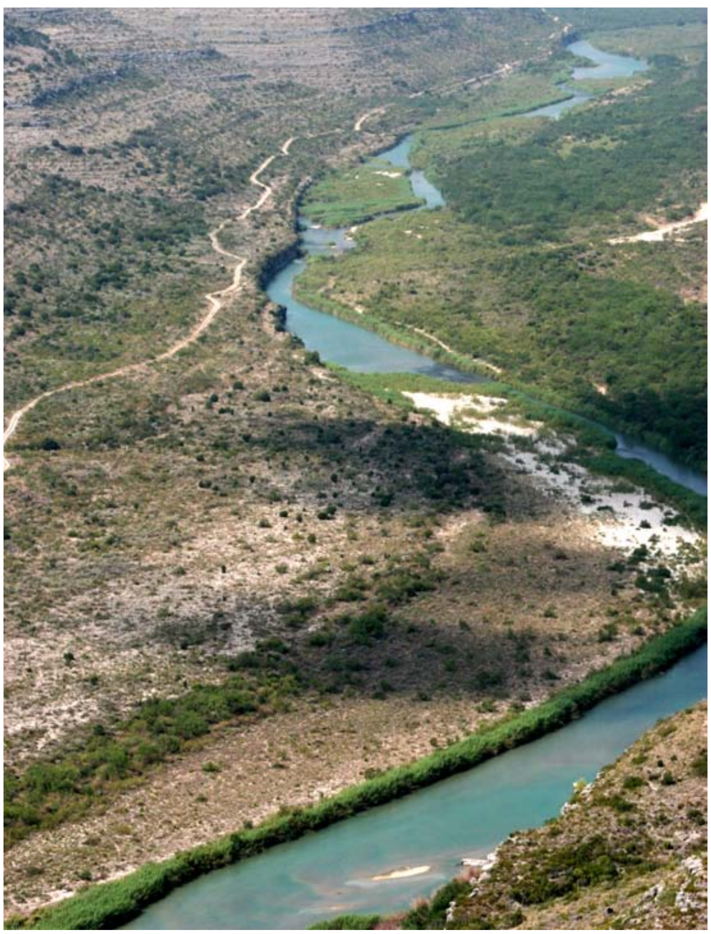
Pecos River Ecosystem Project

Applying saltcedar control along the Pecos banks

by
Danielle Supercinski

In the early 1900s, government agencies and private landowners began planting saltcedar to control stream bank erosion along rivers, such as the Pecos. Through the 20th century, an estimated 14,000 acres of water-consuming saltcedar thrive along the banks of the Pecos River in Texas and quickly dominated the area, out-competing native plants for sunlight, moisture and nutrients.

The Pecos River Ecosystem Project was conceived in 1997 to address alternatives for saltcedar control along the Pecos. In September 1999, North Star



The Pecos River banks are green with water-consuming saltcedar trees, which are out-competing native plants for sunlight, moisture and nutrients.

Helicopters from Jasper, Texas applied aerial Arsenal® treatments to 655 acres. Since that time, saltcedar treatments continued along the Pecos River and throughout the whole basin. From 1999 through 2005 approximately $2,693,915 had been spent treating 13,497 total acres along the river and the entire basin.

"As of the end of the 2005 spray season, my estimate is that we've completed treating approximately 75 percent of saltcedar on the entire Pecos River in Texas," said Charles Hart, professor and Extension range specialist in Fort Stockton.

Research continues, but current estimates show that each acre of saltcedar uses an average of 3 to 4 acre feet of water annually. Through the Pecos River management program, researchers hope to salvage at least 50 percent of this annual loss, he said.

"At this point, about all I can estimate is that we are salvaging about 2 acre feet (of water) for every acre of saltcedar we have treated," Hart said.

This project has already seen significant water savings from these treatments. Throughout the project's first seven years, total water salvage estimates are between 54,268 to 81,402 acre feet (17.7 to 26.5 billion gallons).

The Pecos River Management Plan focuses on three key areas: 1) Herbicide application on saltcedar, 2) debris removal through prescribed burning, and 3) long-term follow-up management through biological control, spot spraying and native plant restoration. A major concern is the revegetation of the river banks with native plants to complete the ecosystem restoration. The treatment methods selected needed to provide a high rate of saltcedar mortality while minimizing detrimental effects on existing native vegetation.

"In summary, saltcedar control using the herbicide application described was successful with an average of 85 to 90 percent apparent mortality of saltcedar two years after treatment," Hart said. "With long-term monitoring, treatment life of the control strategies should be further evaluated and follow-up management alternatives explored."

Saltcedar control efforts continue along the river banks, as well as in other infested areas in the Pecos River Basin. Numerous agencies, organizations and companies are involved in helping along these project efforts.

"The Rio Grande Basin Initiative allowed us to enhance our monitoring and research efforts and helped to provide base data important in obtaining additional funding," Hart said.

Major partners include the Upper Pecos Soil and Water Conservation District, Texas Cooperative Extension, Texas Department of Agriculture, USDA Natural Resources Conservation Service, Red Bluff Water and Power Control District, U.S. Environmental Protection Agency, Pecos River Compact, International Boundary and Water Commission, BASF, local landowners, and irrigation districts in Loving, Reeves, Ward and Pecos Counties.

For more information on the Pecos River Ecosystem Project please visit http://pecosbasin.tamu.edu or contact Charles Hart at cr-hart@tamu.edu.

Photos courtesy of Charles Hart

These brown banks have been treated for saltcedar.

Faces of RGBI

NMSU's 'go to' person for reporting and budgeting

When reporting or budgeting time rolls around for the Rio Grande Basin Initiative project, faculty and staff in the NMSU-RGBI can count on Leeann DeMouche to be knocking on their door. They can also be assured of getting lots of program ideas and feedback when they call Leeann with questions.

When Leeann began her work with the RGBI, she was initially involved as Co-P.I. on Frank Ward's look at institutional constraints to water conservation. Recognizing Leeann's enthusiasm and hard work, Craig Runyan, NMSU project manager, pirated 50 percent of Leeann's time to assist with project management.

"Life hasn't been the same since," Runyan said. "She develops and delivers programs, balances budgets, rides herd on renegade faculty and just about anything else that's thrown her way."

As an economist, Leeann is particularly skilled at project fiscal management. Beth Chorey, assistant director in the business office, said, "Leeann is the 'go to' person in dealing with the financial and grant related details for the program."

David Cowley of NMSU's Fisheries and Wildlife Sciences agrees. "We're lucky to have Leeann with the RGBI. Her keen eye toward budgets has helped keep P.I.s on a good fiscal track," Cowley said.

Leeann's hard work and dedication to the success of the RGBI helped earn her recent promotion to the college rank faculty position of Extension Water Resource Specialist. Her continued work in the RGBI, NMSU Water Task Force and other statewide water programs has earned Leeann recognition as a cooperative, 'can-do' professional.

Increasing Irrigation Efficiency in the Rio Grande Basin through Research and Education

Through Extension and research efforts, the Texas A&M University System Agriculture Program and the New Mexico State University College of Agriculture and Home Economics are implementing strategies for meeting present and future water demand 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
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B.L. Harris, Project Director,
Associate Director,
Texas Water Resources Institute

Craig Runyan, Project Director,
Water Quality Coordinator,
New Mexico State University Plant Sciences

Danielle Supercinski, Editor

Send comments or subscription requests to *Outcomes* Editor, Texas Water Resources Institute, 2118 TAMU, College Station, Texas, 77843-2118. Call (979) 845-1851 or e-mail riogrande@tamu.edu.

http://riogrande.tamu.edu

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Texas Water Resources Institute
1500 Research Parkway, Suite A240
2118 TAMU
College Station, Texas 77843-2118

Student Support

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	2	0	0	0	2
Masters	7	2	0	0	9
Ph.D.	3	1	0	0	4
Post-Doc.	0	0	0	0	0
Total	12	3	0	0	15

Notable Awards and Achievements

Jeremy Hudgeons

First Place Poster - TAMU Student Research Week Poster Competition, College Station, Texas,March 2005.

Presenations

Aquatic Plant Management Society Meeting (July 2005, San Antonio, Texas) Dept. of Entomology Graduate Student Forum (August 2005, College Station, Texas) SW Branch of the Entomological Society of America (February 2006, Austin, Texas) Saltcedar Biological Control Consortium (March 2006, Austin, Texas)

Additionally, this project and related work were featured in two Texas newspapers in July 2005: the Lubbock Avalanche Journal and the San Antonio Express. Parts of the San Antonio Express article were circulated in additional newspapers throughout the state. These articles can be found at the following link: http://insects.tamu.edu/feature/saltcedar

Thad Scott

First prize, student paper competition. Society of Wetland Scientists South Central Chapter Meeting, October 2005, San Marcos, Texas. Paid travel expenses to the SWS 2006 International Congress in Cairns, Queensland, Australia.

Xuesong Zhang

Second place award, Student Research Week Poster Competition, Texas A&M University, College Station, Texas, March, 2006.

Publications from Prior Projects