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Arroyo Colorado Agricultural Nonpoint Source Assessment Final Report

Allen Berthold
Texas Water Resources Institute

Texas Water Resources Institute
make every drop count

Arroyo Colorado
Agricultural Nonpoint Source Assessment
Final Report

By Allen Berthold
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Technical Report No. 429
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Funding provided through a Clean Water Act Section 319(h) Nonpoint Source Grant from the Texas State Soil and Water Conservation Board and the U. S. Environmental Protection Agency

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Acronyms

BMP – Best Management Practice
BOD – Biochemical oxygen demand
DOQ – Digital Orthophoto Quadrangle
DQO – Data Quality Objective
EFCE – Environmental Flow Dynamic Code
EQIP – Environmental Quality Incentives Program
GIS – Geographic Information Systems
LULC – Land use / Land Cover
MRCL – Multi-Resolution Land Characteristics
NEXRAD – Next Generation Radar
NPDES – National Pollutant Discharge Elimination System
NPS – Nonpoint Source Pollution
QAPP – Quality Assurance Project Plan
SWAT – Soil and Water Assessment Tool
SWCD – Soil and Water Conservation District
TAMU-K – Texas A&M University- Kingsville
TCEQ – Texas Commission on Environmental Quality
TNRIS – Texas Natural Resource Information System
TPWD – Texas Parks and Wildlife Department
TSS – Total Suspended Solids
TSSWCB – Texas State Soil and Water Conservation Board
TWDB – Texas Water Development Board
TWRI – Texas Water Resources Institute
USDA-APHIS – U.S. Department of Agriculture – Animal and Plant Health Inspection Service
USDA-NRCS – U.S. Department of Agriculture – Natural Resources Conservation Service
USGS – United States Geological Survey
WPP – Watershed Protection Plan
WQMP – Water Quality Management Plan

Executive Summary

The Texas Water Resources Institute (TWRI), Texas AgriLife Research, the Texas AgriLife Extension Service, and Texas A&M University-Kingsville conducted an Arroyo Colorado nonpoint source assessment of agricultural sources. Since the Arroyo Colorado Watershed Protection Plan has been completed, the Arroyo Colorado Watershed Partnership has worked to implement best management practices on cropland to reduce the amount of nutrients entering the Arroyo Colorado.

This program focused primarily on evaluating the effectiveness of best management practices on row crop fields, evaluating nutrient removal in vegetated drainage ditches, and determining which management practice scenarios would be most effective in keeping nutrients from entering the Arroyo. The program team found that two management practices, nutrient management and irrigation management, were the most effective practices in keeping nutrients from running off cropland and into drainage ditches. Drainage ditches were monitored, and it was determined that they could act as constructed wetlands by removing nutrients through natural processes if properly maintained. If not properly maintained, drainage ditches could release nutrients, previously absorbed, back into the water that eventually makes its way into the Arroyo. Scenarios were modeled using the Soil and Water Assessment Tool (SWAT) that demonstrated which suite of practices through 2025 need to be adopted to provide necessary loading reductions. Lastly, the land use data for the Arroyo Colorado Watershed was updated and used as an input file to the SWAT model and can be used in a variety of other methods.

Future steps for the Arroyo Colorado Watershed include further assessment of using cropland as an actual source of pollution reduction. Observing some already elevated levels of nutrients in irrigation water, proper management of nutrient and irrigation, and installation of management practices play vital roles in keeping nutrients from entering the water body. Money for incentive programs is a huge need as producers continue to adopt management practices with the help of cost share. Additionally, educational programs will continue to be in high demand as best management practice demonstrations are important to show producers the benefits of adoption. Finally, further assessment of what the local needs are should be conducted to identify what the most effective approach to reaching local stakeholders, as they are the population that will make the difference.

Introduction

The Arroyo Colorado flows through Hidalgo, Cameron, and Willacy counties in the Lower Rio Grande Valley of Texas into the Laguna Madre. Flow in the Arroyo Colorado is sustained by wastewater discharges, agricultural irrigation return flows, urban runoff, and base flows from shallow groundwater. The Arroyo Colorado is the major source of fresh water to the lower Laguna Madre, an economically and ecologically important resource to the region. The Laguna Atascosa National Wildlife Refuge and several county and city parks are located within the Arroyo Colorado watershed. The mild climate, semi-tropical plants and animals, and many recreational opportunities draw large numbers of people to the Arroyo Colorado Watershed. One third of the water body is also used for shipping from the Gulf Intracoastal Waterway to the Port of Harlingen.

As a result of low dissolved oxygen levels, the tidal segment of the Arroyo Colorado (Segment 2201), does not currently meet the aquatic life use designated by the State of Texas and described in the Texas Water Quality Standards. This has been the case for every 303(d) list prepared by the State since 1986. There have also been concerns for high nutrient levels in this water body as documented on every 305(b) assessment prepared by the State since 1988. To meet the dissolved oxygen criteria (24-hour average of 4.0 mg/L and minimum of 3.0 mg/L) at least 90% of the time between the critical period of March through October, Texas Commission on Environmental Quality (TCEQ) (2003) estimates a 90% reduction in nitrogen, phosphorous, oxygen-demanding substances and sediment will be necessary.

In response to this impairment, a local effort was initiated to develop a watershed protection plant (WPP) to improve conditions in the Arroyo Colorado. Working with the TCEQ, the Texas State Soil and Water Conservation Board (TSSWCB) and other agencies, a local steering committee has and will continue devise and implement strategies to increase dissolved oxygen in the Arroyo Colorado and improve its environmental conditions.

The Arroyo Colorado Watershed Steering Committee has established several work groups to address the six major components of the WPP: wastewater infrastructure; agricultural issues; habitat restoration; refinement of the Total Maximum Daily Load analysis; land use; and public education. The project has significant financial support from federal nonpoint source grants under CWA §319(h). Already, the stakeholders have made great progress. The Education and Outreach Work Group has developed an outstanding multimedia presentation about pollution problems in the Arroyo Colorado and how to get involved in addressing them. In May 2004, the TCEQ and the Habitat Restoration Work Group established contracts with Texas A&M University's Sea Grant Program and the Texas Parks and Wildlife Department (TPWD) to provide an independent watershed coordinator and a habitat restoration specialist to assist in the development of the WPP. TPWD has contracted with Alan Plummer Associates, Inc. to develop a habitat restoration feasibility study. Funding for this study was obtained from the National Oceanic and Atmospheric Administration through the Texas General Land Office A draft Wastewater Infrastructure plan has been developed. In September 2005, the TSSWCB and the Agricultural Issues Work Group established contracts with (1) Hidalgo and Southmost Soil and Water Conservation Districts (SWCDs) to provide technical and financial assistance to landowners to aid in the development and implementation of Water Quality Management Plans (WQMPs) and (2) TWRI and AgriLife Extension to provide education on best management practices (BMPs). Since this project began, the Arroyo Colorado WPP was published in January 2007 and implementation efforts have been ongoing since.

Project Overview

The primary focus of this project was to better characterize agricultural runoff in the Arroyo Colorado, assess and demonstrate the effects of BMP implementation at the field and sub-watershed level, and measure progress towards meeting WPP goals. A second focus was to evaluate the natural phosphorus reduction capabilities of drainage ditches on runoff from irrigated cropland in the Arroyo Colorado watershed.

This project also provided storm and routine monitoring of drainage ditches that contribute nonpoint source (NPS) loading to the Arroyo Colorado in order to better assess agricultural NPS loadings and reductions resulting from BMP implementation. Monitoring was primarily directed at evaluating areas with significant irrigated cropland acreage.

This project was consistent with the WPP and highly coordinated with the Arroyo Colorado Watershed Partnership and Arroyo Colorado Agricultural Issues Workgroup as well as the educational and implementation projects already in the watershed.

Monitoring efforts have used numerous automated sampling systems that Texas A&M University- Kingsville (TAMU-K) possessed. Historical and non-direct data obtained from other projects have also been used to supplement this project when needed. Data collected for this project was and will be used to determine the reduction of NPS pollution associated with implementation efforts and inform TSSWCB of areas where reduction efforts are most needed. This project also supported additional educational efforts in the watershed.

The four subwatersheds for this study represented predominately irrigated cropland within the Arroyo Colorado watershed with two sites being located in Cameron County and two sites in Hidalgo County.

Subwatershed monitoring activities of this project consisted of automated stormwater sampling, monthly ambient grab sampling, and instantaneous streamflow measurements. Field measurements of dissolved oxygen, water temperature, specific conductance, and pH were collected with each grab sample. All water samples were analyzed for various nutrient forms (e.g., total phosphorus, dissolved orthophosphate phosphorus [frequently referred to as soluble reactive phosphorus] total Kjeldahl nitrogen, dissolved ammonia, dissolved nitrite plus nitrate), and total suspended solids. In addition, monthly grab samples were analyzed for biochemical oxygen demand (BOD). Nitrogen forms were included in the laboratory analyses to provide a more complete indication of macronutrient conditions in the watershed, evaluate whether agricultural BMPs are reducing nutrients, and ensure that efforts to reduce one nutrient is not inadvertently increasing another.

This project provided result-oriented demonstrations to landowners in the Arroyo Colorado watershed. The edge-of-field monitoring represented both tiled and non-tiled irrigation cropland fields that drain to both drainage ditches and directly into the Arroyo Colorado. Surface runoff, along with outflow from the tile drainage system, was retrieved on a storm-event basis and flow composited into a single sample. All water samples were analyzed for various nutrient forms.

Throughout the project, staff has maintained equipment to record instantaneous water level information and gather the required physical measurements and flow data needed to develop, maintain and update, as it was needed, the stage-discharge relationships (rating curves) at all stations.

The results of this study are being used to support ongoing educational and implementation efforts and future modeling efforts planned for the watershed.

A final component of this project includes the completion of the recalibrated Arroyo Colorado SWAT model. The model, funded under TSSWCB project 02-21 *SWAT Model Simulation of the Arroyo Colorado Watershed,* completed and delivered a calibrated/validated SWAT model for the Arroyo Colorado based on a variety of newly collected data sources; however, the project was not able to run various BMP scenarios due to the project grant period ending in April 2009. This model uses information gathered in the TSSWCB project 06-10 as inputs to the SWAT model, as well as finish some remaining tasks from the 02-21 project, which includes simulating load reduction scenarios for a suite of management measures and providing flow and watershed loadings to the Arroyo Colorado, as determined by SWAT, for future input by TCEQ into the Environmental Flow Dynamic Code (EFDC) model.

Project Coordination and Administration

TWRI facilitated this project through continued communication, consistent and timely reporting, fiscal oversight, and active involvement in the WPP implementation process. TWRI organized an Agricultural Monitoring Oversight Committee that coordinated project efforts with all project participants, including AgriLife Research, TAMU-K, AgriLife Extension, TCEQ, Texas Department of Agriculture, Texas Sea Grant, TSSWCB, Nueces River Authority, producer groups, irrigation districts, and drainage districts. In 2007, a draft list of members to include in this committee was developed, and the first meeting was held in conjunction with the Arroyo Colorado Watershed Partnership Agricultural Issues Workgroup on July 24, 2007. During that meeting, it was determined that for efficiency sake, the Agricultural Monitoring Oversight Committee would meet in conjunction with the Agricultural Issues Workgroup. From then on, the Agricultural Monitoring Oversight Committee (Agricultural Issues Workgroup) continued to meet on a biannual basis. Meeting minutes for these meetings can be found at: http://arroyocolorado.org/partnership/agriculture-workgroup/.

TWRI drafted and submitted reports each quarter to TSSWCB that provided summaries of related activities during the previous 3 months. Those reports can be found at http://www.arroyocolorado.org/projects/agricultural-nps-assessment/. Additionally, TWRI hosted a project meeting with the TSSWCB project manager, as needed, to review project status, deliverables and discuss other issues. During quarters when no Agricultural Monitoring Oversight Committee meetings were scheduled, meetings were held with project participants to discuss project activities, project schedule, lines of responsibility, etc.

Through this project, monitoring results have been transferred to AgriLife Extension and AgriLife Research for development of educational materials and presentation to stakeholders. Based on the results of the monitoring, AgriLife Extension has and will continue to hold workshops demonstrating the impacts of implementing BMPs in the watershed. It will also coordinate periodic meetings of agricultural producers to bring awareness concerning the impact of the drainage ditches on the mitigation of pollution from the Arroyo Colorado. Specific educational activities have occurred through TSSWCB-funded project 05-10 and will continue through TSSWCB-funded project 10-11.

Finally, TWRI has developed, hosted and maintained a website for dissemination of information on educational, monitoring and demonstration activities taking place across the Arroyo Colorado Watershed. The Arroyo Colorado website includes:

- PDF versions of all reports, journal articles, faculty papers and presentations generated from the project, as well as those from other Arroyo Colorado projects
- Links to all cooperating and/or participating agencies
- Links to all project primary investigators
- Links to university academic departments that are involved in the project
- Links to other related websites:
    - Texas State Soil and Water Conservation Board
    - Texas Water Resources Institute
    - U.S. Environmental Protection Agency, Office of Water, CWA §319
    - Soil and Water Conservation Districts
- Schedule of upcoming meetings/programs dealing with this project

The project website came online in December 2007, but analytics have only been collected since April 2009. Between April 2009 and February 2012, there have been 8,577 visits to the webpage. As projects came online and materials became available, they were added to the website. The website address is http://arroyocolorado.org/. Figure 1, shown below, is a visual of the number of website visitors during the duration of the project.

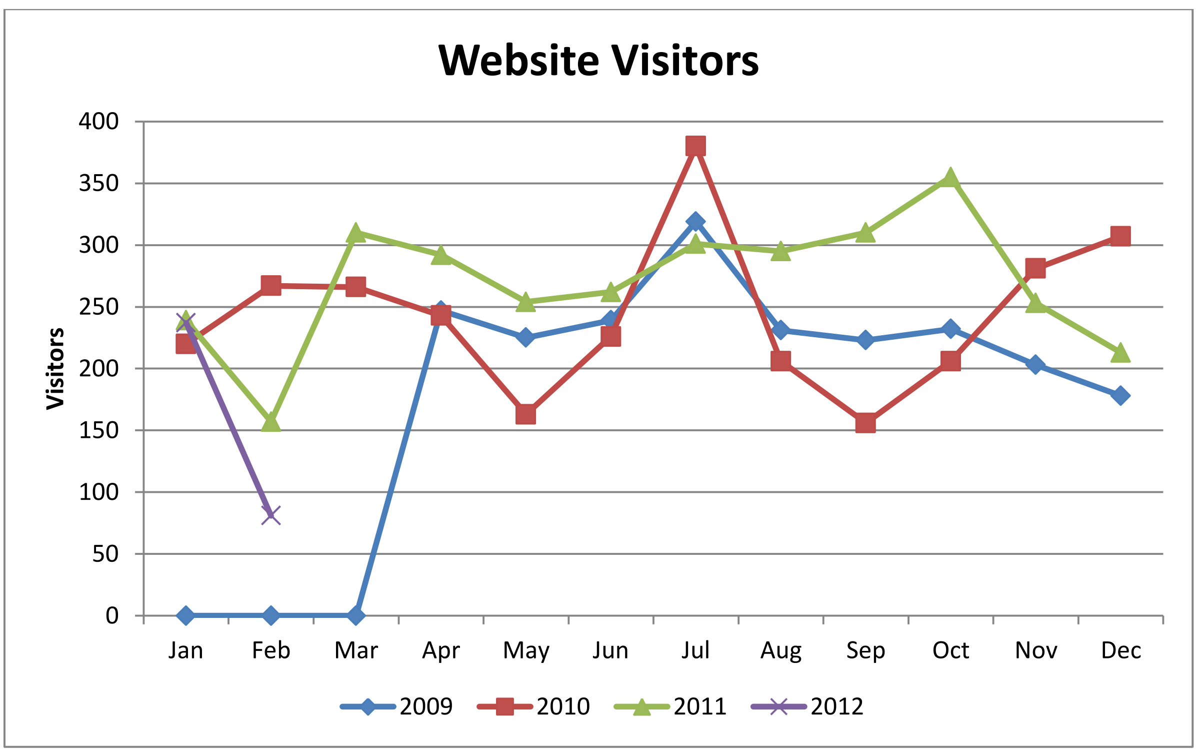

Figure 1: Website Visitors from March 2009 through February 2012

Compilation and Evaluation of Historical Data and Prior Studies

TWRI, along with the assistance from members of the Agricultural Monitoring Oversight Committee, compiled historical water quality data and information from previous studies and conducted an analysis of the most significant water quality parameters to investigate trends and different biological and physical processes taking place in the watershed that contribute to the changes in water quality. Graphs were developed for various parameters collected at various sites along the Arroyo Colorado. Those graphs can be found at http://arroyocolorado.org/data/.

TWRI, with the assistance from members of the Agricultural Monitoring Oversight Committee, has organized the results from the earlier NPS pollution projects conducted in the Arroyo Colorado Watershed and summarized the results and conclusions of these studies within the historic data report. Additionally, through the development of this report, data gaps were identified that need to be filled. This report can be found at http://twri.tamu.edu/reports/2012/tr421.pdf.

Inventory of Conservation Practice Implementation

AgriLife Research in Temple, along with the assistance from AgriLife Extension, USDA-Natural Resources Conservation Service (NRCS), USDA-Farm Service Agency the TSSWCB Harlingen Regional Office and the SWCDs have identified agricultural producers in the watershed and compiled information on the location and types of conservation practices implemented in the watershed since 1995 in the form of GIS shapefiles. This included practices implemented through the USDA-NRCS Environmental Quality Incentives Program (EQIP) and the TSSWCB WQMP Program. An example of a map created with these GIS shapefiles can be seen below.

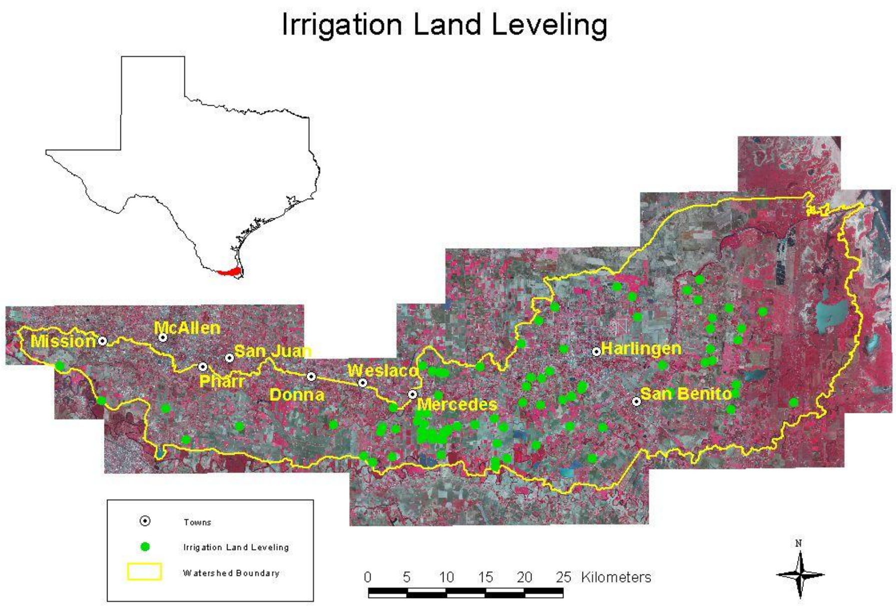

Figure 2: Sample Map of Irrigation Land Leveling Practice Implementation Sites

AgriLife Research in Temple transferred the assembled geo-referenced database and developed maps to be given to AgriLife Extension for use in prioritizing educational activities, which so far, have been in the form of field days at BMP sites demonstrating the importance of adoption. Various management practices are adopted annually and with an ever-changing land use, other practices are lost. Because of the dynamic nature of BMPs, there was and still is a need to update the database periodically.

Update of Land Use/Land Cover Data

Updating the Land use/Land Cover (LULC) categories for the Arroyo Colorado Watershed was done by first obtaining the 1998 LULC and all the data used to produce it. Working with TPWD and the Arroyo Colorado Watershed Partnership Habitat Workgroup to obtain other relevant data, major changes from 1998–2005 were identified. Further, the Spatial Sciences Laboratory at Texas A&M University worked to add available cropland, citrus production, sugarcane, irrigation districts, tile drained areas, *colonia's*, non-*colonia* areas, land applications from wastewater, and updates from the Lower Rio Grande Valley Development Council to the LULC map.

Similar to the dynamic nature of BMPs, LULC is continuously changing in the Lower Rio Grande Valley as the population is growing very rapidly. Cities and local officials need to continually update maps to increase management efficiency; however, they typically do not update them at the watershed scale. Updating is needed periodically so that trends can be identified, regional managers can plan appropriately within the watershed, and modelers can develop tools for those managers to use.

Subwatershed Monitoring and Measuring Pollutant Attenuation in Drainage Ditches

An important component to the project was to perform routine grab and storm event samples to assess water quality assimilation that occurs in drainage ditches in the watershed. Four drainage ditch sites were chosen and water quality samples were collected when water was flowing. When water was not flowing during the monthly sampling water as not collected, but it was documented that the water body was pooled or dry. Routine grab samples were analyzed for nutrients, Total Suspended Solids (TSS), and BOD. Additionally, field constituents including dissolved oxygen, pH, conductivity, and water temperature were recorded.

TAMU-K also periodically operated automated samplers and water-level recorders at the different sites to characterize the runoff generated by high stormflow pulses. In doing so, an existing rain gauge was used along with remotely sensed NEXRAD data to identify optimal periods for carrying out such sampling. Given the variable nature of the rainfall process, it was difficult to estimate the exact number of samples that were going to be obtained. However, attempts were made to carry out at least one sampling campaign quarterly during each sampling period. At each drainage site, individual runoff and flow samples were collected daily during storm events, then composited into one sample that was analyzed for nutrients, BOD, and TSS. Care was taken to ensure that the data loggers were programmed to capture the effects of rainfall pulses and not respond to minor water level fluctuations caused due to irrigation flooding. The monthly water level was collected as part of this task and hydrograph techniques were used to identify optimal response frequencies to capture high-intensity rainfall pulses.

Also within this task, nitrogen and phosphorus mitigation processes in drainage ditches at the sites were assessed, and a suite of BMPs was developed that incorporate the information from the above mentioned monitoring. Furthermore, specific activities that occurred for this task and results from analysis can be found in Appendix A.

Evaluation of BMPs to Reduce NPS Pollution at the Farm Level

AgriLife Research at Weslaco worked with AgriLife Extension to select suitable demonstrations sites to assess loadings from agricultural runoff and leachate produced by different BMPs. These loadings were then compared to traditional practices with innovative BMPs for the three most representative crops in the watershed. Six representative sites were selected and characterized for their physical characteristics such as topography, soil texture, salinity and fertility levels, water quality and crops.

At each site, AgriLife Research at Weslaco installed sensors, flow meters, rain gauges, piezometers, and soil water sensors. By using this equipment, samples were collected and analyzed from runoff and leachate samples for the different practices. A laboratory analysis was performed to determine agricultural loadings such as nutrients and solutes. BMPs and traditional practices were compared economically, and their relationship with nutrient loadings was established.

Finally, at least one field day and one result demonstration per year were held to demonstrate and transfer the results to producers and interested persons. These results can be found in Appendix B.

SWAT Model Simulation of the Arroyo Colorado Watershed

AgriLife Research at Temple used the SWAT model to simulate load reduction scenarios for a suite of management measures based on the Arroyo Colorado WPP for a period after the calibration and validation periods. Results from scenarios were provided to TSSWCB with the flow and watershed loadings to the Arroyo Colorado for input into the EFDC model. Outputs include a time series of daily flow and sediment, nutrients and other loadings at the Port of Harlingen and for each sub-basin downstream of the Port of Harlingen. Specific results for these simulations can be found in Appendix C.

Conclusions

Overall, this project is one of high interest to local stakeholders. Providing high quality localized data and demonstrations allows for a large impact on the community, as they gain a better understanding of the factors that affect water quality in the Arroyo Colorado. Additionally, demonstrating the effectiveness of tools, such as irrigation and nutrient management, is necessary for them to make informed decisions, leading to the success of the Arroyo Colorado Watershed Protection Plan.

Monitoring and modeling scenarios for the Arroyo Colorado Watershed proved to be a project that many stakeholders had a high interest in. These types of projects continue to not only advance what it known about BMP implementation, but they also help target implementation dollars so that the biggest impacts can be seen in water quality.

This project supported implementation of BMPs though monitoring of nutrients and other parameters at different sites containing BMPs. With the results, personnel showed producers how to not only minimize their impact to water quality, but minimize their input while still maximizing crop yields. Results from this component of the project showed that proper nutrient management and irrigation management had the largest reduction of nutrients leaving the field in irrigation water.

Additionally, drainage ditch monitoring demonstrated the potential for these ditches to remove nutrients before entering the water body, if properly maintained. The natural functions of wetlands can be duplicated in drainage ditches in each drainage district, and they will thus mitigate agricultural impacts to water quality. If drainage ditches are not properly maintained though, nutrients absorbed by vegetation can be released back into the water, which eventually makes it to the Arroyo Colorado.

Finally, through modeling various BMP scenarios, AgriLife Research at Temple has developed recommendations on the most effective suite of BMPs that will help achieve Arroyo Colorado Watershed Protection Plan goals. The suite of BMPs will help decision makers implement practices that will remove the most nutrients with the least investment.

The need to continue these projects is important as we can localize BMP implementation to have the greatest impact on water quality and more accurately predict management measures that need to take place. Investing in cost share opportunities would allow managers to properly maintain nutrient input to crops, irrigation runoff from cropland, and drainage ditches, all keeping elevated levels of nutrients from entering the Arroyo Colorado. Further, educational programs are and will continue to be needed so that decision makers can learn about the various methods for removing nutrient inputs to waterbodies. Finally, further assessment is needed to learn about the local needs and find the most effective approach to reach local stakeholders, who are the ultimate audience that make the difference.

Lastly, the agricultural community is making progress to meeting its goals and such projects provide the concepts and cost savings necessary to do so.

Appendix A

A Multivariate Water Quality Investigation of

Select Drainage Ditches

in the Arroyo Colorado River Watershed, Texas

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A Multivariate Water Quality Investigation of Select Drainage Ditches in the Arroyo Colorado River Watershed, Texas

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Arroyo Colorado Agricultural Nonpoint Source Assessment

The report highlights the accomplishment of Task 7 of Project number 06-10 administered by TSSWCB

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List of Symbols and Abbreviations

Symbol	Description	Symbol	Description
TMDL	Total Maximum Daily Load	WPP	Water Protection Plan
CC1	Cameron County Site 1 (Harding Ranch Road 3 mi N. of 508 and 1420)	CC2	Cameron Count Site 2 (ABD Rd & FM 1479 4 mi S. of Hwy 83)
HC1	Hidalgo County Site 1 (Mile 4 North FM 491)	HC2	Hidalgo County Site 2 (3 mi. N of US Military Hwy 281 & 493)
DO	Dissolved Oxygen	CBOD	Carbonaceous Biochemical Oxygen Demand
TSS	Total Suspended Solids	OP	Orthophosphate Phosphorous
TP	Total Phosphorous	TKN	Total Kjeldahl Nitrogen
ANOVA	Analysis of Variance	KW	Kruskal Wallis
FDC	Flow Duration Curves	LDC	Load Duration Curves
ACF	Auto Correlation Function	TSSWCB	Texas State Soil and Water Conservation Board
TCEQ	Texas Commission on Environmental Quality	USEPA	United States Environmental Protection Agency
QAPP	Quality Assurance Protection Plan		

Introduction

Drainage ditches are widely used for agricultural water management to help remove excess water from fields, which mitigates the effects of water logging and salinization. These ditches act as a direct hydraulic link between the agricultural field and streams and rivers. As such, there is an increasing concern that drainage ditches can act as conduits for nutrient transport and, in conjunction with other point and nonpoint sources, can contribute to eutrophication and decreased dissolved oxygen levels in receiving water bodies. Studies have linked drainage ditches to hypoxia in the Gulf of Mexico and eutrophication of the Great Lakes (Dagg and Breed, 2003; Moore et al., 2010). However, there is also evidence suggesting that drainage ditches can help attenuate the loadings of phosphorus and suspended sediments (R. Kröger et al., 2008) and thus foster water quality improvements at a watershed scale. There is a growing interest in understanding the nutrient behavior in drainage ditches both in the United States (Bhattarai et al. 2009; Moore, et al. 2010; Ahiablame et al. 2011) as well as other parts of the world (Nguyen and Sukias 2002; Leone et al. 2008; Bonaiti and Borin 2010).

The Arroyo Colorado River is a distributary of the Rio Grande River whose flows are sustained primarily by discharges from wastewater treatment plants and nonpoint source loadings from urban and agricultural sources. The Arroyo Colorado River watershed along the US-Mexico border region is not only one of the fast-growing urban areas in the United States, but it also has a strong agricultural base. Nearly 80% of the approximately 700 sq. mile watershed is designated as cropland (Figure 1). Being in a semi-arid region, rainfall is highly erratic and often occurs as high intensity, short duration storms (Norwine et al. 2007). As such, farmers rely on irrigation to grow cotton, grain (corn and sorghum), sugar cane, citrus and vegetables. Figure 1 also depicts the labyrinth of drainage ditches within the watershed that transport water, sediment, and nutrients away from the farmlands. The tidal segment of the Arroyo Colorado River is listed as impaired for low dissolved oxygen on the State of Texas 303(d) list. The low dissolved oxygen in the tidal segment is primarily linked to high loadings of nutrients and oxygen demanding substances in the upland (non-tidal) areas of the watershed (Raines and Miranda 2002). Watershed modeling studies conducted to estimate TMDLs in the region have indicated that over 90% pollutant load reductions are necessary to improve dissolved oxygen conditions in the tidal segment (Raines and Miranda 2002; Hernandez 2007). Given the impracticality of such drastic reductions, a multistakeholder watershed planning group was designated to develop a watershed protection plan (WPP) that seeks to improve water quality through better land and wastewater management in the watershed (ACWPP 2007).

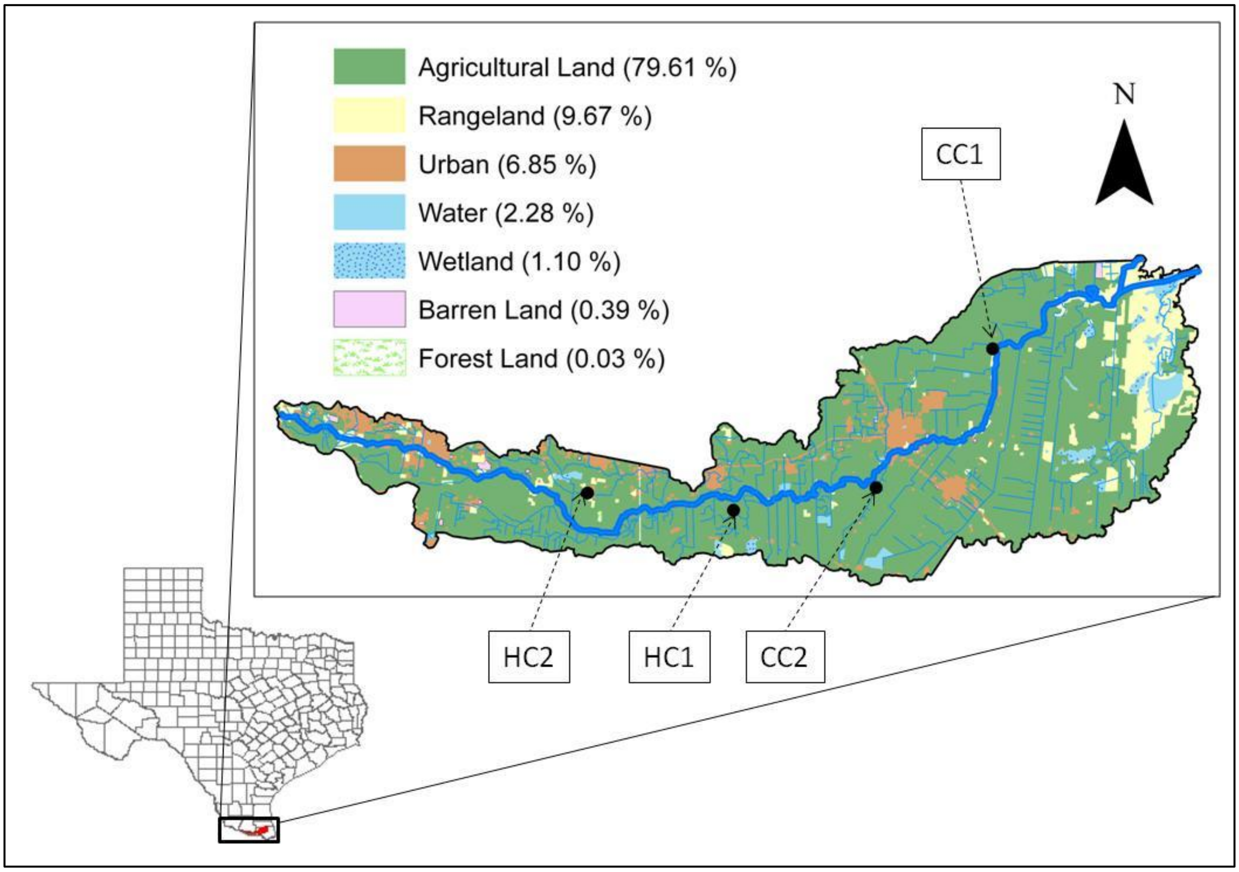

Figure 1: Land use and Land cover view of the Arroyo Colorado River Watershed, Lower Rio Grande Valley, Texas

An important component of the Arroyo Colorado WPP is to evaluate and quantify the nature and extent of nutrient loadings from agricultural activities in the region. This information is fundamental to promote best management practices and foster sustainable agricultural activities (Hernandez and Uddameri 2010). As most agricultural runoff is carried to the Arroyo Colorado River through the drainage ditches, quantifying nutrient dynamics in the drainage ditches is of paramount importance. Previous efforts aimed at quantifying nutrient loadings from drainage ditches have been limited to a few synoptic measurements and as such provide limited information. Therefore, a long-term (multiyear), multisite, multivariate water quality sampling campaign was undertaken through this study with the broad goal of understanding the spatio-temporal variability of nitrogen species (Total Kjeldahl Nitrogen (TKN), ammonia-nitrogen (NH_3-N), nitrite + nitrate-nitrogen), phosphorus compounds (total and dissolved phosphorus) and other water quality parameters. More specifically, the focus of the study was to develop fundamental insights about the role of hydraulic controls (flows) on nutrient concentrations. An edge-of-field water quality monitoring program was also carried out in conjunction with the drainage ditch monitoring to evaluate whether drainage ditches attenuated or exacerbated nutrient loadings from croplands.

Field Sites and Sampling Design

Four representative drainage ditches were selected for extensive monitoring based on recommendations from the Texas State Soil Water Conservation Board (TSSWCB). Two of these sites were located in Cameron County and two were in Hidalgo County (Figure 1). Approximate contributing drainage areas (sub-watersheds) corresponding to these monitoring locations were delineated using ArcGIS V 9.3 (ESRI Inc., Redlands, CA) and integrated with recent land use land cover (LULC) data to obtain sub-watershed characteristics (Figure 2). The contributing sub-watersheds were predominantly agricultural, varied in size, and provided a representative sample of different drainage ditches in the area.

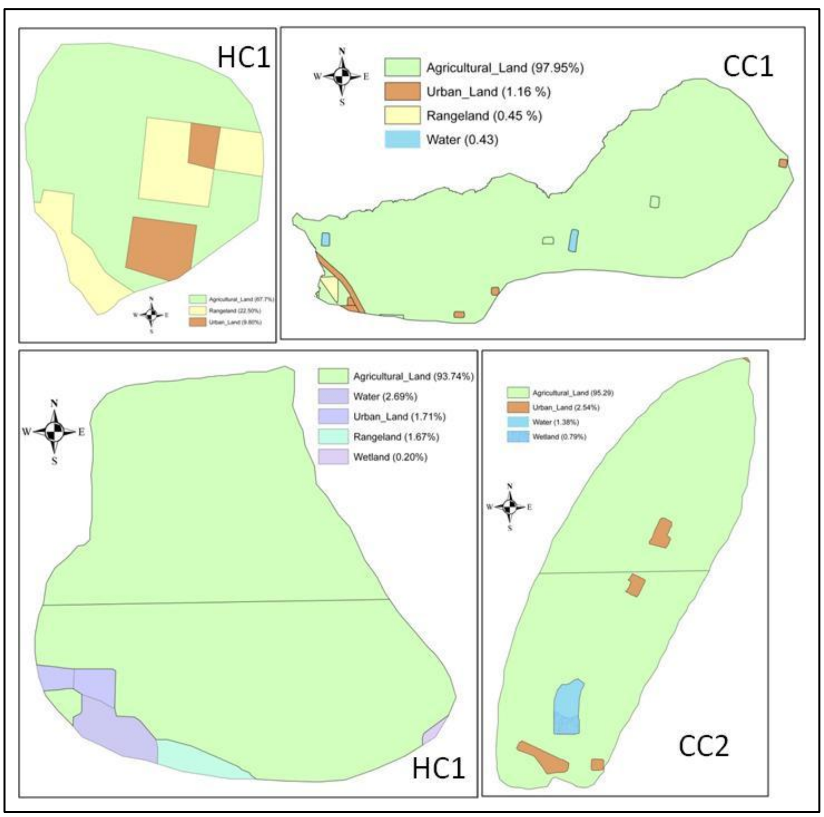

Figure 2: Contributing sub-watershed characteristics for the monitored drainage ditches

A modified, stratified, random sampling approach was adopted to collect data over time. According to this approach, sampling was carried out monthly (stratified design), but the sampling date within the month was selected at random to avoid any sampling bias (randomized design). However, the sampling dates were spaced sufficiently far apart (at least two weeks) to minimize auto-correlation effects and ensure independence among sampling events. A total of 37 sampling events were carried out during August 2008 – November 2011. The sampling was carried out on the same day at all sites to facilitate paired comparisons. While the number of locations sampled and the frequency of sampling were clearly limited by fiscal and logistic constraints, the design captured variability over a 2-year period, which included a protracted period of drought and two major storm events (Hurricane Dolly in 2008 and Tropical Storm Ike in 2010).

In addition to monthly grab sampling, the project also evaluated the water quality characteristics of time-averaged composite samples on select dates and locations. The composite sample was obtained using a field autosampler, which took samples from the ditch every 30 minutes over a 24-hour period. The autosampler and the collection set up are presented in Figure 3. The sample was filtered at the end of the collection period and analyzed for nutrients using the same analytical methods listed in Table 2. Every attempt was made to obtain these composite samples around a major rainfall event. However, the erratic characteristics of the rainfall events (i.e., either large tropical storms that prevented access to sites) or very low intensity events that did not yield considerable runoff added difficulties to the collection process. A total of eight sampling events were carried out in all and are summarized in Table 1. However, the data from two of these events were not used in the analysis due to instrument failures in the field. A grab sample was also collected at the end of the composite sampling period to facilitate pairwise comparisons between the two sampling methods.

Figure 3: Composite sample collection set up at one of the sites (HC1)

Table 1: Summary of Composite samples collected to account for storm water events

Date	Site	Last Rainfall Event (in)	Remarks
19 September, 2009	CC1	0.06	Instrument Failure
23 January, 2011	CC1	1.22	
27 February, 2011	CC1 & HC1	0.02	
27 March, 2011	CC2 & HC1	0.01	
28 August, 2011	CC2* & HC1	0.04	*Instrument Failure at CC2; HC1 successful

Table 2: Field and laboratory protocols used to measure water quality parameters

Component	Units	Analysis Method	Equipment Used
pH	Standard Units	EPA 150.1 TCEQ SOP	YSI 556 MPS
DO	mg/L	EPA 150.1 TCEQ SOP	YSI 556 MPS
Conductivity	µS/cm	SM 2520B	YSI 556 MPS
Turbidity	NTU		HACH 2100P
Temperature	C	EPA 170.1 TCEQ SOP	YSI 556 MPS
Flow	cfs	TCEQ SOP	Marsh McBirney Flowmate
CBOD, 5-day	mg/L	5210B Standard Method	YSI 5100
TSS	mg/L	EPA 160.2	Hot oven, glass fibre filters
Ortho Phosphate	mg/L	4110 B Std. Methods	Spectrophotometer (Ascorbic Acid Method)
Total Phosphorous	mg/L	4110 B Std. Methods	Spectrophotometer (Ascorbic Acid Method)
Total Nitrite + Nitrate Nitrogen	mg/L	4110 B Standard Methods	Spectrophotometer and Nitrate Electrode method
Ammonia Nitrogen	mg/L	EPA 350.3	Ammonia Electrode
Total Kjehdahl Nitrogen	mg/L	EPA 351.3	Labconco Rapid Still II and Spectrophotometer

A suite of 13 water quality parameters, as listed in Table 2, were measured at each site using approved field and laboratory protocols. All measurements were made in duplicate both in the field and at the lab. Three sets of grab samples (one unfiltered, one unfiltered but preserved at pH < 2 and one field filtered using 0.45 µm filters) were collected in the field for laboratory analysis of nutrients, total suspended solids (TSS) and carbonaceous-biological oxygen demand (CBOD). Instantaneous velocity measurements were also made in duplicate using the Marsh McBirney FloMate® instrument and used to compute flow via the area-velocity method. All field probes were routinely calibrated and maintained per manufacturer's specifications. Laboratory analysis used approved standard methods for water and wastewater analysis (AHPA, 2010) and adhered to USEPA approved QA/QC protocols as stated in the QAPP (QAPP, 2008). Consistency checks such as total phosphorus (TP) being greater than or equal to orthophosphate phosphorus (OP) and NH_3-N being less than or equal to the TKN were also used as appropriate. Other relevant hydro-meteorological data such as rainfall, relative humidity and temperature were compiled from a nearest weather station located within the watershed (Agrilife Extension 2011). The edge-of-field sampling was carried out by personnel from Texas AgriLife Extension Service as part of another task in the 06-10 *Arroyo Colorado Agricultural Nonpoint Source Assessment* project.

Conceptual Model and Hypotheses Development

Three of the four drainage ditches (CC1, CC2, and HC1) exhibited perennial flow throughout the period of study even when significant drought conditions persisted in the area. One site, HC2, had a stagnant water column during the study period, but had no measurable flow. The depth of the water column and the flow rates were noted to vary considerably throughout the sampling period. The flows in the drainage ditch could therefore be conceptualized to include relatively short flow paths, comprised of overland flow near the sampling points, long flow paths, which brought water from farther portions of the contributing drainage area, and deeper flow paths. The longer flow paths (particularly the subsurface components) can be viewed as the cause for persistent flow in the ditches during dry periods while shorter flow paths (overland flow) can be envisioned to mostly control flow under wet weather conditions.

Based on the flow regime conceptualization, the concentration of pollutants between high and low flow regimes are hypothesized to be different particularly for TSS, which either are filtered out in the subsurface or settled out in the ditch under low flow conditions. Phosphorus compounds are known to undergo a variety of reactions including sorption and co-precipitation with calcite ($CaCO_3$) and are generally strongly correlated with suspended solids (Kadlec and Wallace 2009). Therefore, it is expected that phosphorus concentrations are also likely to exhibit differences with flow regimes. However, unlike TSS, the uptake of phosphorus by plants and subsequent release during senescence are likely to have some impacts in masking flow-related differences as periods of senescence will likely occur during months when the flows are going to be low (i.e., moisture stresses on the vegetation). Furthermore, if the soils in the contributing drainage area are low in phosphorus, then high flow events will have a dilution effect and lead to smaller concentrations.

As drainage ditches are open to atmosphere and biologically active systems, they are generally known to contain relatively greater amounts of oxidized forms of nitrogen (nitrite+nitrate) than reduced forms (TKN). Agricultural streams in many parts of the United States are reported to be major contributors of nitrates (NO_3-N) to rivers and lakes (David et al. 1997; Goolsby et al. 1997; Goolsby et al. 2001; Mitsch et al. 2001; Royer et al. 2006). However, drainage ditches under investigation exhibit density-driven stratification due to the presence of salts and sediments. Therefore, the upper portions of the ditch are hypothesized to be under oxidizing conditions conducive to nitrification reactions, while the deeper sections may be under reduced conditions facilitating denitrification reactions (Jetten et al. 1997). The denitrification process in natural waters is known to occur even before all the oxygen in the water column is completely depleted (Kuenen and Robertson 1988). However, the extent of denitrification is also critically controlled by the availability of organic carbon source (Kadlec and Wallace 2009).

Based on the above discussion, it is clear that certain conditions found in the drainage ditches, such as deeper flow channels, lower flow rates (lesser oxygenation) and higher organic matter due to detritus, can facilitate removal of nitrates via the process of denitrification, particularly in comparison with direct runoff from agricultural fields where nitrate attenuation is less favorable. Therefore, it is hypothesized that nitrate concentrations in the drainage ditches are likely to be lower than those collected at the edge-of-field. The amount of dissolved oxygen in the stream is inversely correlated to temperature. Furthermore, nitrate concentrations in the stream are likely going to be lower in summer months than in winter months (if all other factors stay the same). However, the nature and extent of nitrate (oxidized nitrogen) removal in drainage ditches can be subject to several confounding factors. While deeper channels are likely to facilitate nitrate reductions, they are likely to have higher flow rates (Chapra, 1996). These higher flow rates can increase the re-aeration rate and facilitate deeper penetration of oxygen molecules, which in turn can limit the amount of denitrification. Higher flow rates can also induce rate limitations on the conversion of TKN to nitrate (nitrification step) as TKN molecules spend less time in the ditch for the reaction to go to completion. As denitrification depends upon the amount of nitrate produced, higher flow rates can also lead to limited denitrification. Considering all these factors it is hypothesized that nitrate concentrations are inversely proportional to the ratio of depth to flow rate, which is referred to as nitrate reduction index in this study and represents the hydraulic residence time per unit area of the channel.

Statistical Analysis

Exploratory data analyses (EDA), which employs a suite of visualization tools such as box plots, quartile (Q-Q) plots, factor separated scatter plots, and autocorrelation functions (ACF) (Cleveland 1993; Qian 2010), were utilized to understand variability in the observed data. In particular, EDA techniques were used to evaluate the reasonableness of data to normality (using Q-Q plots), independence (ACF plots) and homoskedasticity, which form the underlying basis of parametric hypothesis tests (Hamilton 1994). Parametric statistical procedures including t-tests, one-way and two-way analysis of variance (ANOVA) have been commonly used to evaluate water quality data in drainage ditches (Smith et al. 2005; R. Kröger et al., 2008; Rocha et al. 2008; Bhattarai et al., 2009; Moore et al., 2010; Ahiablame et al., 2011).

The selection of statistical parametric methods over non-parametric methods is generally based on that they typically exhibit greater power to discern true changes (i.e., lower type-II errors) when the underlying assumptions are true (Hamilton 1994). While parametric methods are generally noted to be robust to deviations from normality, outliers or extreme values can still significantly impact the results of these tests (Hamilton 1994). Non-parametric counterparts to t-test (Mann-Whitney test), one-way ANOVA (Kruskall-Wallis test) and two-way ANOVA (Friedman's test) have been proposed in the literature and are useful when the dataset has considerable variability and does not fully satisfy the parametric assumptions (Conover 1980). The study area in semi-arid South Texas is known to exhibit considerable climatic variability (Norwine et al., 2007). Therefore, the flow, vegetation and water quality characteristics in the drainage ditches exhibit significant fluctuations. As such, non-parametric tests were primarily employed in this study. The statistical analyses were performed using R statistical language version 2.14.1 due to easy access to various EDA and hypothesis testing tools (Hornik 2011). The statistical data analyses were used to evaluate various hypotheses related to water quality in the ditches, the results of which are discussed next.

Results and Discussion

Exploratory Data Analysis and Evaluation of Parametric Assumptions

A comprehensive exploratory data analysis was performed to obtain initial insights into the observed dataset and evaluate the assumptions of normality, independence and homoskedasticity. Comparison of parametric and non-parametric summary statistical measures indicated that the data are not normally distributed and typically skewed (Table 3). Chemical concentrations are known to manifest as a multiplicative effect of several random processes and as such are likely to follow log-normal distribution (Ott, 1995). Q-Q plots were therefore generated using log-transformed data and compared to theoretical normal distribution function. An illustrative Q-Q plot is presented in Figures 4-6 for one site (Q-Q plots for other sites can be seen in Appendix A, Figures AF 1 - AF 9).

The departures from normality at upper and lower quartiles is evident for most water quality parameters in Figures 4-6, and these are indicative of heavy tails and presence of extreme values in the dataset. This behavior is reflective of the climatic variability in the region, which can be gleaned from deviations in flows and temperature. Behavior such as this suggests that water quality is greatly influenced by hydro-climatic conditions, particularly flows. Also, data pertaining to concentrations of Orthophosphate-Phosphorous and NH3-N in the drainage ditches indicate several non-detects at the sites and as such the distributions show negative skewness. Except in the case of CBOD, log-transformation of the data is not likely to be sufficient to make the water quality parameters be represented using the normal distribution.

Table 3: Descriptive statistics for the monitored water quality parameters for the drainage ditches

	Mean	Median	Std. Dev	IQR	Kurtosis	Skewness
	CC1					
Temperature (oC)	22.549	23.760	5.350	8.490	-0.714	-0.573
Turbidity (NTU)	65.678	62.267	44.488	39.407	3.415	1.496
Dissolved Oxygen (mg/L)	4.748	4.520	1.832	2.006	0.159	0.018
Specific Conductance (µS/cm)	5418.024	4178.000	2659.216	4960.000	-1.237	0.582
pH	7.582	7.760	0.666	0.432	4.858	-1.701
Flow (cfs)	4.572	3.759	4.022	2.260	8.409	2.611
CBOD (mg/L)	70.579	48.880	57.064	55.746	-0.034	1.107
TSS (mg/L)	80.161	80.000	40.855	45.000	1.103	0.900
OP (mg/L)	0.045	0.010	0.065	0.053	13.288	3.276
TP (mg/L)	0.551	0.249	0.606	0.643	3.598	1.879
Total Kjeldahl Nitrogen (mg/L)	0.445	0.431	0.131	0.104	1.965	0.191
Ammonia Nitrogen (mg/L)	0.038	0.010	0.045	0.039	2.455	1.775
Nitrite + Nitrate Nitrogen (mg/L)	1.138	0.400	1.298	1.273	1.249	1.440
	CC2					
Temperature (oC)	24.063	24.900	5.265	9.305	-0.792	-0.360
Turbidity (NTU)	111.043	69.500	109.370	87.699	2.643	1.757
Dissolved Oxygen (mg/L)	4.999	5.020	2.225	2.230	0.248	-0.387
Specific Conductance (µS/cm)	5310.565	4921.000	2174.413	3733.000	-0.822	0.284
pH	7.205	7.260	0.515	0.577	2.760	-1.523
Flow (cfs)	2.619	2.001	2.441	1.996	10.240	2.742
CBOD (mg/L)	69.077	64.965	40.745	62.481	-0.856	0.441
TSS (mg/L)	113.629	85.000	84.137	105.000	1.195	1.331
OP (mg/L)	0.122	0.088	0.093	0.139	0.041	0.833
TP (mg/L)	0.881	0.622	0.777	0.861	1.473	1.412
Total Kjeldahl Nitrogen (mg/L)	0.418	0.410	0.141	0.121	1.543	0.604
Ammonia Nitrogen (mg/L)	0.118	0.010	0.425	0.055	29.883	5.426
Nitrite + Nitrate Nitrogen (mg/L)	1.331	0.632	2.205	1.053	19.561	4.116
	HC1					
Temperature (oC)	25.601	25.510	5.580	8.940	-0.698	-0.413
Turbidity (NTU)	154.909	149.000	73.148	103.834	-0.539	0.091
Dissolved Oxygen (mg/L)	4.521	4.790	2.067	2.645	-0.523	-0.763
Specific Conductance (µS/cm)	2785.113	2401.000	1005.133	818.000	0.761	1.236
pH	7.183	7.300	0.536	0.600	0.267	-0.561
Flow (cfs)	11.119	9.497	9.307	10.671	6.181	2.114
CBOD (mg/L)	65.502	60.281	37.625	43.235	0.984	0.848
TSS (mg/L)	118.952	115.000	55.407	67.500	0.616	0.543
OP (mg/L)	0.157	0.165	0.093	0.165	-0.633	0.103
TP (mg/L)	1.344	0.734	1.172	1.547	1.368	1.307
Total Kjeldahl Nitrogen (mg/L)	0.441	0.429	0.148	0.150	0.387	0.260
Ammonia Nitrogen (mg/L)	0.044	0.010	0.064	0.034	6.783	2.513
Nitrite + Nitrate Nitrogen (mg/L)	0.978	0.661	1.082	0.922	2.003	1.653
	HC2					
Temperature (oC)	27.298	27.660	6.644	22.826	-0.547	-0.387
Turbidity (NTU)	194.929	166.000	156.738	140.365	7.500	2.390
Dissolved Oxygen (mg/L)	4.909	4.920	2.519	2.785	-0.317	-0.264
Specific Conductance (µS/cm)	4597.194	3182.000	3750.590	4383.500	3.646	1.861
pH	7.325	7.310	0.728	0.715	0.547	-0.385
Flow (cfs)	No Measurable flow					
CBOD (mg/L)	65.850	49.167	45.429	65.677	-0.555	0.690
TSS (mg/L)	181.528	135.000	137.266	117.500	0.867	1.326
OP (mg/L)	0.198	0.119	0.166	0.219	0.764	1.150
TP (mg/L)	1.810	1.360	2.133	1.594	17.034	3.715
Total Kjeldahl Nitrogen (mg/L)	0.422	0.400	0.174	0.225	0.326	0.465
Ammonia Nitrogen (mg/L)	0.034	0.010	0.037	0.039	1.138	1.506
Nitrite + Nitrate Nitrogen (mg/L)	1.431	0.686	1.511	2.053	-0.006	1.156

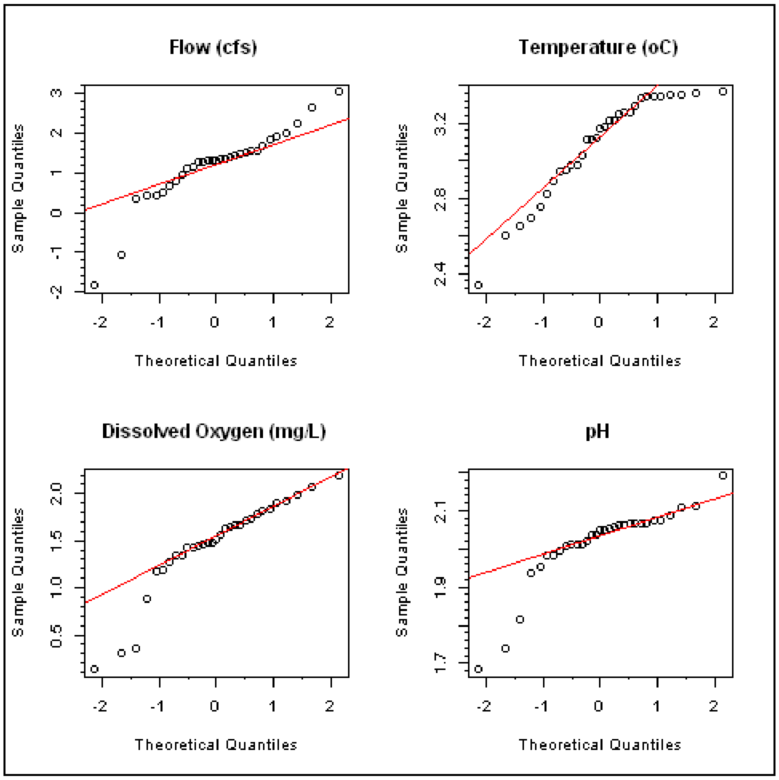

Figure 4: Q-Q plots for measured field parameters at CC1

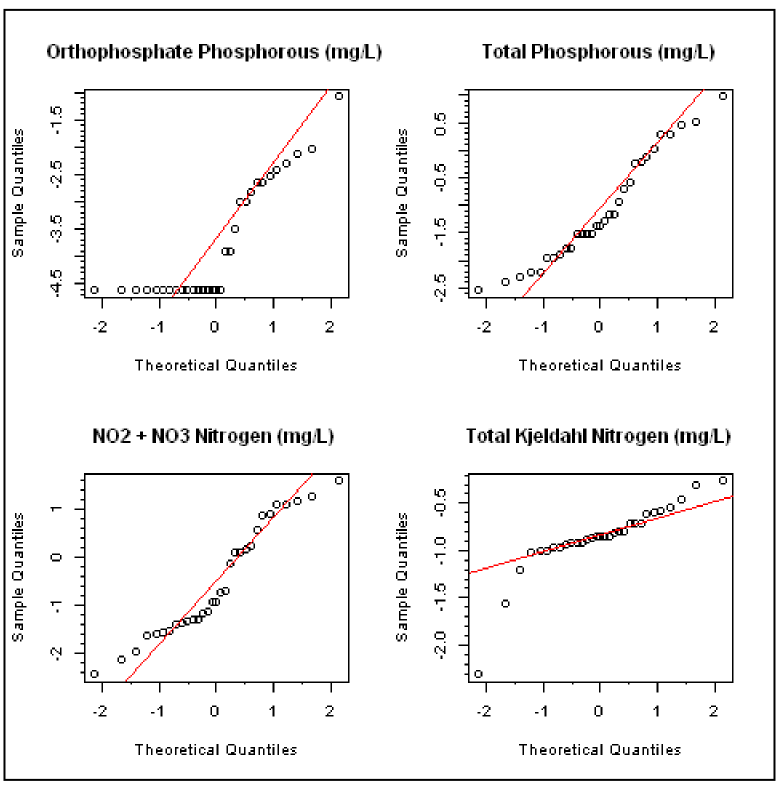

Figure 5: Q-Q plots for measured nutrients at CC1

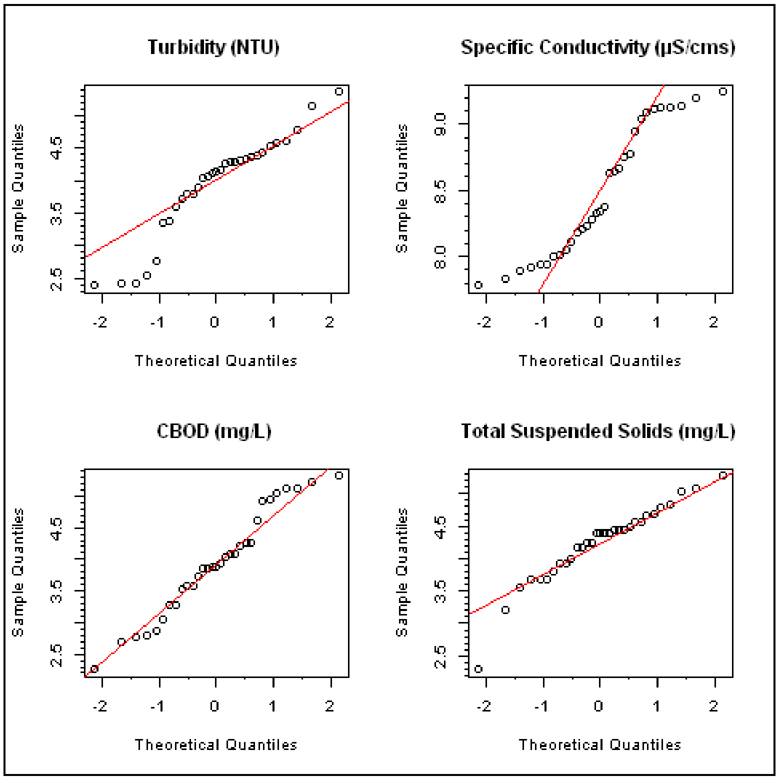

Figure 6: Q-Q plots for measured water quality indicators at site CC1

ACF plots depict how data collected at a certain time are correlated to values observed at previous times (lags). As data were collected on a monthly scale, each lag in Figures 7–9 correspond to a specified number of months (e.g., lag 1 previous month, lag 2 two previous months). ACF plots are useful to detect the presence of seasonality and independence of sampling events. The ACF plots for one site are presented in Figures 5 and 6 and the autocorrelation functions for other plots are summarized in Appendix A, figures AF 10-AF 18.

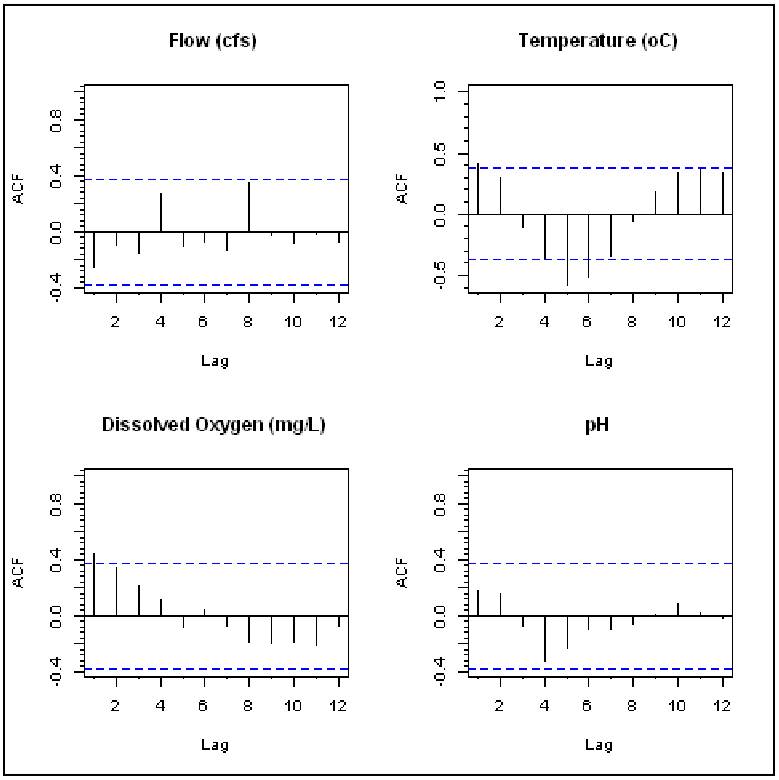

Figure 7: ACF plots for measured field parameters at site CC1

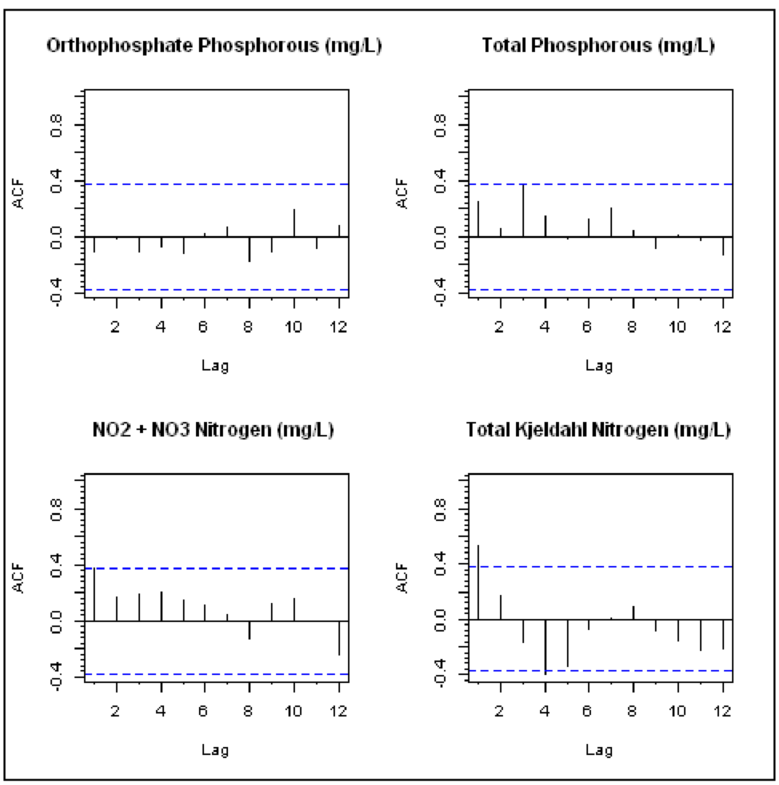

Figure 8: ACF plots for measured nutrients at site CC1

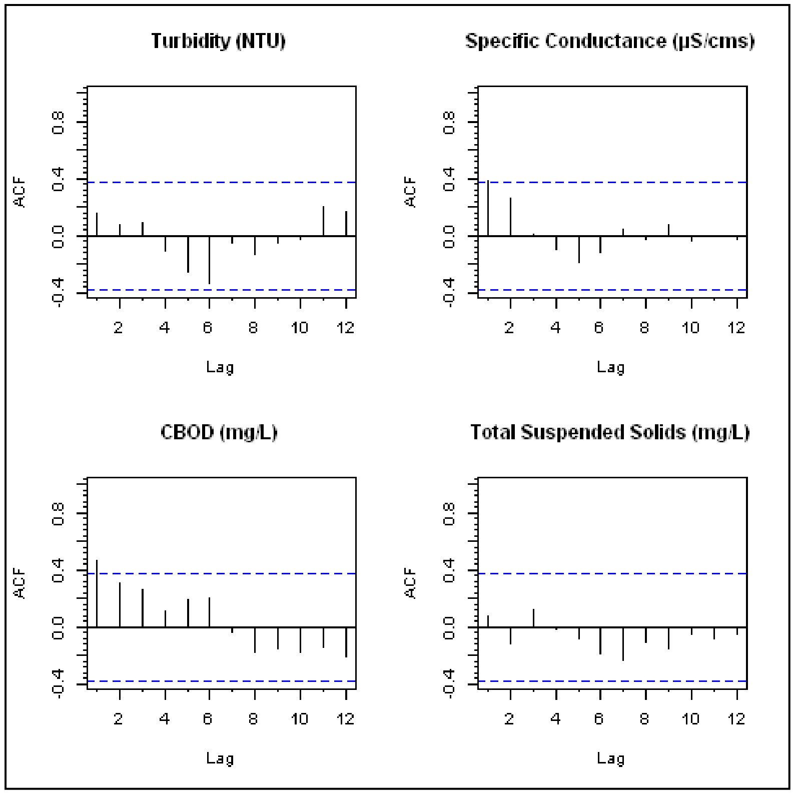

Figure 9: ACF plots for measured water quality indicators at CC1

The results presented in Figures 8 and 9 indicate that statistically significant lag-1 correlations are noted only for CBOD and TKN. This result points towards the increased persistence of physicochemical processes in the deeper (reductive) sections of the drainage ditch. In particular, sample collection at the CC1 site were carried out at a retaining wall, which led to settling and persistence of detritus and other organic matter that contribute to CBOD and TKN production. The persistence of CBOD, ammonia and TKN was also evident at HC2 site. There were no appreciable flows at the HC2 site, which also leads to persistence of detritus within the ditch. The pH data at CC2, HC1 and HC2 sites show consistent values. This result is to be expected given the buffering action of alkaline soils and sediments commonly found in South Texas. Overall results from the ACF analysis indicated that the collected samples were either minimally correlated or generally not correlated to each other and can therefore be considered independent measurements. This result validates the adopted sampling strategy as the assumption of independence is critical for both parametric and non-parametric statistical tests (Dudewicz and Lin 1981). Box-Plots were developed for all salient water quality parameters to visualize central tendencies and obtain preliminary insights with respect to inter-site and intra-site variability and are presented in Figures 10 and 11.

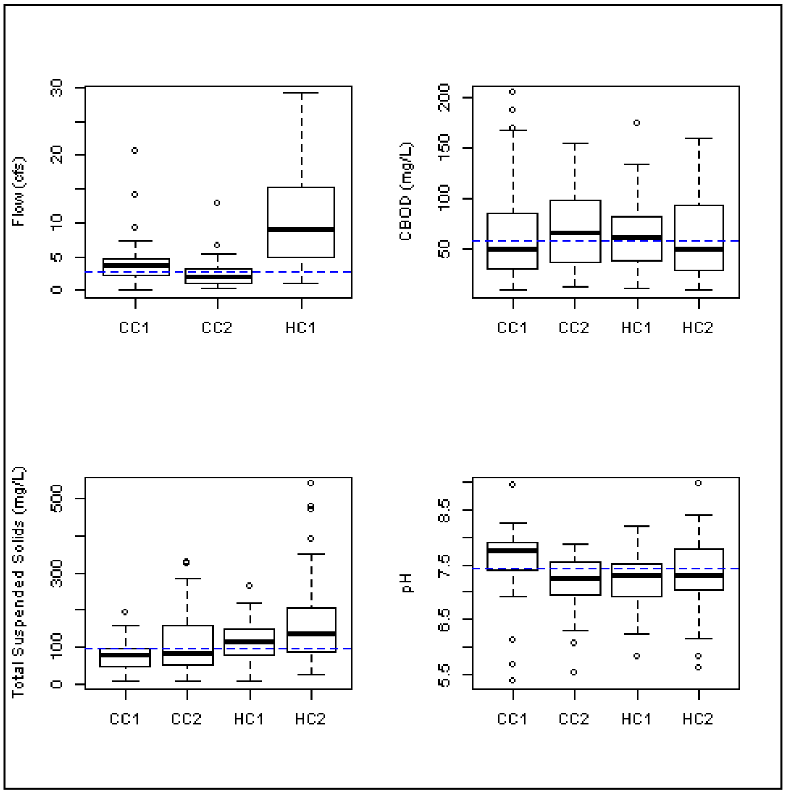

Figure 10: Inter and intra site variability of salient water quality parameters

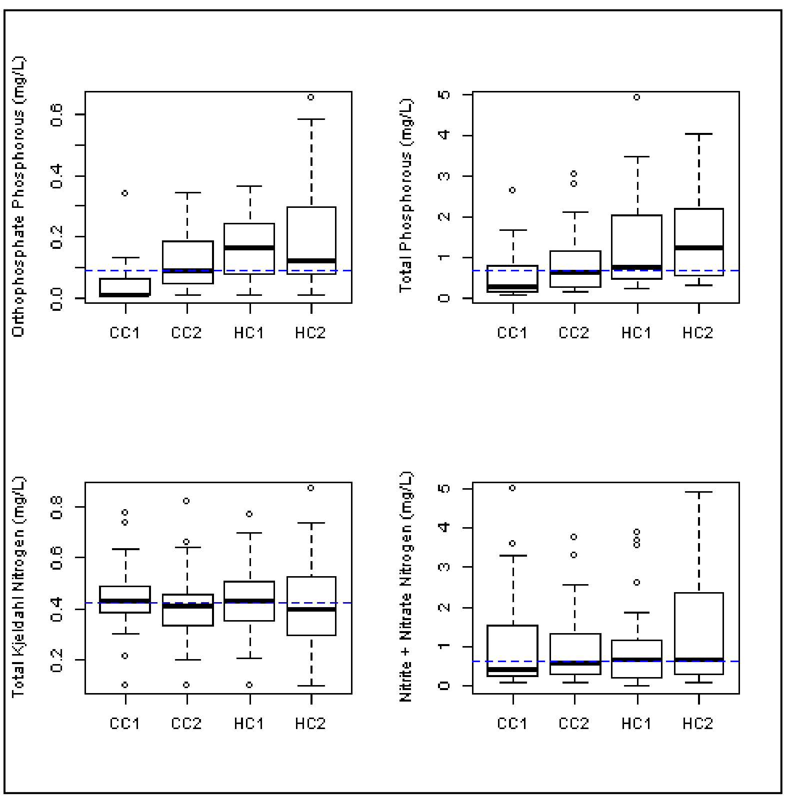

Figure 11: Inter and intra site variability for measured nutrient concentrations

A common characteristic evident in all plots presented in the Figures 10 and 11 is the high degree of variability noted at each site. Clearly, the temporal variability at each site is significantly greater than spatial variability across the sampled drainage ditches. The TSS, TP and NO_2+NO_3 were somewhat higher in the drainage ditches in Hidalgo County than those in Cameron County were. More intense agricultural activities were noted near the Hidalgo County sites during the sampling period, which partly explains the observed spatial differences. The variability of measurements at the HC2 site was generally higher than the other sites and was partly caused from measurement difficulties emanating from limited water in the ditch, which sometimes resulted in having to grab samples from near the sediment bed. As can be seen from the first box plot, the flows at the HC1 site were significantly higher than the other two flowing ditches (CC1 and CC2) and also more variable. The bottom of the drainage ditches (HC1 and HC2) were comprised of fine-grained sediments that are more amenable to settling and re-suspension and thus partially contributed to observed variability in TSS at these sites. The lower Rio Grande Valley region of South Texas experienced the effects of several major storms including Hurricane Dolly and Tropical Storm Ike and was also subject to one of the most severe droughts in recent history during the study period that spanned from 2009–2011. These meteorological events contributed to extreme values in the box plots that extend beyond the 5th and 95th percentile whiskers. The high degree of variability in the observed flow and water quality data are indicative of hetroskedasticity (non-homogeneous variances) across different flow regimes.

Flow Duration Curves (FDC) Analysis to Identify Major Flow Regimes

The pollutant loads to a receiving water body are directly related to flow patterns. Flow duration curves (FDC) plot the magnitude of flow against the frequency of its exceedance. As such, their use is recommended in total maximum daily load (TMDL) assessment studies (USEPA 2007). Figure 12 depicts the FDCs developed for the three flowing drainage ditches (CC1, CC2 and HC1) of this study.

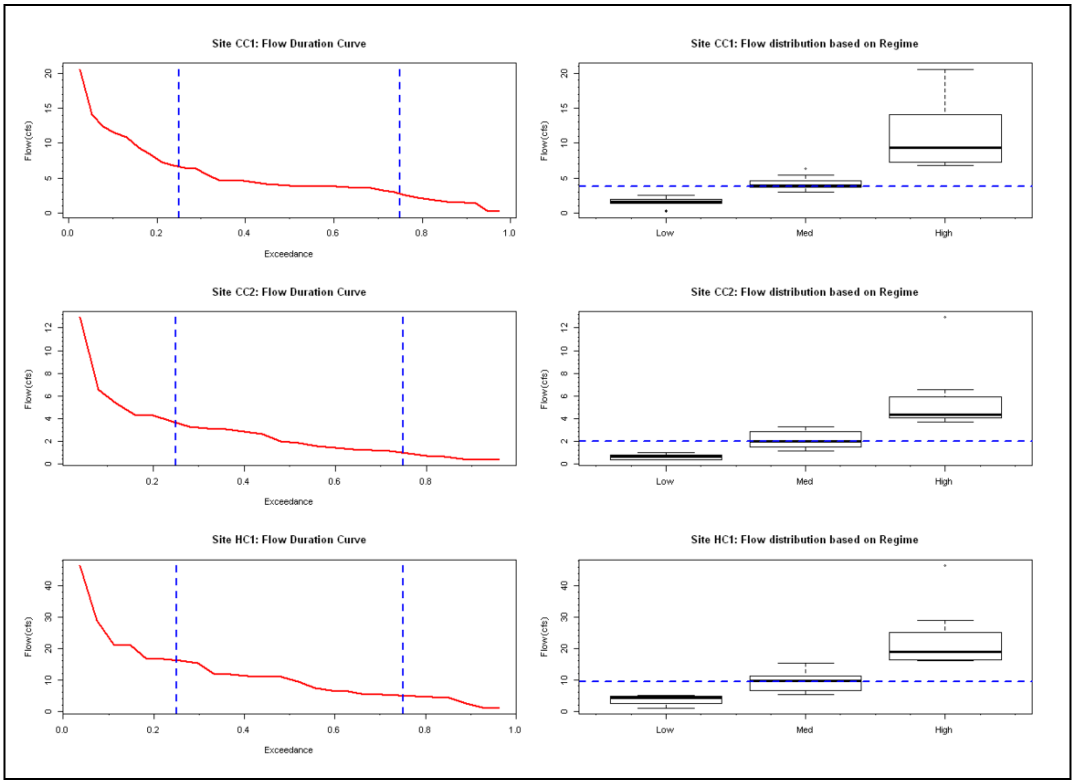

Figure 12: Flow Duration Curves and Flow Variability at CC1, CC2 and HC1 sites

The 25th and the 75th percentile exceedances were used as cut-offs to delineate high, medium and low flows. The box-plots presented in Figure 12 demonstrate that the variability in flows associated with different flow regimes (USEPA 2007). The low flows exhibit the least amount of variability, which indicates that they are controlled by sustained sources such as subsurface (shallow groundwater) discharges or unregulated peri-urban sources (colonias). On the other hand, the high flows exhibit the greatest variability and are likely controlled by intermittent rainfall and irrigation events. The variability in high flows is largest at the CC1 site, which has the largest contributing drainage area. The variability is clearly controlled by the extent of runoff generated due to rainfall variability and different irrigation events corresponding to various crops grown within the drainage area.

Role of Flow Characteristics in Defining Drainage Ditch Water Quality Behavior

As discussed earlier, higher flows correspond to direct surface runoff from contributing drainage area and lower flows are characteristic of longer subsurface flow paths. Box-Plots of various water quality parameters were constructed at each site using the flow classification developed using FDCs (Figures 13 and 14) to visually evaluate the effects of flows. From the figures, the median values of various water quality parameters, most notably–CBOD, TSS, TP, OP and NO_2+NO_3–are higher for high flow conditions. These results provide preliminary evidence that runoff from contributing drainage areas can enhance loadings of nutrients and oxygen demanding substances in the drainage ditches. However, the box plots also suggest that there is no appreciable difference among various flow regimes with regards to reduced forms of nitrogen (i.e. TKN, NH_3-N), again highlighting the importance of in-stream processes (e.g. decay of organic matter) in controlling the reduced forms nitrogen.

The non-parametric Kruskall-Wallis (KW) multiple comparison tests was used to formally evaluate the null hypothesis. There is no difference in water quality parameters across different flow regimes against the alternative than there are differences between various flow regimes. The KW multiple comparison tests was then used to compare pair-wise differences (Table 4) among different flow regimes and is based on Siegel and Castellan (Siegel and Castellan 1988).

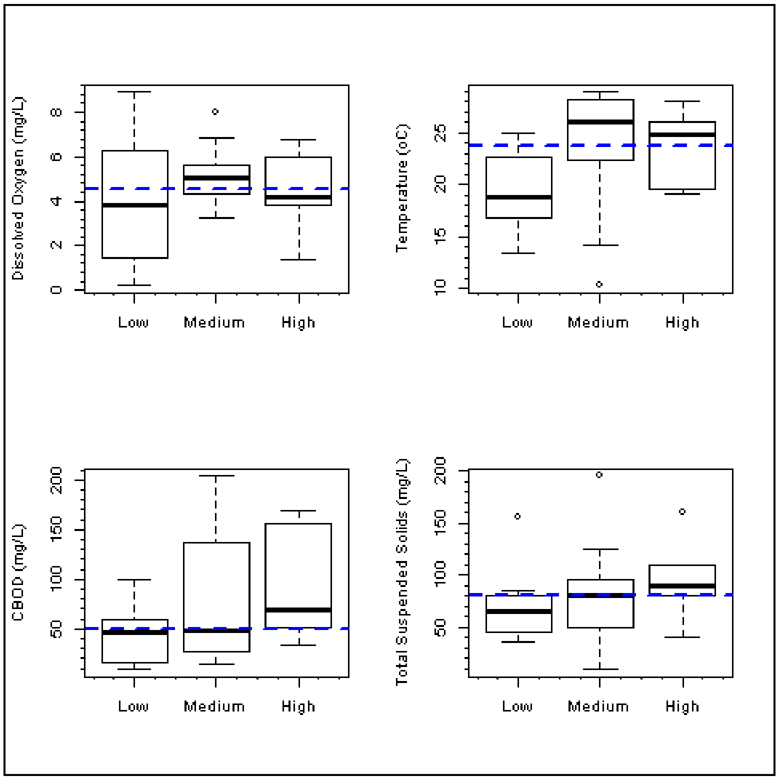

Figure 13: Water quality characteristics pertaining to different flow regimes at Site CC1

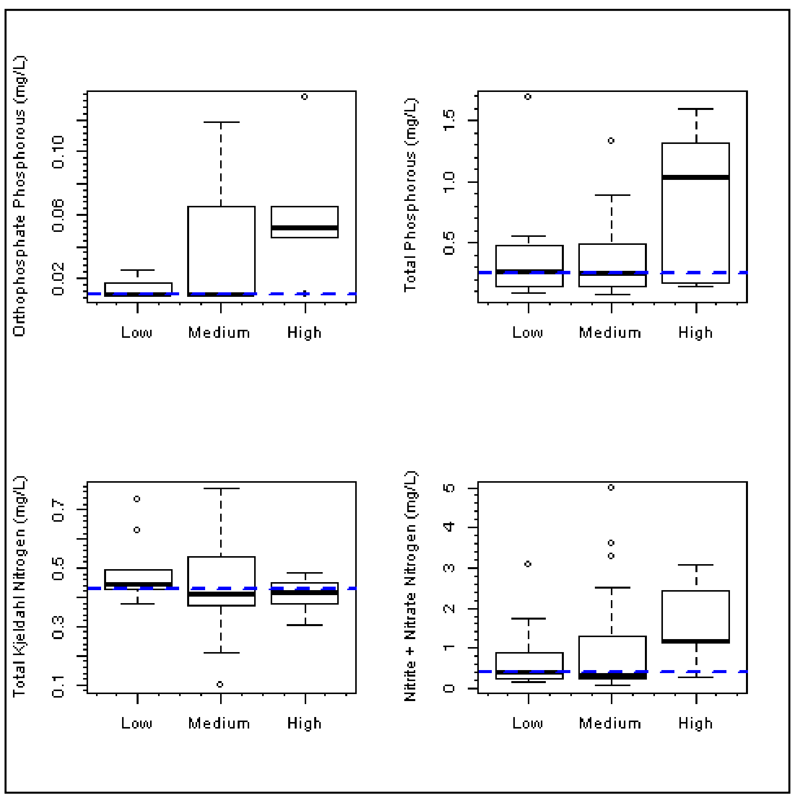

Figure 14: Nutrient characteristics pertaining to different flow regimes at Site CC1

Table 4: Results of the Kruskall-Wallis and Pairwise Comparison Tests

	Site CC1					Site CC2					Site HC1				
	KW chisq	P	Low-High	Medium - High	Medium-Low	KW chisq	P	Low-High	Medium-High	Medium-Low	KW chisq	P	Low-High	Medium-High	Medium-Low
Temperature (°C)	6.300	0.043	F	F	T	5.314	0.070	T	F	F	7.138	0.028	T	T	F
Turbidity (NTU)	2.968	0.227	F	F	F	7.988	0.018	T	F	F	2.857	0.240	F	F	F
DO (mg/L)	1.921	0.383	F	F	F	4.744	0.093	F	F	F	4.730	0.094	F	F	F
Specific Conductance (µS/cm)	2.877	0.237	F	F	F	1.770	0.413	F	F	F	1.490	0.475	F	F	F
pH	4.149	0.126	F	F	F	0.333	0.846	F	F	F	1.117	0.572	F	F	F
CBOD (mg/L)	2.714	0.258	F	F	F	1.161	0.560	F	F	F	0.196	0.907	F	F	F
TSS (mg/L)	2.079	0.354	F	F	F	7.043	0.030	T	F	F	5.748	0.056	F	T	F
OP (mg/L)	2.830	0.243	F	F	F	11.312	0.003	T	T	F	1.966	0.374	F	F	F
TP (mg/L)	1.393	0.498	F	F	F	10.070	0.007	T	T	F	5.422	0.066	T	F	F
Total Kjeldahl Nitrogen (mg/L)	1.568	0.457	F	F	F	2.494	0.287	F	F	F	2.155	0.341	F	F	F
NH3 - N (mg/L)	2.118	0.347	F	F	F	0.829	0.661	F	F	F	2.413	0.299	F	F	F
NO2+NO3 as N (mg/L)	1.886	0.389	F	F	F	4.178	0.124	F	F	F	2.048	0.359	F	F	F

The highlighted boxes indicate a significance level of less than 0.1

The hypothesis testing results in Table 4 essentially corroborate the visual analysis and particularly highlight that the loadings of TP and TSS could be controlled by runoff from surrounding agricultural areas. The visual differences noted in nitrogen compounds could not be statistically confirmed via hypothesis testing due to large observed variability. The results presented in Table 4 highlight significant temperature differences between high flow and low flow events. The statistical difference noted in temperature stems from the fact that low flows are generally observed during winter months while high flows correspond to runoff from high intensity convective storms and larger irrigation activities that mostly occur during summer months. The difference in timing between high and low flow events help explain the significant differences noted in DO at CC2 and HC1 sites using the KW test. Even though the pair-wise comparison test lacked sufficient statistical power to discern the differences, the median DO concentrations were noted to be higher for low flows than high flows at these sites (see Figures AF 19 and AF 21 in Appendix A). This result also implies that dissolved oxygen in the ditches is controlled by climate (temperature) and any additional mixing associated with increased flows are unlikely to enhance re-aeration in the ditches.

To summarize, direct runoff from contributing drainage areas generally have a significant impact on TSS and phosphorus compounds in the drainage ditch. On the other hand, the concentrations of nitrogen compounds are affected by both processes operating at both watershed and drainage-ditch scales. In particular, drainage ditch processes, such as detritus decay, could play a major role in defining the concentrations of reduced nitrogen compounds (TKN). The DO concentrations in the ditches are largely controlled by temperature and enhanced mixing associated with higher flows are unlikely to overcome the higher de-oxygenation rates during summer months.

Evaluation of Differences between Edge-of-Field and Drainage Ditch Nutrient Water Quality

An independent field study to assess water quality characteristics of irrigation runoff from six different fields primarily growing four different crops (cotton, sugarcane, corn and vegetables) and employing different irrigation technologies commonly used in the Lower Rio Grande Valley region was carried out during the same period (2009-2010). Further details of the irrigation field sampling campaign can be found in (Ensico et al. 2011). Most importantly, water quality characteristics of the irrigation runoff at the edge-of-field were collected and analyzed using the same sampling and analytical methods used in this investigation and by the same personnel. Therefore, an evaluation of the differences in water quality observed in agricultural farm runoff and drainage ditches was carried out again using visualization and statistical hypothesis testing tools. The box-plots presented in Figure 15 clearly demonstrate that the concentration of both phosphorus and nitrogen compounds are higher in the runoff water leaving the edge of field than what is observed in the drainage ditch flows.

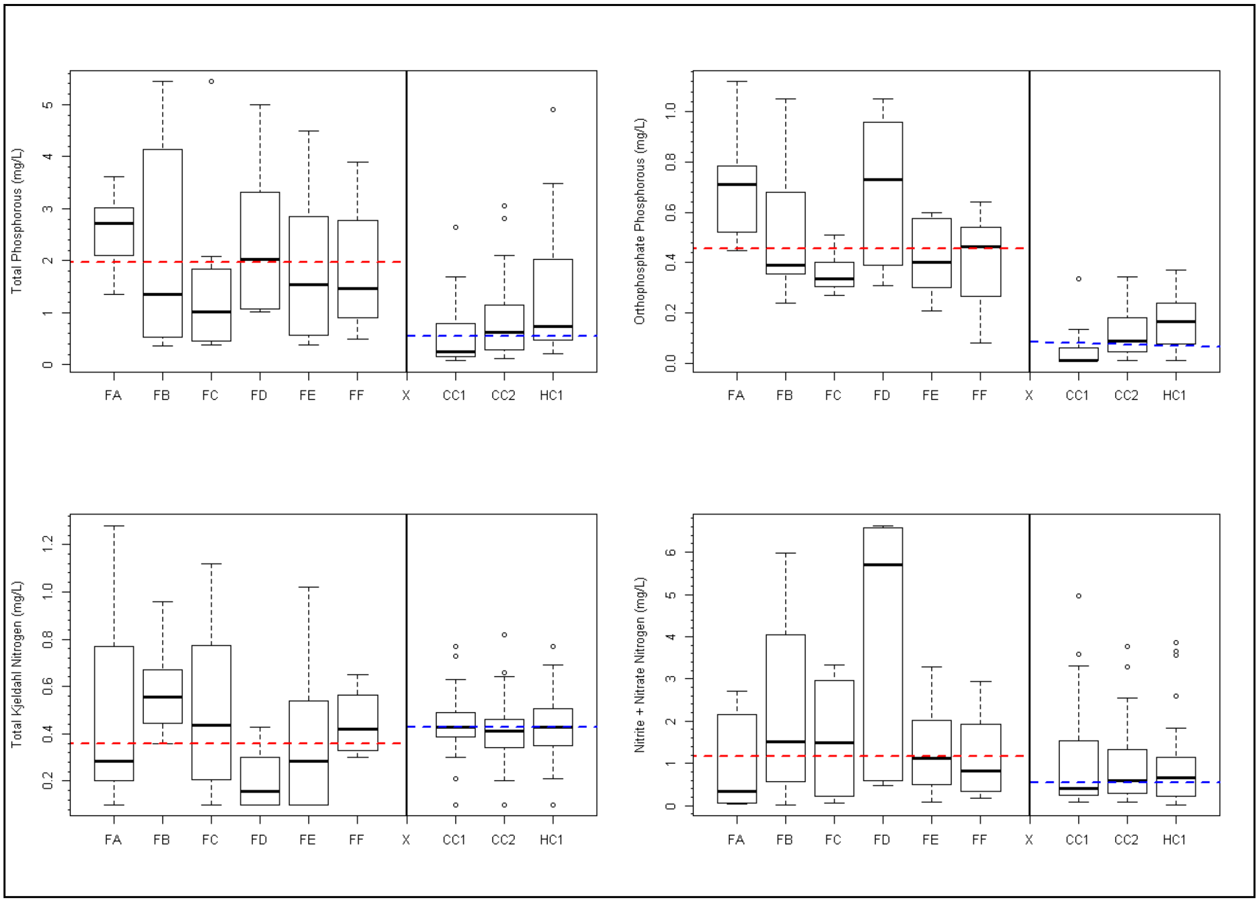

Figure 15: Comparison of Observed Nutrient Water Quality at Edge of Field Agricultural Sites and Drainage Ditches

A two-sided Mann-Whitney U test was also carried out to test the null hypothesis that the nutrient water quality leaving the agricultural farms was no different from the nutrient water quality measured in drainage ditches against the alternative hypothesis of significant differences between the two sets. The results indicated that the drainage ditch concentrations are significantly different for OP ($W = 150$, $p < 0.001$), TP ($W=1012$, $p < 0.001$) and oxidized nitrogen compounds ($W = 1688$, $p = 0.044$) than those measured in agricultural runoff leaving the farmlands. The alternative hypothesis could not be rejected for TKN ($W = 2375$, $p = 0.235$). These results once again reiterate the previous findings that the loadings of phosphorus compounds are more controlled by watershed scale processes while the reduced forms of nitrogen in the drainage ditches are influenced to a greater extent by in-channel processes. Furthermore, the large differences in phosphorus concentrations between the edge-of-field and drainage ditch measurements is consistent with reports from other studies elsewhere which indicate the ability of drainage ditches to remove phosphorus compounds (Smith et al. 2005; Bhattarai et al., 2009; Ahiablame et al. 2011).

The result that the nutrient water quality in drainage ditches is generally less than those measured at the edge-of-field is certainly promising and points towards the attenuation capabilities of these ditches. However, it is important to remember that fiscal and logistic constraints precluded a paired experimental design. The data collection in the drainage ditches was systematic and occurred over a larger period while the edge-of-field monitoring was limited to specific events spanning few days each time. Even during the periods when the sampling campaigns were coordinated, logistic constraints precluded the isolation and tracking of flows emanating from the edge-of-field study sites in the drainage ditches. Generally speaking, the flows in the drainage ditches can be viewed as an agglomeration from several agricultural sites and other sources (e.g., urban runoff) within the contributing drainage area. Given these sampling limitations, it is important to not construe the magnitude of observed differences in nutrient levels as a measure of the degree of nutrient attenuation occurring within the ditches. Nonetheless, the results presented here highlight that drainage ditches play an influential role in altering the timing and extent of nutrient releases from agricultural practices to receiving water bodies. In particular, they help transform high intensity, highly variable intermittent loadings arising during rainfall and irrigation activities to a more sustained lower-intensity slow release pattern and help increase the time the nutrients spend in the watershed before being discharged into the receiving water body.

Factors Affecting Phosphorus Concentrations in Drainage Ditches

The results presented in this study indicate that drainage ditches can receive significant phosphorus loadings during irrigation and high intensity rainfall activities. The TP concentration is positively and significantly correlated to the concentration of TSS for high flow regimes. The ability of drainage ditches to settle out TSS is therefore an important phosphorus removal mechanism and this result is consistent with the findings from other studies reported in the literature (Smith et al. 2005; Leone et al. 2008; Robert Kröger and Moore 2011). However, the drainage ditches can also act as a phosphorus source when particles become re-suspended or diffuse from the sediments into base flows (i.e. groundwater discharges) that generally have lower concentrations of phosphorus.

Phosphorus is an essential but often limiting nutrient for plant growth. As such, the uptake of phosphorus by plants is another major attenuating mechanism in drainage ditches. The extent of uptake is largely controlled by the amount of dissolved phosphorus or the OP. One of the monitored drainage ditches, HC2, had no appreciable flows, but a significant amount of biomass in the form of standing emergent vegetation (grasses). The observations at the site provided a unique opportunity to evaluate the role of vegetation in the ditches on nutrient uptake and removal without having to deal with the confounding effects of flows.

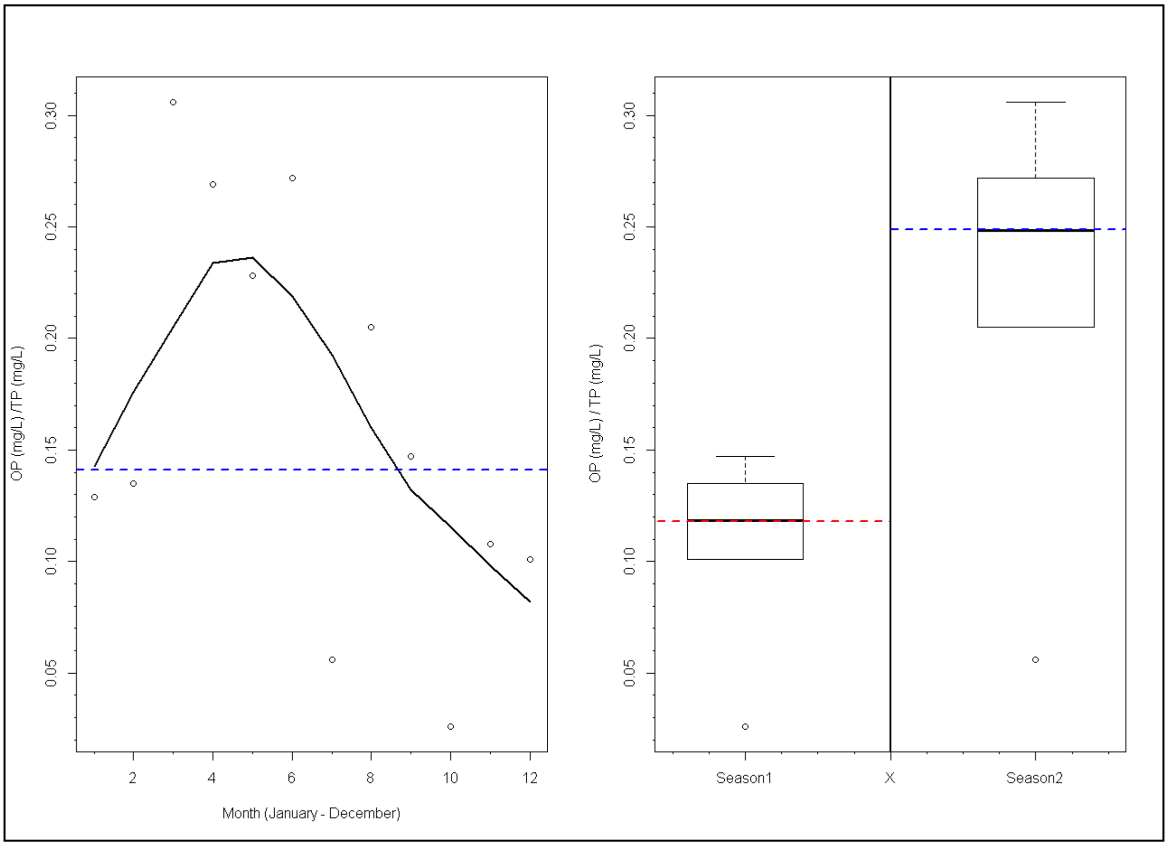

Figure 16: Temporal Behavior of Average OP at Site HC2
(Season1 corresponds to September-March and Season2 from April-October)

Figure 16 represents the average temporal behavior observed during each month of sampling. The OP concentrations in each month were normalized with respect to the TP concentrations to block the effects of differences in TP between different months. The seasonal variation in phosphorus concentrations is evident from the Figure 17. The concentrations are lower in season 1, which corresponds to the relatively colder months of September–February. On the other hand, the concentrations are higher during the relatively hot months of March–August. The Mann-Whitney test for differences in concentrations between the two seasons was statistically significant ($U = 5$, $p = 0.041$) and corroborates the box plot observations in Figure 17. Visual observations at the site indicated a larger and healthy biomass (green grass) during season 1 (cooler period) than during dry summer months where the amount of biomass in the ditch was significantly lower and unhealthy (yellow and brown grass stalks). Therefore, it is likely that uptake of phosphorus by emergent vegetation is a significant mechanism for phosphorus removal during cooler periods. However, these plants are likely to act as sources of phosphorus (release due to biomass decay) during hot summer months. Emergent vegetation in the drainage ditches can therefore play a major role in attenuating phosphorus concentrations, but can also act as source of phosphorus.

The in-channel biomass was noted to be low in flowing drainage ditches (CC1, CC2, and HC1), and as such the relative importance of vegetation is likely to be not as prominent. Literature on constructed wetlands indicates that plant uptake accounts for about 10% of the overall phosphorus removal and can serve as an important tertiary treatment mechanism (Vyzamal 2005). As the primary purpose of drainage ditches is to reduce flooding, irrigation and drainage districts engage in periodic biomass harvesting as part of channel maintenance activities. It is recommended here that such maintenance schedules be coordinated in a manner that maximizes the plant uptake but also minimizes their ability to act as sources. This coordination should not be too difficult, as high intensity convective storms and large irrigation events are more likely to occur in the summer months, which also corresponds to lower biomass uptake. Also allowing smaller sections of healthy biomass to occur intermittently in the drainage ditches, where possible, could potentially be beneficial.

Factors Affecting Nitrogen Concentrations in Drainage Ditches

The concentrations of reduced forms of nitrogen (TKN and NH_3-N) were generally low in drainage ditches relative to the oxidized forms (nitrite+nitrate-nitrogen), and drainage ditches provide suitable conditions for the oxidation to take place. This result is again consistent with findings reported in the literature (Goolsby et al. 2001; Jarvie et al. 2010) where drainage ditches, as being potential sources of nitrate, have been highlighted. The comparison of edge-of-field and drainage ditch concentrations provide some evidence of nitrate reduction capabilities of the drainage ditches. Furthermore, statistically significant differences in nitrogen concentrations were noted between different flows regimes, indicating that under suitable conditions there is a potential for nitrate removal by drainage ditches. As discussed earlier, nitrate reduction occurs in the deeper sections of the ditch in the presence of sufficient organic carbon and limited oxygen conditions. Also, lower flow rates limit the amount of re-aeration and reduce the amount of oxygen in the ditch. Therefore, the average water column depth in the channel to flow ratio (d/Q) was used as a hydraulic reduction index (HRI) for assessing nitrate reduction capabilities of the ditch. The HRI represents the hydraulic residence time per unit plan-view area of the watershed. Spearman rank correlations were established between the hydraulic reduction index (HRI) and deficit dissolved oxygen (Deficit DO) and the observed correlations $\rho = 0.341$, ($p = 0.061$) at CC1; $\rho = 0.263$, ($p = 0.152$) at CC2 and $\rho = 0.0.294$ ($p = 0.105$) corroborated the utility of the developed index to characterize reduced conditions in the ditch.

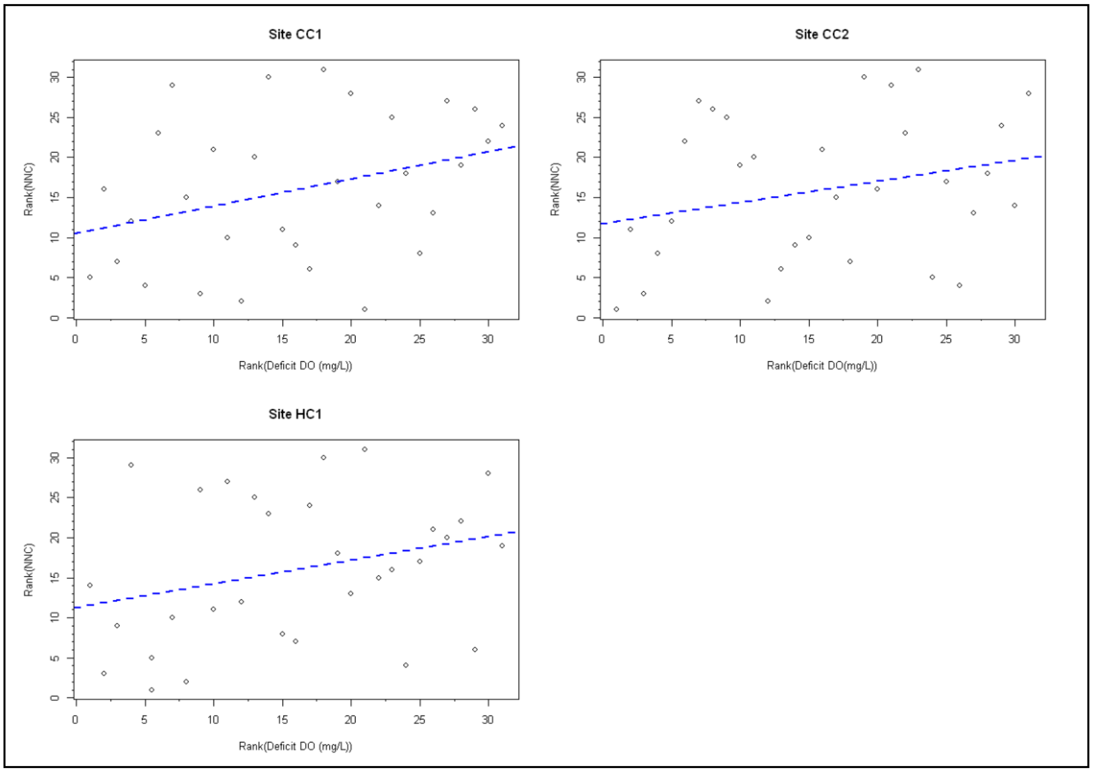

Figure 17: Correlation between Deficit Dissolved Oxygen and Normalized Nitrate Concentration (NNC)

Clearly, larger depths and/or lower flow rates result in a higher value of the hydraulic nitrate reduction index and must depict an inverse correlation to nitrate concentrations. Figure 17 plots the nitrate reduction index against the ratio of total oxidized nitrogen concentration (NO_3+NO_2) to TKN. The rank transformation was used to mask the effects of outliers and highlight the correlation between the hydraulic characteristics of the ditch and the nitrogen concentrations. Again, the ratio of oxidized to reduced nitrogen forms (i.e., normalized nitrate concentrations (NNC)) were used to block for the variability in nitrate sources in the ditches. The inverse relationship between the index and oxidized nitrate concentrations is evident from Figure 18. The spearman rank correlation coefficients, ρ, between the two parameters was equal to $\rho = -0.18$ ($p=0.33$) for CC1; $\rho = -0.54$ ($p = 0.002$) and $\rho = -0.35$ ($p = 0.05$) and confirm the statistical significance of the observed correlations. The presence of internal sources (decay of detritus) at CC1 site appears to have an impact on the observed correlation.

Based on the above results, it is clear that the nitrate reduction efficiency can be enhanced by making certain structural modifications to the drainage ditches. It is therefore recommended that periodic deepening or widening of the drainage ditch channels along the length of the drainage ditch when and where possible would be beneficial as it leads to slowing of flows and creation of deeper (anoxic) zones. However, as flood control is the primary function of the drainage ditches, a detailed hydraulic evaluation of the impacts of periodic deepening (e.g., (Rodriguez et al. 2008)) is necessary to fully evaluate the feasibility of this recommendation.

Nitrogen is also an essential nutrient for plants, and therefore the uptake of nitrogen could be an important attenuation mechanism within the drainage ditches as well. Plants are known to use both ammonium and nitrate with the former being generally preferred than latter (Kadlec and Wallace 2009). However, the uptake by plants is not a sustainable removal process as decay of biomass leads to the release of nitrogen into the ditch. The role of vegetation on nitrogen compounds was studied at HC2 site, which had no confounding effects of flows. The results presented in Figure 14 demonstrate the seasonal influence of the biomass on nitrogen concentrations. As shown similarly with phosphorus, lower nitrate concentrations were noted when the standing biomass was healthy (uptake). However, the nitrogen cycle is not congruous with the phosphorus cycle possibly due to heterogeneities in the biomass types within the ditch. The Mann-Whitney U test ($U = 0$, $p = 0.002$) confirmed the differences in concentrations between the two seasons.

The results of the analysis again point towards the important role of vegetation in controlling nitrogen concentrations in the ditch. However, vegetation can also serve as a nitrogen sink and as such must be properly managed. Based on the data presented in Figure 16 and Figure 18, both phosphorus and nitrogen concentrations are simultaneously higher during the months of June–October and therefore represent the best months for biomass harvesting in drainage ditches.

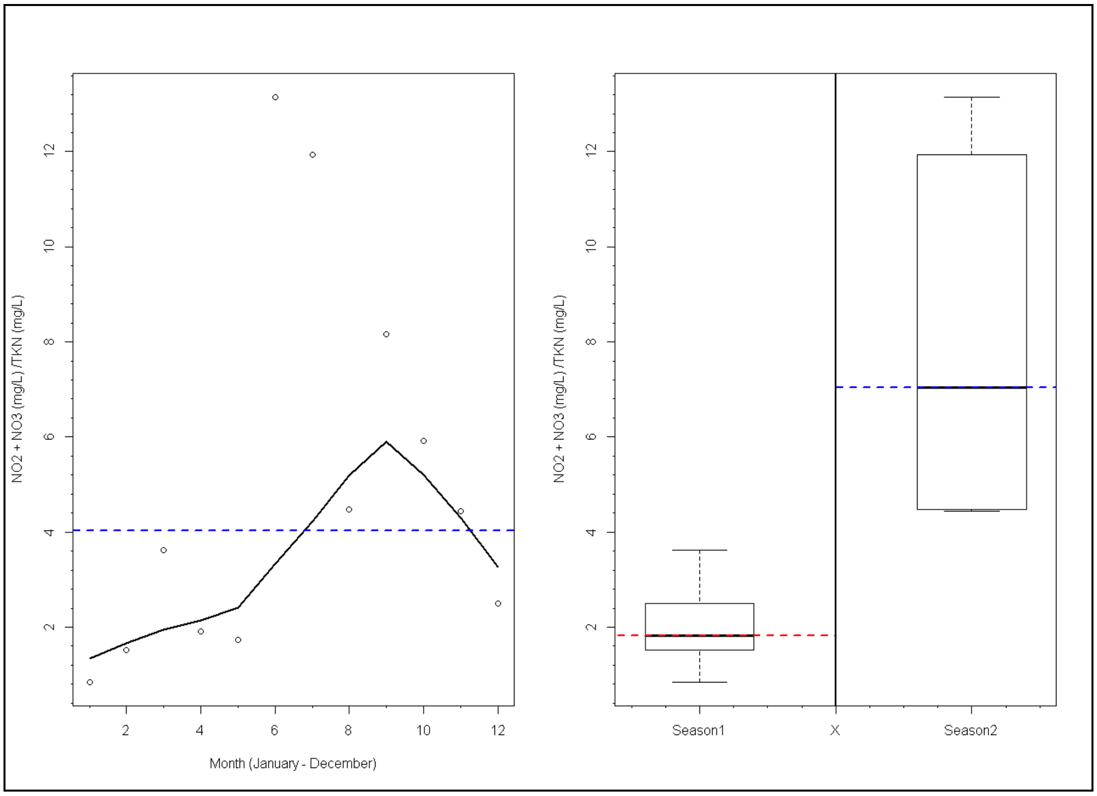

Figure 18: Cyclical Behavior of Nitrate Concentrations and Visualization of Seasonal Differences (Season1: December–May; Season2: June–November)

Comparison between Grab and Composite Sampling

The summary characteristics of the collected data are visualized in Figures 19–21. The variability in the composite samples were higher for temperature, turbidity, TSS, NH_3-N, OP and pH while the variability was either higher or similar for the grab samples for other compounds. This result is to be expected because temperature and TSS can exhibit diurnal fluctuations. Also, the plant metabolism varies diurnally which in turn controls the oxygen levels in the ditch and affects the uptake by the plants. This diurnal variability in uptake in turn affects ammonia and orthophosphate levels in the ditch over the short-term. The DO variability in the grab samples was noted to be somewhat higher than the composite samples and this result arises because the paired grab samples were obtained at different times at each site.

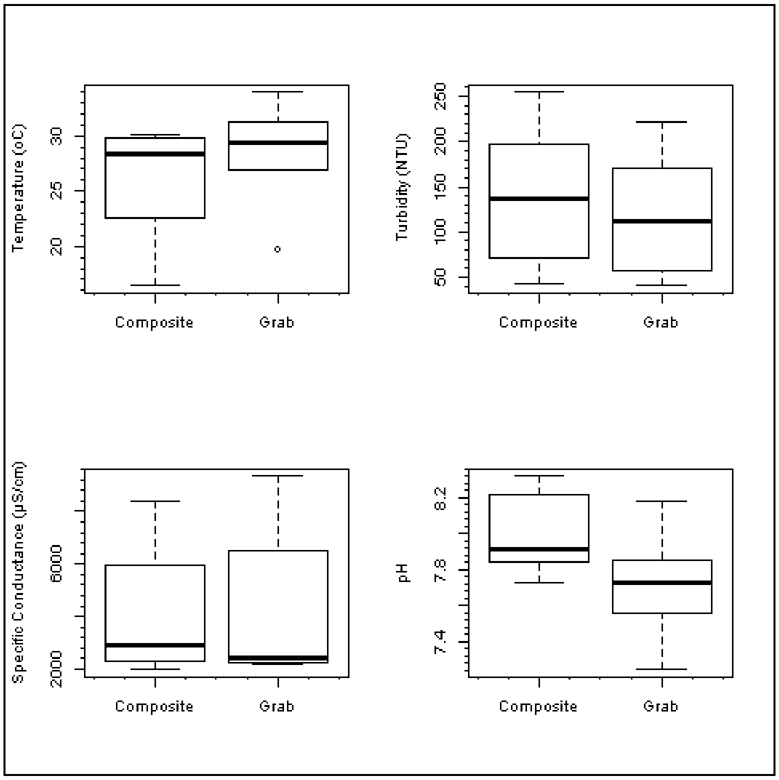

Figure 19: Measured field water quality comparison between grab and composite sampling events

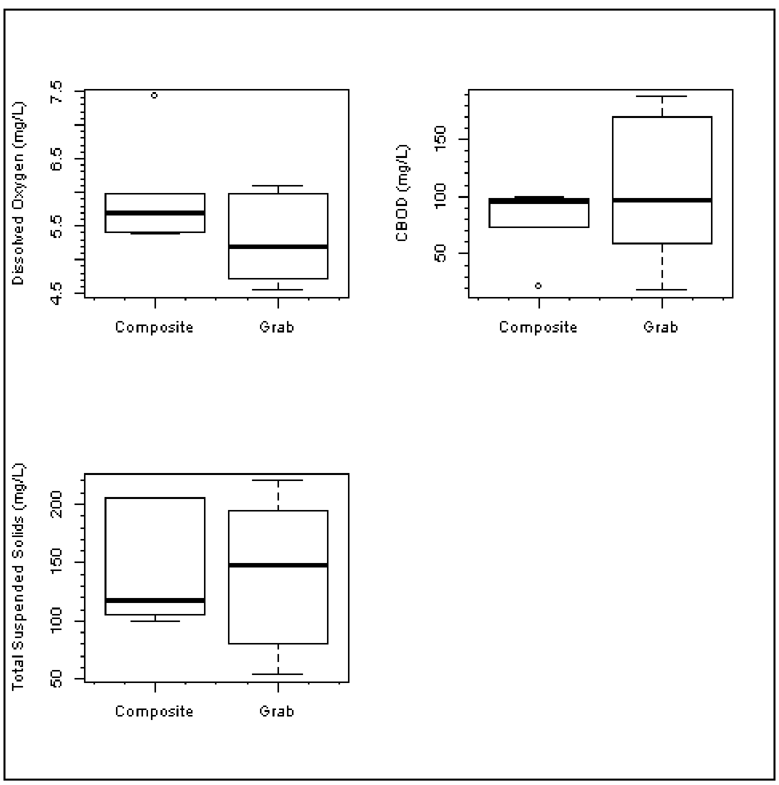

Figure 20: Measured water quality parameter comparison between grab and composite sampling events for Oxygen dependent parameters and suspended solids

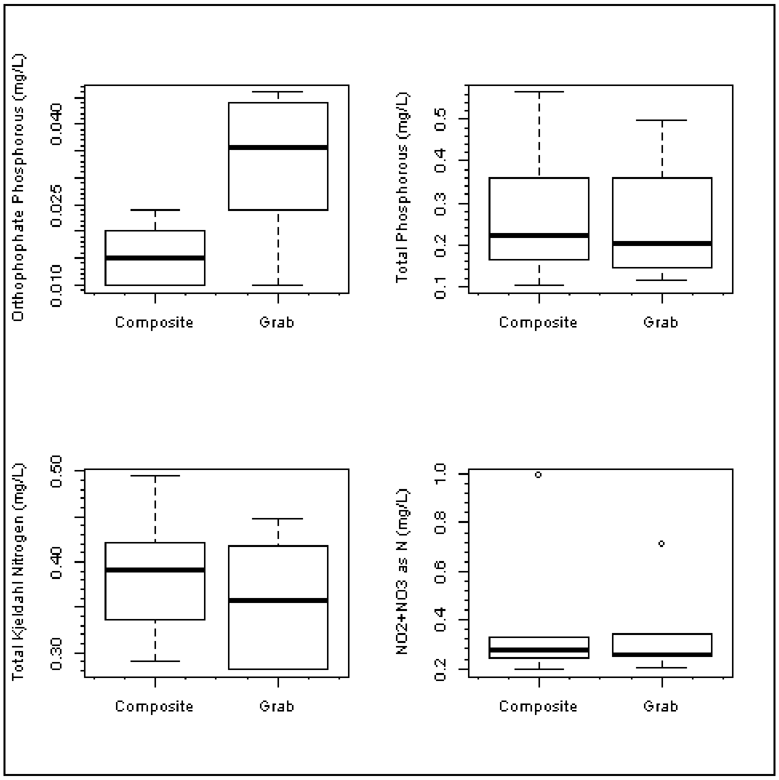

Figure 21: Comparison of measured nutrient concentration between grab and composite sampling events

The Wilcoxson Paired Rank Sum Test was used to formally evaluate the observed differences between grab and composite samples. The null hypotheses that there is no appreciable difference in the observed median values of grab and composite samples could only be rejected for turbidity at 0.05 significance levels and for temperature, OP and pH at 0.1 significance levels (see Table 5). This result again corroborates that the adopted sampling strategy is reasonable to make inferences about most water quality parameters. However, a 24-hour averaged sampling of DO and temperature is recommended for future studies.

Table 5: Mann-Whitney test results comparing corresponding grab and composite events

Wilcoxson Rank Sum Test Results		
Parameter	**U**	**p-value**
Temperature (^{o}C)	1	0.063
Turbidity (NTU)	21	0.031
Dissolved Oxygen (DO) (mg/L)	18	0.156
Specific Conductance (µS/cm)	9	0.844
pH	19	0.094
Carbonaceous Biochemical Oxygen Demand (CBOD) (mg/L)	7	0.563
Total Suspended Solids (TSS)(mg/L)	12	0.834
Orthophosphate Phosphorous (mg/L)	0	0.059
Total Phosphorous (mg/L)	12	0.281
Total Kjeldahl Nitrogen (mg/L)	16	0.313
Ammonia Nitrogen (mg/L)	5	0.590
Total Nitrite and Nitrate ($NO_2 + NO_3$) as N (mg/L)	11	> 0.999

The highlighted boxes indicate a significance level of less than 0.1.

Summary and Conclusions

The broad goal of this study was to conduct a comprehensive multiyear, multivariate, multisite field investigation to evaluate the behavior of nutrients in the Lower Rio Grande valley region of Texas. The study used a modified, stratified random sampling design to collect flow and 11 water quality parameters including TP, OP, TKN, NH_3-N, and nitrite+nitrate-nitrogen. Three ditches (CC1, CC2, and HC1) had perennial flows, while one ditch (HC2) had no observable flows and was therefore used to evaluate the effects of vegetation on nutrient dynamics. The results from the drainage ditch monitoring program were also compared to an overlapping edge-of-field investigation focusing on characterizing water quality in runoff leaving different agricultural farm lands. A suite of statistical methods including flow duration curves, box-plots and non-parametric hypothesis testing (including Kruskall-Wallis, ANOVA, and Spearman Rank Correlation Significance tests) were used to evaluate non-random differences.

The results of the study indicate that the loadings of phosphorus and suspended solids are controlled by runoff from the contributing drainage areas. Both contributing drainage areas and in-channel processes impact the concentrations of nitrogen compounds. The comparison of concentrations observed in agricultural runoff leaving the farms and those in the drainage ditches highlight the attenuation capabilities of the drainage ditches particularly about phosphorus compounds. The drainage ditches also effectively assimilate reduced forms of nitrogen (i.e., TKN and NH_3-N). The removal of oxidized forms of nitrogen (nitrate-nitrogen) is linked to the hydraulic characteristics of the ditches. Nitrate reduction is enhanced under lower flows and deeper water columns, which lead to lower dissolved oxygen and thus improved reducing conditions in the ditches. In addition to hydraulic characteristics, standing vegetation (macrophytes) can also have a significant influence on nutrient concentrations. The presence of in-channel vegetation introduces seasonality in observed nutrient concentrations. While in-channel vegetation acts as a sink during relatively cooler periods, they act as sources during hot, dry summer months. While both nitrogen and phosphorus concentration exhibit cyclic behavior, a phase-lag between phosphorus and nitrogen cycles was also noted and could possibly be due to heterogeneous biomass in the ditches.

From an operational standpoint, drainage ditches alter the flow and chemical transport characteristics of runoff emanating from agricultural fields. They help attenuate shock loadings of direct runoff from the fields and lead to a more uniform nutrient loadings that is spread out over a larger period. Therefore, drainage ditches can act as both nutrient sources and sinks. Proper maintenance and management of drainage ditches is an important regional-scale best management practice strategy for reducing nutrient loadings due to agricultural activities. Deepening certain sections of the ditch (where possible and feasible) can help improve nitrogen removal capabilities. Harvesting of biomass in the drainage ditches is routinely carried out by irrigation and drainage districts for flood control purposes. It is beneficial if these harvesting activities are optimized to minimize nutrient sources within the ditch. Biomass removal during the months of June–October could be beneficial for mitigating both nitrogen and phosphorus loadings. It is recommended that harvesting activities focus on the removal of necrophytes (dead biomass) to reduce nutrient sources within the ditches and the necrophytes be segmented to exploit the removal capabilities of plants.

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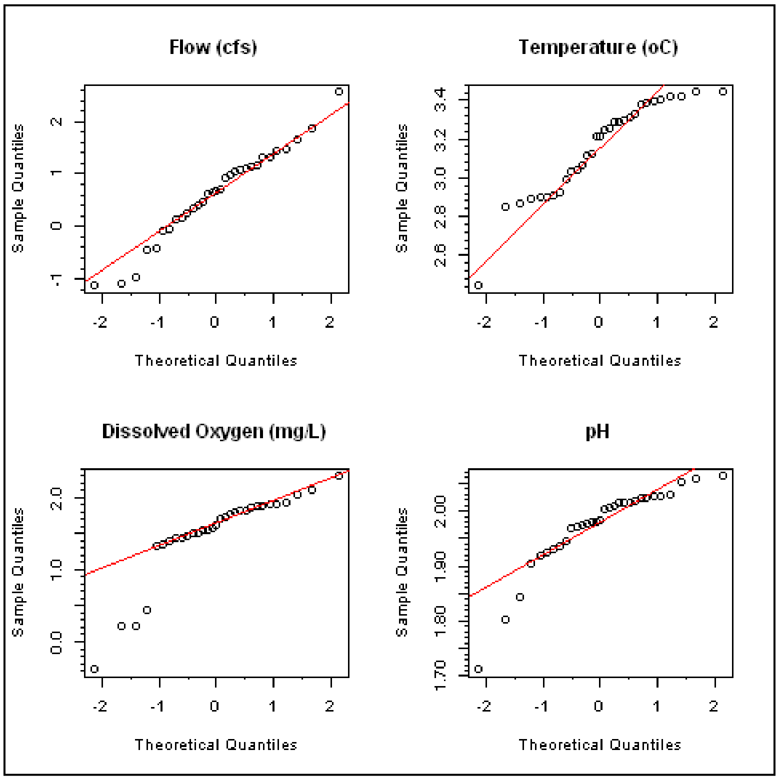
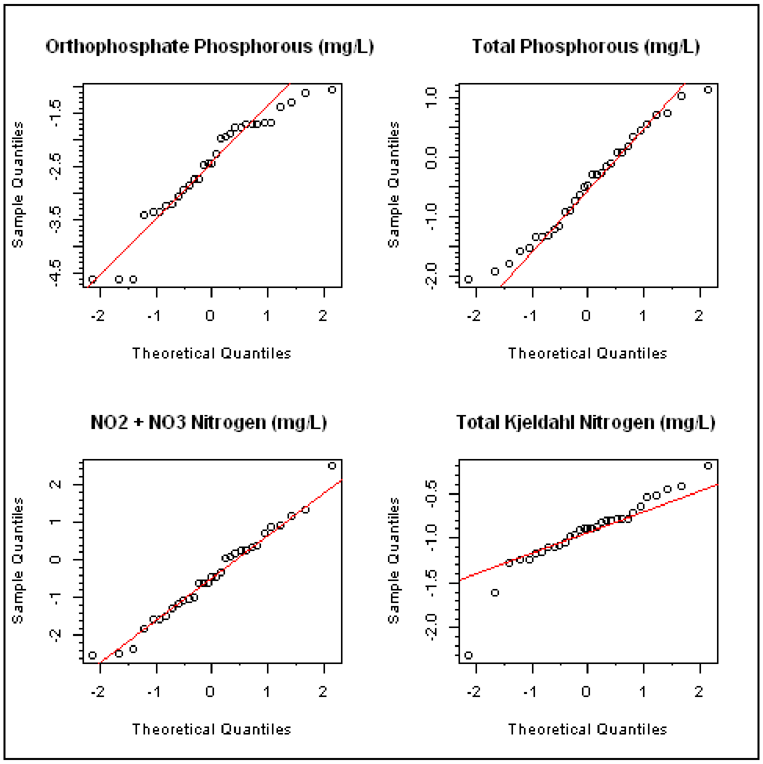
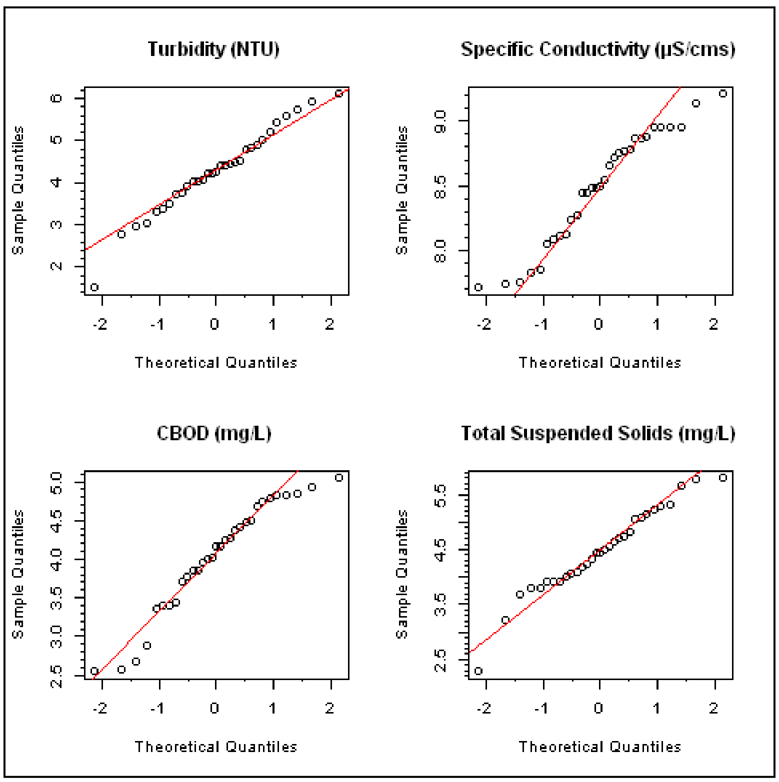
Appendix A



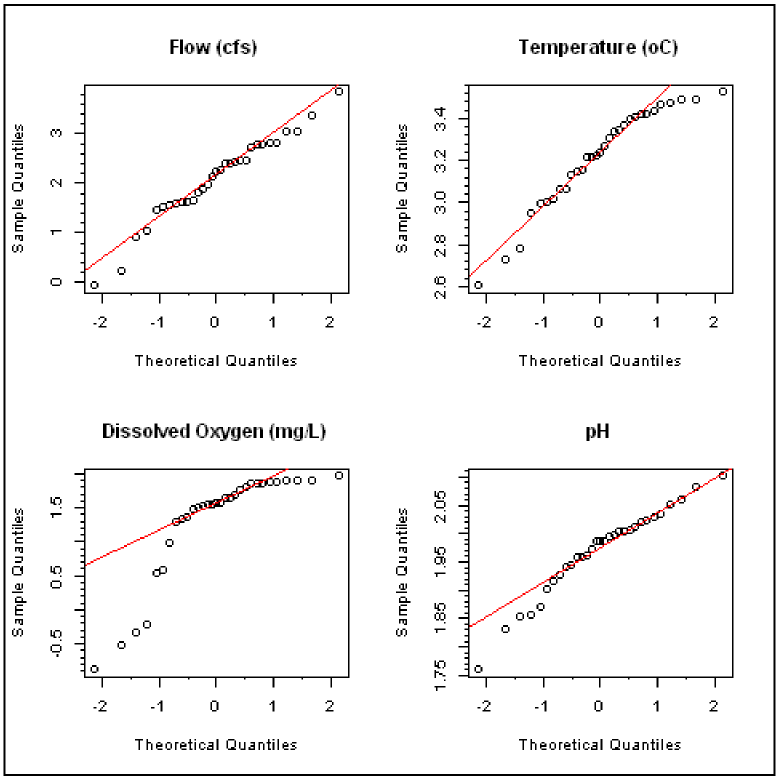
AF 1: Q-Q plots for the measured field parameters at Site CC2



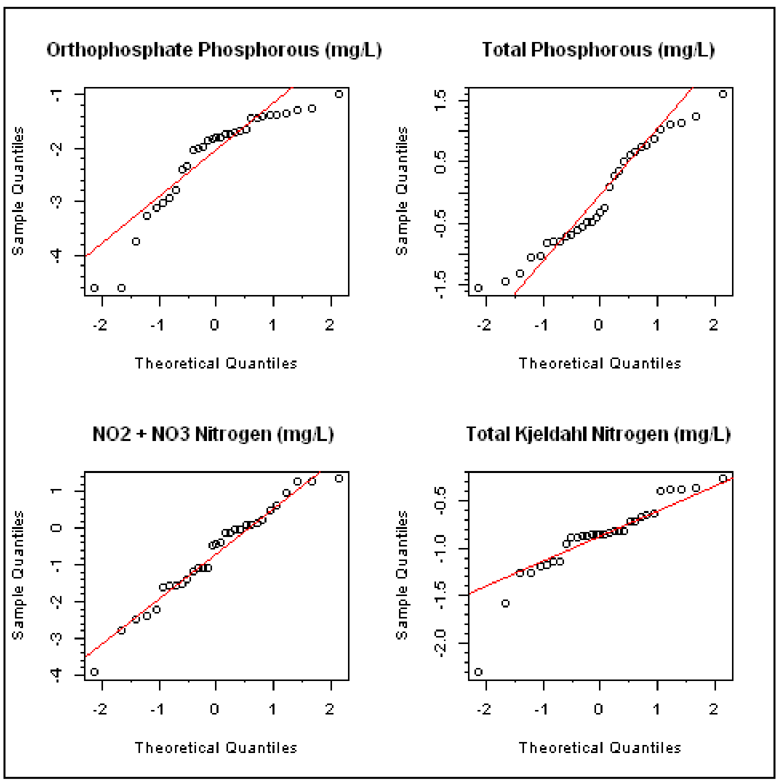
AF 2: Q-Q plots for measured nutrients at Site CC2



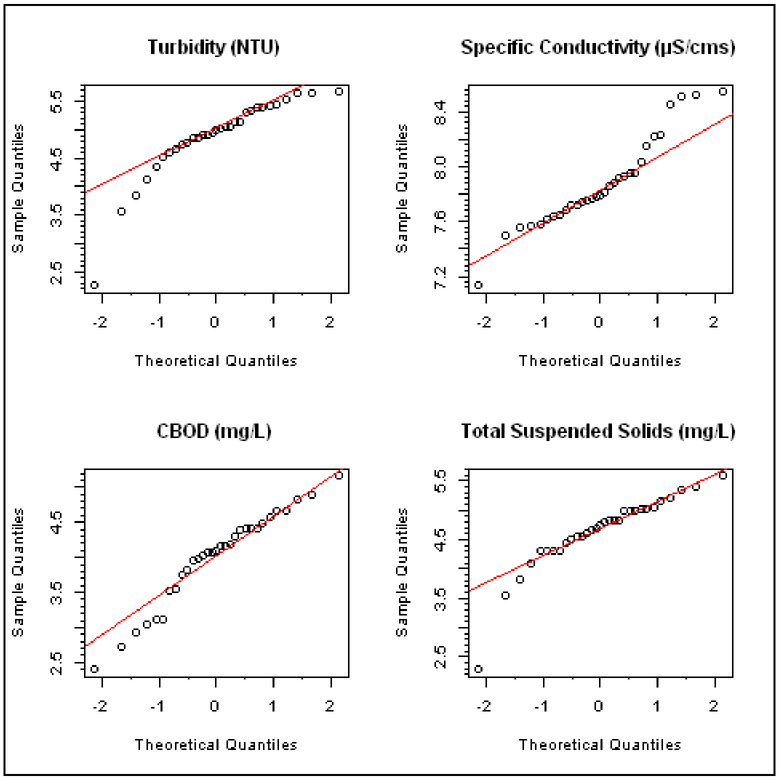
AF 3: Q-Q plots for the measured water quality indicators at Site CC2



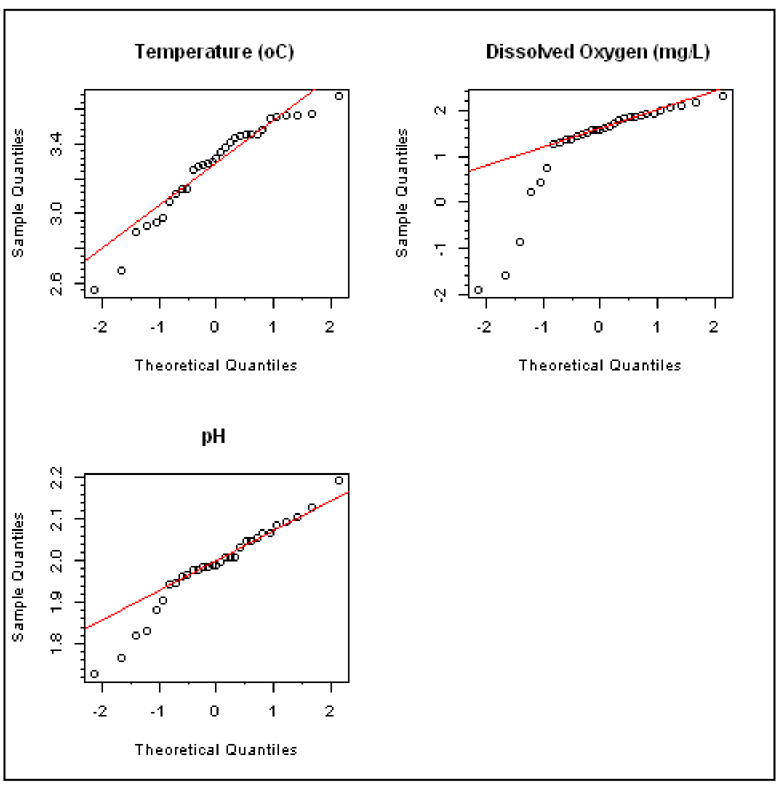
AF 4: Q-Q plots for the measured field parameters at Site HC1



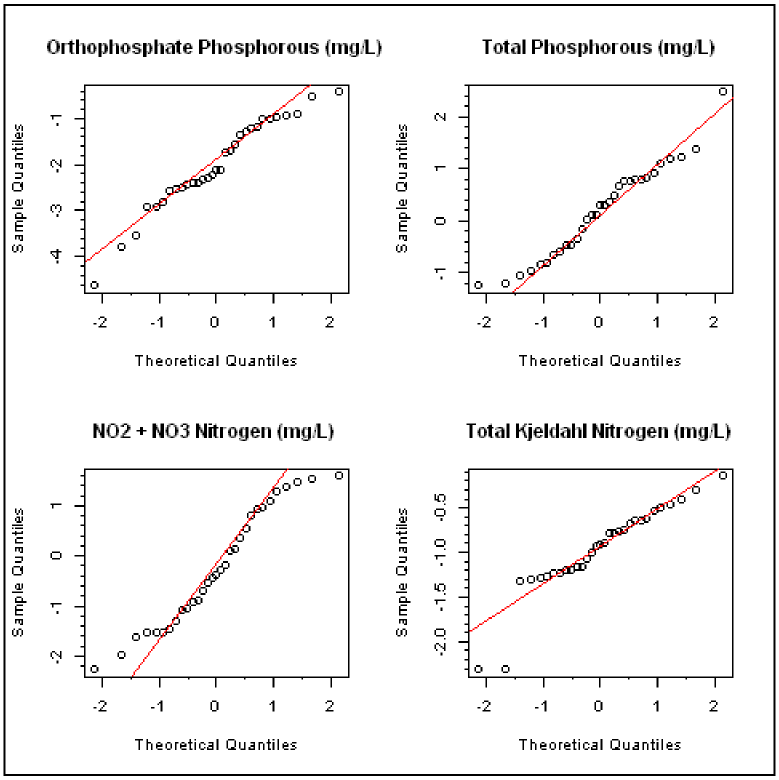
AF 5: Q-Q plots for the measured nutrients at Site HC1



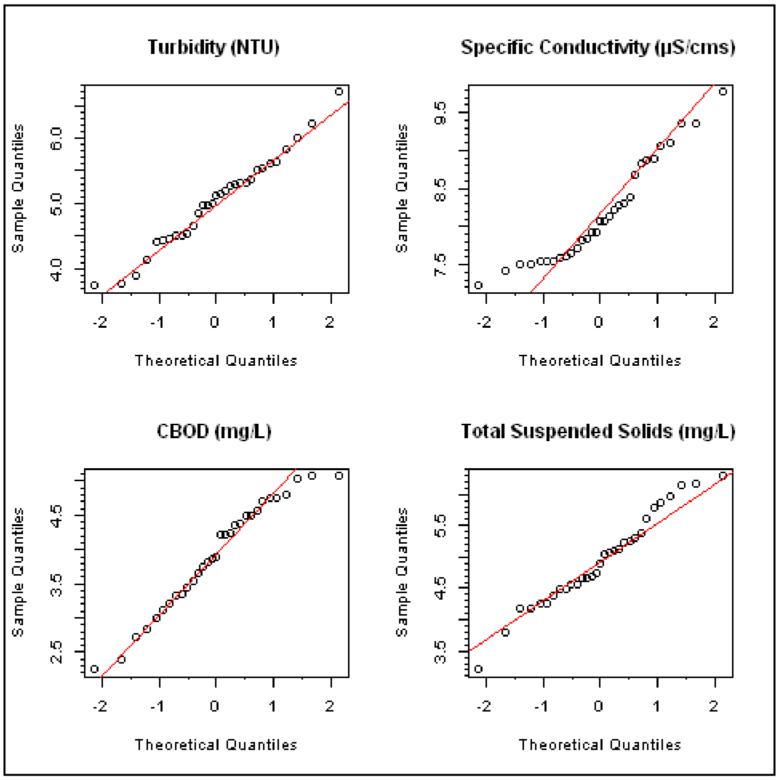
AF 6: Q-Q plots for the measured water quality indicators at Site HC1



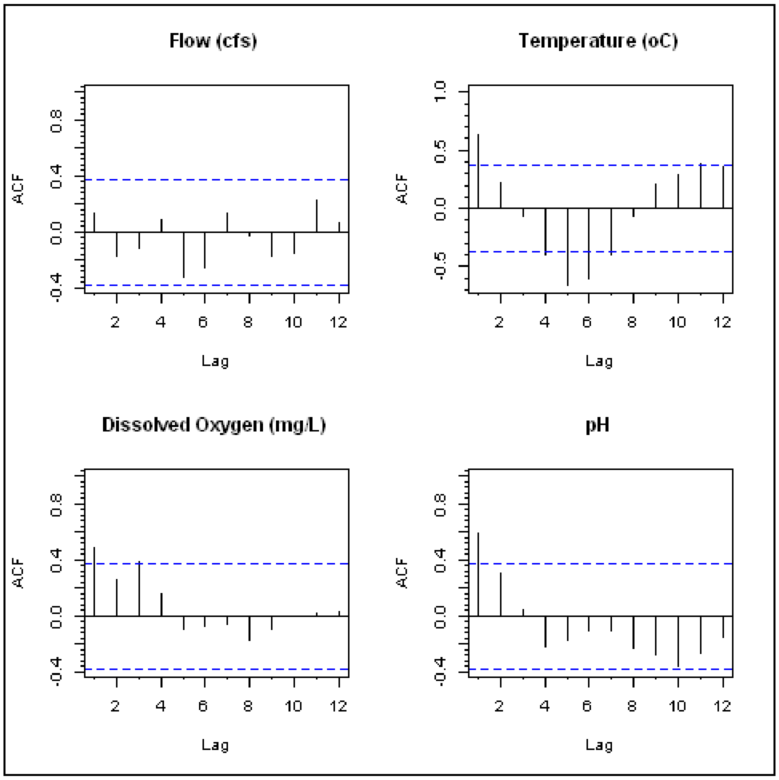
AF 7: Q-Q plots for the measured field parameters at Site HC2



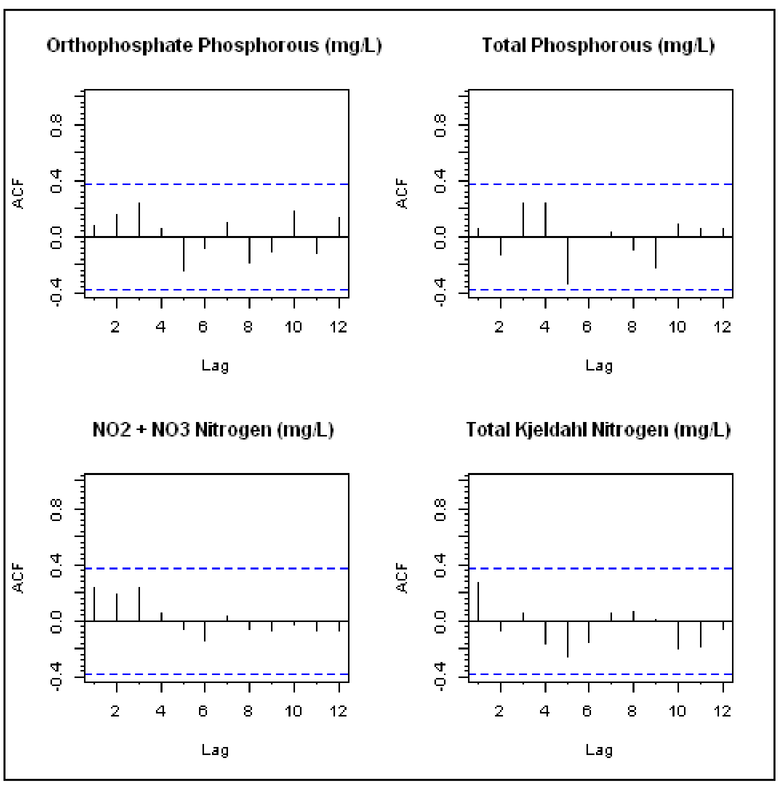
AF 8: Q-Q plots for the measured nutrients at Site HC2



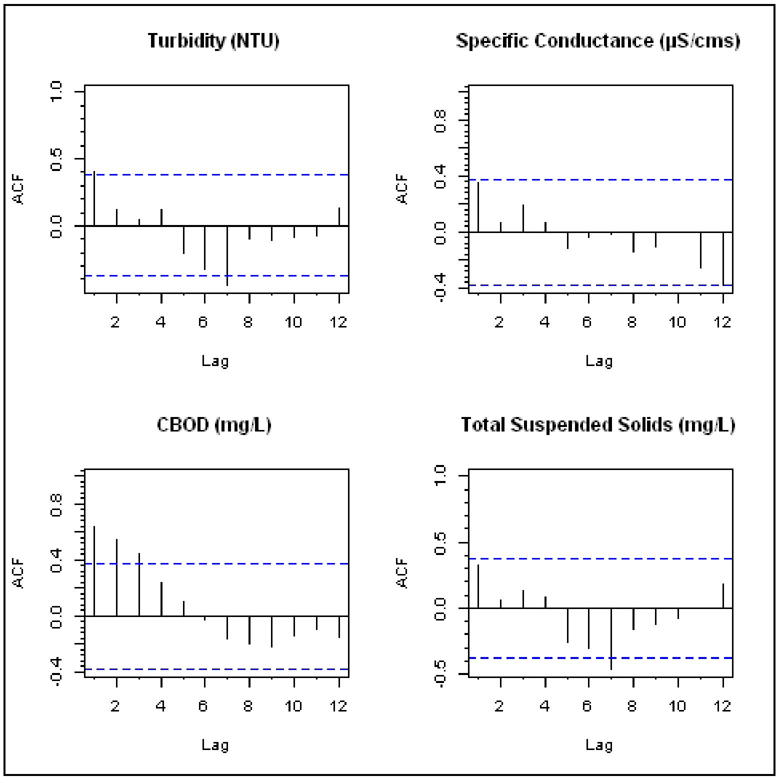
AF 9: Q-Q plots for measured water quality indicators at Site HC2



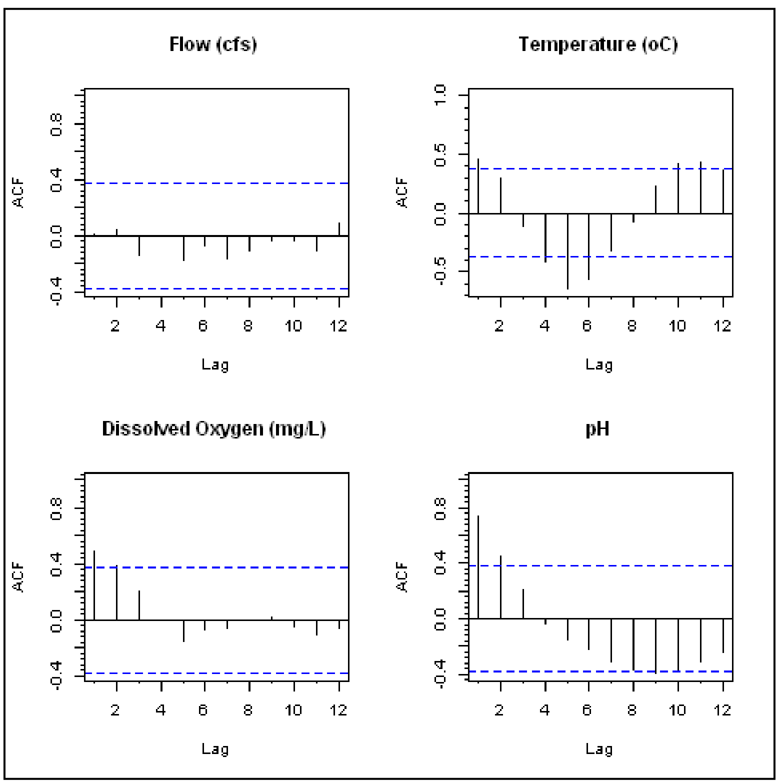
AF 10: ACF for measured field parameters at Site CC2



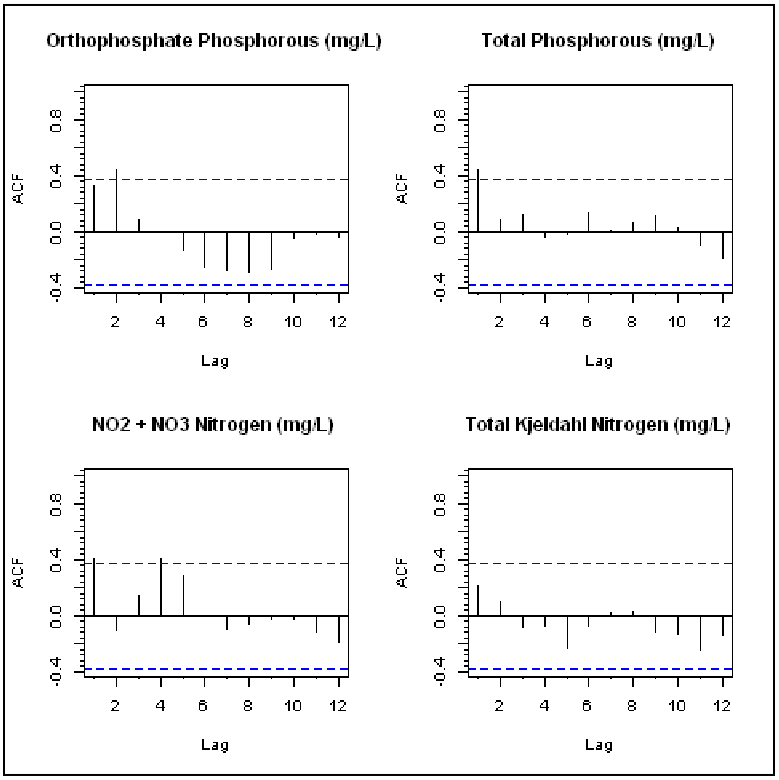
AF 11: ACF for the measured nutrients at Site CC2



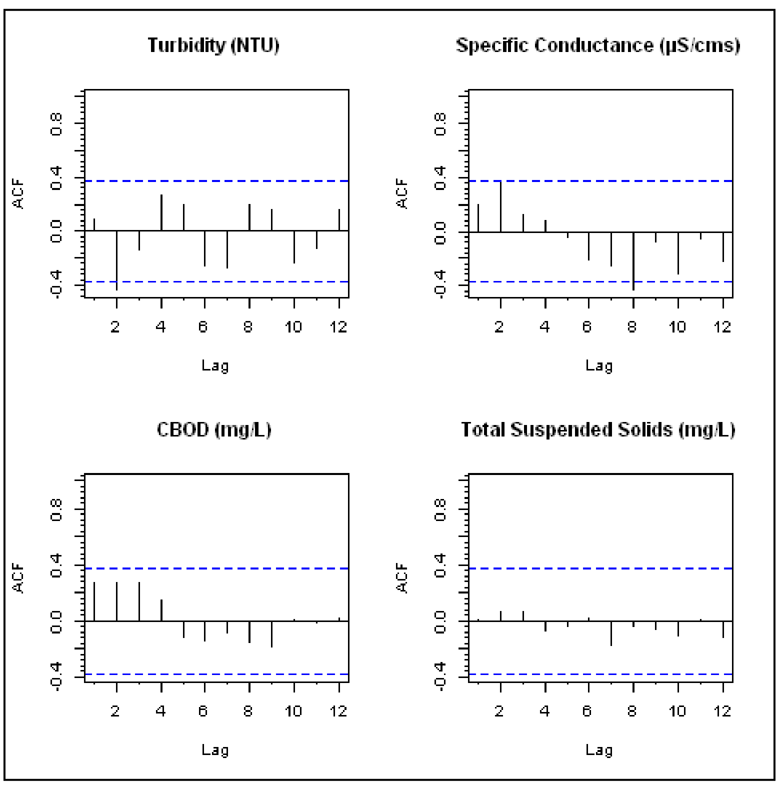
AF 12: ACF for measured water quality indicators at Site CC2



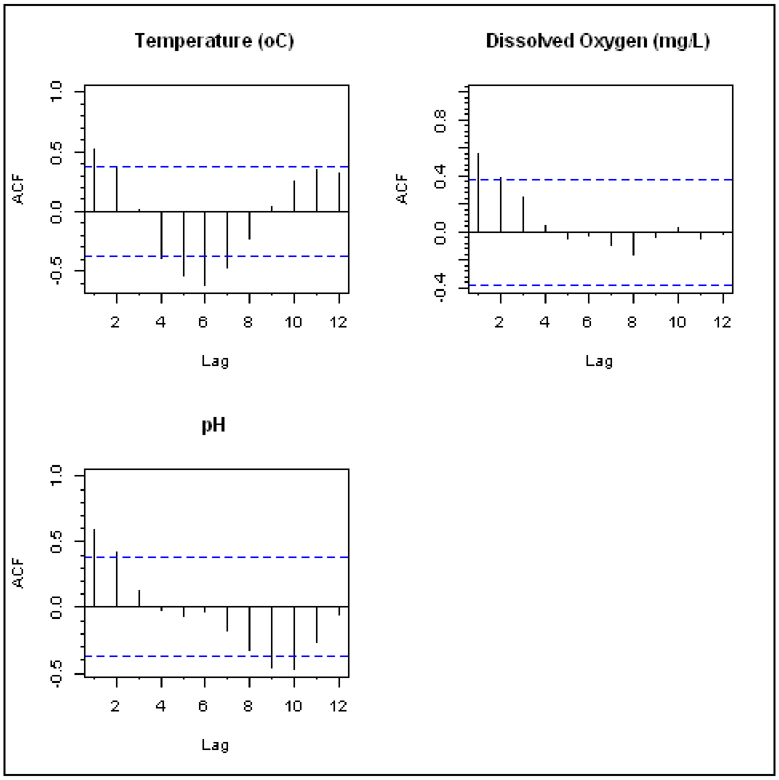
AF 13: ACF plots for measured field parameters at Site HC1



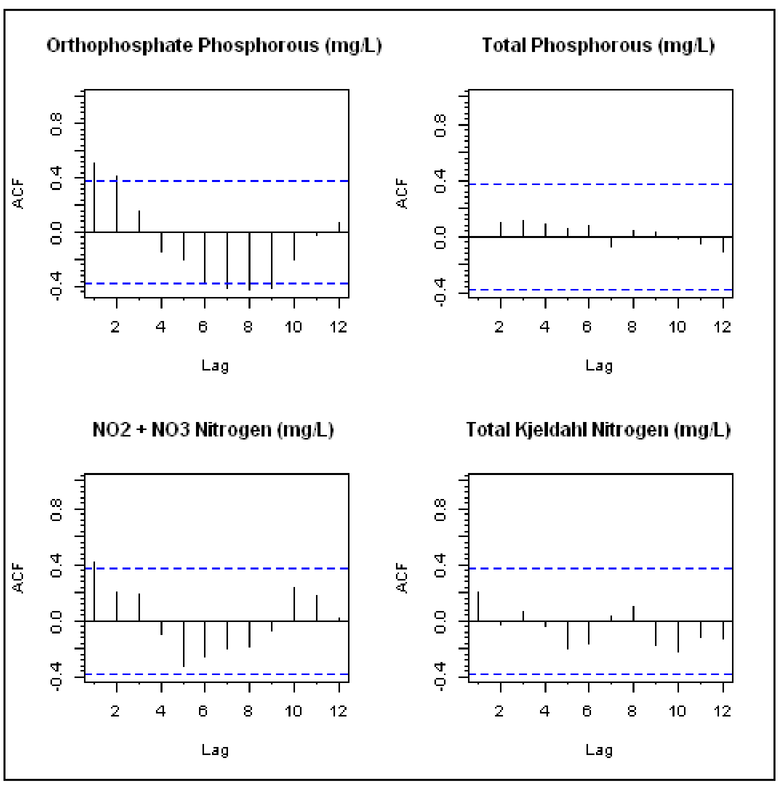
AF 14: ACF for measured nutrients at Site HC1



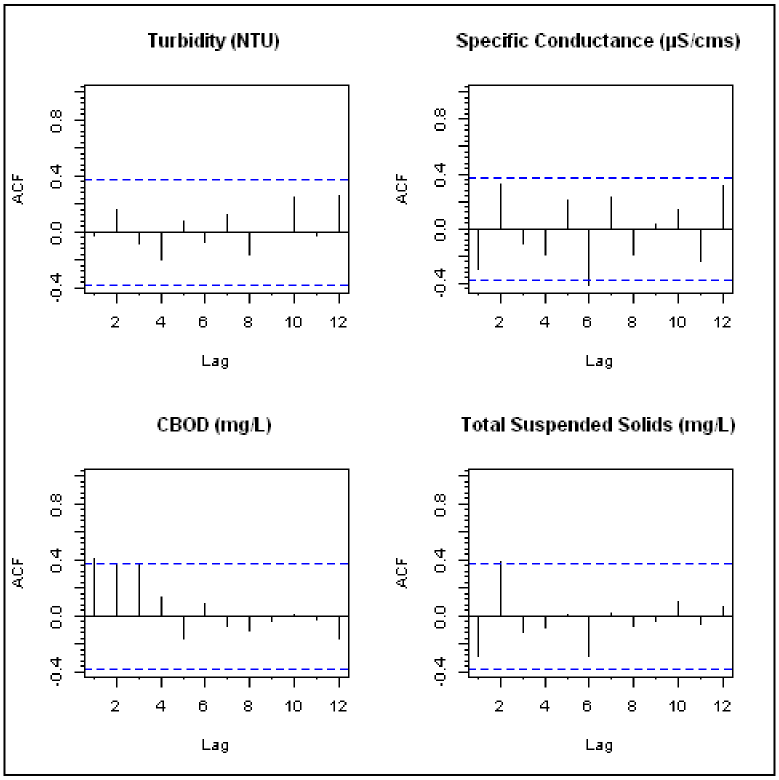
AF 15: ACF for the measured water quality indicators at Site HC1



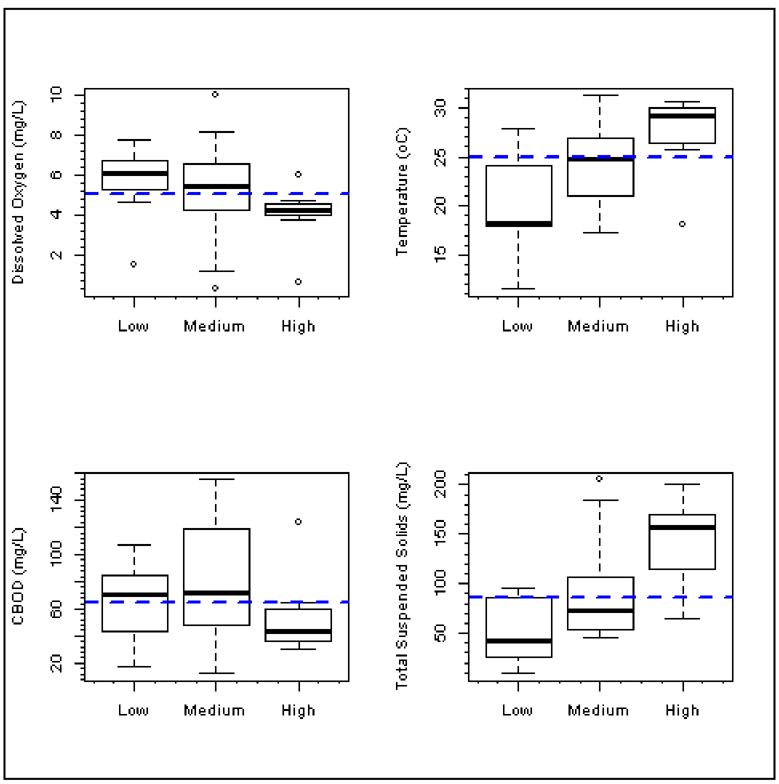
AF 16: ACF for measured field parameters at Site HC2



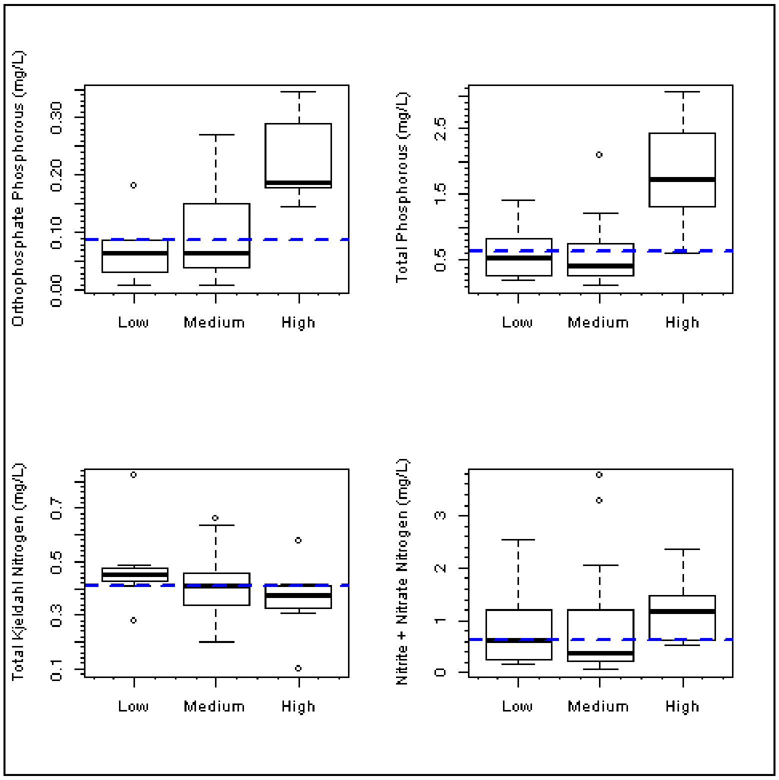
AF 17: ACF for measured nutrients at Site HC2



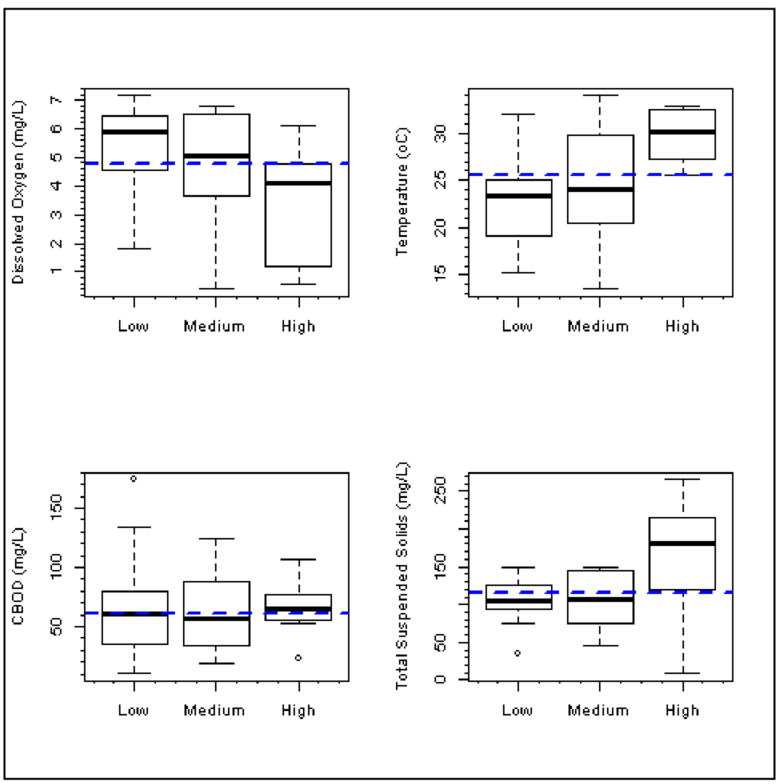
AF 18: ACF plots for the measured water quality indicators at Site HC2



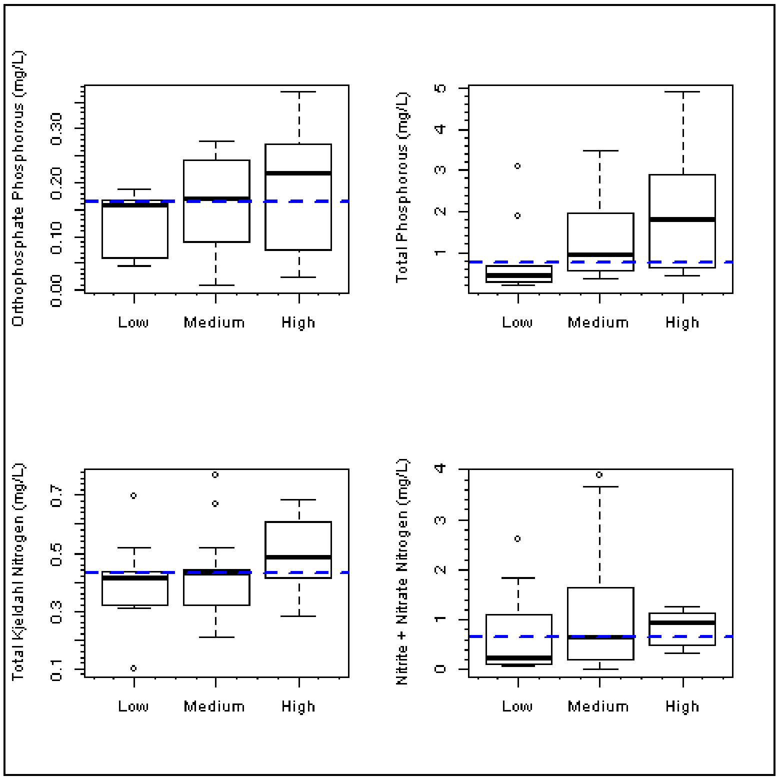
AF 19: Water quality characteristics pertaining to different flow regimes at Site CC2



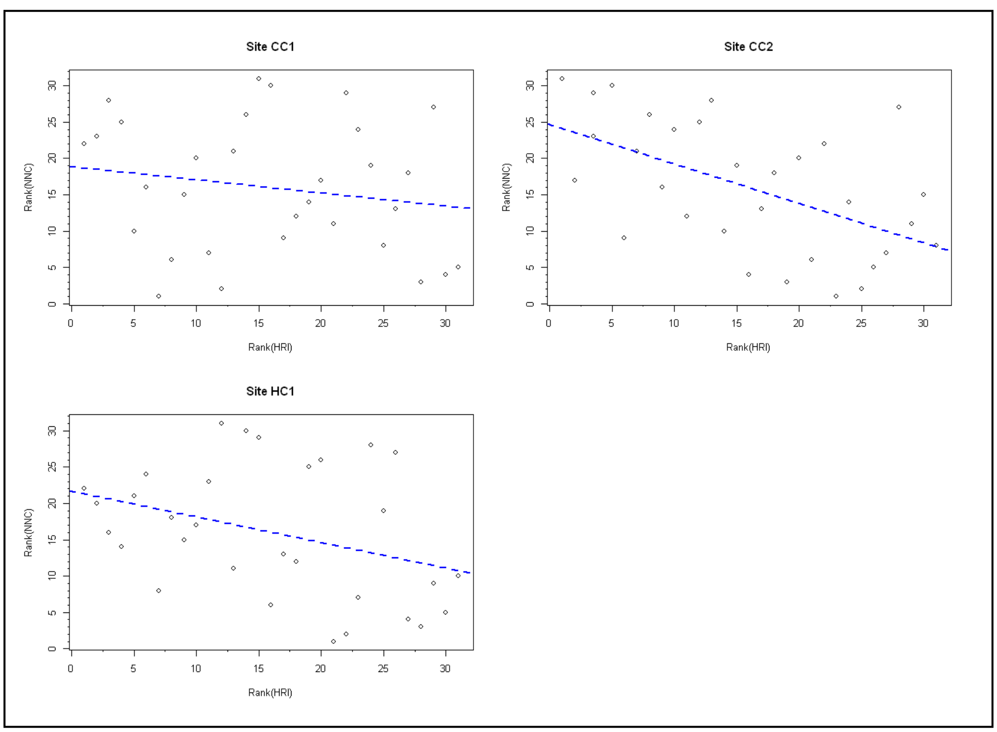
AF 20: Nutrient characteristics pertaining to different flow regimes at Site CC2



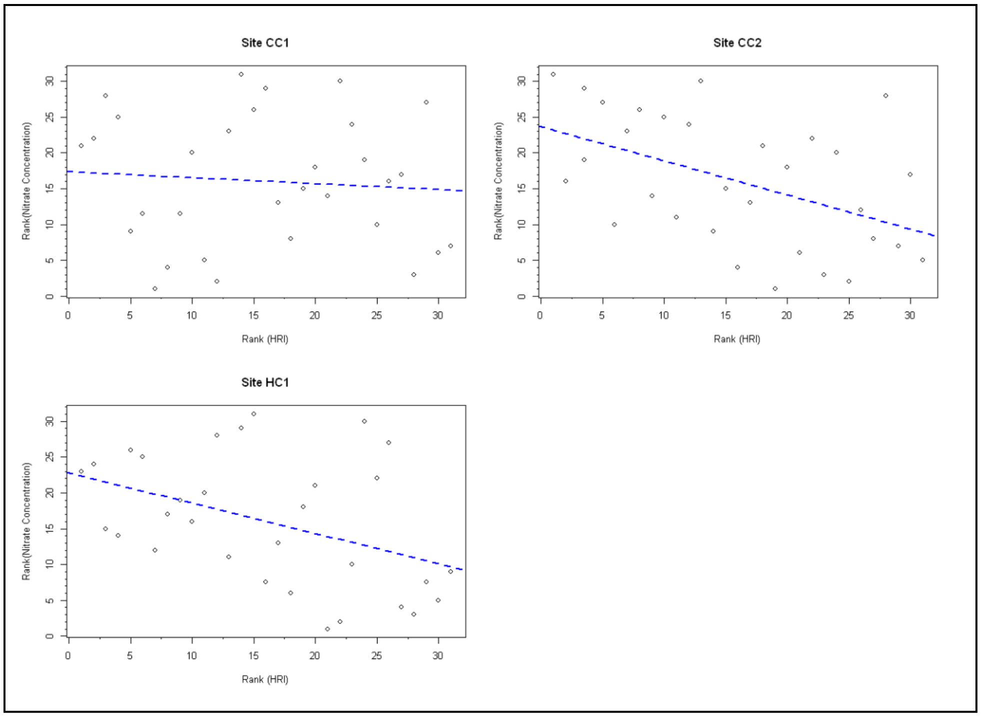
AF 21: Water quality characteristics pertaining to different flow regimes at Site HC1



AF 22: Nutrient characteristics pertaining to different flow regimes at Site HC1



AF 23: Correlation between Normalized Nitrate Concentration and Hydraulic Nitrate Reduction Index



AF 24: Correlation between Nitrate Concentration and Hydraulic Nitrate Reduction Index (HRI)

Appendix B

Evaluation of BMPs to Reduce NPS Pollution at the Farm Level

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AND LIFE SCIENCES

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2012


Evaluation of BMPs to Reduce NPS Pollution at the Farm Level

By

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Associate Professor and Extension Agricultural Engineer
Biological and Agricultural Engineering Department
Texas AgriLife Research and Extension Center
Weslaco, TX

Texas Water Resources Institute Technical Report No. 423
May 2012

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Evaluation of BMPs to Reduce NPS Pollution at the Farm Level

Arroyo Colorado Agricultural Nonpoint Source Assessment
FY 06 CWA 319(h)
TSSWCB Agreement No. 06-10-07-05
Task 7 Report

By

Juan Enciso, Ph.D., PE
Associate Professor and Extension Agricultural Engineer
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Texas AgriLife Research and Extension Center
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May 2012

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Table of Contents

INTRODUCTION

The Arroyo Colorado flows through Hidalgo, Cameron and Willacy Counties in the Lower Rio Grande Valley of Texas into the Laguna Madre and is the major source of fresh water to the lower Laguna Madre. The Arroyo Colorado is an economically and ecologically important resource to the region, having water exchange with the Gulf of Mexico. One third of the stream is also used for shipping from the Gulf Intracoastal Waterway to the Port of Harlingen. Most of the flow water in the Arroyo Colorado is also sustained by wastewater discharges, agricultural irrigation return flows, urban runoff, and base flows from shallow groundwater (Webster et al. 2000; Filteau 1995; Charbonnet et al. 2006; Rosenthal and Garza 2006). The Arroyo Colorado watershed has been on the state's list of impaired water bodies for low dissolved oxygen since the state began assessing water bodies in 1974. Moreover, the Laguna Atascosa National Wildlife Refuge and several county and city parks are located within the Arroyo watershed; its mild climate, semi-tropical plants and animals, and many recreational opportunities draw large numbers of people.

The Arroyo Colorado contributes significant amounts of agricultural, municipal, and industrial contaminants to the Laguna Madre (Custer and Mitchell 1991). Some efforts to implement best management practices (BMPs) have been taken to reduce nonpoint source (NPS) pollution in the region (Rosenthal and Garza 2007). In 1998, the Texas Commission on Environmental Quality (TCEQ) initiated an effort to develop total maximum daily load (TMDL) to address low dissolved oxygen (DO) levels in the tidal segment of the Arroyo (Rosenthal, et al. 2001, Matlock et al. 2003).

The TCEQ presented water quality data that indicated high levels of nutrients in the tidal segment (2201) and the above tidal segment (2202) (Figure 1), which exceeded the state's screening criteria, resulting in high chlorophyll-a and low levels of DO (TCEQ 2003). These high levels of nutrients are results of runoff from agricultural farms and urban areas. The impact of BMPs could be assessed indirectly with water savings between the water applied and the water used for beneficial purposes such as crop evapo-transpiration and salinity leaching. Excess water is lost through deep percolation, which eventually may carry nutrient loadings to the aquifer and runoff to the drainage, carrying loadings to ditches and to the Arroyo Colorado (TCEQ 2006).
Segments 2201 and 2202 have not met water quality standards in several years because of the presence of *E. coli* bacteria and low levels of DO. To meet the DO criteria (24-hour average of 4.0 mg/L and minimum of 3.0 mg/L) at least 90% of the time between the critical period of March through October, TCEQ (2003) estimated that a 90% reduction in nitrogen, phosphorous, oxygen demanding substances, and sediment would be necessary. The adoption of agricultural BMPs would help contribute to the reduction coming from agricultural areas.

This project monitored the water quality of irrigation, runoff, and percolation water of six irrigated farms that have adopted different combinations of BMPs. The main objective of this study was to assess the impact of these BMPs on water quality at these selected agricultural fields located in the Arroyo Colorado watershed during two irrigation events in 2009 and 2010.

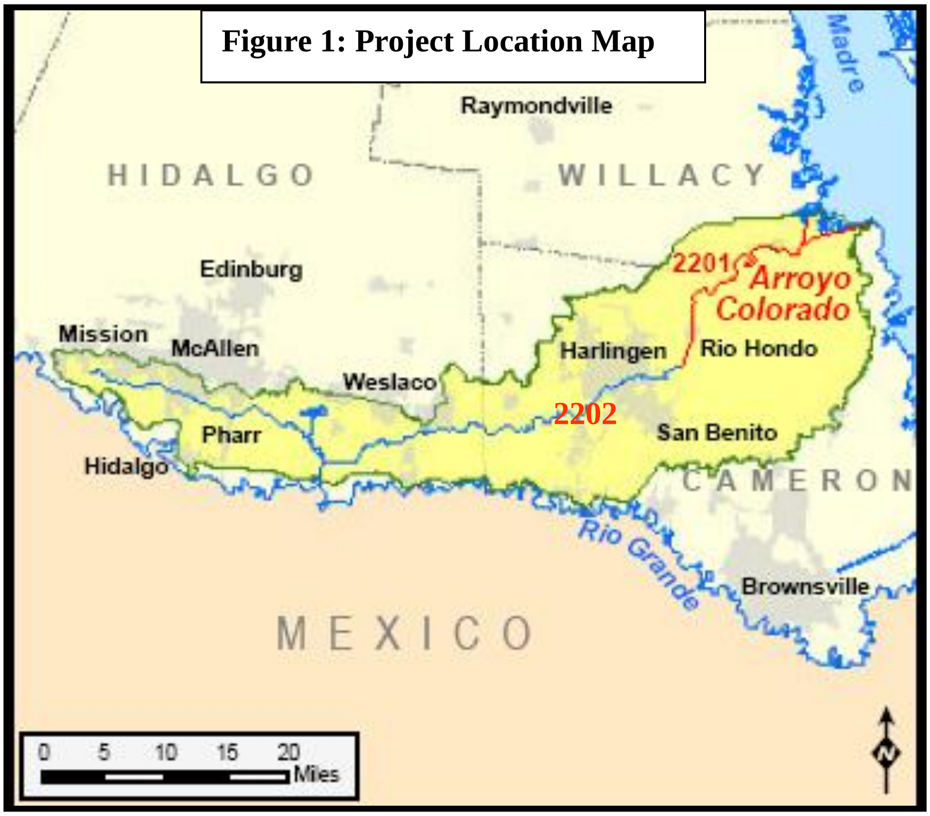


Figure 1. Location map of the Arroyo Colorado

MATERIAL AND METHODS

In addition to providing loading reductions resulting from BMPs, this project also provided result demonstrations to landowners in the Arroyo Colorado watershed. This data collection effort involves monitoring irrigation water inflow and outflow (via either tile drains or shallow groundwater) from agricultural fields to aid in evaluating BMP effectiveness and assessing agricultural loadings. Monitoring was conducted to represent both tiled and non-tiled irrigated cropland fields that drain to both drainage ditches and directly into the Arroyo. General guidelines followed in selection of the six fields are as follows:

- Sites are irrigated;
- Sites represent the primary production crops raised in the Lower Rio Grande Valley (LRGV), i.e., grain/sorghum, cotton, corn, and sugar cane;
- Sites represent both conventional and innovative irrigation BMPs in the LRGV;
- Sites are farmed by willing participants in the study; and
- Sites are within the Arroyo Colorado Watershed.

Texas AgriLife Extension Service (Extension), Texas AgriLife Research -Weslaco (AgriLife Research-Weslaco), and Texas A&M University-Kingsville (TAMUK) selected six suitable demonstration sites to assess loadings from agricultural runoff and leachate produced by different BMPs and to compare them with traditional practices. Six sites were selected by Texas State Soil and Water Conservation Board (TSSWCB), Texas Sea Grant, AgriLife Research and Extension, Harlingen Irrigation District, and Texas A&M Kingsville. The BMPs for the three most representative crops of the watershed were selected on March 30, 2007. Six representative sites were characterized and physical characteristics such as topography (slopes, coordinates and distances), soil texture, salinity and fertility levels, water quality and crops were obtained and evaluated. The six fields that were selected for the evaluation of agricultural BMPs are shown in Table 1 and Figure 2. Cultural practices such as irrigation timing, crop fertilization, and pest management used by the cooperating farmers in the recent past were documented. The layout and slopes of the sites with sampling points are shown in Figures 3 through 7. The BMPs for each site are shown in Table 2. Information regarding the type of BMPs adopted by the farmers were provided by the farmers and then corroborated with the Harlingen office of the TSSWCB.

Table 1. Site identification and description for BMP demonstration/evaluation.

Site ID	Location	Management Practices
FA	Rangerville: FM 800	Land leveled, IPM, poly-pipe, furrow irrigation
FB	Rangerville: FM 800	Land leveled, poly-pipe, furrow irrigation
FC	Simmons Rd/ FM 1479	Reduced till, poly-pipe, furrow irrigation, irrigation scheduling, Doppler meter
FD	South of San Juan. Hwy 281	Poly-pipe, furrow irrigation, drain tile
FE	South of Weslaco (FM 1015)	Poly-pipe, furrow irrigation
FF	N. of Harlingen (FM 508 & FM 507 N)	Poly-pipe, furrow irrigation, tile drained

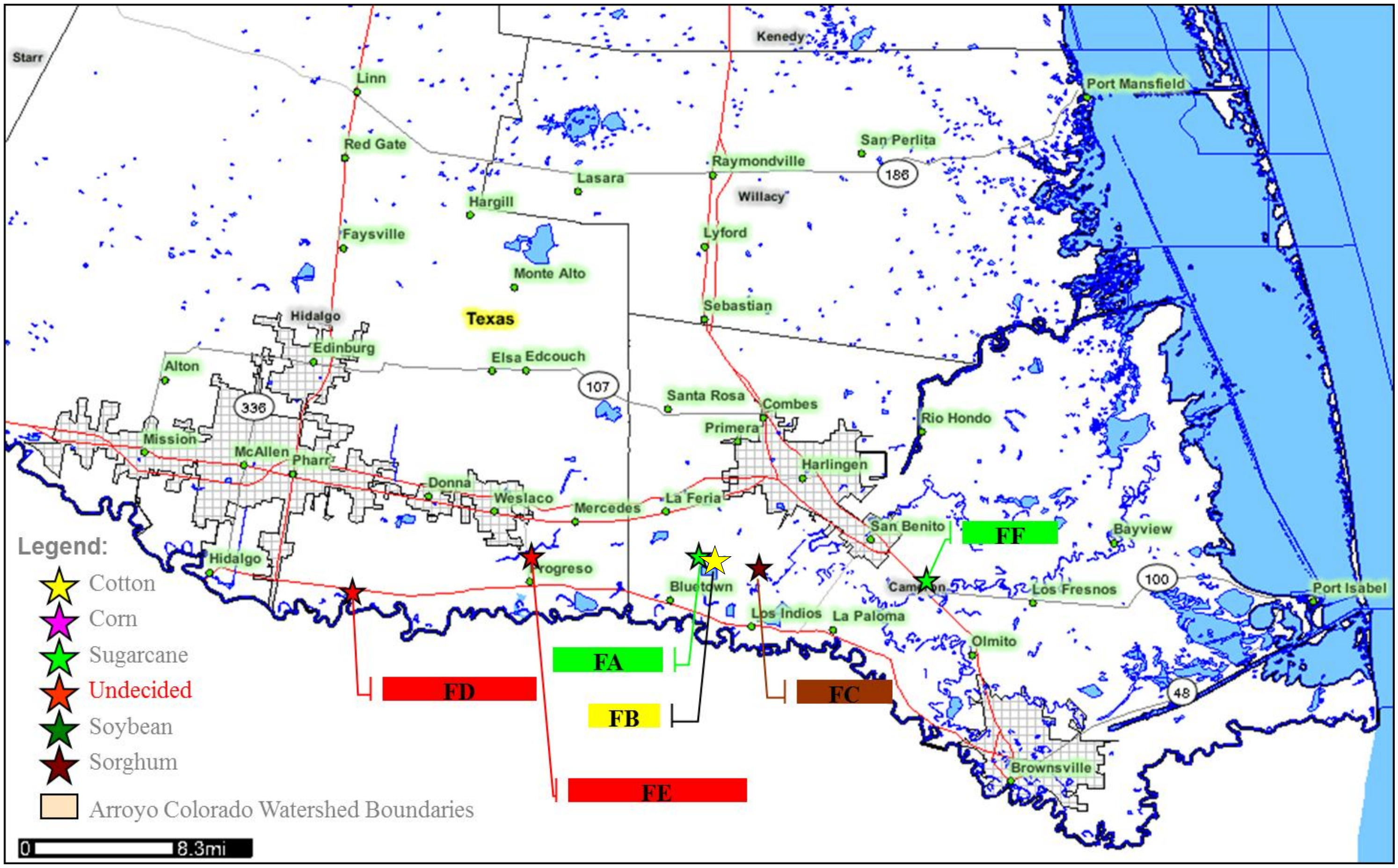


Figure 2. Cooperators sites in the Arroyo Colorado located in the Lower Rio Grande Valley, TX.

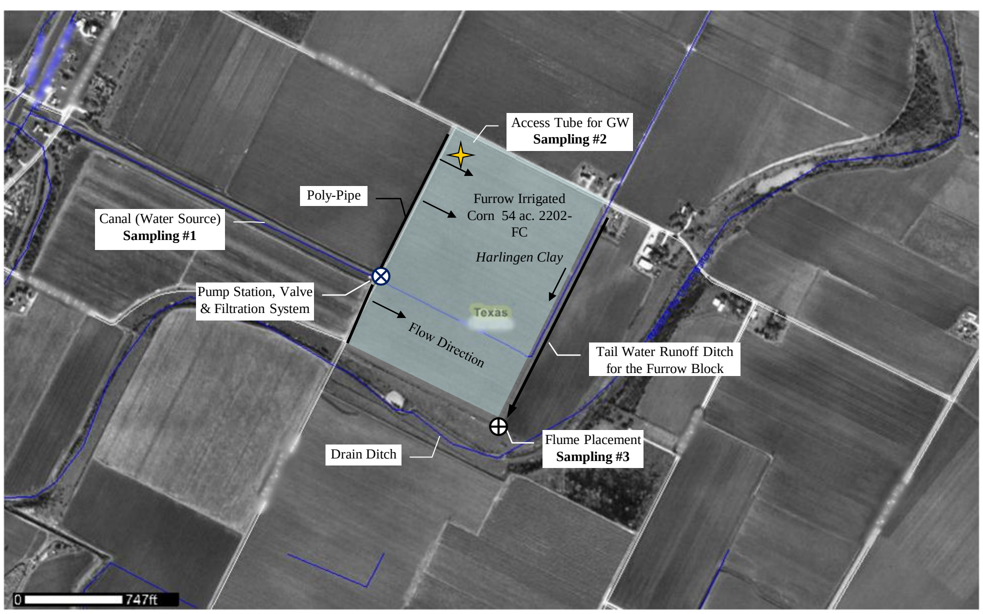
Table 2. Survey of BMPs practices at the six demonstration sites during 2009 and 2010.

BMPs in place	**FA**	**FB**	**FC**	**FD**	**FE**	**FF**
	2009					
Conservation Crop Rotation	X	X	X	X	X	X
Residue Management		X	X			X
Nutrient Management			X	X		X
Pest Management	X	X	X	X		
Irrigation Land Leveling	X	X	X	X	X	X
Irrigation Water Management	X	X				
Irrigation with Poly-pipe	X	X	X		X	X
Subsurface Drain				X		X
Filter Strip			X			
	2010					
Conservation Crop Rotation	X	X	X	X	X	X
Residue Management		X	X			X
Nutrient Management	X	X	X	X	X	X
Pest Management	X	X	X	X	X	X
Irrigation Land Leveling	X	X	X	X	X	X
Irrigation Water Management	X	X	X	X	X	X
Irrigation with Poly-pipe	X	X	X		X	X
Subsurface Drain				X		X
Filter Strip			X			

2202-FA ⊕ Location N.W. corner, by drop structure N 26°07.806' / W 097°44.403' / Elev. 38 ft. ⊗ Location S.E. corner stand pipe (1/3) N 26°07.611' / W 097°44.144' / Elev. 38 ft. ✦ Location N.W. corner, 50' from drop-off N 26°07.716' / W 097°44.162' / Elev. 34 ft.

2202-FB ⊕ Location S.W. corner, by drop structure N 26°07.306' / W 097°44.538' / Elev. 38 ft. ⊗ Location N.E. corner stand pipe (1/2) N 26°07.588' / W 097°44.389' / Elev. 35 ft. ✦ Location central East, 10th row N 26°07.560' / W 097°44.615' / Elev. 33 ft.

Figure 3. Sites FA and FB selected for the Agricultural Nonpoint Source Assessment Project.



2202-FC ⊕ Location S.E. corner, by drop structure N 26 07.684' / W 097 42.795' / Elev. 44 ft. ⊗ Location gate above canal N 26 07.867' / W 097 42.965' / Elev. 50 ft. ✦ Location 20th row from N.W corner, 20 steps in N 26 08.039' / W 097 42.847' / Elev. 46 ft.

Figure 4. Site FC selected for the Agricultural Nonpoint Source Assessment Project.

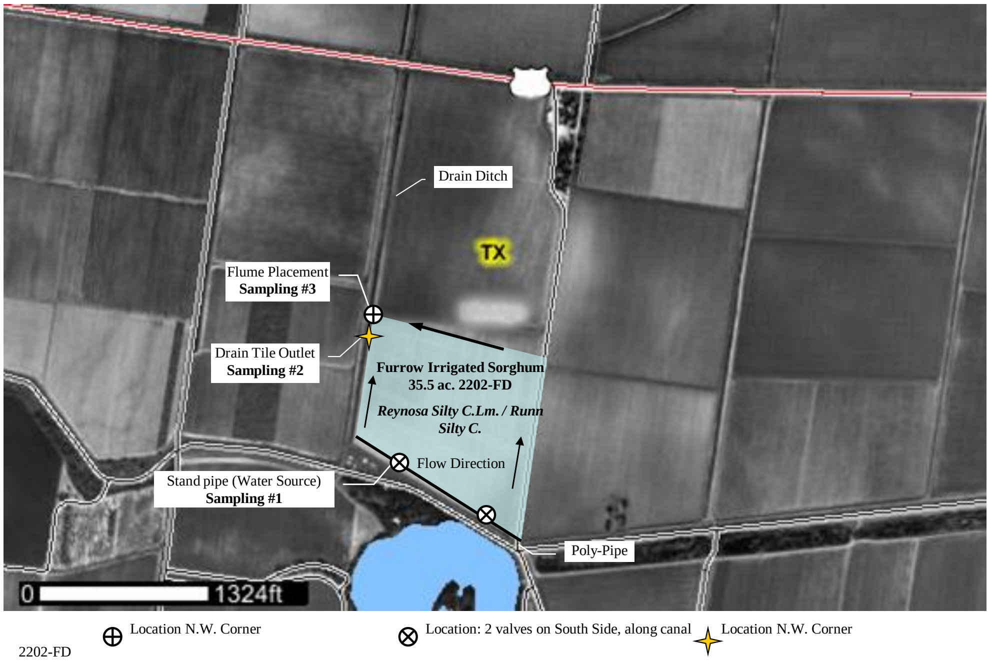


Figure 5. Site FD selected for the Agricultural Nonpoint Source Assessment Project.

Figure 6. Sites FE selected for the Agricultural Nonpoint Source Assessment Project.

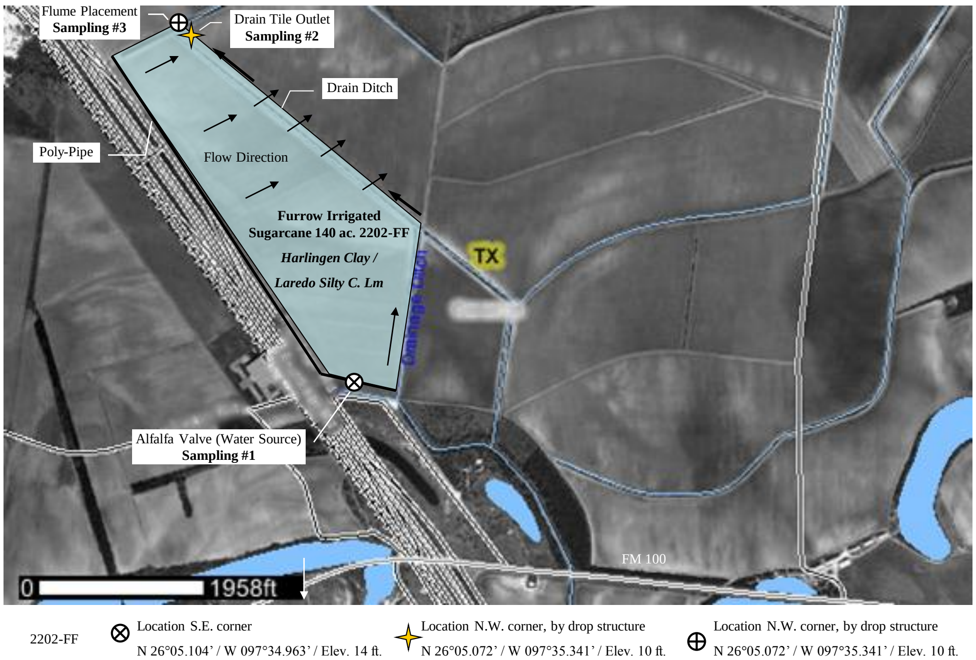


Figure 7. Site FF selected for the Agricultural Nonpoint Source Assessment Project.

Installation of Sensors

Flow meters, rain gauges, piezometers, soil water sensors were installed by Research-Weslaco on the demonstration sites.

Additionally the following actions were conducted:

a. **Site FA** (site with no drain tiles): a 2-inch PVC access tube was installed to a depth of 10 feet to collect samples from the groundwater. Watermark sensors were installed on one location at 6 and 12 inches deep to monitor soil moisture along the season. The topography of the 40-acre site was measured.
b. **Site FB** (site with no drain tiles): a 2-inch PVC access tube was installed to a depth of 10 feet to collect samples from the groundwater. Watermark sensors were already installed on one location at 6 and 12 inches deep to monitor soil moisture along the season.
c. **Site FC** (site with no drain tiles): a 2-inch PVC access tube was installed to a depth of 10 feet to collect samples from the groundwater. Corn was planted and Watermark sensors were installed on one location at 6 and 12 inches deep to monitor soil moisture along the season.
d. **Site FD** (site with no drain tiles): The previous crop was harvested and disked in mid-March. A pre-irrigation occurred afterwards to ensure a good germination of sorghum when it was planted. After planting, a 2-inch PVC access tube was installed to a depth of

10 feet to collect groundwater samples. Watermark sensors were installed on one location at 6 and 12 inches deep to monitor soil moisture along the season.

e. **Site FE** (site with drain tiles). Sorghum was planted and Watermark sensors were installed on one location at 6 and 12 inches deep to monitor soil moisture along the season.
f. **Site FF** (site with drain tiles): The outlet was under water most of the time.
g. AgriLife Research installed signs at all of the participating producer sites (in English and Spanish) to notify the producers to contact AgriLife Research before irrigating (Figure 8).

Figure 8. English Sign used during the result demonstration reports

Collection and Analysis of Data

Irrigation water inflow, surface runoff and outflow from the tile drainage system or through shallow groundwater, were monitored by AgriLife Research-Weslaco on selected irrigation events. The crops were monitored continuously to determine the optimum time for irrigation and for water sampling. The irrigation dates were not previously known because (1) fields have different crops with different water requirements, (2) fields were operated under different water management schemes, and (3) irrigation dates were highly dependent on climate, growth stage, and the operation of the irrigation district. Two irrigation events were selected for sampling each year. Sample numbers and frequency for the BMP demonstration are shown in Table 3.

Table 3. Sample type & frequency for demonstration and evaluation of BMPs.

Sample Type	Number of Sites	Sampling Frequency	Total # Samples (2 years)
Surface water runoff into Drainage Ditch for specific crops	6	2 samples per event, 2 different irrigation events per year	48
Subsurface drainage from different crops (tile drain outlet)	2	2 per year	8
Irrigation water	6	2 per year	24
Shallow groundwater (access tube)	4	2 per year	16

All water samples were analyzed for various nutrient forms (i.e., total phosphorus, dissolved orthophosphate phosphorus [frequently referred to as soluble reactive phosphorus], total Kjeldahl nitrogen, dissolved ammonia, dissolved nitrite plus nitrate), and total suspended sediments (TSS). In addition, monthly grab samples were analyzed for Biochemical Oxygen Demand (BOD), dissolved oxygen, water temperature, specific conductance, and pH. The nitrogen forms were included in the laboratory analyses to provide a more complete indication of macronutrient conditions in the watershed, evaluate whether agricultural BMPs were reducing both nutrients (nitrogen and phosphorus), and ensure that efforts to reduce one nutrient is not inadvertently increasing another.

A water sample was collected in a clean LDPE bottle and rinsed to measure temperature, conductivity, DO, and salinity on the field. Field parameters were measured in-situ using a portable hand-held YSI 85 meter for temperature, conductivity, DO, and salinity; and a YSI 60 meter for pH (Figure 9). Duplicate field measurements were taken and recorded. This is done to monitor potential water and meter variability. Additionally, water samples were collected immediately after recording those measurements and shipped to TAMU-K for analysis of total phosphorus, dissolved orthophosphate phosphorus, total Kjeldahl nitrogen, dissolved ammonia, dissolved nitrite plus nitrate, TSS and BOD5 (Table 4).

Figure 9. Left: Apparatus used to measure electrical conductivity of the water table. Right: apparatus used to monitor pH and BOD.

Table 4. Monitoring frequency for BMP demonstration/evaluation.

Station ID	Nutrients	Sediment	Flow Measurement
FA-I	2 per year	2 per year	Continuous 2 per year
FA-S	4 per year	4 per year	Continuous 2 per year
FA-GW	2 per year	2 per year	NA (well sample)
FB-I	2 per year	2 per year	Continuous 2 per year
FB-S	4 per year	4 per year	Continuous 2 per year
FB-GW	2 per year	2 per year	NA (well sample)
FC-I	2 per year	2 per year	Continuous 2 per year
FC-S	4 per year	4 per year	Continuous 2 per year
FC-GW	2 per year	2 per year	NA (well sample)
FD-I	2 per year	2 per year	Continuous 2 per year
FD-S	4 per year	4 per year	Continuous 2 per year
FD-TD	2 per year	2 per year	NA (well sample)
FE-I	2 per year	2 per year	Continuous 2 per year
FE-S	4 per year	4 per year	Continuous 2 per year

Station ID	Nutrients	Sediment	Flow Measurement
FE-GW	2 per year	2 per year	Instantaneous 2 per year depending on conditions (submerged or not)
FF-I	2 per year	2 per year	Continuous 2 per year
FF-S	4 per year	4 per year	Continuous 2 per year
FF-TD	2 per year	2 per year	Instantaneous 2 per year depending on conditions (submerged or not)

Nutrients = NO_2+NO_3, TKN, NH_3, PO_4, TP
Sediment = TSS
Field = dissolved oxygen, pH, conductivity, temperature, turbidity

Irrigation Water

The volume of water used during each irrigation event was measured using propeller flow meters (McCrometer) such as the ones shown in Figure 10. The volumes were then converted to irrigation depth. The quality of irrigation water was measured directly from the irrigation pipe (Figure 11). In case the farmer was applying fertilizer with the irrigation water, the sample was taken before it was mixed with fertilizer.

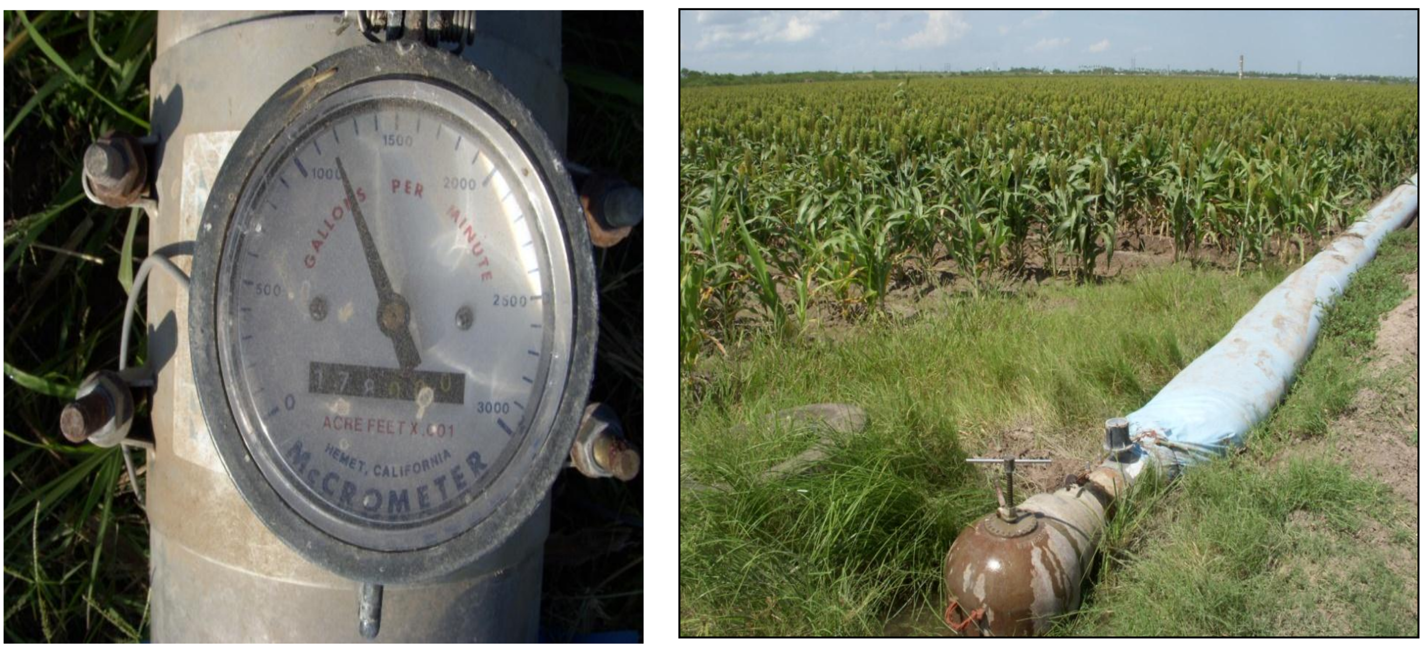


Figure 10. Propeller flow meters used to measure irrigation depth.


Figure 11. Collection of a water sample from irrigation.

Surface Runoff

Runoff was collected at the end of the surface drain before flow reached the Arroyo Colorado. A PVC mobile circular flume placed at the drainage ditch was used to measure runoff flow-rate using a data logger and a pressure transducer. This flume presented a discharge-head relationship for critical flow conditions by reducing the flow cross section (Hager 1988; Samani et al. 1991). Samani et al. 1991 described the construction and testing of these devices for different nominal sizes with different column pipes of external diameters. The flume measured water depth passing through and the water depth readings were recorded and directly related with the runoff flow rate. Two water samples were collected per irrigation event: a first sample collected during the early stage of the runoff event and a second sample at the peak runoff flow. Only the peak runoff was reported in this study. Peak runoff was taken from the drainage stream ditch where furrow discharge was in excess of irrigation water. See Figure 12 for schematic of the flume that was used to measure irrigation return flows. To assure that the circular flume measured accurately and with less than 10% error, the flow meter was calibrated in the Harlingen Irrigation District (Figure 13). The runoff depth was recorded with a data logger that was installed on the flume (Figure 14). The runoff volume was calculated from the hydrograph. Two water samples were collected per irrigation event: the first sample collected during the early stage of the runoff event and the second sample at the peak runoff flow (Figure 13). This is done because of the variability in runoff due to changing soil moisture conditions.

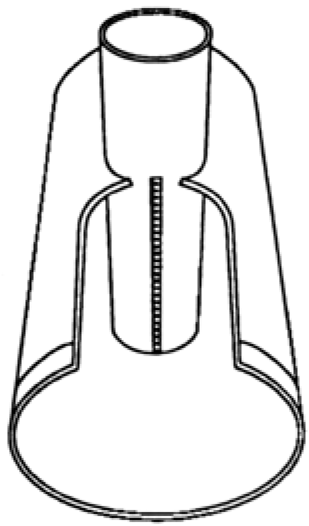


Figure 12. Circular Flume used to measure runoff.

Figure 13. Calibration of the circular flow meter in the Harlingen Irrigation District.

Measurement of Tail Water (Run-off) with a Flume

3rd Step: Field application & results: 2 samples/event, 2 irrigation events/year

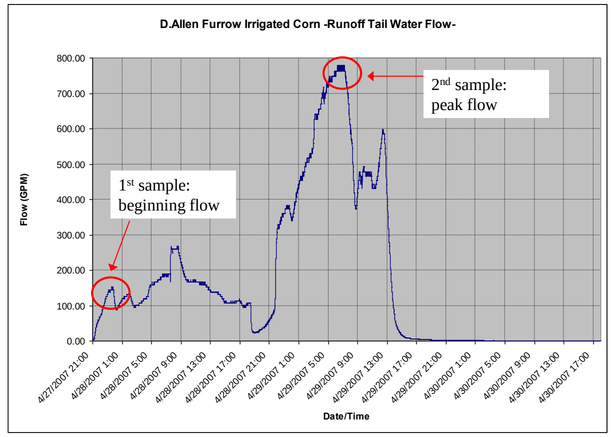


Figure 14. Left: Circular flume measuring runoff with a data logger. Right: Hydrograph obtained during the irrigation event.

Water samples were collected during initial runoff from one furrow. It was generally the faster row to reach the lower end of the field first (Figure 15). The peak runoff was taken from the earthen ditch that collected the runoff from all the rows that were being irrigated at the approximate time when the peak runoff was achieved (Figure 16).

Figure 15. Collecting a water sample from initial runoff with a syringe at the end of the furrow.

Figure 16. Collecting a water sample to determine peak runoff.

Subsurface Drainage

Field sites with tile drains installed were sampled during selected irrigation events at the main outlet of the tile drains (Figure 17). In the fields that did not have tile drains, groundwater samples were collected from a 2-inch well that was dug in the field to a depth of 6 feet. The well was cased with a perforated PVC access tube. The groundwater sampling and monitoring method was done using the method described by Harter (2003). The installation of the piezometer to monitor the shallow ground is shown in Figure 18. Shallow groundwater was sampled from the project fields with no tile drains using EPA standard methods (Figure 19).

Figure 17. Outlet that received the water drain from the field during the irrigation event.

Figure 18. Left: Installing a piezometer to obtain groundwater samples. Right: Probe to measure the depth of the water table.


Figure 19. Collecting a groundwater sample with a variable flow pump from a 2-inch well.

RESULTS

The irrigation dates and the crops grown in the six sites during the 2009 and 2010 growing seasons are shown in Table 5. Some pictures taken during the evaluations of the six sites are shown in Figures 20 to 26.

Table 5. Timing of irrigation and crops irrigated for each BPM demonstration site.

Site	First irrigation	Second irrigation	Crop 2009	Fertilizer	First irrigation	Second irrigation	Crop 2010	Fertilizer
FA/ 39.5 acres Clay texture	01/13/09	04/16/09	Corn		3/27/10 Post germination	6/03/10 1st bloom	Cotton	Injection of N32 during the second irrigation (8 gallons/acre equivalent to 29 lbs of nitrogen/acre)
FB/ 43 acres Clay texture	03/15/09	04/29/09	Sugarcane		7/26/10	8/17/10	Sugarcane	
FC/54 acres Clay soil	01/13/09	03/18/09	Sorghum		04/05/10 Post-plant	5/06/10	Corn	
FD/35 acre Silty clay loam soil	10/27/09		Onions		3/24/10		Onions	
FE/34 acres Clay soil	01/09/09	04/09/09	Collar green		5/02/10 Post-planted	5/31/10 bloom	Sorghum	
FF/ 140 acres Clay soil	02/04/09	03/23/09	Sugarcane	N32 was knifed prior to first irrigation 50 gal/ac (Feb 2009)	8/06/10 2nd irrigation	6/15/10 Post harvest	Sugarcane	N32 - 60 gal/ac (May 2010)

Figure 20. Site FA fertigating during the first irrigation. Right: Shows the flume to measure runoff volume at the corner of the field.

Figure 21. Upper Left: Site FB Irrigating with poly-pipe; Upper Right: Showing how water is pumped from the groundwater to collect samples for analysis. Lower Left: The lower left picture shows the installation of a flume to measure runoff volume. Lower Right: The lower right shows a vegetation strip where runoff is discharged.

Figure 22. Upper Left: Site FC irrigation with poly-pipe; Upper Right: Showing the downstream end of the field where runoff was collected.

Figure 23. Upper Left and Right: Site FD Irrigation with earth ditches and siphon tubes. Bottom Left: The bottom left shows an irrigation starting a siphon tube; Bottom Right: The right picture shows a pressure transducer used to measure drainage water from an outlet of a drain tile.

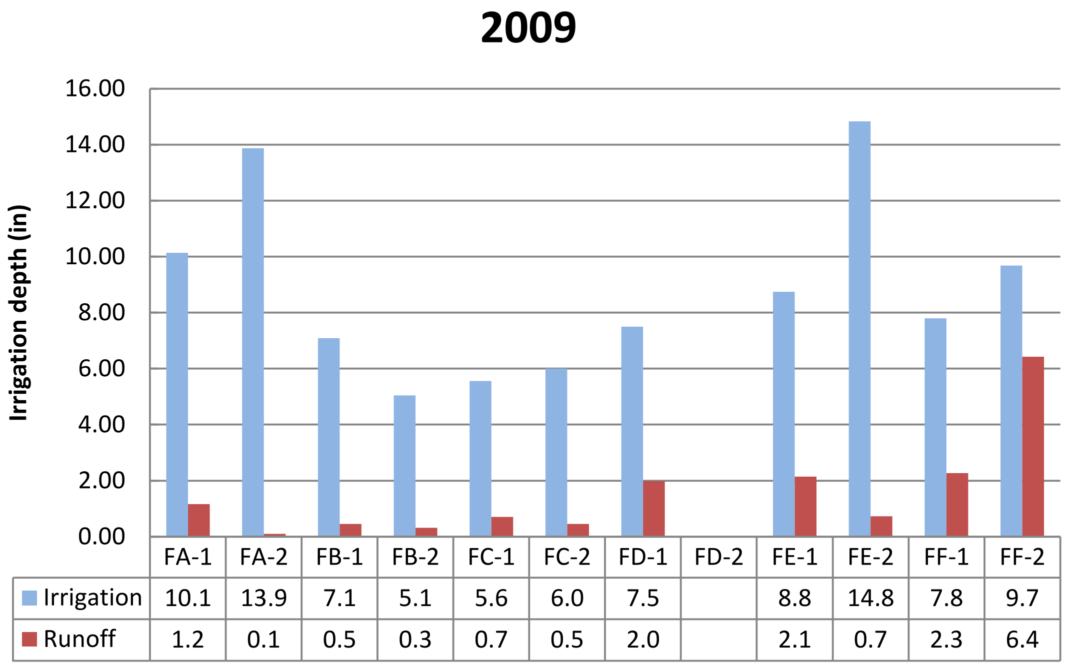
Figure 24. Site FE irrigated with poly-pipe and right picture showing the runoff from the field.

Figure 25. Site FF irrigated with poly-pipe and right picture showing the place where runoff was going to be measured.

Irrigation and Runoff Water Amounts

The highest irrigation depths were observed in site FA during the first and second irrigations and in site FE during the second irrigation in 2009 (Figure 26). Irrigation depths higher than 10 inches were observed in these two sites. Site FA has a clay texture that has a potential capacity of about 2.2 inch per foot depth. If we consider a root depth of 3 feet, this soil can hold up to 6.6 inches of water. Site FE also has a clay soil and it can also hold up to 6.6 inches of water in the 3 feet root zone. Therefore, the irrigation application of over 10 inches of water is excessive considering that the runoff amounts of sites FA and FE were very small. Most of the water at these sites was probably lost through deep percolation. In site FA, the rows were 1,305 feet long (Table 6) and it took 15 hours and 15 minutes for the water to reach the lower end of the row. The long irrigation time produced deeper water percolation. In 2009, it was also observed that the runoff amount was higher for site FF-2 during the second irrigation (Figure 27). The reason for this higher volume of runoff could be that the irrigator applied more water per row (25 gpm in one site and 16.7 gpm at another site) and the length of the rows were much less. The irrigator also left this site unattended, thus impacting the amount of runoff.

Most of the farmers applied small irrigation depths and the runoff amounts were also small in 2010 (Figure 27). This improved management was likely influenced as farmers received written reports regarding the amount of water that needs to be applied from AgriLife Research-Weslaco during the 2009 growing season. The data is not reported for sites FB during first and second irrigation and site FF during the second irrigation because the water meters and water level sensors did not work properly.



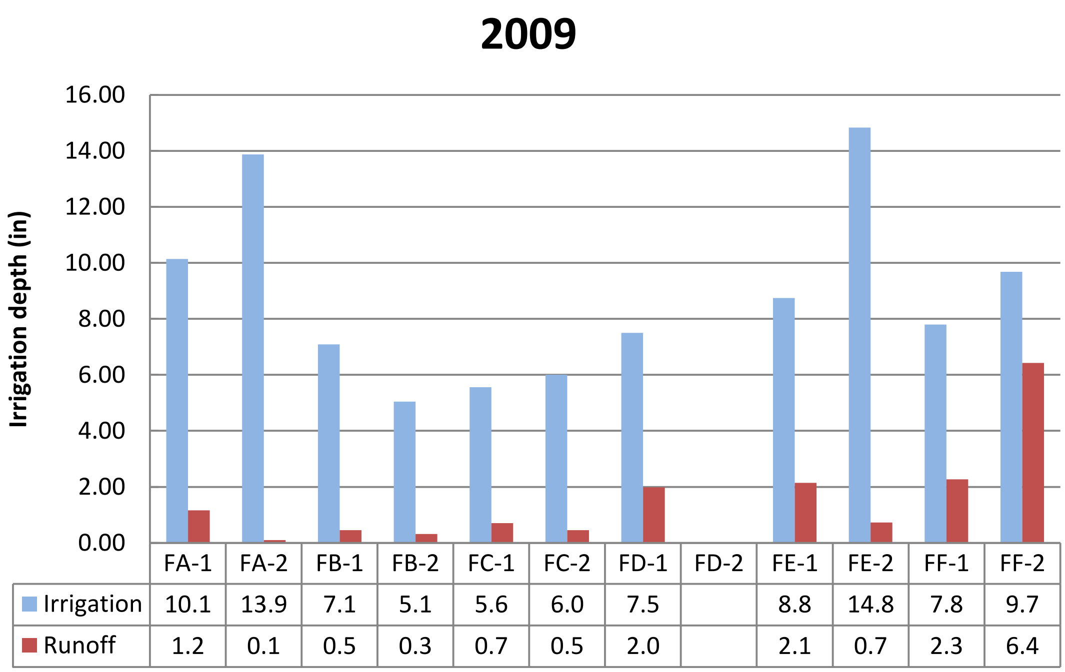
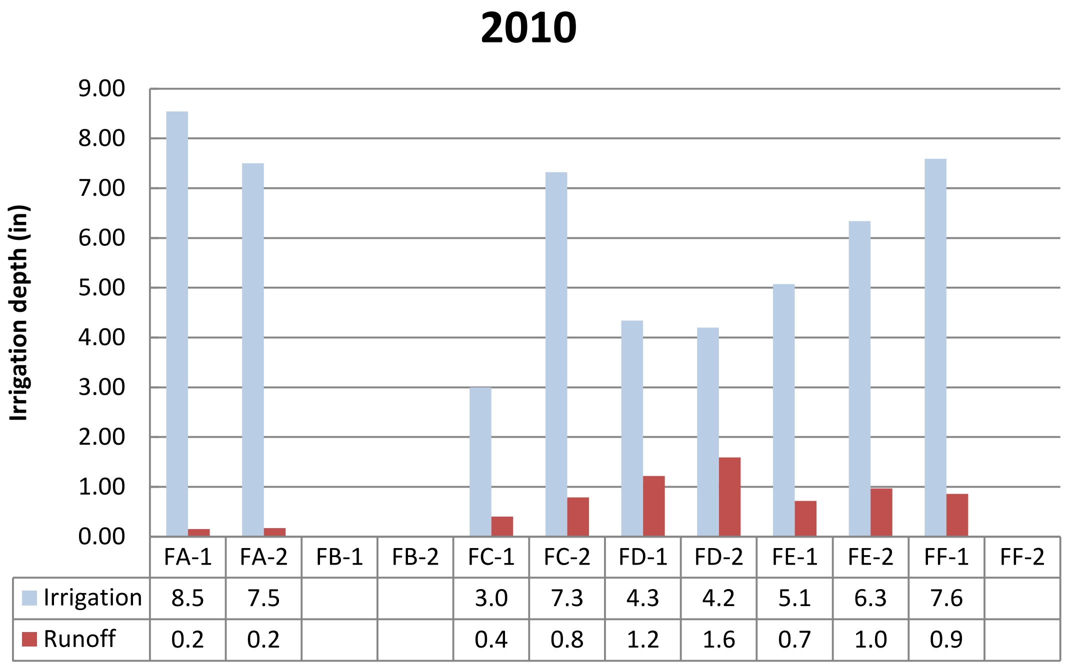


Figure 26. Irrigation depth versus surface runoff recorded on the six demonstration sites during two irrigation events in 2009.

Table 6. Flow-rates applied per row and run lengths for the furrows for 2009. Some fields are not square and the lengths of both sides are reported.

Site	Flow (gpm)	Rows	Flow-rate per row (gpm)	Maximum length (ft)	Minimum length (ft)
FA-1	1100	60	18.3	1305	1305
FA-2	1000-1200	54-63	20.4-17.5		
FB-1	N/A	77	----------	1589	1396
FB-2	N/A	N/A			
FC-1	1100	63	17.4	1290	1290
FC-2	1100	74-80-97	14.9		
FD-1	2100	160-270	13.1-7.7	1426	1305
FD-2	No irrigation	No irrigation	No irrigation		
FE-1	1200	101	11.8	817	210
FE-2	1600-1900	151	11.6		
FF-1	600 to 1000	66-122	12.1-6.5	755	743
FF-2	1300 to 2000	66-102	25-16.7		



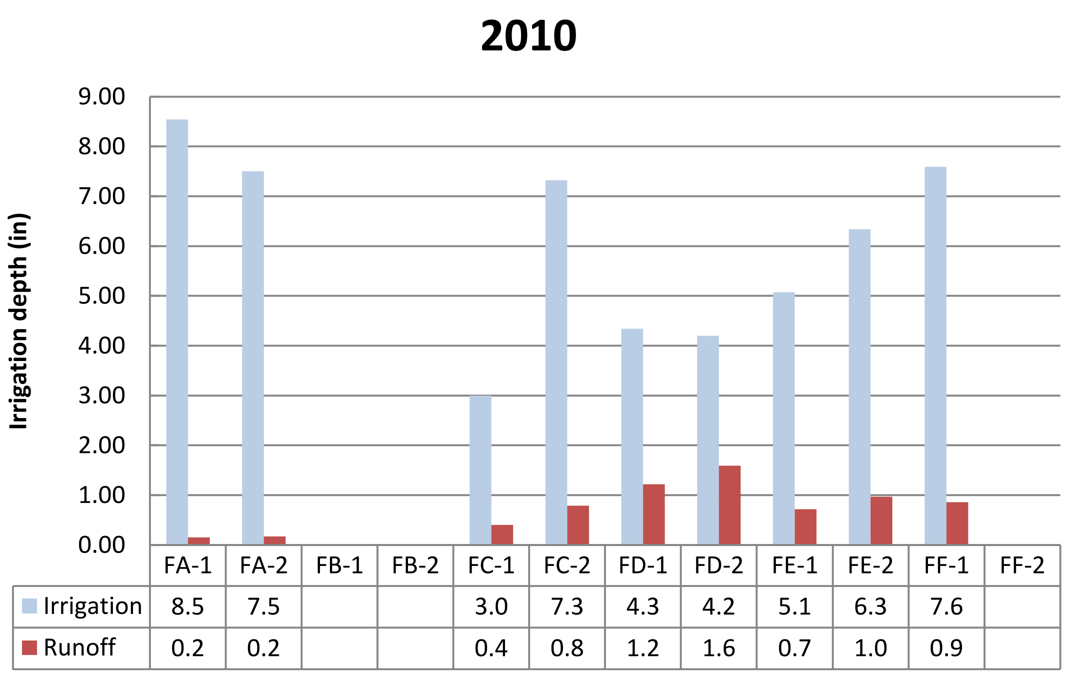
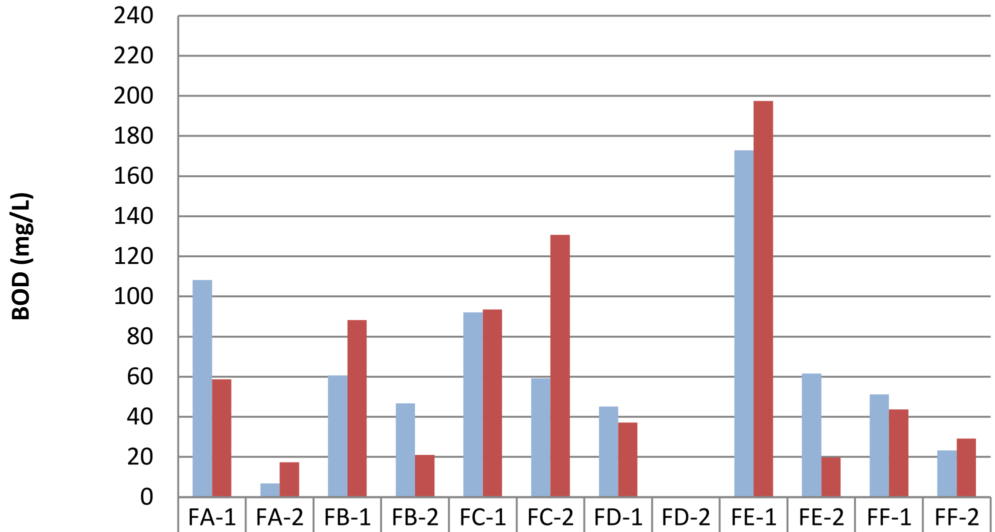


Figure 27. Irrigation depth versus surface runoff recorded on the six demonstration sites during two irrigation events in 2010.

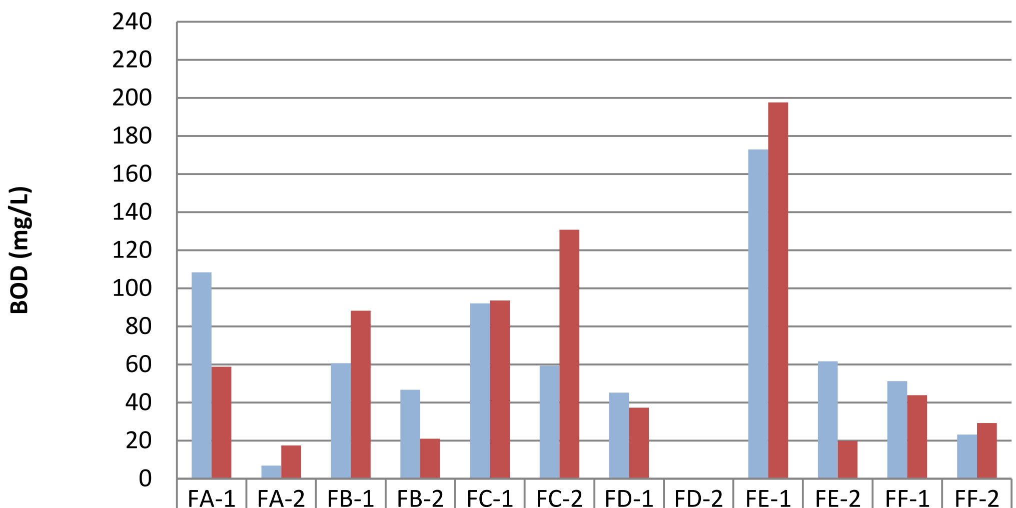
Irrigation and Runoff Water Quality Parameters

Biochemical Oxygen Demand

Biochemical oxygen demand is a chemical procedure for determining the amount of dissolved oxygen needed by aerobic biological organisms in a body of water to break down organic material present in a given water sample at certain temperature over a specific time period. This parameter is used as an indication of the organic quality of water. It is commonly expressed in milligrams of oxygen consumed per liter of sample during 5 days of incubation at 20 °C and is often used to determine the degree of organic pollution in water. The BOD of all the sites was less than 100 mg/l in 2009. Few exceptions were sites FA for irrigation water during the first irrigation, site FC for runoff water during the second irrigation, and site FE for irrigation and runoff during the first irrigation due to already high levels in water supplied for irrigation. When the irrigation water entered the field, the BOD only increased in sites FB during the second irrigation, site FC during the second irrigation and site FE during the first irrigation. In the rest of the sites, BOD was almost the same or decreased with runoff. Most rivers with good water quality will have a BOD below 1 mg/L. Moderately polluted rivers may have a BOD value in the range of 2 to 8 mg/L. Untreated sewage can have BOD that varies around 600 mg/L in Europe and as low as 200 mg/L in the U.S. (Sawyer et al., 2003). The water used for irrigation in this study comes from the Rio Grande where it is pumped and then distributed through a network of canals. It is possible that the Rio Grande had already high levels of BOD or it increased within the irrigation canals. Mostly it can be said that the BOD decreased in the sites during 2009 (Figure 28); however, BOD increased in most of the sites in 2010 (Figure 29). The most noticeable were sites FB and FE.

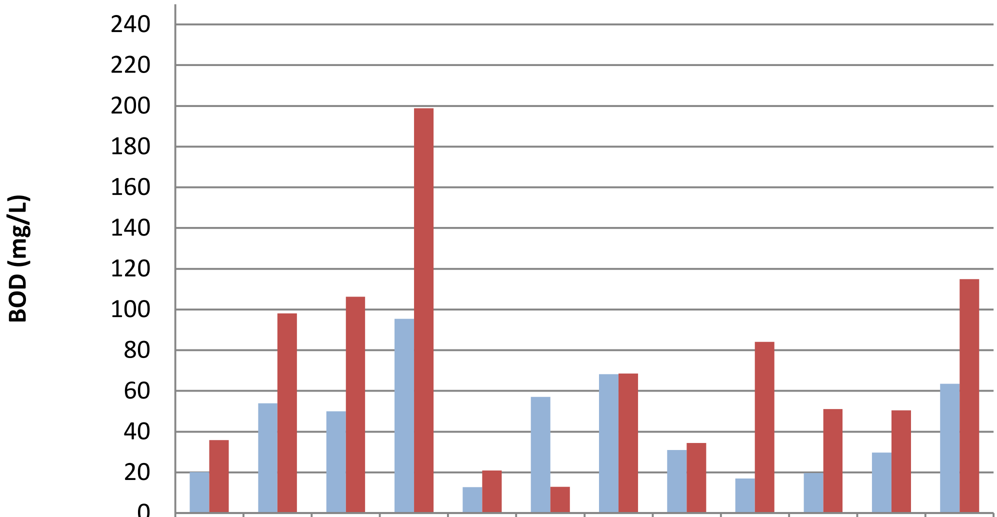


	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	108.2	6.84	60.67	46.71	92.04	59.17	45.13		172.9	61.54	51.24	23.17
Peak runoff	58.74	17.31	88.17	20.95	93.54	130.6	37.17		197.5	19.69	43.74	29.17

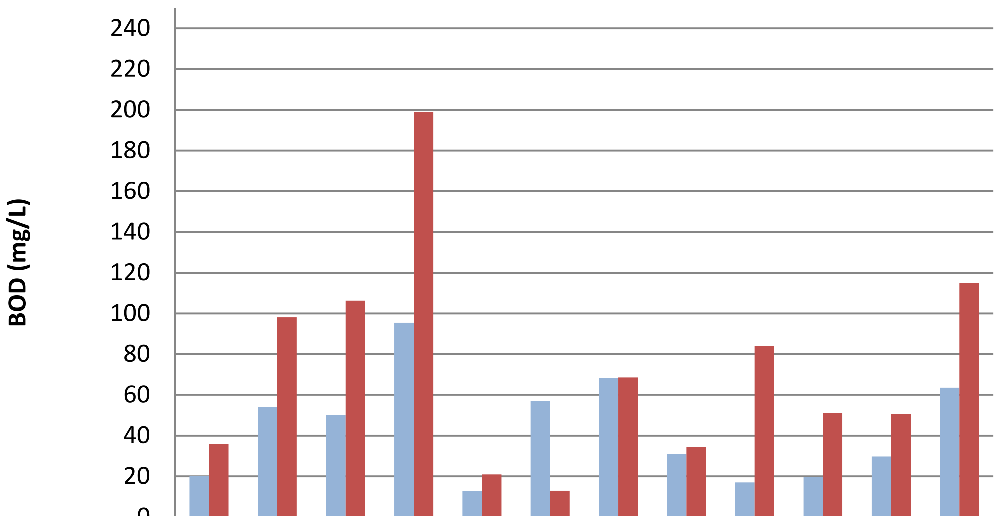


	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	108.2	6.84	60.67	46.71	92.04	59.17	45.13		172.9	61.54	51.24	23.17
Peak runoff	58.74	17.31	88.17	20.95	93.54	130.6	37.17		197.5	19.69	43.74	29.17

Figure 28. Biochemical oxygen demand of irrigation water and of peak runoff for six sites and two irrigation events in 2009.



	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	20.06	53.94	49.97	95.34	12.78	57.06	68.16	31.03	16.97	19.62	29.70	63.56
Peak runoff	35.81	98.04	106.2	198.8	20.88	12.96	68.53	34.41	84.09	51.12	50.40	114.9



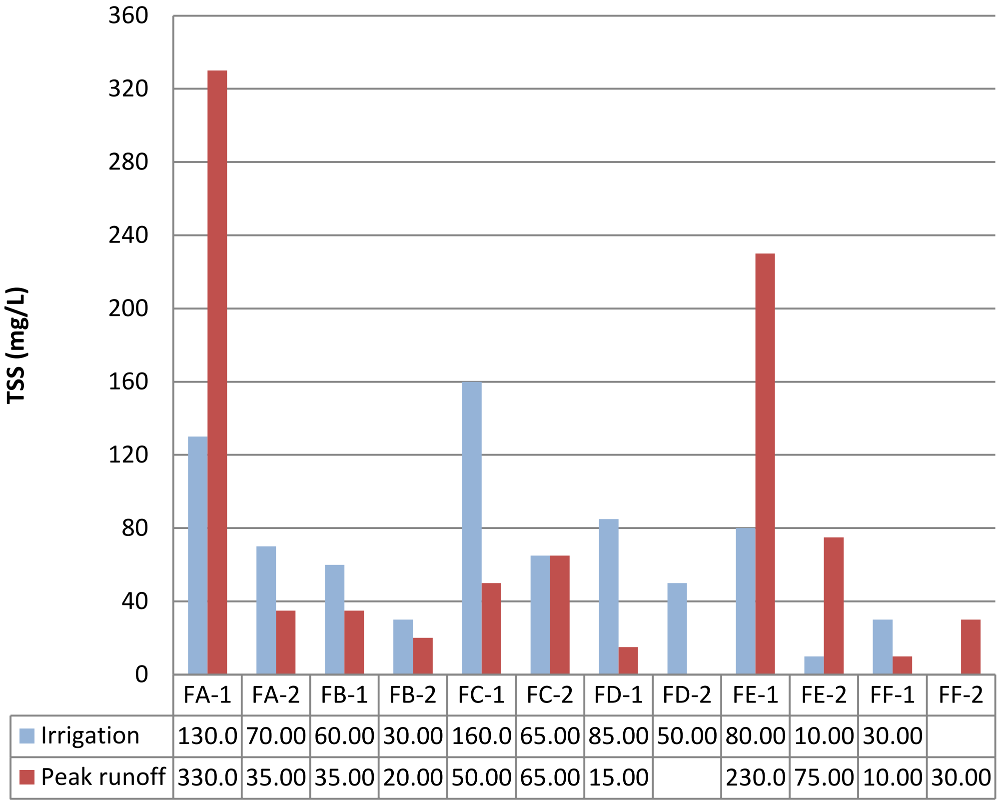
	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	20.06	53.94	49.97	95.34	12.78	57.06	68.16	31.03	16.97	19.62	29.70	63.56
Peak runoff	35.81	98.04	106.2	198.8	20.88	12.96	68.53	34.41	84.09	51.12	50.40	114.9

Figure 29. Biochemical oxygen demand of irrigation water and of peak runoff for six sites and two irrigation events in 2009.

Total Suspended Solids (TSS)

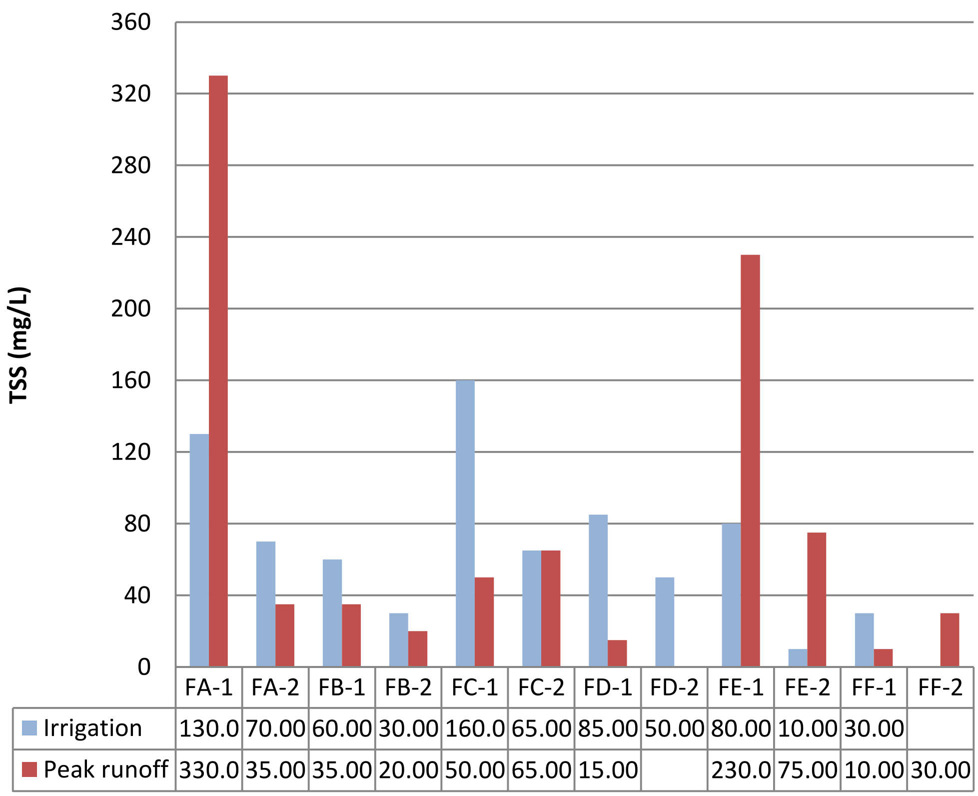
Total suspended solid is a parameter used to measure water quality and includes all the particles suspended in water retained by a filter per unit volume of water. In surface irrigation, water flow detaches particles of soil, which are transported downstream changing the cross section area of the furrow. This process is called erosion. One of the main contributors to erosion in surface irrigated systems is the stream size; treatment typically consists of settling prior to discharge the water through runoff (Strelkoff and Bjorneberg, 1999).

Water, as it advances down the furrows, detaches soil particles from sides causing the particles to settle in the bottom of the row or be transported elsewhere. This happens because the rapid wetting of the soil, as irrigation water travels down the furrow, traps air inside the clods making them explode (especially during the first irrigation). The transport process is called erosion. One of the main contributors to erosion in surface irrigated systems is the stream size. Farming practices such as no-till, minimize soil erosion and practices such as improved irrigation management using non-erosive stream sizes (smaller stream sizes), could reduce TSS and protect water quality. Most people consider water with a TSS concentration less than 20 mg/l to be clear. Water with TSS levels between 40 and 80 mg/l tends to appear cloudy, while water with concentrations over 150 mg/l usually appears dirty. The nature of the particles that comprise the suspended solids may cause these numbers to vary. In general, the TSS numbers of the runoff water were smaller than the ones of the supply water in 2009 (Figure 30). However there were some exceptions; most notably were sites FA for the first irrigation event and site FE for the second irrigation event, which increased from 130 to 330 mg/l and from 80 to 230 mg/l, respectively. In 2010, only two sites appeared to have high TSS in runoff; these were sites FA for the first irrigation and site FC during the second irrigation (Figure 31). The reason could be that the first and second irrigation of the season generally produce more erosion. Site FD also added some TSS in the runoff water. It is likely that this site increased its TSS value in runoff water compared to the supply water. This can be attributed to using earth ditches and siphon tubes instead of the poly-pipe and erosion at the upstream side increased.



TSS (mg/L)
360
320
280
240
200
160
120
80
40
0

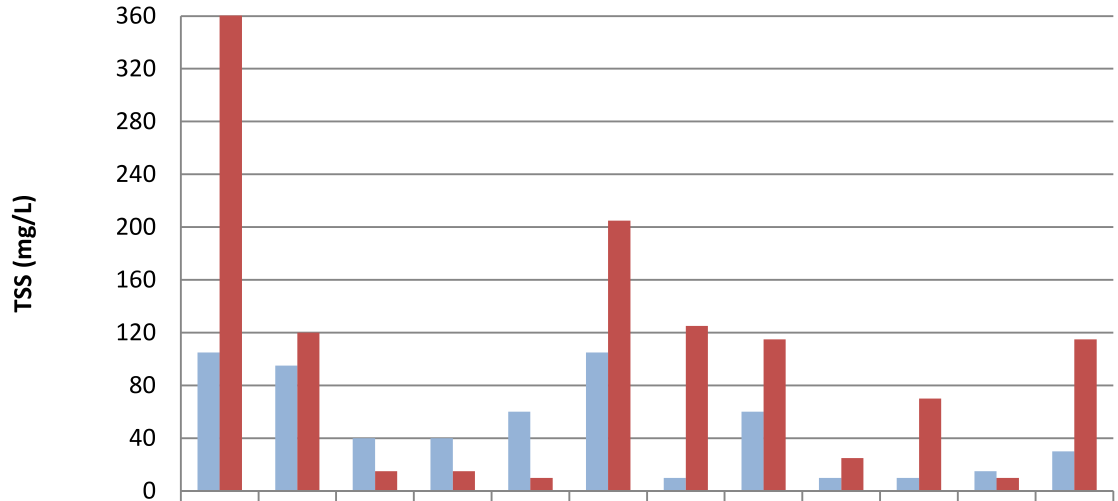
	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	130.0	70.00	60.00	30.00	160.0	65.00	85.00	50.00	80.00	10.00	30.00	
Peak runoff	330.0	35.00	35.00	20.00	50.00	65.00	15.00		230.0	75.00	10.00	30.00



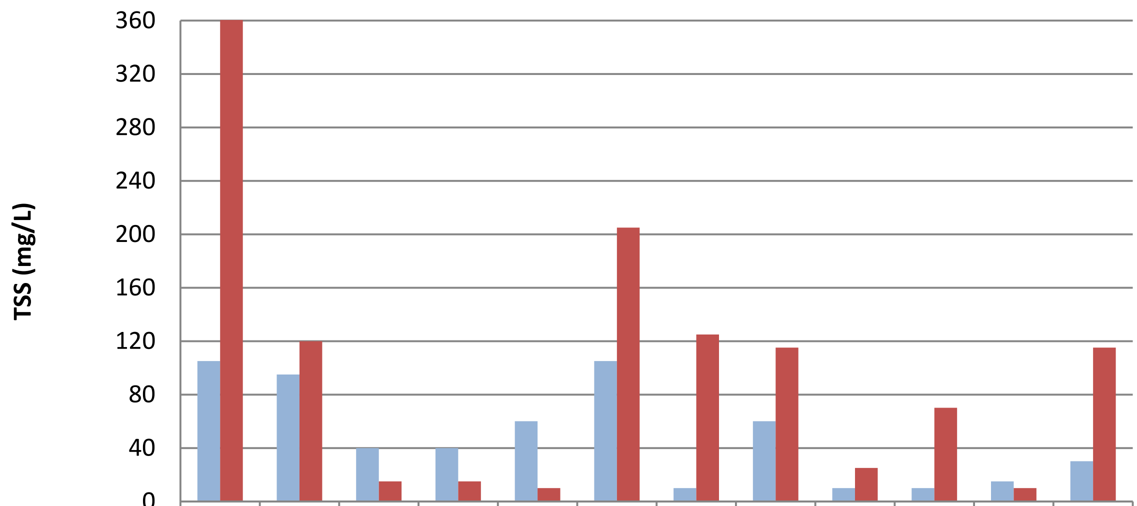
TSS (mg/L)
360
320
280
240
200
160
120
80
40
0

	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	130.0	70.00	60.00	30.00	160.0	65.00	85.00	50.00	80.00	10.00	30.00	
Peak runoff	330.0	35.00	35.00	20.00	50.00	65.00	15.00		230.0	75.00	10.00	30.00

Figure 30. Total suspended solids of irrigation water and of peak runoff for six sites and two irrigation events in 2009.



	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	105.00	95.00	40.00	40.00	60.00	105.00	10.00	60.00	10.00	10.00	15.00	30.00
Peak runoff	1230.0	120.00	15.00	15.00	10.00	205.00	125.00	115.00	25.00	70.00	10.00	115.00



	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	105.00	95.00	40.00	40.00	60.00	105.00	10.00	60.00	10.00	10.00	15.00	30.00
Peak runoff	1230.0	120.00	15.00	15.00	10.00	205.00	125.00	115.00	25.00	70.00	10.00	115.00

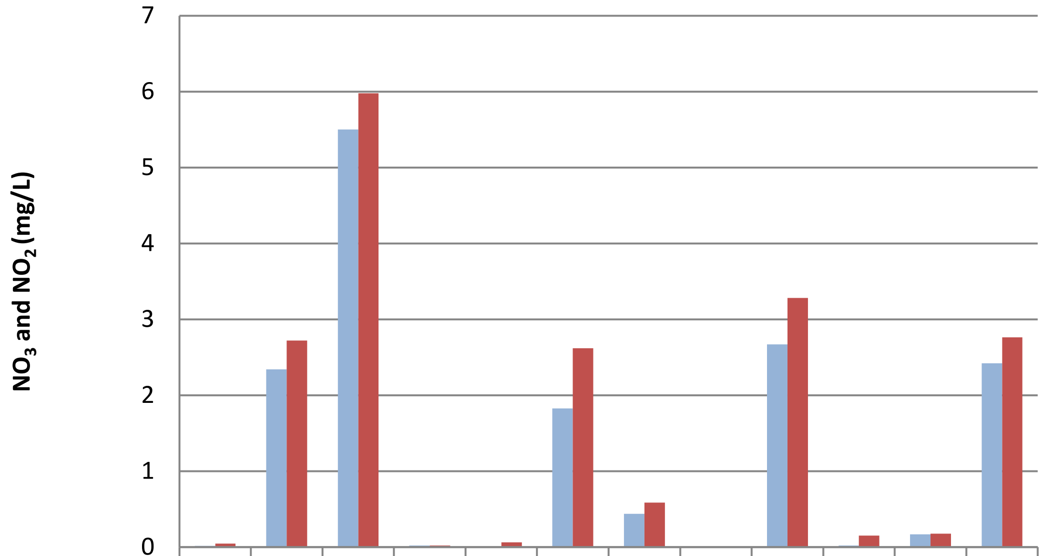
Figure 31. Total suspended solids of irrigation water and of peak runoff for six sites and two irrigation events in 2010.

Nitrates and Nitrites

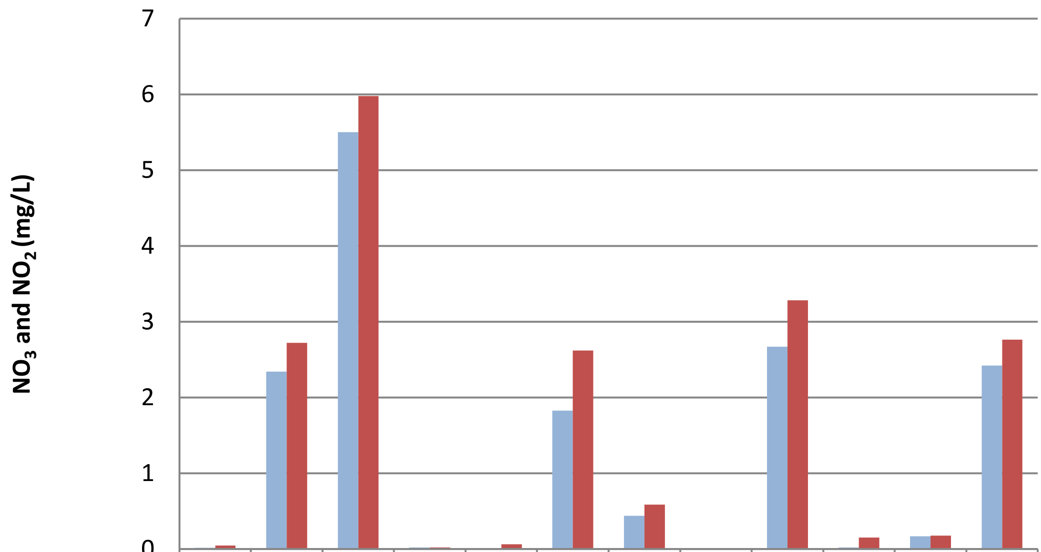
Nitrate (NO_3^-) and nitrite (NO_2^-) are naturally occurring inorganic ions that are part of the nitrogen cycle. Microbial action in soil or water decomposes waste containing organic nitrogen into ammonia, which is then oxidized to nitrite and nitrate. Because nitrite is easily oxidized to nitrate, nitrate is the compound predominantly found in groundwater and surface waters.
The U.S. Environmental Protection Agency (EPA) drinking water standard for nitrates is 10 parts per million (ppm). The concentration of nitrate in the water can be increased by contamination with nitrogen-containing fertilizers, human organic wastes, organic animal wastes and contamination from septic sewer systems. Nitrate containing compounds in the soil are generally soluble and readily leach with infiltration.

For 2009, the sum of nitrates and nitrites for all the sites were lower than 6 mg/l (Figure 32). The highest was in site FB in which the irrigation and peak runoff water collected was 5.5 and 6.0 mg/l respectively. The nitrates and nitrites of the supply water and peak runoff were about the same for most sites. Even if nitrates and nitrites were high for site FB-1, the impact on nutrient loadings were low (0.6 lbs/ac), because the runoff volume was low (0.5 in). The highest nitrate and nitrite loadings were observed for site FE for the second irrigation with a loading of 4 lbs/acre due to high volumes of runoff (6.43 in). It is important to mention that the nitrates and nitrites of the irrigation water were already high and little loadings were added on the farm during irrigation. The net additions at site FE were just 1.3 lbs/ac of nitrates and nitrites. The second highest nitrates loading was site FE-1 with 1.6 lbs/ac in the runoff water; however, the nitrates and nitrites of the irrigation water were 5.3 lbs/ac. The rest of the sites presented nitrate and nitrite loadings of the runoff water of less than 0.3 lbs/ac.

The same trend was observed in 2010 (Figure 33) with the exception of site FA for the first irrigation event. At this site, the nitrates and nitrites increased from 6.45 mg/l for the irrigation water to 13.72 mg/l in the runoff water. However, at site the nutrient loadings were low (0.5 lbs of nitrates and nitrites per acre) because of the low runoff produced (0.15 in). At site FD, the nitrate and nitrite loadings were 1.8 and 2.4 lbs/acre for the runoff water of the first and second irrigation respectively due to high volumes of runoff produced (1.2 and 1.6 inches). Nutrients were previously high on the irrigation water and the field helped to filter some of these high contents of nitrates and nitrites. The results indicate that the irrigation water already had high contents of nitrates and nitrites and this was variable from irrigation to irrigation. The gains of nitrates and nitrites loadings on the farm were small and the management practice that could impact nutrient loadings the most is the volume of runoff reduced. If irrigation is well attended, runoff can be reduced considerably.

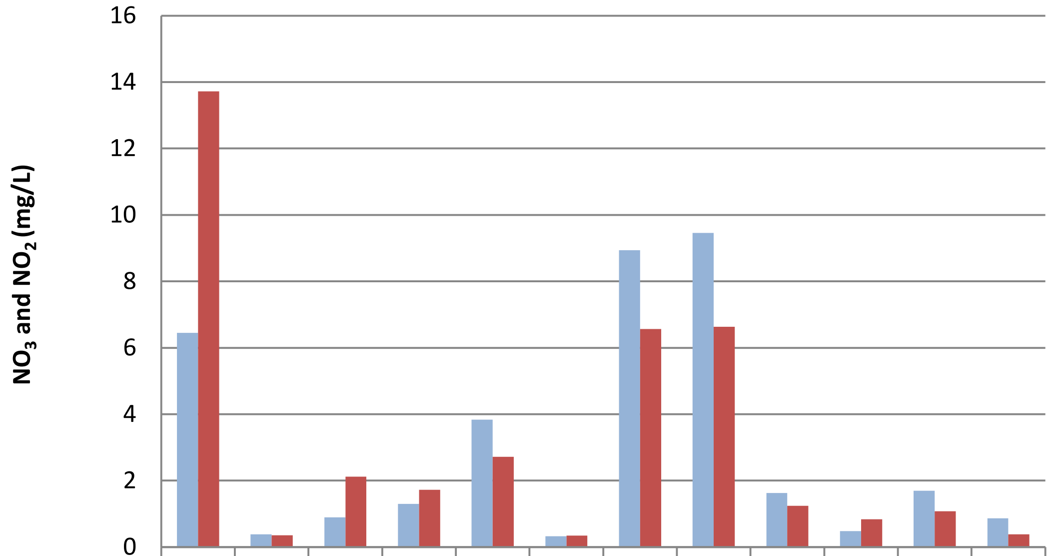


	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	0.02	2.34	5.50	0.02	0.00	1.83	0.44		2.67	0.02	0.17	2.42
Peak runoff	0.05	2.72	5.98	0.02	0.06	2.62	0.59		3.28	0.15	0.18	2.76

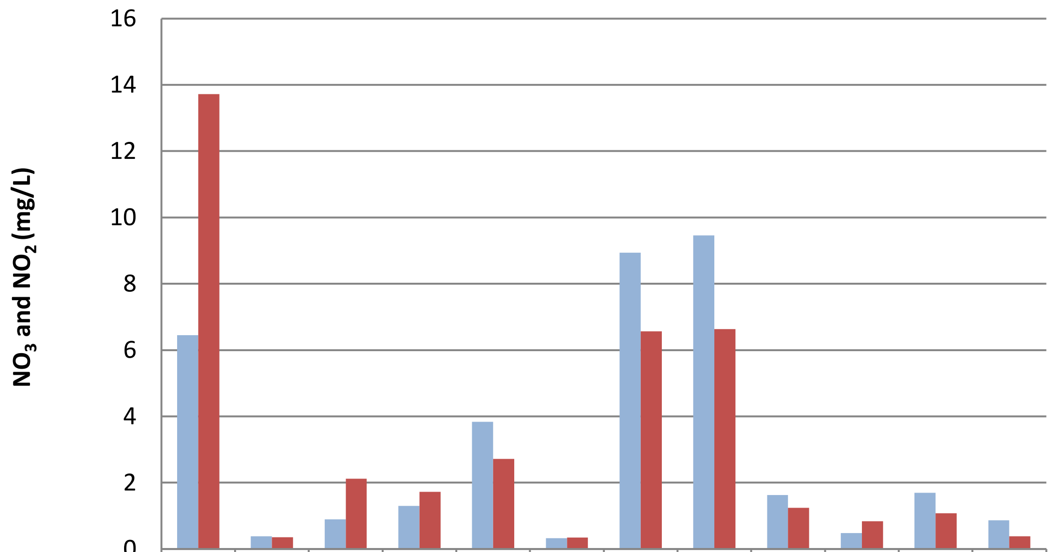


	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	0.02	2.34	5.50	0.02	0.00	1.83	0.44		2.67	0.02	0.17	2.42
Peak runoff	0.05	2.72	5.98	0.02	0.06	2.62	0.59		3.28	0.15	0.18	2.76

Figure 32. Nitrates and nitrites of irrigation water and of peak runoff for six sites and two irrigation events in 2009.



	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	6.45	0.39	0.89	1.30	3.83	0.32	8.93	9.45	1.62	0.48	1.70	0.86
Peak runoff	13.72	0.36	2.12	1.72	2.72	0.35	6.57	6.63	1.24	0.84	1.08	0.38

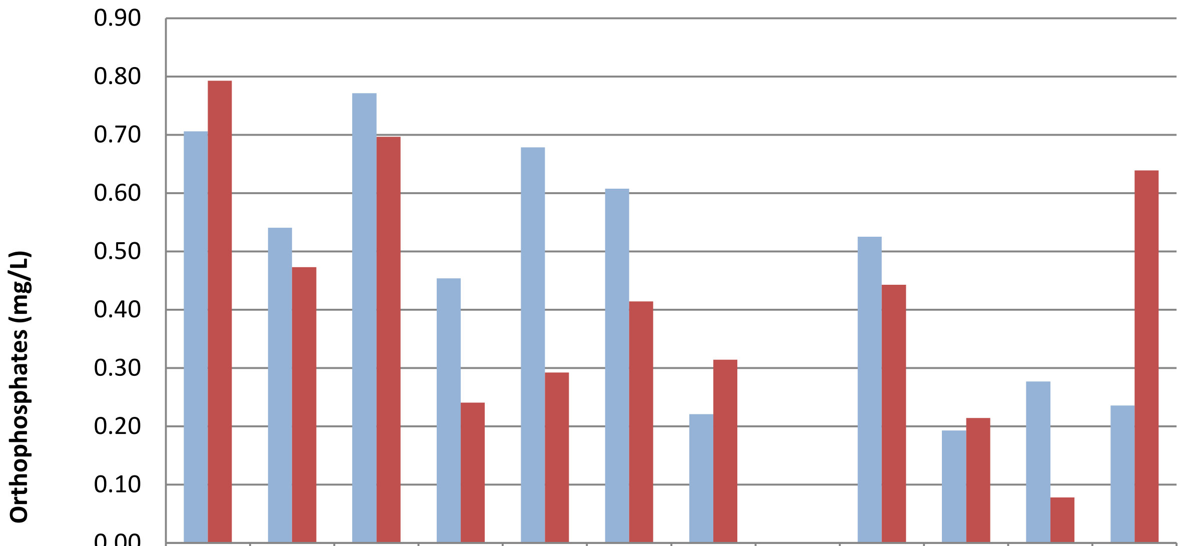


	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	6.45	0.39	0.89	1.30	3.83	0.32	8.93	9.45	1.62	0.48	1.70	0.86
Peak runoff	13.72	0.36	2.12	1.72	2.72	0.35	6.57	6.63	1.24	0.84	1.08	0.38

Figure 33. Nitrates and nitrites of irrigation water and of peak runoff for six sites and two irrigation events in 2010.

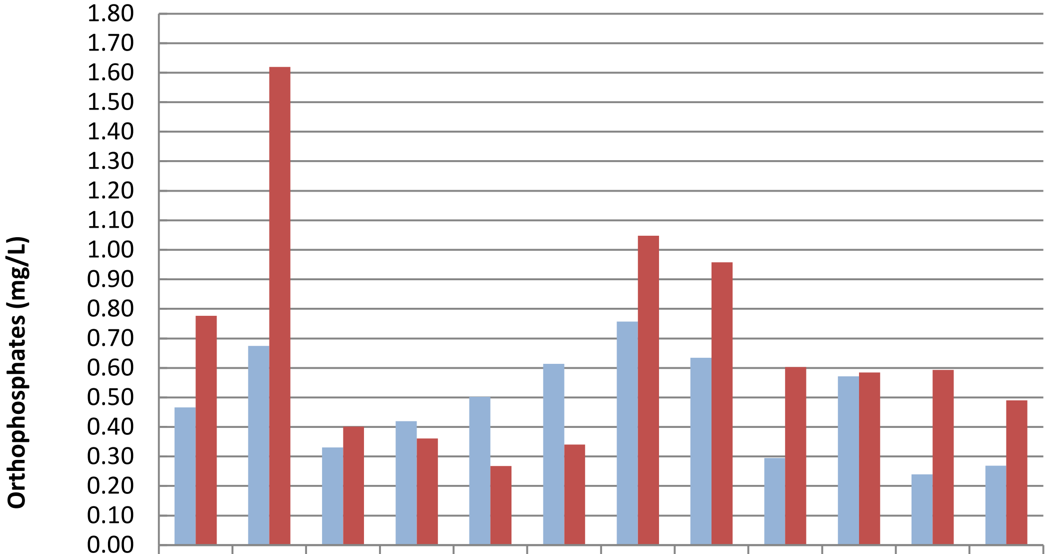
Orthophosphate

Orthophosphate ion $(PO_4)^{-3}$ is the simplest of a series of phosphates. In 2009, the orthophosphates were less than 0.8 mg/l and peak runoff contained almost the same or less orthophosphates than the irrigation water (Figure 34). The only exceptions were sites FA for the first irrigation event, and site FF for the second irrigation event in which orthophosphates increased from 0.71 to 0.79 mg/l and from 0.24 to 0.64 mg/l, respectively. The nutrient loadings due to orthophosphates were extremely low for all sites. The highest concentration was 1.2 lbs/ac for site FF during the second irrigation, which was impacted by the highest runoff volume collected at this site. However, if the orthophosphates that irrigation water had already contained were subtracted, the orthophosphates loadings were just 0.4 lbs/ac. Similar to 2009, the nutrient loadings due to orthophosphates were extremely low in 2010. The orthophosphates increased in the peak runoff in sites FA and FD in 2010 (Figure 35). Excluding these two sites, the orthophosphates were also lower than 0.8 mg/l. Site FA produced more erosion and TSS, probably because of higher furrow stream size, which resulted in higher orthophosphates carried by sediments. Site FD also produced the highest runoff of all sites in 2010. This impacted the orthophosphate loadings, which were highest of all sites at 0.2 and 0.3 lbs/ac for the first and second irrigation. Like the nitrate and nitrites loadings, the orthophosphates loading is highly influenced by the amount of runoff.

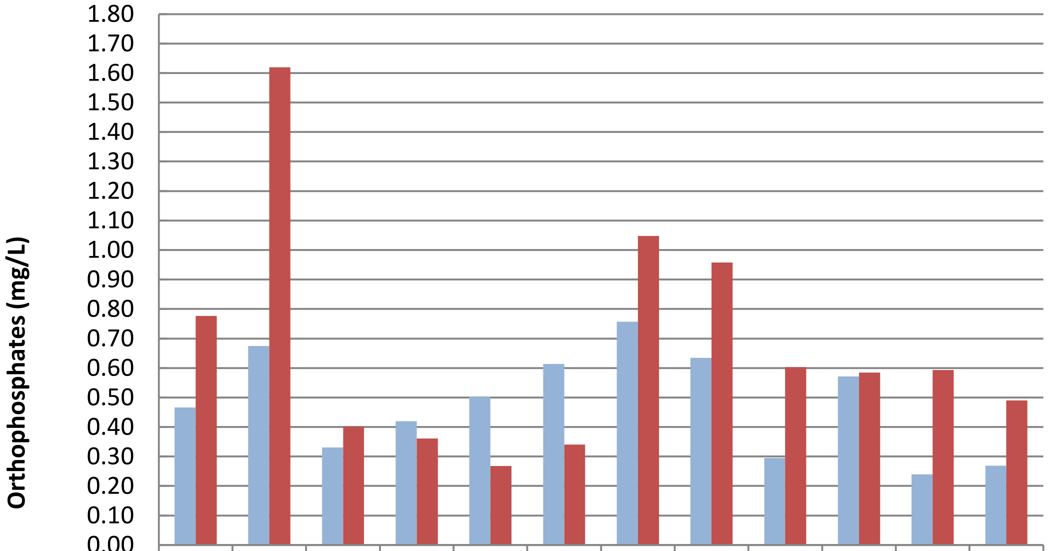


	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	0.71	0.54	0.77	0.45	0.68	0.61	0.22		0.53	0.19	0.28	0.24
Peak runoff	0.79	0.47	0.70	0.24	0.29	0.41	0.31		0.44	0.21	0.08	0.64

Figure 34. Orthophosphates of irrigation water and of peak runoff for six sites and two irrigation events in 2009.



	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	0.47	0.68	0.33	0.42	0.50	0.61	0.76	0.63	0.29	0.57	0.24	0.27
Peak runoff	0.78	1.62	0.40	0.36	0.27	0.34	1.05	0.96	0.60	0.58	0.59	0.49

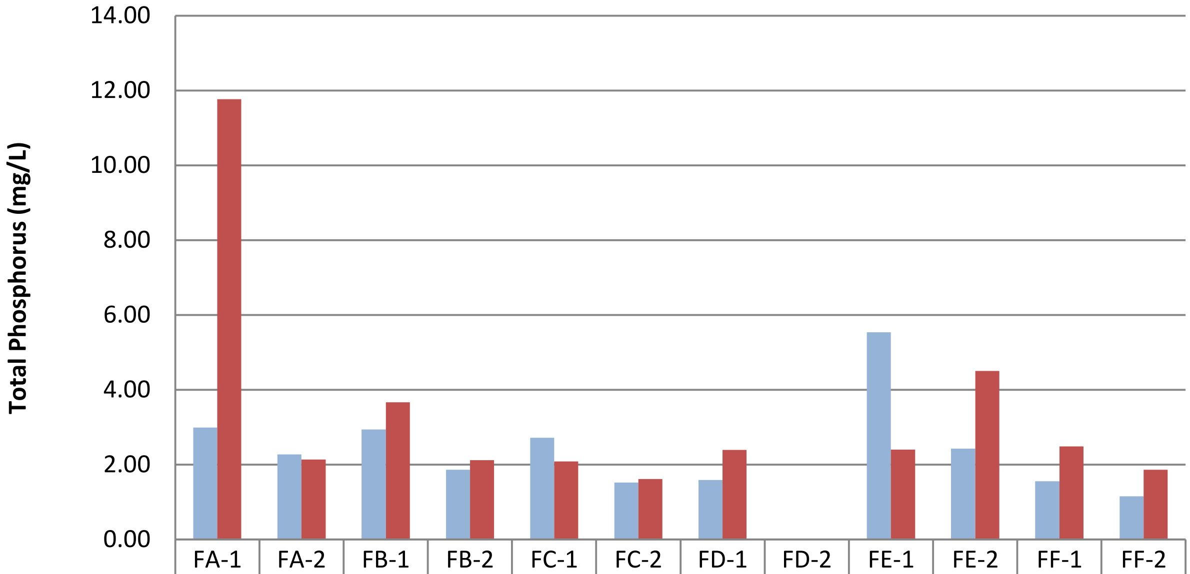


	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	0.47	0.68	0.33	0.42	0.50	0.61	0.76	0.63	0.29	0.57	0.24	0.27
Peak runoff	0.78	1.62	0.40	0.36	0.27	0.34	1.05	0.96	0.60	0.58	0.59	0.49

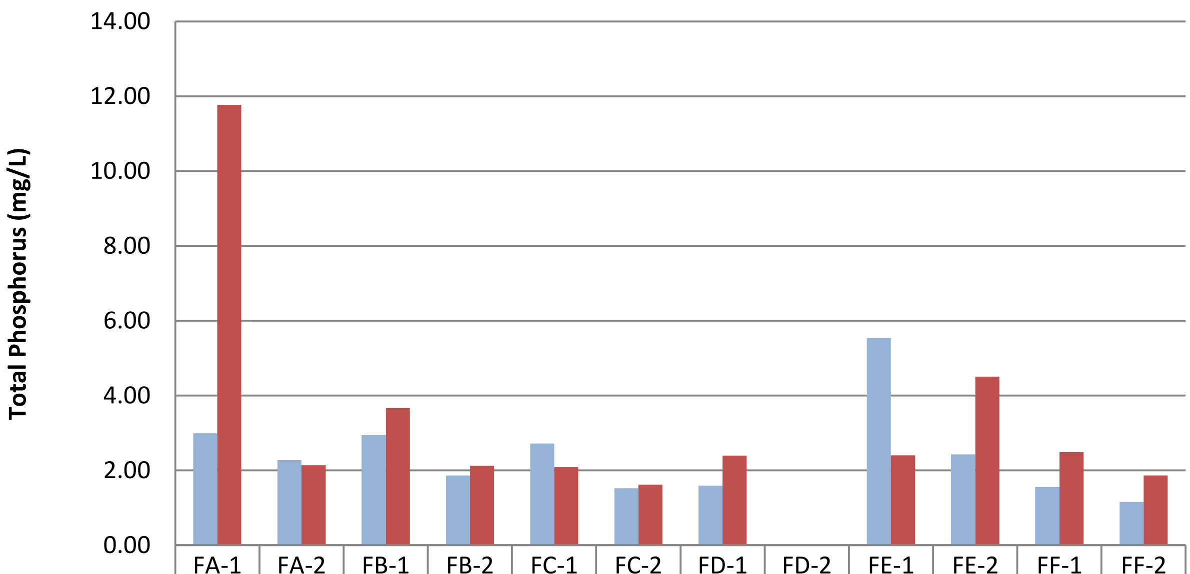
Figure 35. Orthophosphates of irrigation water and of peak runoff for six sites and two irrigation events in 2010.

Total Phosphorus

The total phosphorus in water was less than 6 mg/l in 2009 and less than 4 mg/l in 2010 (Figures 36 and 37). The highest increases from peak runoff occurred at site FA for the first irrigation event and at site FE for the second irrigation event in 2009. At most of the sites, the total phosphorus of the irrigation water and runoff were very similar. The total phosphorus of the peak runoff only increased significantly at sites FA-1 and FE-2. There is a relation between total suspended solids and total phosphorus. It may be possible to reduce the total phosphorus by decreasing the stream size in rows, especially during the first two irrigations. The highest nutrient loadings were observed at Site FA during the first irrigation, followed by site FF during the first and second irrigation and FE-1 with 3.1, 2.7, 1.3 and 1.16 lbs of total phosphorus per acre, respectively. This site also produced the highest runoff (1.2, 6.4, 2.3, 2.1 inches). In 2010, the sites that produced the higher total phosphorus levels were sites FA and FD. However, the highest total phosphorus loadings were for site FD during the first and second irrigation with 0.3 and 0.6 lbs/ac and this site also produced the largest runoff volumes. A similar trend was observed with orthophosphates and TSS.

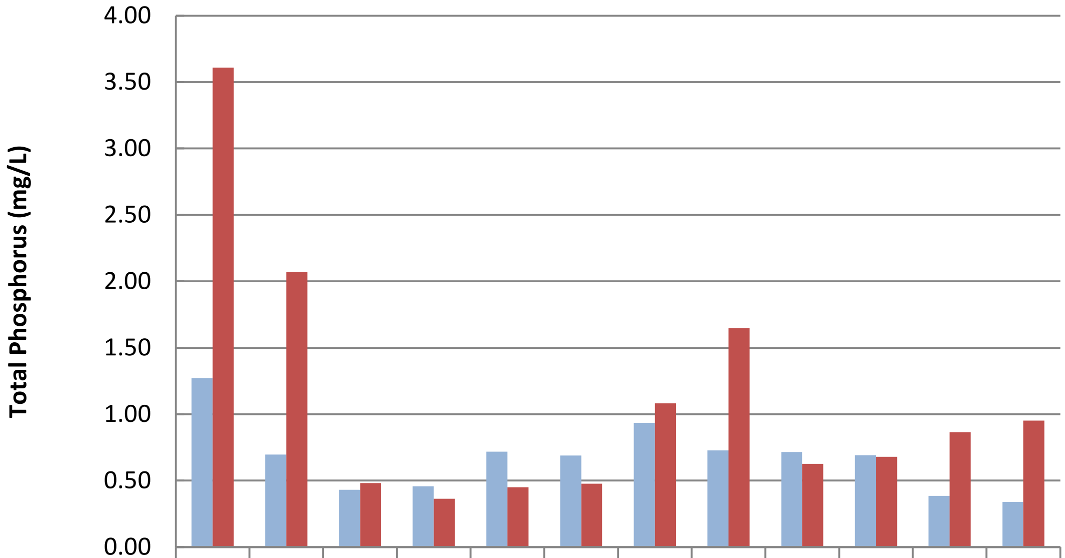


	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	2.99	2.27	2.94	1.86	2.72	1.52	1.59		5.54	2.43	1.55	1.16
Peak runoff	11.76	2.14	3.67	2.12	2.08	1.61	2.39		2.40	4.50	2.48	1.86

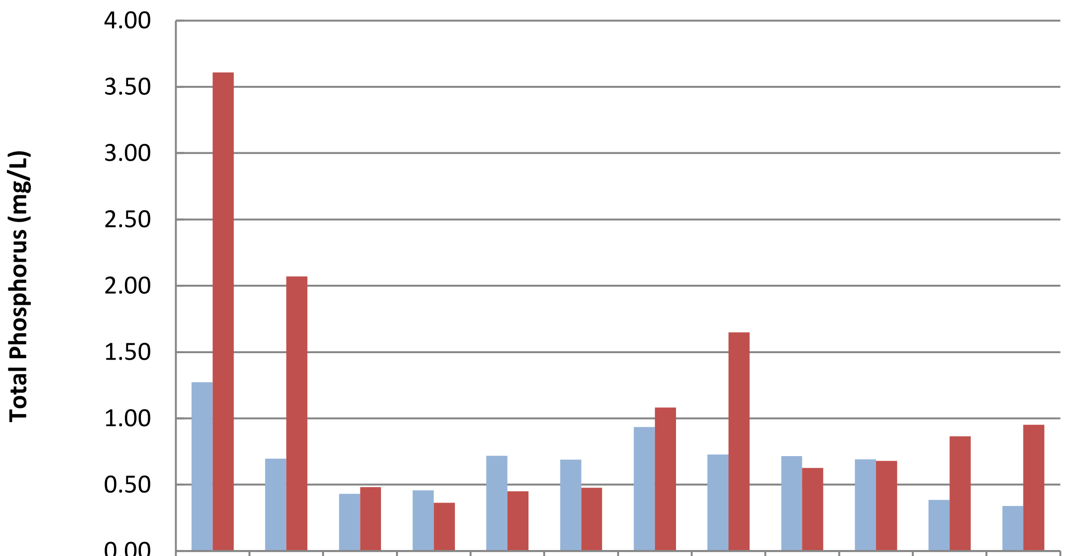


	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	2.99	2.27	2.94	1.86	2.72	1.52	1.59		5.54	2.43	1.55	1.16
Peak runoff	11.76	2.14	3.67	2.12	2.08	1.61	2.39		2.40	4.50	2.48	1.86

Figure 36. Total phosphorus of irrigation water and of peak runoff for six sites and two irrigation events in 2009.



	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	1.27	0.70	0.43	0.46	0.72	0.69	0.93	0.73	0.71	0.69	0.38	0.34
Peak runoff	3.61	2.07	0.48	0.36	0.45	0.48	1.08	1.65	0.63	0.68	0.87	0.95

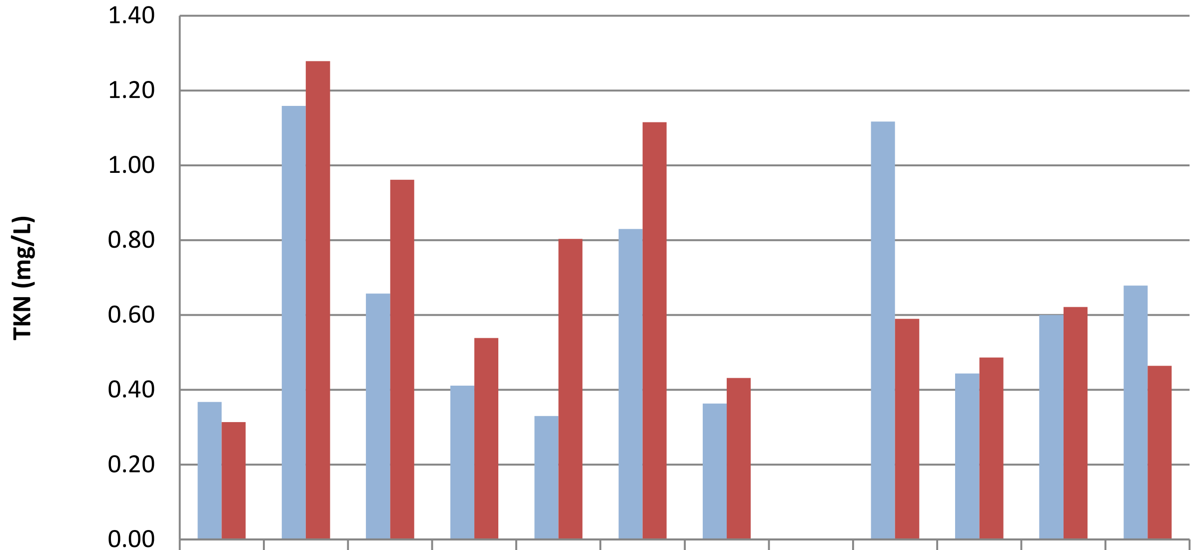


	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	1.27	0.70	0.43	0.46	0.72	0.69	0.93	0.73	0.71	0.69	0.38	0.34
Peak runoff	3.61	2.07	0.48	0.36	0.45	0.48	1.08	1.65	0.63	0.68	0.87	0.95

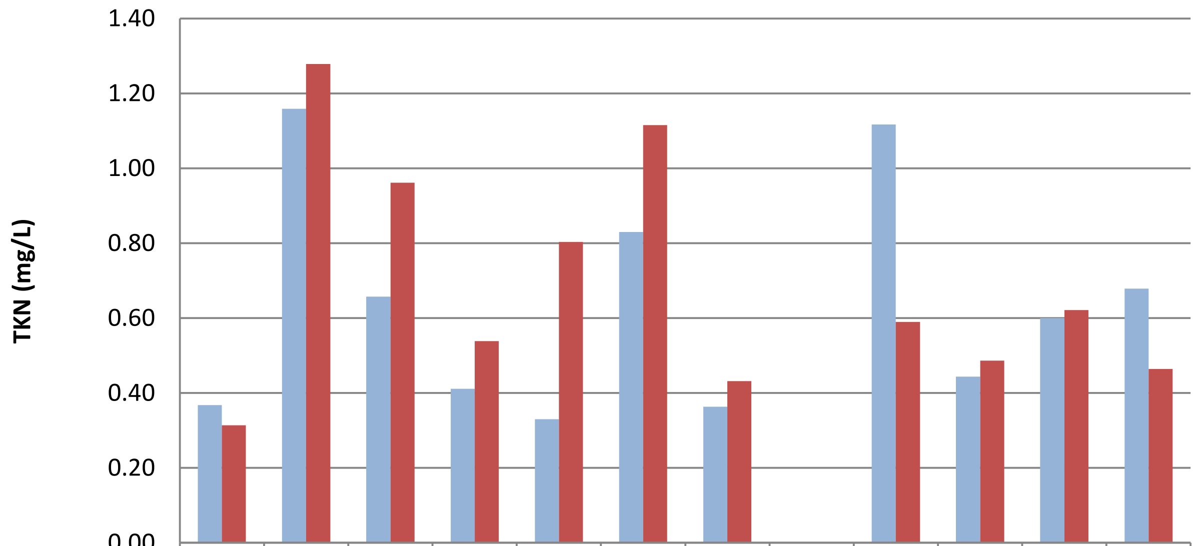
Figure 37. Total phosphorus of irrigation water and of peak runoff for six sites and two irrigation events in 2010.

Total Kjeldahl Nitrogen

Total Kjeldahl Nitrogen (TKN) analysis is the total of the organic nitrogen plus any ammonia-nitrogen in a sample. The ammonia-nitrogen samples were practically zero for all the sites and the values are not shown. Therefore, very small TKN values were observed during 2009 and 2010 (Figures 38 and 39). The values were less than 1.4 mg/l in 2009 and less than 0.6 mg/l in 2010. The TKN nutrient loadings of runoff water in 2009 were highest for site FF during the second irrigation with 0.7 lbs/ac. In 2010, the TKN nutrient loadings of the runoff water were less than 0.6 kg/ac for all sites and were influenced by low runoff amounts due to improved irrigation management. Most of the irrigation and runoff values were almost similar or the irrigation had higher TKN values than the runoff water with a few exceptions.

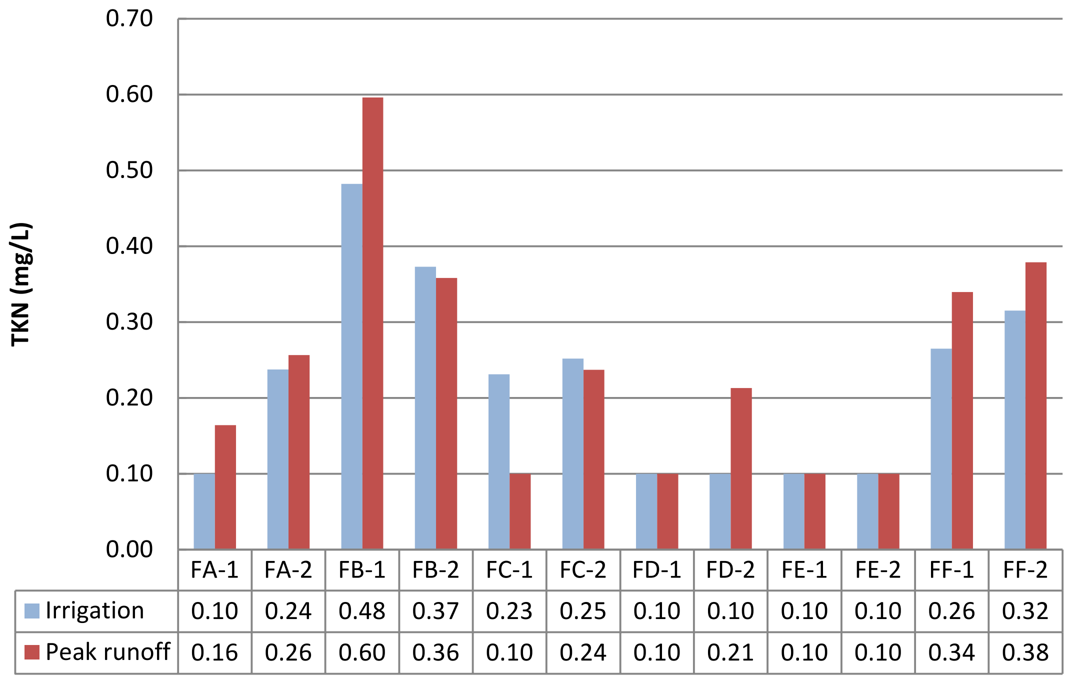


	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	0.37	1.16	0.66	0.41	0.33	0.83	0.36		1.12	0.44	0.60	0.68
Peak runoff	0.31	1.28	0.96	0.54	0.80	1.12	0.43		0.59	0.49	0.62	0.46



	FA-1	FA-2	FB-1	FB-2	FC-1	FC-2	FD-1	FD-2	FE-1	FE-2	FF-1	FF-2
Irrigation	0.37	1.16	0.66	0.41	0.33	0.83	0.36		1.12	0.44	0.60	0.68
Peak runoff	0.31	1.28	0.96	0.54	0.80	1.12	0.43		0.59	0.49	0.62	0.46

Figure 38. Total Kjeldahl nitrogen of irrigation water and of peak runoff for six sites and two irrigation events in 2009.



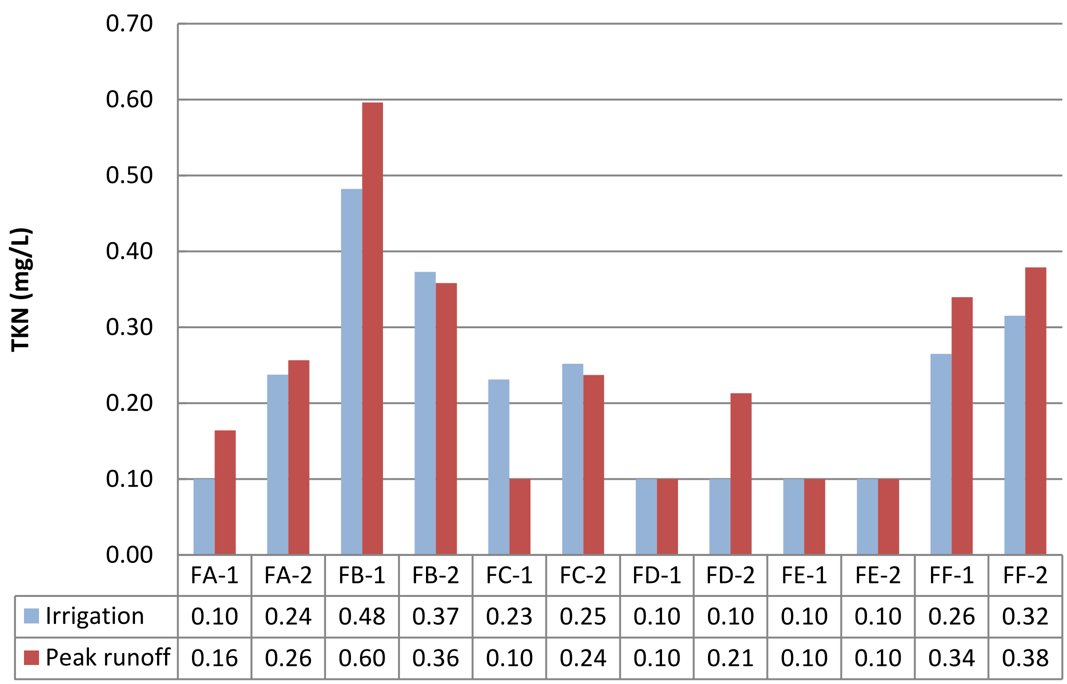


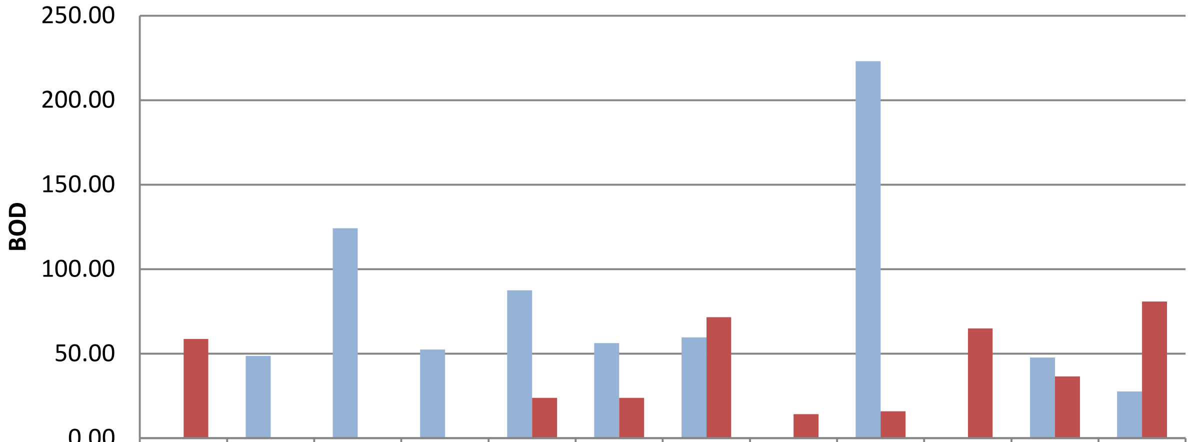
Figure 39. Total Kjedahl nitrogen of irrigation water and of peak runoff for six sites and two irrigation events in 2010.

Groundwater Quality (Water table and tile drains)

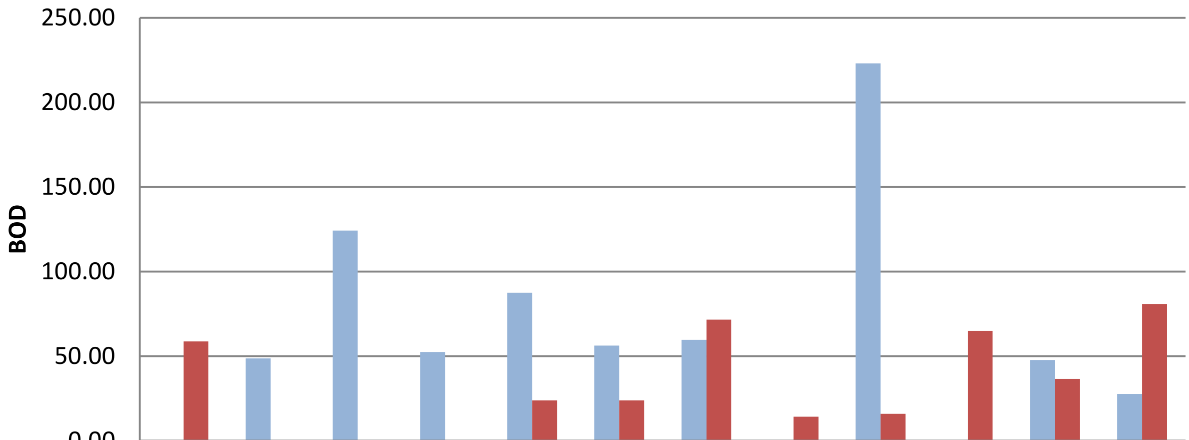
Water that percolates from the irrigation system reaches the water table. Groundwater samples were collected from the groundwater table in sites FA, FB, FC and FE. An observation well was drilled in these sites and the water samples were taken from the groundwater table by pumping. Sites FD and FF had drain tiles and the water sample was taken from the drain outlet that discharged to the drainage ditches.

Biochemical Oxygen Demand in Groundwater

The laboratory could not determine the values for all the samples. This is the reason that some values are not shown on the following figures. It can be observed that the values fluctuate year to year (Figure 40). The highest values were observed in 2009 for site FB with 124 mg/l and site FE with 223 mg/l.



	FA-1-GW	FA-2-GW	FB-1-GW	FB - 2-GW	FC-2-GW	FC-1-GW	FD-1-TD	FD-2-TD	FE-1-GW	FE-2-GW	FF-1-TD	FF-2-TD
2009	0.00	48.74	124.17	52.38	87.54	56.17	59.66		223.02		47.64	27.67
2010	58.69	0.00	0.00	0.00	23.76	23.76	71.53	14.16	15.84	64.92	36.60	80.81

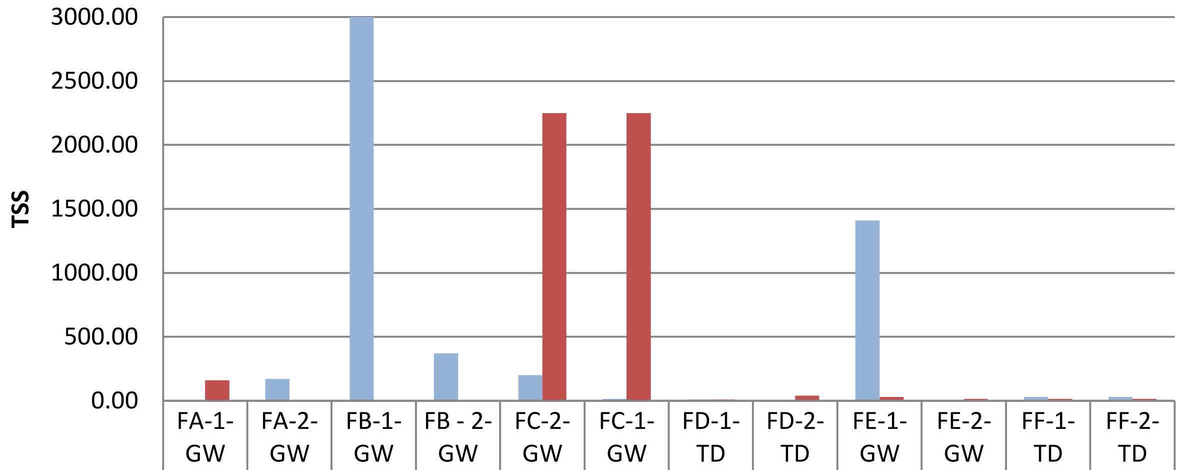


	FA-1-GW	FA-2-GW	FB-1-GW	FB - 2-GW	FC-2-GW	FC-1-GW	FD-1-TD	FD-2-TD	FE-1-GW	FE-2-GW	FF-1-TD	FF-2-TD
2009	0.00	48.74	124.17	52.38	87.54	56.17	59.66		223.02		47.64	27.67
2010	58.69	0.00	0.00	0.00	23.76	23.76	71.53	14.16	15.84	64.92	36.60	80.81

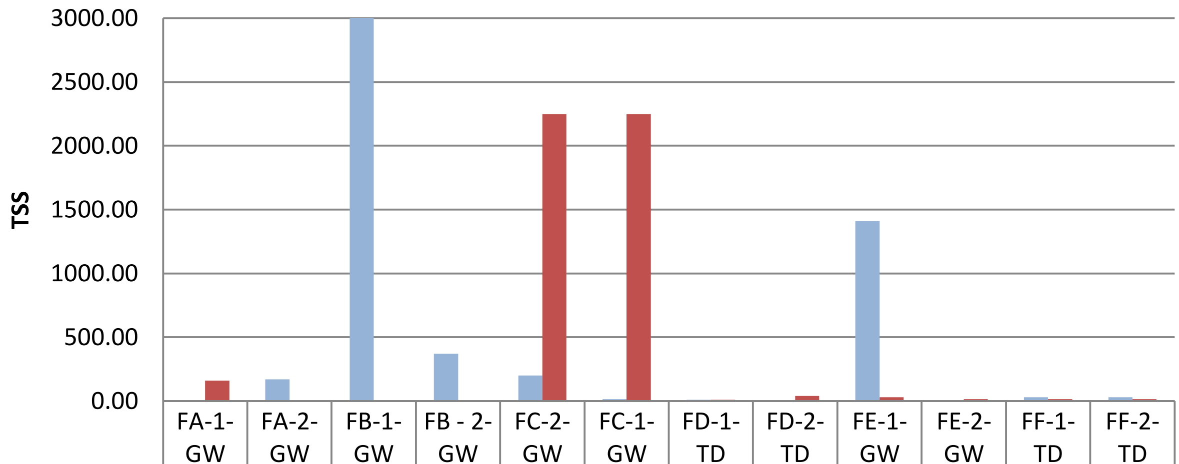
Figure 40. Biochemical oxygen demand of groundwater for six sites and two irrigation events during 2009 and 2010. GW samples were taken from the water table and the TD samples from the tile drain.

Total Suspended Solids in Groundwater

The total suspended solids of groundwater were relatively small for all the sites (Figure 41). A few exceptions were sites FE and FE in 2009 and site FC in 2010.



	FA-1-GW	FA-2-GW	FB-1-GW	FB - 2-GW	FC-2-GW	FC-1-GW	FD-1-TD	FD-2-TD	FE-1-GW	FE-2-GW	FF-1-TD	FF-2-TD
2009	0.00	170.00	53000.	370.00	200.00	15.00	10.00		1410.0		30.00	30.00
2010	160.00				2250.0	2250.0	10.00	40.00	30.00	15.00	15.00	15.00

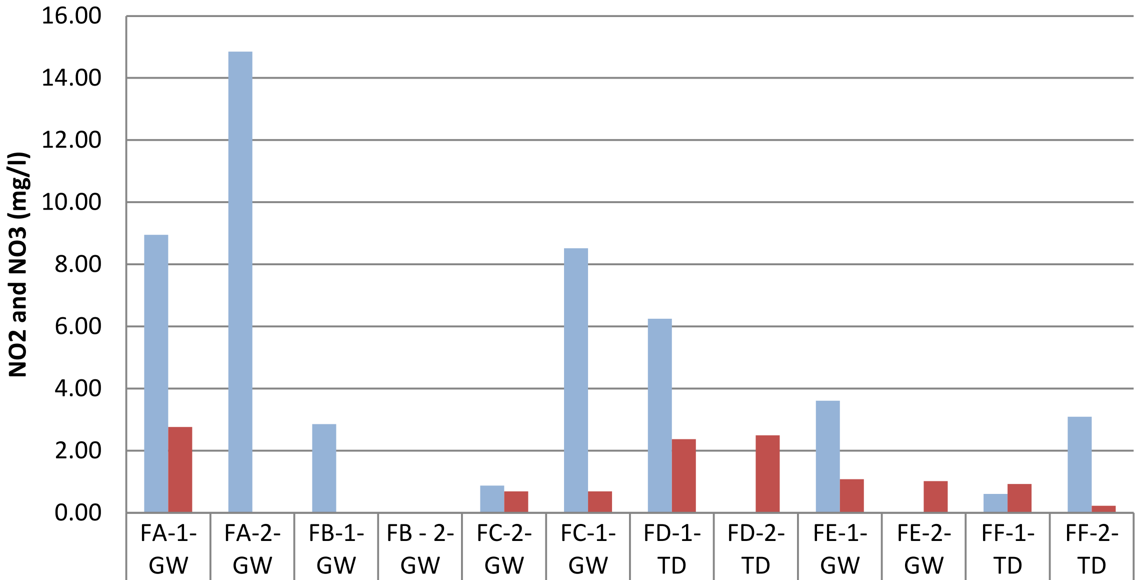


	FA-1-GW	FA-2-GW	FB-1-GW	FB - 2-GW	FC-2-GW	FC-1-GW	FD-1-TD	FD-2-TD	FE-1-GW	FE-2-GW	FF-1-TD	FF-2-TD
2009	0.00	170.00	53000.	370.00	200.00	15.00	10.00		1410.0		30.00	30.00
2010	160.00				2250.0	2250.0	10.00	40.00	30.00	15.00	15.00	15.00

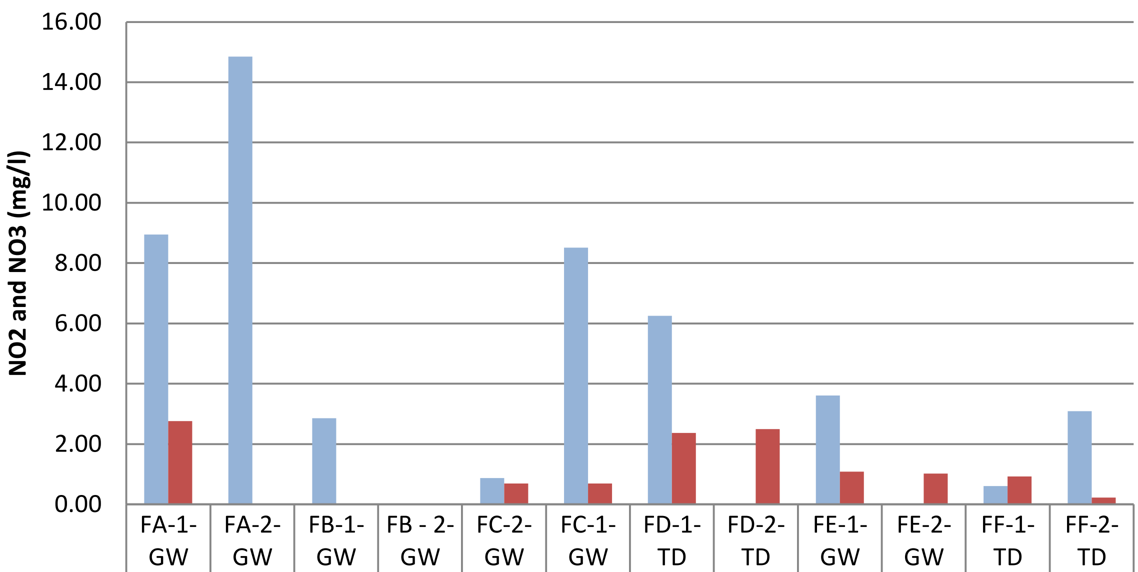
Figure 41. Total suspended solids of groundwater for six sites and two irrigation events during 2009 and 2010. Some values are not shown because the samples could not be analyzed. GW samples were taken from the water table and the TD samples from the tile drain.

Nitrates and Nitrites in Groundwater

The nitrates and nitrites of groundwater were less than 9 mg/l for most of the sites (Figure 42). The exception was site FA during the second irrigation in 2009. The increase in nitrates could be that this field may be over-fertilized over several years.



	FA-1-GW	FA-2-GW	FB-1-GW	FB - 2-GW	FC-2-GW	FC-1-GW	FD-1-TD	FD-2-TD	FE-1-GW	FE-2-GW	FF-1-TD	FF-2-TD
2009	8.95	14.85	2.85	0.02	0.87	8.51	6.25		3.61		0.61	3.09
2010	2.77				0.69	0.69	2.37	2.50	1.08	1.02	0.92	0.22

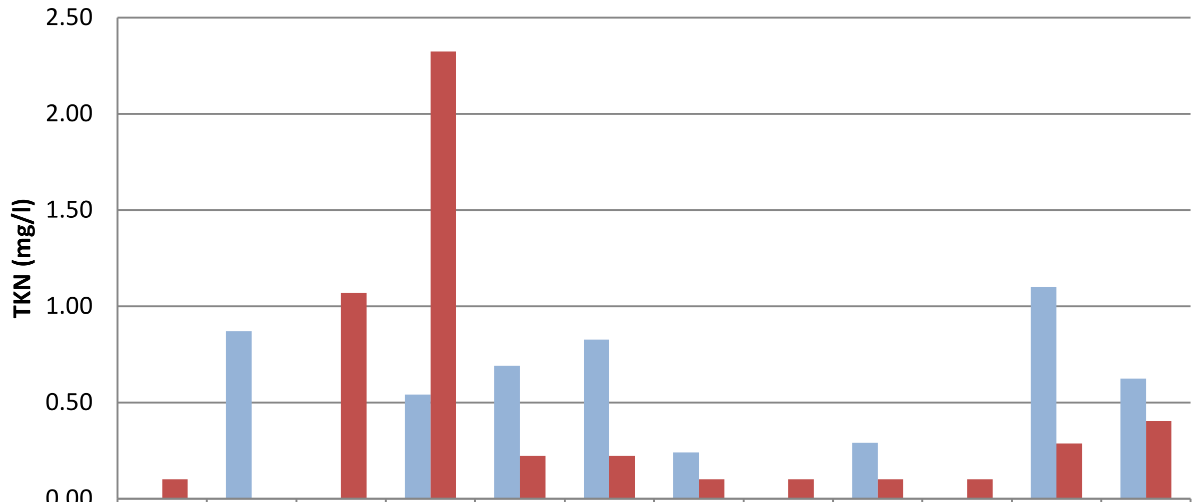


	FA-1-GW	FA-2-GW	FB-1-GW	FB - 2-GW	FC-2-GW	FC-1-GW	FD-1-TD	FD-2-TD	FE-1-GW	FE-2-GW	FF-1-TD	FF-2-TD
2009	8.95	14.85	2.85	0.02	0.87	8.51	6.25		3.61		0.61	3.09
2010	2.77				0.69	0.69	2.37	2.50	1.08	1.02	0.92	0.22

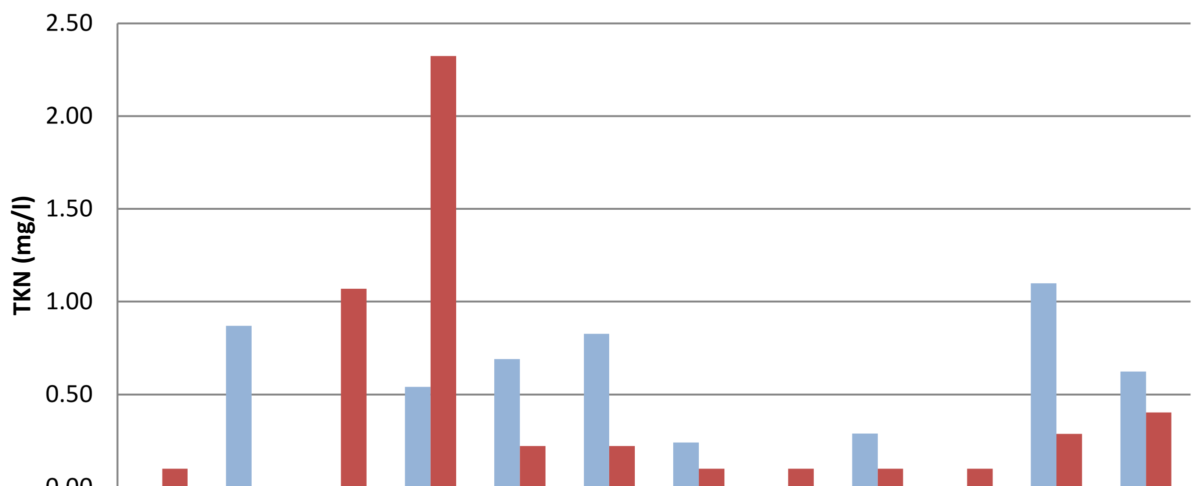
Figure 42. Nitrates and nitrites of groundwater for six sites and two irrigation events during 2009 and 2010. Some values are not shown because the samples could not be analyzed. GW samples were taken from the water table and the TD samples from the tile drain.

Total Kjedahl Nitrogen in Groundwater

Total Kjedahl nitrogen values were low and less than 1.1 mg/l for most of the soils (Figure 43). The only exception was site FB, which presented a high value during 2010. During this year, the TKN value of irrigation water was 0.37 mg/l during the first irrigation.



	FA-1-GW	FA-2-GW	FB-1-GW	FB - 2-GW	FC-2-GW	FC-1-GW	FD-1-TD	FD-2-TD	FE-1-GW	FE-2-GW	FF-1-TD	FF-2-TD
2009	0.00	0.87	0.00	0.54	0.69	0.83	0.24		0.29		1.10	0.62
2010	0.10		1.07	2.32	0.22	0.22	0.10	0.10	0.10	0.10	0.29	0.40

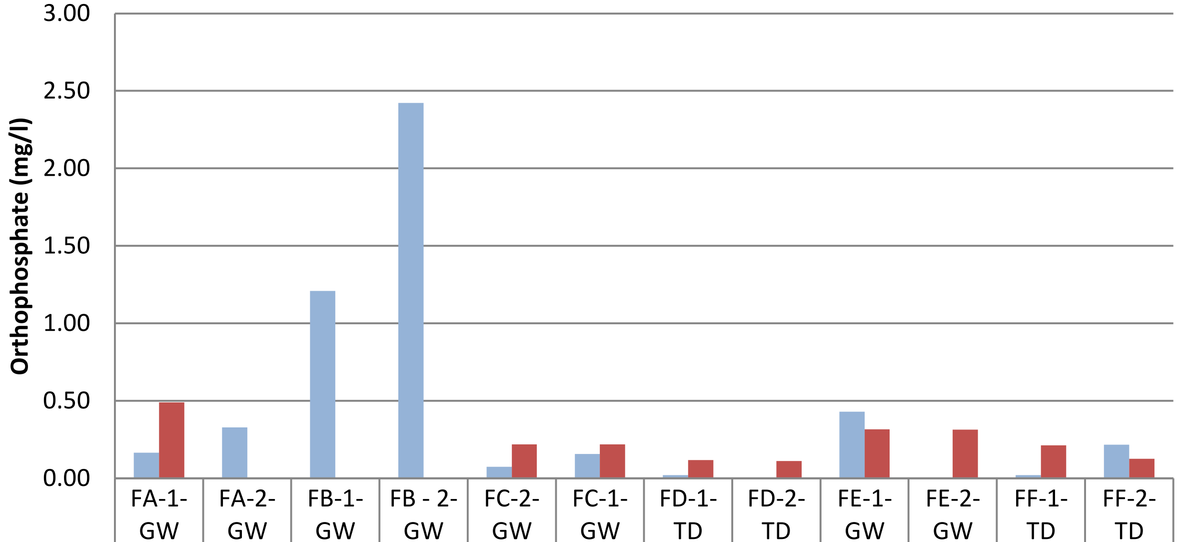


	FA-1-GW	FA-2-GW	FB-1-GW	FB - 2-GW	FC-2-GW	FC-1-GW	FD-1-TD	FD-2-TD	FE-1-GW	FE-2-GW	FF-1-TD	FF-2-TD
2009	0.00	0.87	0.00	0.54	0.69	0.83	0.24		0.29		1.10	0.62
2010	0.10		1.07	2.32	0.22	0.22	0.10	0.10	0.10	0.10	0.29	0.40

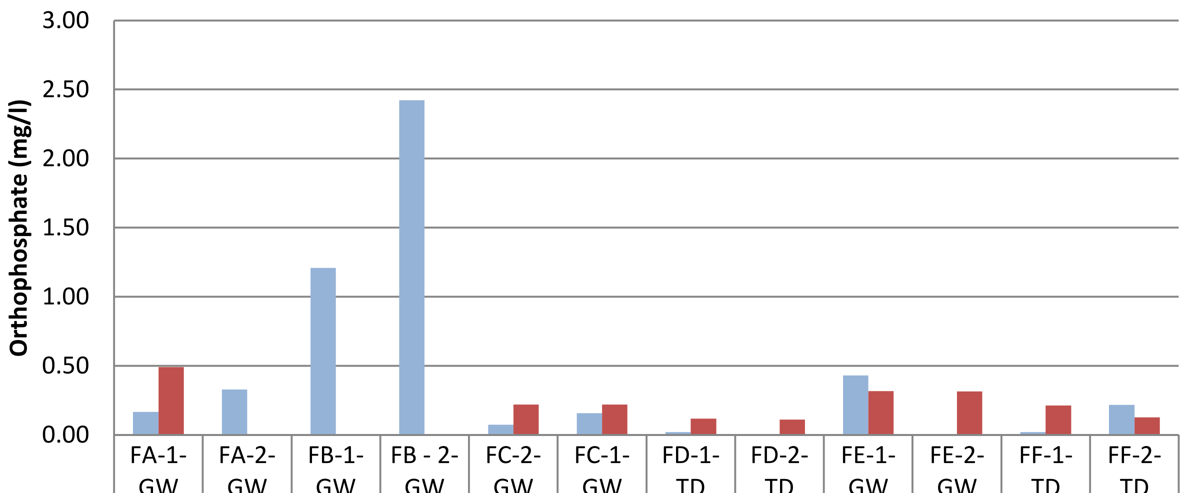
Figure 43. Total Kjedahl nitrogen of groundwater for six sites and two irrigation events during 2009 and 2010. Some values are not shown because the samples could not be analyzed. GW samples were taken from the water table and the TD samples from the tile drain.

Orthophosphate in Groundwater

The total orthophosphates values were low and less than 0.43 mg/l for most of the soils. The only exception was site FB, which presented a high value during 2009 (Figure 44). During this year, the TKN value of irrigation water was 1.21 and 2.42 mg/l during the first and second irrigation. In the rest of the sites, orthophosphates in groundwater were lower than levels of irrigation and peak runoff.



	FA-1-GW	FA-2-GW	FB-1-GW	FB - 2-GW	FC-2-GW	FC-1-GW	FD-1-TD	FD-2-TD	FE-1-GW	FE-2-GW	FF-1-TD	FF-2-TD
2009	0.17	0.33	1.21	2.42	0.07	0.16	0.02		0.43		0.02	0.22
2010	0.49				0.22	0.22	0.12	0.11	0.32	0.31	0.21	0.13

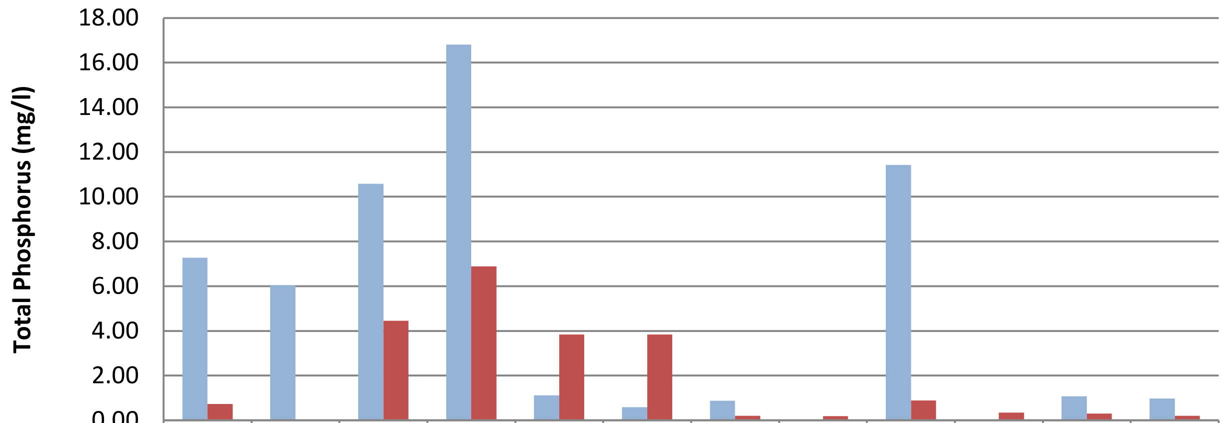


	FA-1-GW	FA-2-GW	FB-1-GW	FB - 2-GW	FC-2-GW	FC-1-GW	FD-1-TD	FD-2-TD	FE-1-GW	FE-2-GW	FF-1-TD	FF-2-TD
2009	0.17	0.33	1.21	2.42	0.07	0.16	0.02		0.43		0.02	0.22
2010	0.49				0.22	0.22	0.12	0.11	0.32	0.31	0.21	0.13

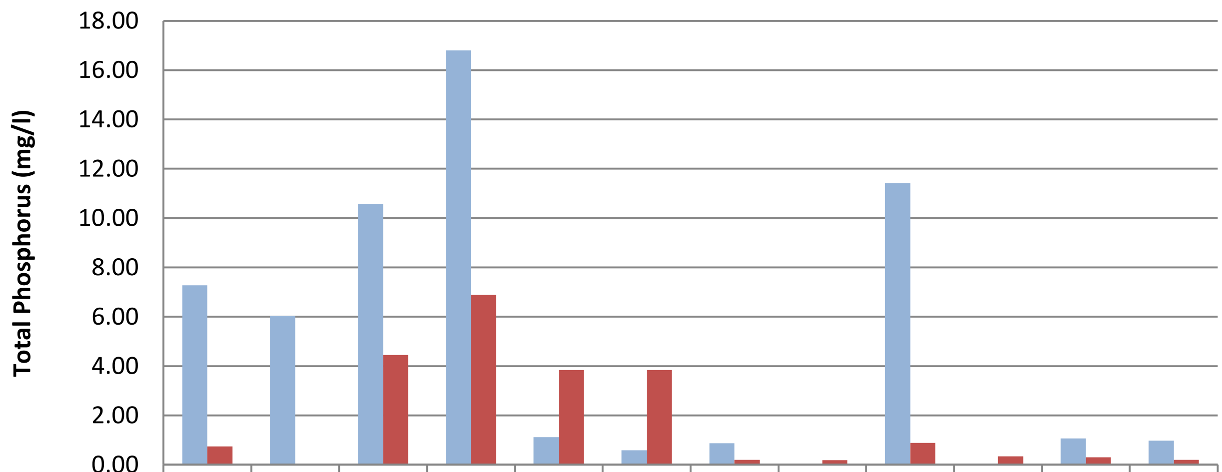
Figure 44. Orthophosphates of groundwater for six sites and two irrigation events during 2009 and 2010. Some values are not shown because the samples could not be analyzed. GW samples were taken from the water table and the TD samples from the tile drain.

Total Phosphorus in Groundwater.

Higher total phosphorus values were observed in 2009 (Figure 45). The highest values were observed in sites FA, FB, and FE. Site FB has sugarcane and also presented high values of orthophosphates and TSS.



	FA-1-GW	FA-2-GW	FB-1-GW	FB - 2-GW	FC-2-GW	FC-1-GW	FD-1-TD	FD-2-TD	FE-1-GW	FE-2-GW	FF-1-TD	FF-2-TD
2009	7.28	6.04	10.59	16.80	1.12	0.59	0.87		11.42		1.07	0.97
2010	0.74		4.45	6.88	3.84	3.84	0.20	0.18	0.89	0.34	0.30	0.20



	FA-1-GW	FA-2-GW	FB-1-GW	FB - 2-GW	FC-2-GW	FC-1-GW	FD-1-TD	FD-2-TD	FE-1-GW	FE-2-GW	FF-1-TD	FF-2-TD
2009	7.28	6.04	10.59	16.80	1.12	0.59	0.87		11.42		1.07	0.97
2010	0.74		4.45	6.88	3.84	3.84	0.20	0.18	0.89	0.34	0.30	0.20

Figure 45. Total phosphorus of groundwater for six sites and two irrigation events during 2009

and 2010. Some values are not shown because the samples could not be analyzed. GW samples were taken from the water table and the TD samples from the tile drain.

Field Days and Result Demonstrations

The following actions were completed:

A 30-minute presentation was conducted on irrigation management and best management practices for sugarcane at the Sugarcane Field Day in Weslaco, Texas on September 24, 2010. Seventy people attended the conference.

Dr. Juan Enciso presented a 30-minute presentation on best management practices and irrigation management during the Irrigation Expo on October 20-22, 2010. About 70 people attended the conference. Dr. Enciso provided an update on the progress of the project and discussed the impact of best irrigation management practices on water conservation and on the reduction of nutrient loadings to the Arroyo Colorado. He also explained how to improve surface irrigation management to reduce deep percolation and runoff water losses. A field day was also conducted at the Irrigation Expo to demonstrate best irrigation management practices. Thirty-five people attended this field day. Among the practices were the use of poly-pipe compared to earth ditches and siphon tubes, the use of metering devices, drip and sprinkler irrigation. Dr. Enciso also provided a demonstration on how to manage fertilizers with irrigation to avoid leaching and transport of fertilizer with runoff water. The tour lasted three hours.

DISCUSSION AND CONCLUSIONS

The predominant irrigation system in the Lower Rio Grande Valley is surface irrigation. The main BMPs adopted by the farmers in the Arroyo Colorado with this irrigation method are conservation crop rotation, irrigation land leveling, the use of poly-pipe and nutrient management. Only one farmer had filter strips at the lower end of the rows, which received irrigation runoff, and the same farmer had residue management including all the BMPs mentioned before. The main conclusions of this study are:

1. Of the six sites, only one farm had excessive runoff (site FF), and this site practically impacted the nutrients loadings of all the nutrients measured in the runoff water. The amount of runoff for this site was (6.4 inches) during the second irrigation in 2009. The same site also had high runoff during the first irrigation (2.4 inches) of the same year.
2. Four out of ten irrigation events evaluated in 2009 applied a depth greater than 9 inches. Considering that those soils cannot hold more than 6.6 inches of water for a soil depth of 3 feet, water only could leave the soil storage capacity through either deep percolation or runoff. Farmer's reports were given to producers in 2009, and this could have influenced the results of the 2010 growing season. All of the irrigation depths applied in 2010 were lower than 8.5 inches and the runoff amounts were lower than 1.6 inches. The highest runoff amount in 2010 was from one of the sites in which irrigation was monitored only for one irrigation event during 2009.
3. The results indicated that the irrigation water had already high contents of nitrates and nitrites, and this was variable from irrigation to irrigation. The gains of nitrates and nitrites loadings on the farm were small and the management practice that could have the highest impact on nutrient loadings is the amount of runoff. If irrigation is well attended, runoff can be reduced considerably. The total concentration of NO3- and NO2- in the irrigation and runoff water for all sites were lower than 6 mg/l in 2009 and lower than 10 mg/l in 2010 (with the exception of site FA in which the runoff concentration during the first irrigation was 13.7 mg/l). In 2009, the runoff water with the highest NO3- and NO2- loadings was site FF during the second irrigation with a concentration of 4.0 lbs/ac because of the large volume of runoff. In 2010, the sites that produced the highest NO3- and NO2- loadings was site FD with 1.8 and 2.4 lbs/ac during the first and second irrigation, and this site produced the largest runoff volume.
4. Most of the TKN values of irrigation and runoff were either similar, or irrigation had slightly higher TKN values than the runoff water, with a few exceptions. The TKN values were less than 1.4 mg/l in 2009 and less than 0.6 mg/l in 2010, and they were primarily influenced by the amount of runoff produced on the farms. The TKN loadings were lower than 0.3 lbs/ac for all sites during both years, with exception of site FF's second irrigation, which produced 0.7 lbs/ac.
5. TSS was higher for sites FA and FD during 2009 and 2010. At site FA, the high stream sizes per furrow (17.5 to 20.4 gpm/row) could have produced erosion and higher TSS that could also resulted in higher orthophosphates and total phosphorus in the runoff water than most other sites. In site FD, the high TSS could be caused by erosion on the upstream side of the farm because it was the only site that did not use poly-pipe, making it difficult to control irrigation and producing the highest runoff in 2010. The water flow detached some of the soil particles from the earth ditches.

6. In general, the nutrient loadings due to orthophosphates were extremely low for all sites during both years. The highest concentration was 1.2 lbs/ac of orthophosphates for site FF during the second irrigation of 2009, and it was impacted by the high runoff on this site (6.4 in). Site FF also produced the highest amount of total phosphorus loadings (2.7 lbs/ac) during the second irrigation.
7. The nutrient values of groundwater fluctuated from year to year and from irrigation to irrigation, but they were generally low. Groundwater had values of less than 9 mg/l of nitrates and nitrites (with the exception of site FA-second irrigation), lower than 1.1 mg/l of TKN (with exception of site FB-second irrigation-2010), lower than 0.49 mg/l of orthophosphates (with exception of site FB-first and second irrigation-2009), and lower than 7.28 mg/l of total phosphorus (with exception of site FB-first and second irrigation and site FE-first irrigation on 2009). The only sites that had nutrient management as BMPs were sites FC and FD, and these sites had one of the lowest nutrient values on the groundwater.
8. All of the evaluated sites had irrigation land leveling and crop rotation as best management practices. Future recommendation for best management practices should include nutrient management programs, which means to apply the fertilizer according to a soil analysis, and the improvement of irrigation management, which implies reducing runoff and using nonerosive stream sizes.

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Appendix C

Swat Modeling of

the Arroyo Colorado Watershed

ARROYO COLORADO
Know it. Respect it. Enjoy it.
Conócelo. Respétalo. Disfrútalo.

SWAT Modeling of the Arroyo Colorado Watershed

Narayanan Kannan, Ph.D.

Texas Water Resources Institute
TR-426
June 2012

SWAT MODELING OF

THE ARROYO COLORADO WATERSHED

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Arroyo Colorado Agricultural Nonpoint Source Assessment
The report highlights the accomplishment of Task 8 of TSSWCB Project number 06-10

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TABLE OF CONTENTS

Summary

A model setup of the Soil and Water Assessment Tool (SWAT) watershed model was developed to simulate flow and selected water quality parameters for the Arroyo Colorado watershed in South Texas. The model simulates flow, transport of sediment and nutrients, water temperature, dissolved oxygen, and biochemical oxygen demand. The model can also be used to estimate a total maximum daily load for the selected water quality parameters in the Arroyo Colorado. The model was calibrated and tested for flow with data measured during 2000–2009 at two streamflow-gaging stations. The flow was calibrated satisfactorily at monthly and daily intervals. In addition, the model was calibrated and tested sequentially for suspended sediment, orthophosphate, total phosphorus, nitrate nitrogen, ammonia nitrogen, total nitrogen, and dissolved oxygen, using data from 2000–2009. The simulated loads or concentrations of the selected water quality constituents generally matched the measured counterparts available for the calibration and validation periods. Two watershed scenarios were simulated for the years 2015 and 2025 after estimation of land cover maps for those years. The scenarios were intended to identify a suite of best management practices (BMPs) to address the depressed dissolved oxygen problem in the watershed.

Purpose and Scope

This report describes the setup, calibration, validation, and scenario analysis using the SWAT model to simulate the flow and water quality of the Arroyo Colorado watershed. The basin was subdivided into 17 subbasins—six in Segment 2201 and eleven in Segment 2202. The basin was characterized by a set of 475 hydrologic response units (HRUs) that are unique combinations of land cover, soil, and slope. For flow, 8 hydrologic process-related parameters were calibrated. A total of 26 process-related parameters were calibrated for water quality. Eleven years (1999–2009) of precipitation, air temperature, streamflow, and water-quality data were used for model calibration and validation. We used precipitation data from three stations; air temperature data from two stations; and streamflow data from two stations. Most of the water quality data used for model calibration and testing came from the station near Harlingen, Texas. Some water quality data available near Mercedes, Texas were also used in the study. Status of water quality in the river at present and for years 2015 and 2025 were projected using estimated land cover maps. Suggested solutions to bring dissolved oxygen in compliance for the stream were also discussed.

Introduction

The Arroyo Colorado watershed, a subwatershed of the Nueces-Rio Grande Coastal Basin, is located in the Lower Rio Grande Valley of South Texas and extends from near Mission, Texas, eastward to the Laguna Madre (fig. 1). Streamflow in the Arroyo Colorado primarily is sustained by municipal and industrial effluents. Additional streamflow results from irrigation return flow, rainfall runoff, and other point-source discharges. The Arroyo Colorado is used as a floodway, an inland waterway, and a recreational area for swimming, boating, and fishing, and is an important nursery and foraging area for shrimp, crab, and several types of marine fish.

The Texas Commission on Environmental Quality (TCEQ) has classified two reaches of the Arroyo Colorado based on the physical characteristics of the stream. Segment 2201, from the Port of Harlingen to the confluence with the Laguna Madre, is tidally influenced and has designated uses of contact recreation and high aquatic life. The nontidal segment of the Arroyo Colorado, Segment

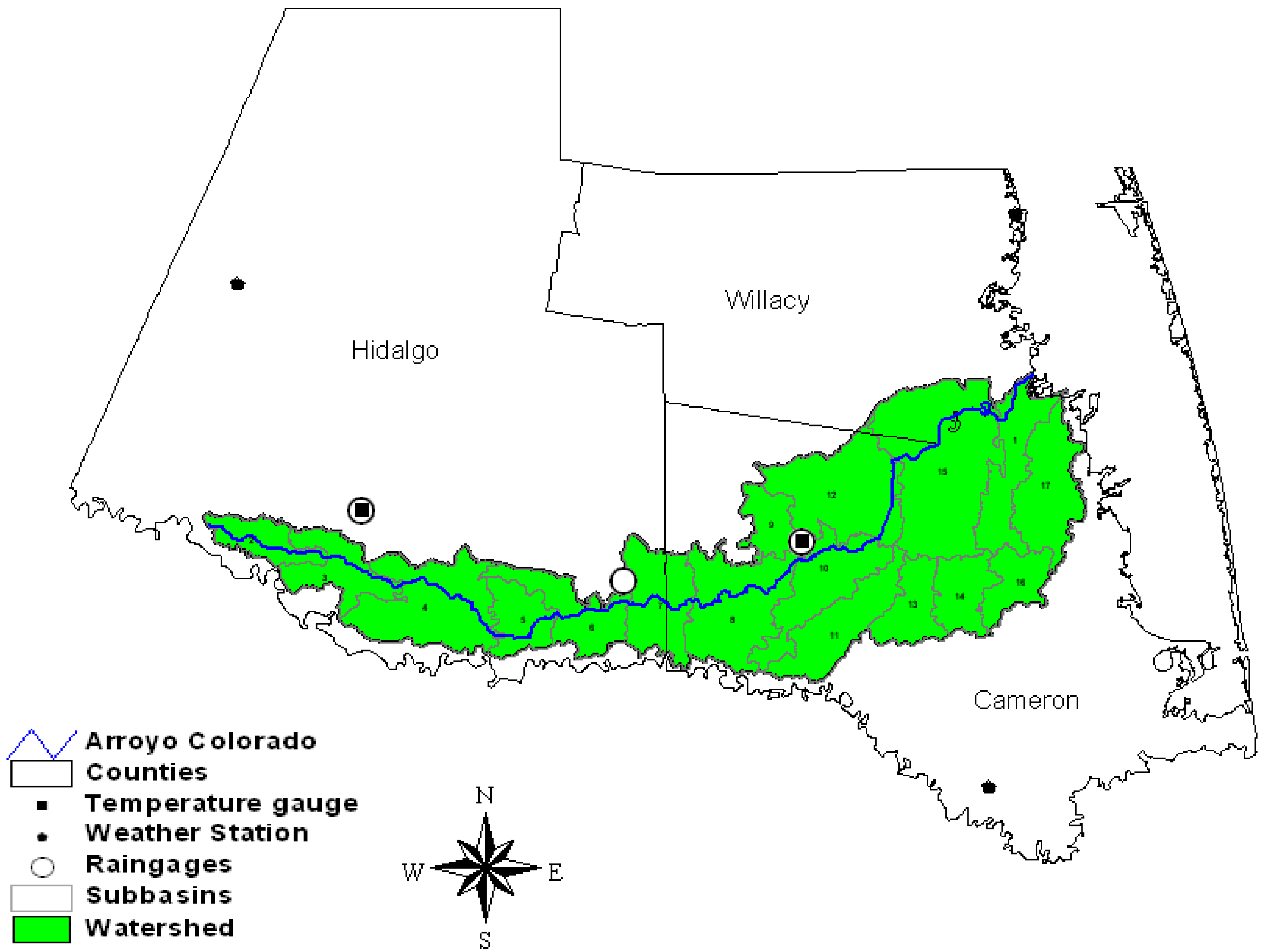

Figure 1. Location of Arroyo Colorado watershed

2202, has designated uses of contact recreation and intermediate aquatic life. The tidal segment of the Arroyo Colorado, Segment 2201, has failed to meet the water quality criteria required for its designated uses and is included on the State 303(d) list of impaired water bodies for dissolved oxygen (DO) levels below the criteria specified in the Texas Surface Water Quality Standards (Texas Natural Resource Conservation Commission, 1997).

Simulation models typically are used to estimate load reductions because the models are developed to represent the cause-and-effect relations between natural inputs to an aquatic ecosystem and the resulting water quality. Several BMP alternatives can be evaluated objectively using simulation models to determine what changes will be needed to meet the water quality standards.

Texas AgriLife Research, in cooperation with Texas State Soil and Water Conservation Board (TSSWCB) and TCEQ, began a study in 2008 to simulate the flow and the water quality of selected constituents in the Arroyo Colorado. The specific objectives of the study were to (1) develop a computer-based watershed model setup of the Arroyo Colorado that would allow representation of different BMPs adopted by growers in the watershed; (2) calibrate and validate a set of process-related model parameters with available streamflow and water quality data for the watershed; and (3) develop a suite of BMPs for changing land cover conditions predicted for 2015 and 2025, which, when progressively implemented in the watershed, would bring the water quality to compliance with current standards.

Study Area

The study area, the Arroyo Colorado watershed, is located in the Lower Rio Grande Valley of South Texas in parts of Hidalgo, Cameron, and Willacy counties (Fig. 1). It is a subwatershed of the Nueces-Rio Grande Coastal Basin, also known as the South (Lower) Laguna Madre Watershed (Hydrologic Unit Code 12110208). It is a 1,692 km^2 agricultural watershed with intensive cultivation. Most of the cultivated area receives irrigation from Rio Grande River through a network of canals, ditches, and pipes under a system of irrigation districts (Fig. 2). Irrigation practices consist of flooding fields with a specified depth of water during periods of insufficient precipitation to produce desired crop yields. Perennial stream flow in the Arroyo Colorado is primarily sustained by effluent from municipal wastewater treatment plants.

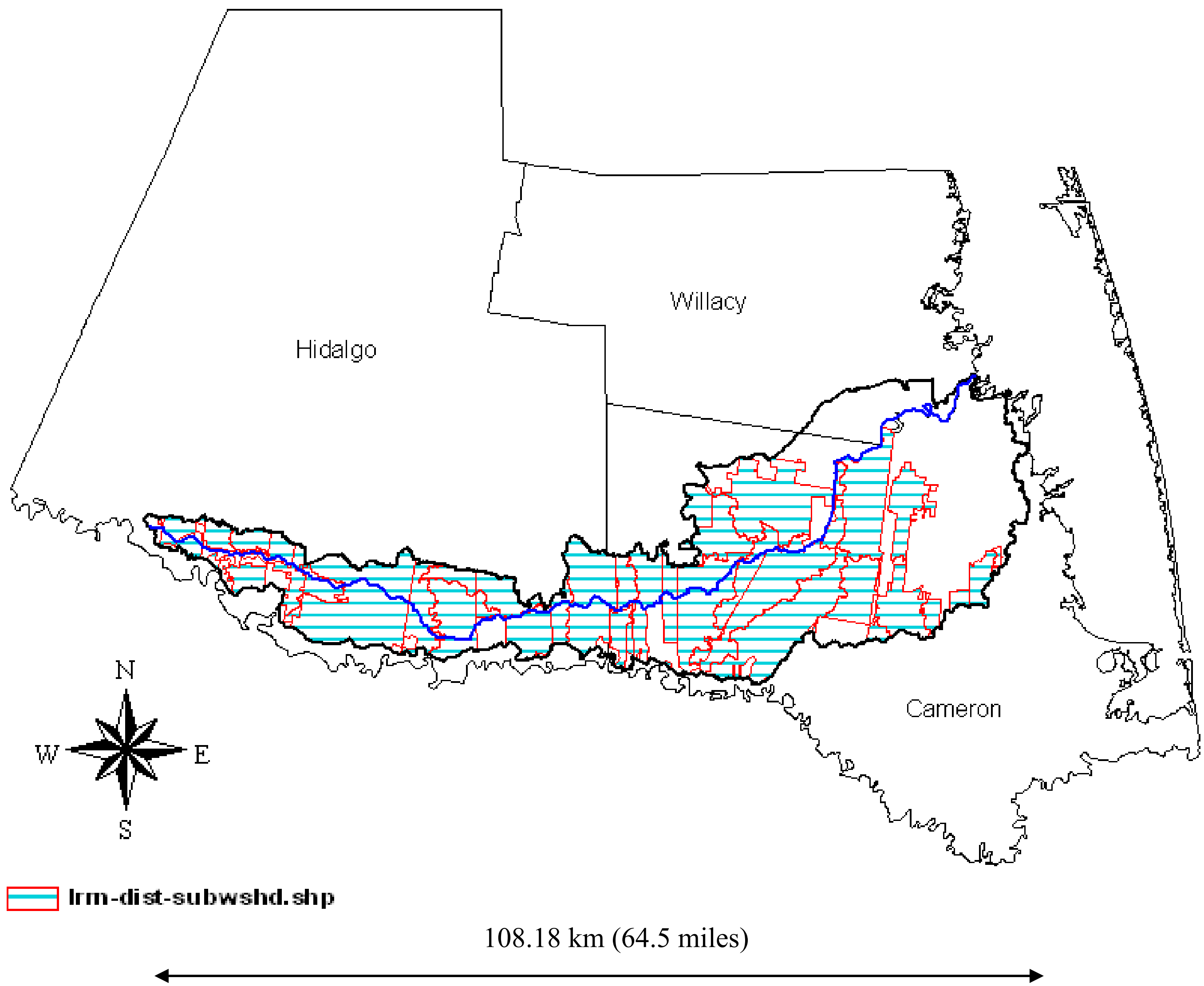

Figure 2. Irrigation districts in the watershed

Irrigation return flow and point source discharges supplement the flow on a seasonal basis. The Arroyo Colorado is used as a floodway, an inland waterway, and a recreational area for swimming, boating, and fishing, and is an important nursery and foraging area for numerous marine species. Urbanization is extensive in the areas directly adjacent to the main stem of the Arroyo Colorado, particularly in the western and central parts of the basin. Principal urban areas include the cities of Mission, McAllen, Pharr, Donna, Weslaco, Mercedes, Harlingen, and San Benito (Rains and Miranda, 2002; Rosenthal and Garza, 2007).

The most dominant land cover category in the watershed is agriculture (54 %) and the main crops cultivated are grain sorghum, cotton, sugar cane, and citrus, although some vegetable and fruit crops are also raised. Most of the cultivated area (including citrus and sugarcane) is irrigated. The watershed soils are clays, clay loams, and sandy loams. The major soil series comprise the Harlingen, Hidalgo, Mercedes, Raymondville, Rio Grande, and Willacy (U.S. Department of Agriculture, Soil Conservation Service, 1977, 1981–82). Most soil depths range from about 1,600 to 2,000 mm.

The mean annual temperature of the watershed is 22.7 degrees Celcius (°C) with mean monthly temperatures ranging from 14.5 °C in January to 28.9 °C in July. Mean annual precipitation ranges from about 530 to 680 mm, generally from west to east, in the basin (National Oceanic and Atmospheric Administration, 1996). Most of the annual precipitation results from frontal storms and tropical storms.

Observations used

Twelve years of weather data and flow, beginning in 1999 to 2010, were used for modeling. We used precipitation data from three and temperature data from two stations (Fig. 1). The weather data was obtained from Texas State Climatologist Office located at Texas A&M University in College Station. Stream flow data for two stations were obtained from International Boundary and Water Commission; one near Llano Grande at FM 1015 south of Weslaco (G1) and the other near US 77 in South West Harlingen (G2) (Table 1). There are 21 permitted dischargers in the Arroyo Colorado Basin, 16 are municipal, three are industrial, and two are shrimp farms. The discharge permit limits of the municipal plants range from 0.4 to 10 million gallons per day. The shrimp farms discharge infrequently (Rains and Miranda, 2002).

Water quality data from limited grab samples were obtained for suspended sediment (SS), nitrogen (ammonia nitrogen (amm N), nitrate-nitrogen (NO_3-N), and total nitrogen (TN)), phosphorus (orthophosphate (OP) and total phosphorus (TP)), water temperature (WT), and dissolved oxygen (DO). Data were available from three stations: the first near Weslaco, the second near Harlingen and the third near Port of Harlingen (Table 1). Out of the three stations, only the station near Harlingen had data for all the water quality variables. The gauge near Weslaco had flow, SS and, amm N only. However, the gauge near Port of Harlingen had very limited data (<10--20 observations) for SS, amm N, and WT, and therefore was not used for the analysis (Table 1).

The observations were available in the form of concentrations (except water temperature). The monitored observations (concentrations) were converted to time series of loads using a continuous time series of flow (typically daily stream flow). There are computer programs to accomplish this that convert flow and concentrations using regression and statistical techniques. They also estimate uncertainties of estimates. One such program is LOAD ESTimator (LOADEST) developed by United States Geological Survey (USGS) (Runkel et al. 2004). In LOADEST, data variables such as various functions of flow, time, and some other user-specified variables can be included. The program develops a regression model for estimation of load after calibration. Once formulated, the regression model is then used to estimate loads for a user-specified time frame. The LOADEST program estimates mean loads, standard errors, and 95 % confidence intervals developed on a monthly or seasonal basis. LOADEST output includes diagnostic tests and warnings to the user in determining correct estimation procedure and ways to interpret the information obtained. The time series of pollutants estimated this way using LOADEST based on grab sample pollutant concentrations and flow is referred to as "observations" throughout this report.

Description of simulation model

The Soil and Water Assessment Tool (SWAT) (Arnold et al. 1993) is a conceptual continuous simulation model developed to quantify the impact of land management practices on surface water quality in large watersheds (Gassman et al. 2007; Neitsch et al. 2004; http://www.brc.tamus.edu/swat).

Table 1. Selected physical and hydrological characteristics of Arroyo Colorado subbasins

SubBasin	Reach length (km)	Drainage area (Km^2)	Name of precipitation station	Streamflow gauging station number	Water quality sampling site number
(Segment 2202 non-tidal)					
2	11.5	50.3			
3	11.5	73.8	Mc Allen		
4	16.7	157.4			
5	9.0	57.7			
6	10.0	82.6	Mercedes	08-4703.00	13081
7	10.8	100.3			
8	19.6	143.3			
9	10.1	47.5	Harlingen		
10	12.7	104.9		08-4704.00	13074
11	20.3	96.9			
12	10.6	155.8			
(Segment 2201 tidal)					
13	10.0	59.4			
14	8.8	59.2			
15	53.4	249.0			
16	7.4	54.3			
17	25.6	110.2			
1	8.5	89.8			

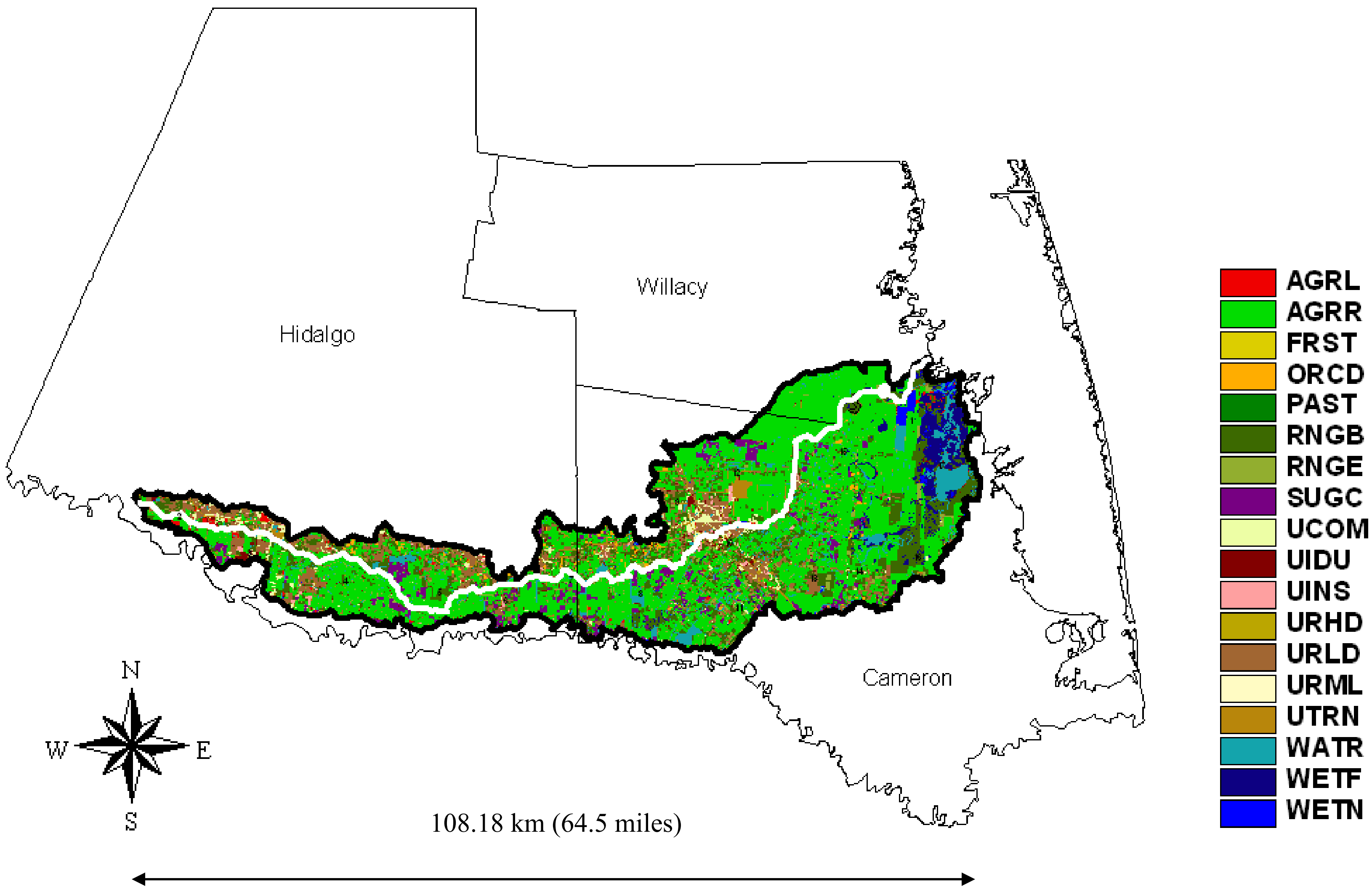

Figure 3. Land cover map of Arroyo Colorado

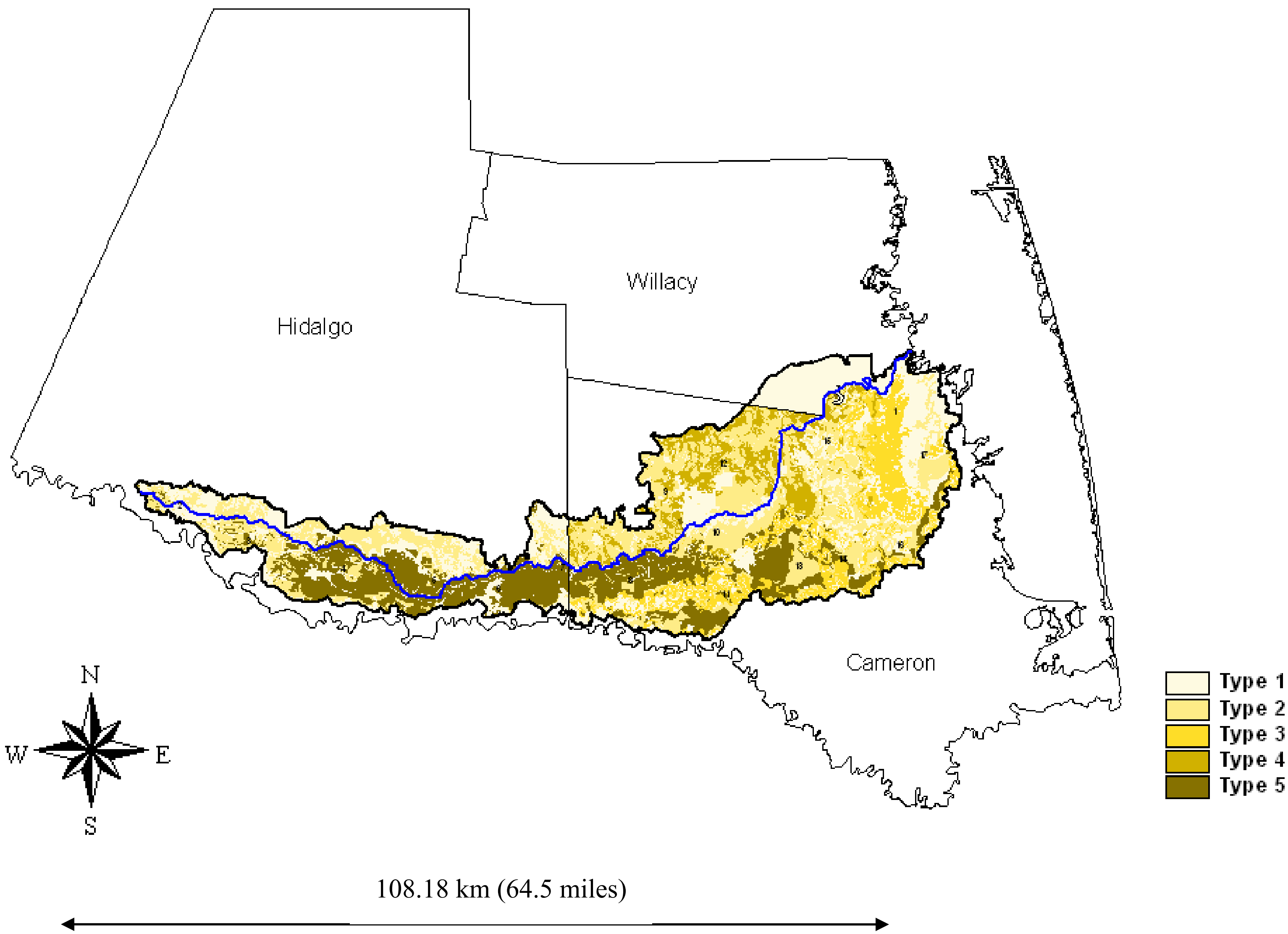

Figure 4. Soil map of the watershed

Table 2. Land cover map legend descriptions

Land Cover Code	Description
AGRL	Generic Agricultural Land
AGRR	Agricultural Land-Row Crops
FRST	Mixed Forest
ORCD	Orchard (Citrus for Arroyo Colorado watershed)
PAST	Pasture
RNGB	Range-Brush
RNGE	Range-Grasses
SUGC	Sugarcane
UCOM	Urban-Commercial facility
UIDU	Urban-Industry
UINS	Urban-Institution
URHD	Urban-High Density Residential
URLD	Urban-Low Density Residential
URML	Urban-Residential Medium/Low density
UTRN	Urban-Transportation
WATR	Water
WETF	Wetland-Forested
WETN	Wetland-Non-forested

SWAT also provides a continuous simulation of processes such as evapotranspiration, surface runoff, percolation, return transport flow, groundwater flow, channel transmission losses, pond and reservoir storage, channel routing, field drainage, crop growth, and material transfers (soil erosion, nutrient and organic chemical and fate). The model can be run with a daily time step, although subdaily model run is possible with Green and Ampt infiltration method. It incorporates the combined and interacting effects of weather and land management (e.g. irrigation, planting and harvesting operations, and the application of fertilizers, pesticides or other inputs). SWAT divides the watershed into subwatersheds using topography. Each subwatershed is divided into HRUs, which are unique combinations of soil, land cover and slope. Although individual HRU's are simulated independently from one another, predicted water and material flows are routed within the channel network, which allows for large watersheds with hundreds or even thousands of HRUs to be simulated.

SWAT model setup of Arroyo Colorado watershed

Input data used

We used ArcSWAT interface to prepare the SWAT model setup of Arroyo Colorado. For delineation of watershed boundary, we used 30-m USGS Digital Elevation Model (DEM). A digitized stream network and a watershed boundary from the previous HSPF modeling study (Rains and Miranda, 2002) were used as supporting information for the delineation of watershed and stream network for the present study. The watershed was eventually discretized into 17 subwatersheds.

Spatial Sciences Lab of Texas A&M University at College Station prepared the land cover map based on satellite data and a field survey. The map incorporates the present land cover conditions (2004–2007) in the watershed. Crop rotation, irrigation, and dates of planting are also available with the land use map on a farm/field basis. The dominant land cover categories in the watershed are agriculture (54 %), range (18.5 %), urban (12.5 %), water bodies (6 %) and sugarcane (4 %) although some vegetable and fruit crops are also raised (Fig. 3, Table 2). The soil survey geographic database (SSURGO) soil map was downloaded from USDA-NRCS for Cameron, Willacy and Hidalgo counties (Fig. 4). The soil properties associated with a particular soil type are derived using the SSURGO soil database tool. 475 HRUs were delineated based on a combination of land cover and soil. In the present delineation, areas as small as 9.1 ha (22.5 acres) are represented as HRUs.

Dates of planting were obtained from the land cover map. The durations of crops were obtained from crop fact sheets from Texas AgriLife Extension Service publications based on the tentative harvest dates as identified for each crop (Stichler and McFarland, 2001; Trostle and Porter, 2001; Stichler et al. 2008; Vegetable Team Production, 2008; Wiedenfeld and Enciso, 2008; Wiedenfeld and Sauls, 2008). Dates of harvest collected during our visits to the watershed were used along with the above information. Typically, there are two tillage operations (in conventional tillage) for each crop, one soon after the harvest of the previous crop and the other midway between the harvest of the previous crop and the planting of the present crop. In conservation tillage, one tillage operation (mostly soon after harvest of the previous crop) or no tillage operation is performed (Andy Garza, Texas State Soil and Water Conservation Board, Harlingen, personal communication).

Modeling Irrigation of crops

Tentative quantity, timing, and frequency of irrigation required for major crops (such as sorghum, cotton and sugar cane) were obtained from NRCS and TSSWCB staff in the watershed. Crop fact sheets published by Texas AgriLife Extension Service were also collected to estimate the irrigation information for the crops (Table 3; Stichler and McFarland, 2001; Trostle and Porter, 2001; Cruces, 2003; Fipps, 2005; Stichler et al. 2008; Vegetable Team Production, 2008; Wiedenfeld and Enciso, 2008; Wiedenfeld and Sauls, 2008). To model canal irrigation, the following procedure is used. We prepared a comprehensive map using the HRU information from the overlaid land cover map, soil map and subbasin map using GIS. An HRU under agriculture land cover can be either irrigated or not irrigated. If irrigated, the model will follow the canal irrigation procedure. Information on irrigation districts for the study area is available in the form of a map from the Irrigation Technology Center, Texas A&M University. In addition, the average water conveyance efficiency for each irrigation district is available separately. This information was combined and merged with the HRU map to identify the irrigation district that comes under each HRU. This has conveyance efficiency information for each HRU. For this study, conveyance efficiency includes all loses in the irrigation distribution system from water diversion river to field. Conveyance efficiency combined with depth of water application for each irrigation event for each crop allowed us to estimate the tentative quantity of water that could have been diverted from the source for irrigating the crop (Fig. A1). We consulted several publications/reports estimating depth, duration, and frequency of irrigation, and estimated the critical crop growth stages at which irrigation is essential. We also estimated the timings based on the probable days of irrigation (identified by looking at the daily water stress values reported by the model for the simulation that involves no irrigation event for any crop in any HRU) to schedule irrigation in the model set up, and the critical crop growth stages requiring irrigation were used as reported in the literature/field data.

Representing Best Management Practices (BMPs) in the model

Irrigation land leveling (NRCS practice code 464)

Irrigation land leveling represents the reshaping of the irrigated land to a planned grade to permit uniform and efficient application of water. It is typically used in mildly sloping land. Primarily it is carried out by agricultural producers who follow surface methods to irrigate their fields. Land leveling is generally designed within slope limits of water irrigation methods used, provide removal of excess surface water and control erosion caused by rainfall. This BMP is modeled in SWAT by reducing the HRU slope (by 8–12.5 % depending on the initial value) and slope length (one tenth of the default value) parameter. In reality, a leveled field infiltrates more water, reduces surface runoff, and therefore decreases soil erosion. When adjusted (reduced), slope and slope length parameters of the watershed model setup will bring similar effects in the predicted model results.

Irrigation Water Conveyance, Pipeline (NRCS practice code 430)

Irrigation water conveyance in pipeline form is installation of underground thermoplastic pipeline (and appurtenances) as a part of an irrigation system to replace canal lining. The decision to line a canal or replace the canal using a pipeline is often made based on how much water is conveyed in the canal. In practice, small district irrigation canals or lateral canals with capacity less than 100 cubic feet per second will be replaced with pipeline. This BMP reduces water conveyance losses and prevents soil erosion or loss of water quality. Some of the design and planning considerations include working pressure, friction losses, flow velocities, and flow capacity. On average, this BMP can save water up to 11 % (Texas Water Development Board, report 362). In a hydrologic modeling study involving a relatively large watershed, it is not possible to practically consider all the pipe network, irrigation appurtenances, and the associated pressure, friction losses, flow velocity, capacity etc. Therefore, irrigation water conveyance in pipeline form is modeled by increasing the conveyance efficiency of an HRU. In other words, the amount of water diverted to the field from the source is decreased.

Irrigation System-Surface Surge Valves

This BMP is often implemented to replace an on-farm ditch with a gated pipeline to distribute water to furrow irrigated fields. A surge irrigation system applies water intermittently to furrows to create a series of on-off periods of either constant or variable time intervals. The system includes butterfly valves or similar equipment that will provide equivalent alternating flows with adjustable time periods. Surge flow reduces runoff by increasing uniformity of infiltration and by reducing the duration of flow as the water reaches the end of the field. It also increases the amount of water delivered to each row and reduces deep percolation of irrigation water near the head of the field. The amount of water saved by switching to surge flow is estimated to be between 10 and 40 % (Texas Water Development Board, report 362) and is dependent upon soil type and timing of operations. Physical representation and modeling the operation of butterfly values for each field in a large watershed system was tedious. Also, methods do not exist to model them from a hydrologic perspective. Therefore, irrigation system-surface surge valves is simulated by increasing the conveyance efficiency while calculating the water diverted for irrigation.

Irrigation Water Management (NRCS practice code 449)

Under this BMP, the landowner will manage the volume, frequency, and application rate of irrigation in a planned, efficient manner as determined from the crop's water requirements complying with federal, state, and local laws and regulations. This BMP is modeled by varying several parameters. The volume of water required for irrigation is adjusted based on the seasonal total rainfall received (total rainfall from planting to harvest date).. If there is considerable rainfall around a scheduled irrigation period, that particular irrigation is skipped. This reduces the frequency of irrigation. Based on the quantity of rainfall and timing, the rate of water application is also adjusted, although this is less frequent.

Table 3. Frequency, timing and amount of irrigation for different crops in the watershed

Crop	Total water requirement, mm (inches)	Number of irrigations	Critical crop growth stages needing irrigation	Irrigation requirement (Days after planting)
Sorghum	458 (18)	3	One week before booting, two weeks past flowering	30, 60, 84
Cotton	508 (20)	3	Stand establishment, prebloom, shortly after boll set	25, 56, 94
Sugarcane	1270 (50)	7	Establishment, grand growth, ripening	75, 105, 145, 190, 235, 275, 305
Corn	508 (20)	3	Tasseling, silking, kernel fill	48, 70, 95
Citrus	1143 (45)	6	Pre-bloom, flower bud induction, fruit set, cell expansion, ripening	65, 100, 135, 195, 250, 320
Sunflower	304 (12)	2	20 days before flowering, 20 days after flowering	45, 85
Onion	635 (25)	5	stand establishment, bulb initiation, maturity	15, 60 (if dry), 90, 115, 135

Table 4. Water Diverted for Irrigation with and without BMPs

Subbasin	Year	Crop	Water diverted without BMPs mm (in.)	Water diverted with BMPs mm (in.)
3	2002	Sugarcane	1,524 (60)	1,160 (46)
3	2004	Sugarcane	1,052 (41)	801 (32)
8	2000	Cotton	677 (27)	552 (22)
8	2001	Corn	677 (27)	552 (22)
8	2002	Cotton	677 (27)	552 (22)

Conservation Crop Rotation (NRCS practice code 328)

This BMP implies growing high-residue-producing crops that produce a minimum of 2800 kg/ha/year (2500 lbs/ac/year) of residue for a minimum of 1 year within a given two year period. Corn and grain sorghum are examples for high-residue-producing crops. Sorghum is the dominant crop in cultivated areas of the watershed. Corn is also cultivated in some areas. The crop rotation in the watershed has sorghum, or corn as per the above-mentioned conditions prescribed for conservation crop rotation. Therefore, no changes were made in the watershed model set up to represent this BMP.

Nutrient Management (NRCS practice code 590)

Nutrient management means managing fertilizer quantity, placement, and timing based on realistic yield goals and moisture prospects. Under this BMP, fertilizer should be applied in split applications throughout the year (early March, late May, late August, and mid October) prior to irrigation or forecasted rain to maximize the use of the fertilizer and minimize the leaching potential. Nitrogen applications will not exceed 112 kg/ha (100 lb/ac) of total nitrogen per application. Specific nutrient recommendations will be given by NRCS when a soil analysis report is provided. A soil analysis is taken a minimum of once every third year by the land owner/renter beginning with the year that the plan or contract is signed. Nutrient management is mimicked in the model as given below.

The fertilizer applications for cultivated fields were already modeled in terms of two or three split applications. For the HRUs that come under this BMP, the split applications were strictly followed according to the guidelines suggested in the BMP practice code. In addition, the initial amount of N and P present in the soil were deducted from the recommended regular fertilizer application rates for different crops (to mimic soil-survey based N and P recommendations). Realistic initial N and P rates were obtained by using the final amount of N and P remaining in the soil (as reported by the model) after several years of model runs. With respect to recommended regular rates of N and P, under this management scenario, less proportion of P than N is applied .. This is because phosphorus is less likely to leach from the soil and more available. A comparison of N and P rates for different crops with and without nutrient management is given in Table 5.

Table 5. Fertilizer rates for different crops under nutrient management and non-nutrient management

Crop	Nitrogen (kg/ha)		Phosphorus (kg/ha)	
	Regular	Nutrient management	Regular	Nutrient management
Sorghum	160	152	69	55
Cotton	150	125	68	34
Sugarcane	224	216	0	0

Residue Management (NRCS practice code 329b)

Residue management-mulch-till is managing the amount, orientation, and distribution of crop and other plant residue on the soil surface year-round while growing crops. The entire field surface is tilled prior to the planting operation. Sometimes the residue is partially incorporated using chisels, sweeps, field cultivators, or similar implements. This BMP is practiced as part of a conservation management strategy to achieve some/all of the following: reduce sheet and rill erosion, reduce wind erosion, maintain or improve soil organic matter content, conserve soil moisture, and provide food and escape cover for wildlife (USDA-NRCS, 2001). This BMP was modeled by harvesting only the crop (no killing of crop; harvesting only the useful yield), and leaving the residue (non-yield portion of crop) until the planting of next crop.

Seasonal Residue Management (NRCS practice code 344)

Seasonal residue management is very similar to residue management. This BMP implies leaving protective amounts of crop residue (30 % ground cover/1,360 kg (3,000 lbs) minimum) on the soil surface through the critical eroding period (Dec. 15 to Jan. 1 or six weeks prior to planting) to reduce wind and water erosion during the raising of a high-residue crop. In the event that a low residue crop is being produced, the residue requirements are not met and soil begins to blow, emergency tillage operations will be performed. Similar to residue management, this BMP was modeled by harvesting only the crop (no killing of crop; harvesting only the useful yield) and leaving the residue (non-yield portion of crop). However, this can happen only during critical eroding period or six weeks prior to the planting of next crop.

Terrace (NRCS Practice Code 600)

Terraces are broad earthen embankments constructed across a slope to intercept runoff and control water erosion. They are intended for both erosion control and water management. Terraces decrease hill slope length, prevent formation of gullies, and intercept, retain, and conduct runoff to a safe outlet, and therefore reduce the concentration of sediment in water. Terraces increase the amount of water available for recharging the shallow aquifers by retaining runoff (Schwab et al., 1995). In this study, terraces are represented in the model by decreasing curve number (CN), reducing Universal Soil Loss Equation (USLE) conservation support practice factor (P factor) and decreasing slope length. Terraces are not one of the common BMPs in the watershed.

Constructed wetlands

Constructed wetlands are of two types: (1) free water surface systems (FWS) with shallow water depth and (2) subsurface flow systems with water flowing laterally through the sand or gravel. In general, constructed wetlands are very effective in removing suspended solids. Nitrogen removal occurs mostly in the form of NH_3 with dominating nitrification/denitrification process. Because of the shallow depth and access to soil, the phosphorus removal is relatively higher for constructed wetlands than natural wetlands. The bacteria attached to plant stems and humic deposits help in considerable removal of BOD_5. Typical pollutant-removal ability of wetlands is available in a report published by USEPA (USEPA, 1988 report EPA/625/1-88/022). For the study area, the probable pollutant removal efficiencies are obtained from the USEPA report based on wastewater inflow to the wetland. For representing the existing constructed wetlands in the watershed, the pollutants discharge from wastewater treatment plants (point source discharge data in the model setup) is discounted based on the typical pollutant removal efficiency estimated from the EPA report. The typical pollutant removal efficiencies used in the model setup to represent constructed wetlands are shown in Table 6. The constructed wetlands in the Arroyo Colorado watershed are assumed to be of FWS type. Effluent polishing ponds were aggregated at subbasin level, and pollutants from point source data were discounted using typical values shown in Arroyo Colorado Watershed Protection Plan report (2007). The total area of each BMP present in the watershed and that represented in the model are shown in Table 7.

Table 6. Typical pollutant removal efficiencies used for representing constructed wetlands

Location of wetland	Effluent inflow (m^3/day)	% removal of				
		SS	NH3 N	NO3 N	TDP	BOD
La Feria (Subbasin 8)	972.7	86	64.5	20	71	64
San Benito (Subbasin 10)	9,621.5	28	64.5	20	71	64

Table 7. Representation of different BMPs in the watershed model setup

Best Management Practice	Actual area (acres)	Represented in the model (acres)	% error (watershed level)
Conservation crop rotation	20,910.8	21,627.3	3.4
Irrigation land leveling	12,185.3	12,455.8	2.2
Irrigation System - Sprinkler - New	396.4	417.9	5.4
Irrigation System - Surge valves	22,931.6	22,636.2	-1.3
Irrigation Water Conveyance, Pipeline	10,470.3	10,750.6	2.7
Irrigation Water Management	23,724.3	24,132.3	1.7
Nutrient Management	12,053.8	11,838.9	-1.8
Pasture and Hay Planting	952.3	805.1	-15.5
Prescribed Grazing	961.0	955.2	-0.6
Residue Management	1,417.1	1,313.9	-7.3
Residue Management, Seasonal	19,357.2	20,654.0	6.7
Subsurface Drain	4,327.6	4,232.3	-2.2
Terrace	130.7	116.5	-10.8

Wastewater reuse

This BMP implies using wastewater for irrigation with the goal of reducing point source nutrient loads to the river. To represent wastewater reuse in the model, we needed to know the quantity of wastewater used and the location from which the wastewater is taken. This information is available for the Arroyo Colorado from the Arroyo Colorado Watershed Protection Plan. In the model, point source flow is discounted in proportion to the wastewater reuse intended from the effluent discharge facilities. The discounted water is then added to the irrigation water in the subbasin. The quantity of nutrients associated with the quantity of reuse is estimated and applied as fertilizer in the same HRU where the irrigation operation was defined. Any sediment associated with the wastewater was not accounted/discounted because the quantity was negligible.

Calibration and validation of model

Calibration of the chosen model and a subsequent validation are necessary to have confidence that the model gives reliable and useful results, and it is worthy to use it to do scenario trials. For the Arroyo Colorado watershed modeling study, the SWAT model was calibrated and validated for flow, sediment, nitrogen (nitrate, ammonia and total nitrogen), phosphorus (total phosphorus and orthophosphate), water temperature, and dissolved oxygen. The model was run at a daily time step from 1999–2010, and the results were aggregated at monthly time steps for the purpose of calibration. Flow calibration was carried out at both monthly and daily time steps. Data from 1999 is used for model warm-up to make state variables assume realistic initial values. Data from 2000–2003 is used for calibration and 2004–2006 for validation. However, the model was run until 2010. From this point onwards, this model setup will be referred to as baseline. The availability of water quality observations was not as good as flow. Therefore, a separate split sample calibration and validation was not carried out. Instead, the observations available (from 2000–2009) were used to verify whether the model gives reasonable results in terms of magnitude, pattern and timing.

Flow calibration and validation was carried out for two gauges: one near Weslaco/Mercedes and the other near Harlingen. The model is able to reproduce the flow observations very well in both gauges during calibration and validation periods (Tables A2 and A3). Similar results were obtained for flow at a daily time step. For sediment, the model-predicted values were good when compared to observations except for a couple of over-estimated peaks. Orthophosphate was predicted well by the model. However, total phosphorus was over-estimated. Also, for nitrogen, the model-predicted values were good enough to use for scenario trials. We did not carry out calibrations for water temperature and dissolved oxygen. SWAT estimates water temperature as an empirical function of air temperature and therefore, no parameter is available for calibration. For dissolved oxygen, the model gave better results without any requirement for calibration. All the calibration and validation results are provided in Figures A2-A14 and tables A1-A7 in Appendix A.

Watershed scenarios for 2015 and 2025

Estimation of future land cover maps

Data used

The data used includes city limits, census data, population projections, and land use/land cover maps from multiple years. City limit information was produced by the Texas Department of Transportation (TxDOT). The Census data was from the 1990 and 2000 census. The population projections were produced by the Texas Water Development Board based on the 2000 census. Projections from 2010, 2020, and 2030 were averaged to create projections for 2015 and 2025. Three different land use maps from 1992, 1998, and 2007 were used. The 1992 map was a subset of the National Land Cover Dataset (NLCD). The 1998 classification was produced by the Texas Commission on Environmental Quality (TCEQ) and the 2007 Classification was produced by the Spatial Sciences Lab at Texas A&M University in College Station (SSL).

Method

To quantify land cover change, the three available land cover maps (for years 1992, 1998 and 2007) needed to be in one format and reclassified into a common scheme. The two vector classifications were converted to raster using the extent and cell size of the 1998 classification, which had the same extent as the watershed boundary. After reclassification, pixel counts were exported and converted to acres. The results were observed in a table with both area and % of watershed values (% of watershed occupied by a certain land use).

The amount of residential land use areas within each city was extracted using the city limits and each of the reclassified maps. Cities with populations greater than 500 as of 2000 were identified and extracted. This was necessary because population projections were not available for cities with populations less than 500. Some did not have a population of 500 in 1990, but did in 2000, so they were included. The trend would simply include one less value. In some cases the population values did not steadily increase and there were some slight declines or no growth. This was because the values were extracted from different sources that were not consistent. If the population declined, it was averaged with the value before and after the decline to achieve steady growth. Each of the city limits was then given a unique identification number of 1000 through 21000. This ID number was then used to convert the city limits to raster. It was necessary to use values of 1000 or greater since the highest class values were three digits long, although the highest observed in the land use maps were two digits. Additional overlay was then used to extract the land uses within the city limits. The residential and nonresidential developed land uses were extracted and the total area of each was calculated individually. These values were then analyzed and used to compute future residential land use acreage.

In order to map probable locations of development or land use change, previous land use change was mapped using combination overlays of classifications with the classification from the previous time period. An overlay was also created using the oldest and most recent classifications. Using combinations makes it possible to identify areas that have changed from or to a specific land use. In this case, areas that changed to residential were extracted from combinations of 1992 and 1998, 1998 and 2007, and 1992 and 2007. Using each of the combinations accounted somewhat for the differences in extent between 1998 and 2007, although not entirely. The combinations identified what land uses were most frequently being developed into residential. Areas where the land use changed to residential as well as potential areas for residential development would both be used in the production of the final future land cover maps (Table 8).

The results show that rapid urban growth is likely to continue in the watershed through 2015 and 2025. Each city will experience growth in residential, infrastructure, and industrial land uses. This growth will require that other land uses decline to accommodate the increase. It also appears that many of the larger urban areas have little available land within their city limits for further development. To accommodate further growth, city limits will need to expand into the rural areas. Agricultural and industrial land uses provide work for the population living in the area so they will likely limit growth to some extent. However, residential expansion is currently occurring in agricultural lands as well as pastures.

Several assumptions were made about residential and urban expansion. Water and wetlands are unlikely to be developed although wetlands may expand in some areas due to the expansion of existing wetlands or the creation of wetlands to help improve water quality near wastewater treatment facilities. Transportation and infrastructure will expand as structures are built and neighborhoods expand, but this cannot be predicted with any confidence. Industry and agribusiness were expanded as part of the infrastructure.

Table 8. Present and estimated future land cover in the watershed

Land Cover	Area in acres		
	Present	2015	2025
Cultivated (CULT)	244,436.3	228,231.6	215,670.7
Range-Brush (RNGB)	67,090.0	63,067.4	58,040.6
Range-Grasses (RNGE)	11,104.9	10,439.1	9,615.5
Urban-Commercial (UCOM)	7,598.1	12,071.1	15,008.1
Urban-Industrial (UIDU)	2,219.4	4,781.6	10,567.4
Urban-High density residential (URHD)	0.0	707.5	1,061.2
Urban-Low density residential (URLD)	37,753.0	41,743.0	45,870.7
Urban-Transportation (UTRN)	5,269.5	12,576.8	17,681.6
Open water (WATR)	25,406.3	25,386.1	25,465.3
Wetland-Forested (WETF)	14,716.1	16,589.1	16,612.4
Wetland-Non-forested (WETN)	2,350.8	2,350.8	2,350.8

Development of model input files for future scenarios

In this study we attempted to predict land cover conditions of the Arroyo Colorado watershed for 2015 and 2025. Estimated land cover maps were the starting point for future scenario files. Soon after estimating future land cover, the input file generation for a future scenario goes as follows. The watershed and subwatershed boundaries are the same as base line. Soil map and slope information are also the same. However, the land cover map will be different (e.g. for scenario-2015 the land cover map to be used is the one that is estimated). The procedure used before for discretizing the subwatersheds to HRUs was also used here. The thresholds used for land cover, soil and slope are kept the same for scenarios as well to prevent any uncertainties arising from spatial discretization of subwatersheds in the scenarios, which might interfere the analysis of water quality results. Once the HRUs are delineated for each scenario, the required input files to run SWAT model are generated this way:

Soon after generating HRUs of scenarios, the procedure starts with base line HRUs that are calibrated for flow and selected water quality constituents. The HRUs of a scenario (say 2015) is compared with the HRUs of base line by matching the land cover, soil and slope. This will identify three sets of information. The HRUs of base line is to be a) kept b) removed and c) created new to represent the scenario conditions. For those HRUs to be kept, it involves changing the HRU area only. For those HRUs to be removed either we can fully delete them from the input files or make the HRU area zero. The later is followed for convenience and automation. The new HRUs to be created can be copied from existing baseline HRUs by carefully looking for land cover, soil and slope combinations. If a similar HRU does not exist in a subbasin, then HRUs can be copied from neighboring subbasins. By generating the model input files this way, we can avoid calibration of scenario files and proceed straight away to analysis of results.

Analysis of present and future water quality trends

Implementation of BMPs in the watershed, improvement in wastewater treatment, access of wastewater treatment to more colonia residents, strict effluent standards, treatment of effluent using polishing ponds and wetlands have improved the quality of water in the Arroyo Colorado over a period of few years. This is evident from the later part of dissolved oxygen trends (consistently close to 7) observed near Harlingen (Fig. A14). The improvements in water quality are also visible from the dissolved oxygen trends estimated from the model and analyzed using binomial method (Table 9). From the table we can see that most sections of tidal Arroyo Colorado are having DO compliance except at reach 13 and 14. These reaches are not on the main Arroyo Colorado, but they drain to reach 15 of the Arroyo Colorado. Nonpoint source transport of nutrients from cultivated fields can be attributed to the DO problem of reaches 13 and 14. The model estimates a threat to DO in some reaches of nontidal portion of the Arroyo Colorado (Table 9). Point source discharge (especially from subbasins 2 and 3) can be attributed to the problem in the nontidal portion of the Arroyo Colorado. It should be noted that any problem in DO due to point source is long lasting and spreads to other reaches downstream. On the other hand, DO problem from nonpoint source nutrient pollution is highly seasonal and mostly localized.

Table 9. Modeled dissolved oxygen compliance in various reaches-Binomial Analysis results (with existing BMPs in the watershed model setup)

Reach	Location	Confidence of Dissolved Oxygen Compliance (%) [Average number of days/year when DO < 4 mg/L]		
		Baseline (present)	**2015**	**2025**
2	Non-tidal	0.0 [316]#	0.0 [342]#	0.0 [334]#
3	Non-tidal	0.0 [237]#	0.0 [273]#	0.0 [274]#
4	Non-tidal	0.0 [106]#	0.0 [145]#	0.0 [161]#
5	Non-tidal	100.0 [34]	0.0 [56]	0.0 [62]
6	Non-tidal	100.0 [34]	96.7 [34]	0.03 [40]
7	Non-tidal	100.0 [24]	100.0 [24]	100.0 [28]
8	Non-tidal	100.0 [27]	100.0 [27]	100.0 [29]
9	Non-tidal	0.0 [45]	0.0 [46]	0.0 [46]
10	Non-tidal	100.0 [27]	100.0 [29]	99.9 [33]
11	Non-tidal	0.0 [226]#	0.0 [250]#	0.0 [171]#
12	Non-tidal	100.0 [24]	100.0 [26]	100.0 [29]
we				
13	Tidal	93.0 [37]	19.0 [38]	0.0 [44]
14	Tidal	85.0 [38]	0.5 [40]	0.0 [43]
15	Tidal	100.0 [22]	100.0 [23]	100.0 [25]
16	Tidal	100.0 [31]	97.8 [34]	100.0 [32]
17	Tidal	100.0 [17]	100.0 [19]	100.0 [16]
1	Tidal	100.0 [16]	100.0 [14]	100.0 [15]

Model over reacted to point source loads. Therefore, care was taken while interpreting the results and translating to recommendations

In 2015, because of land cover change and population increase, the water quality is expected to be worse, which is correctly estimated by the model. Although the trends in DO for 2015 are similar to base line, the average number of days per year during which DO concentration is less than 4 mg/L is more for 2015 than base line for most reaches (Table 9). It should be noted that the proposed wastewater polishing ponds, regional wetlands and better emission standards for effluents to the Arroyo Colorado watershed as described by the watershed protection plan are going to be very helpful to protect the water quality of the Arroyo Colorado. As a part of this study, we carried out the suite of BMPs required to bring the DO in compliance . The subbasins of the Arroyo Colorado were prioritized for implementation of BMPs based on model-predicted average number of days when DO is less than 4 mg/L (Table 10) in the reach. The BMPs to be implemented in the cultivated area were also prioritized based on the extent of load reductions they can bring to the Arroyo Colorado (Table 11).

Table 10. Prioritized implementation of BMPs by subbasin in the watershed

Prioritization of BMPs based on		
Dissolved Oxygen	**Total Nitrogen**	**Total Phosphorus**
2	8	8
3	7	5
11	5	7
4	4	6
9	10	10
14	12	4
13	11	11
5	15	15
6	6	2
16	3	9
10	2	3
8	9	16
12	13	13
7	14	14
15	16	12
17	17	17
1	1	1

Table 11. Possible load reductions from different BMPs and their prioritization for implementation

Best Management Practice	% of load reductions obtained from BMPs in		
	Total Nitrogen	**Total Phosphorus**	**Sediment**
Residue management	22.05	45.1	20.2
Irrigation BMPs	11.85	4.25	3.00
Nutrient management	4.1	19.85	0.25
Seasonal residue management	3.25	24.15	4.75
Land leveling	34.75	*	42.4
Tile drains*	6.6	1.7	0.8

* Negative results (increase in nutrient loads) possible sometimes. Therefore, care should be taken while choosing these BMPs.

Not all BMPs are fully effective in controlling nutrient loads or dissolved oxygen in the Arroyo Colorado. For example, tile drains, when implemented for reducing water table, will transport more soluble nitrogen to the river than when there are no drains. Also, residue management is much more effective than seasonal residue management. Therefore, care should be taken while choosing BMPs for implementation in a subbasin.

Discussion of mitigation of dissolved oxygen problems

Table 12 shows the suite of BMPs required by 2015 to bring DO compliance for the Arroyo Colorado. The study identified a set of BMPs for different subbasins where they can work better. Irrigation BMPs in Table 12 is a collection of three different BMPs, namely irrigation water management, irrigation water conveyance (in the form of) pipeline, and irrigation system-surface surge valves.

Table 12. Suite of additional BMPs needed by 2015 to meet dissolved oxygen criteria

Subbasin	**Scenario 2015-Area of different BMPs (acres)**			
	Land leveling	**Residue management**	**Irrigation BMPs**	**Nutrient management**
2	1,902	1,902	----	----
3	682	----	----	1,460
4	16,119	----	16,715	----
5	8,107	9,238	----	9,315
9	1,757	509	----	633
11	1,632	7,463	----	6,099
13	489	4,374	489	4,373
14	7,003	2,452	51	1,667
Total	37,691	25,938	17,254	23,549

Implementation of additional BMPs can take care of the DO problem in the tidal portion of the Arroyo Colorado. However, for the nontidal portion of the Arroyo Colorado, implementation of BMPs alone is insufficient to address the DO problem. An integrated approach of reducing/reusing/better treating of point source discharge along with implementation of BMPs is needed to address the nontidal DO problem. This study recommends reducing/reusing/treating at least 40% of pollutants from point sources associated with subbasins 2, 3, 9, and 11. The same recommendations are suggested for scenario 2025 as well. However, it is recommended to implement additional BMPs (in addition to whatever suggested for 2015 (see Table 12) in the watershed to take care of nonpoint source transport of nutrients and sediments from cultivated areas (Table 13).

Table 13. BMPs needed by 2025 to meet DO criteria (in addition to those of 2015)

Subbasin	Scenario 2025-Area of different BMPs (acres)			
	Land leveling	**Residue management**	**Irrigation BMPs**	**Nutrient management**
2	1,415	1,415	----	----
3	1,282	----	----	105
4	5,289	16,729	1,593	----
5	1,098	----	----	81
6	9,464	7,462	----	----
7	11,101	----	----	11,029
8	3,019	16,849	----	14,750
11	24	----	----	1,484
13	3,772	----	----	----
Total	36,464	42,455	1,593	27,450

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Appendix A

Figure A1. Modeling canal irrigation

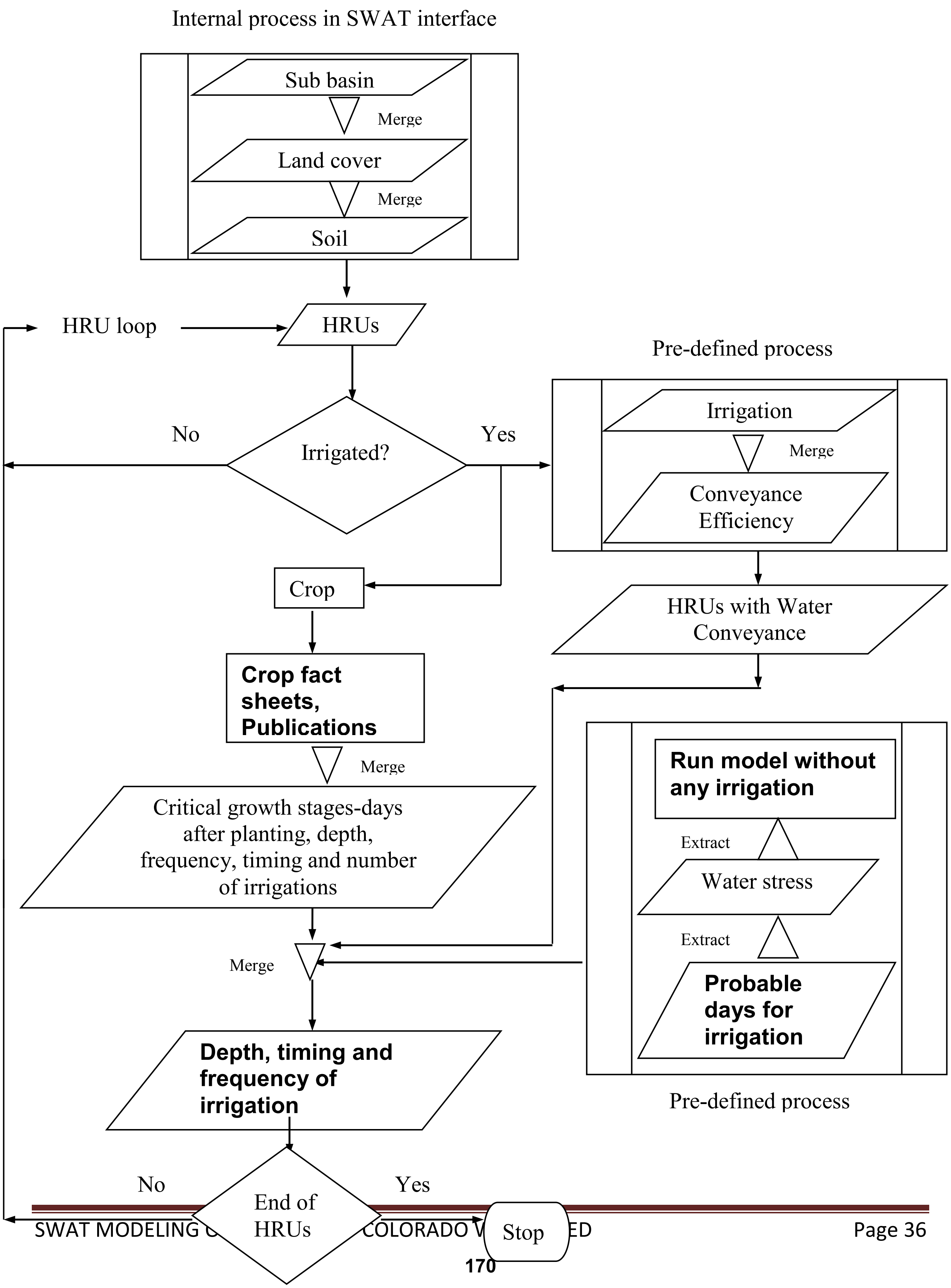

Figure A2. Monthly flow for Arroyo near Mercedes-Calibration period

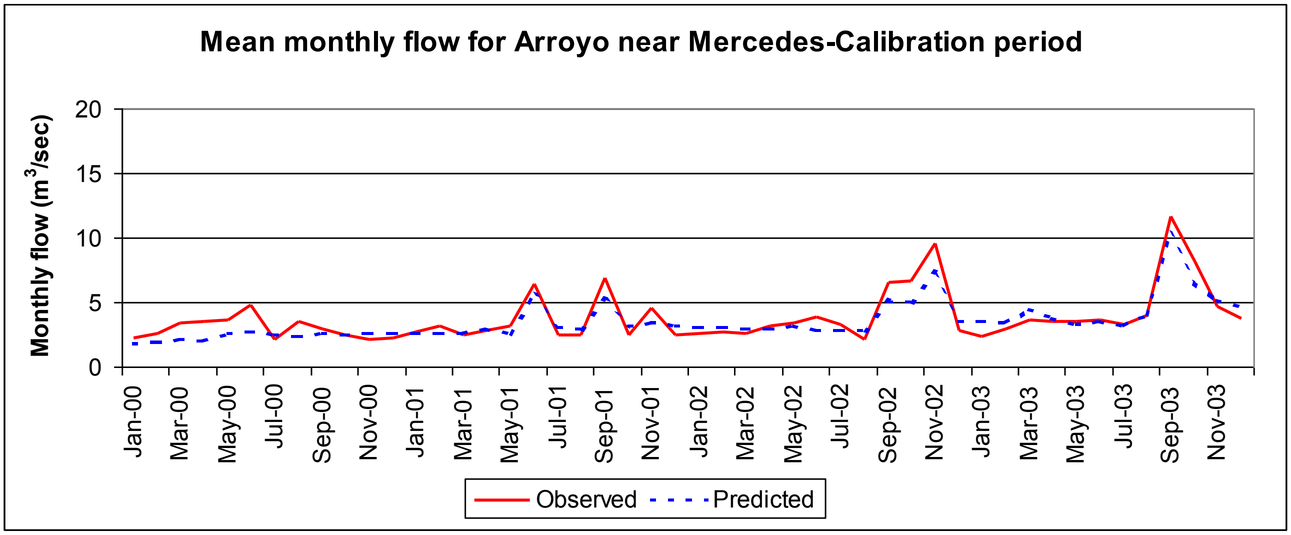

Figure A3. Monthly flow for Arroyo near Harlingen-Calibration period

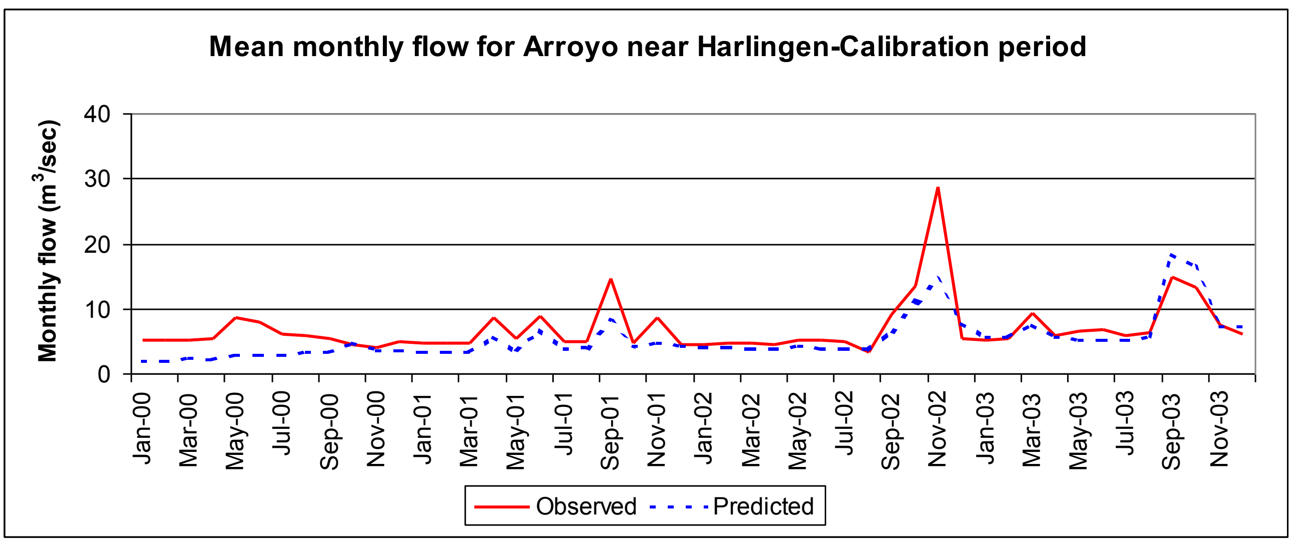

Figure A4. Monthly flow for Arroyo near Mercedes-Validation period

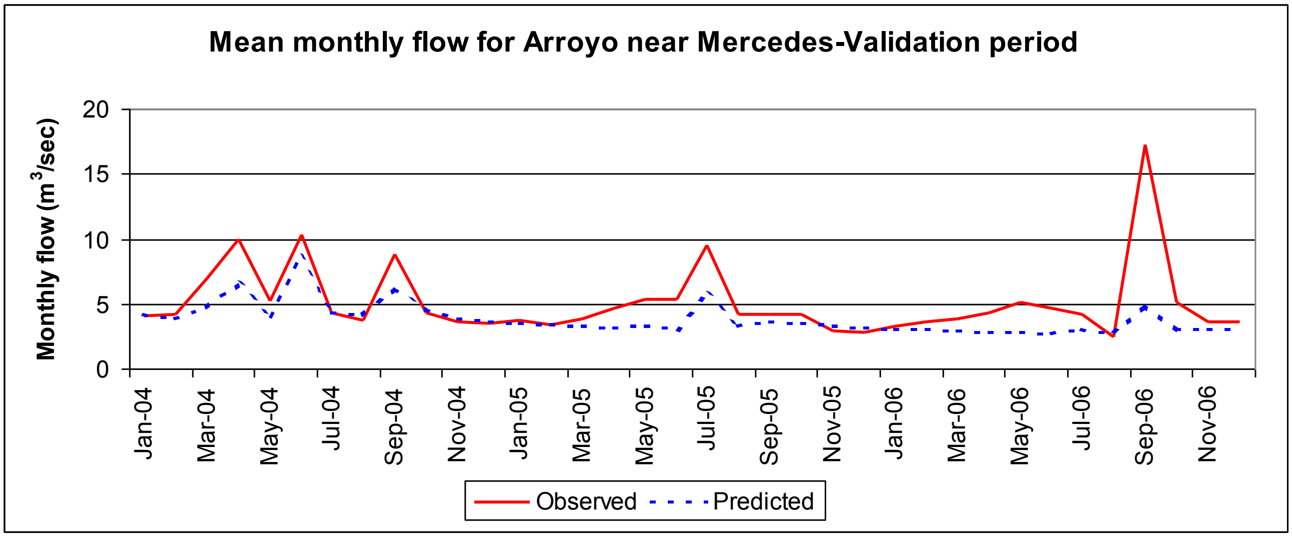

Figure A5. Monthly flow for Arroyo near Harlingen-Validation period

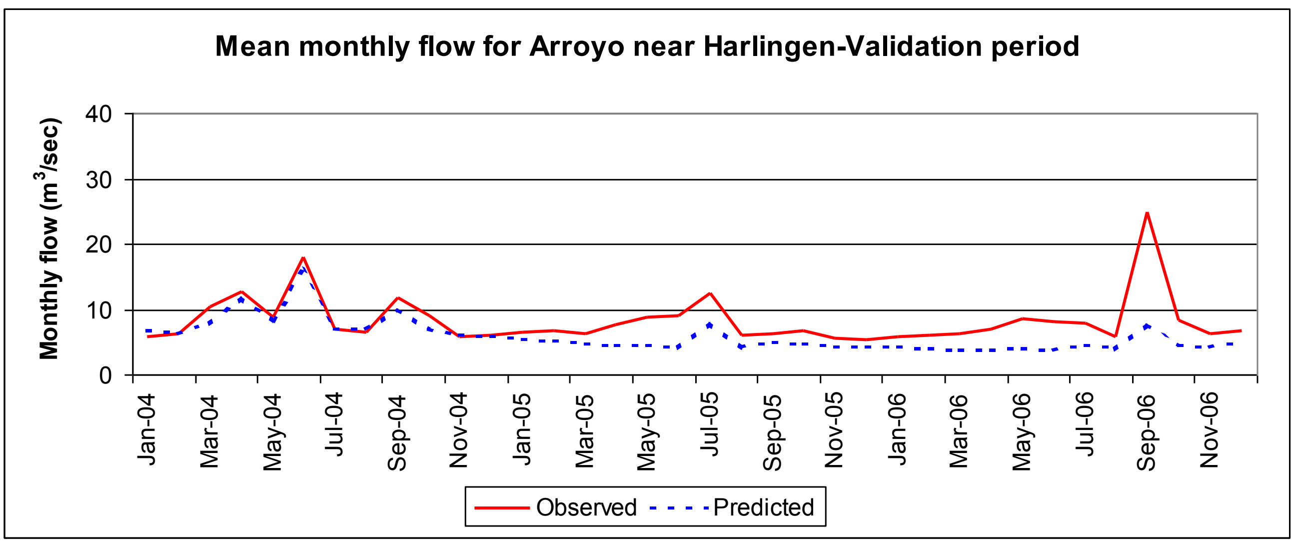

Figure A6. Monthly sediment load for Arroyo near Mercedes

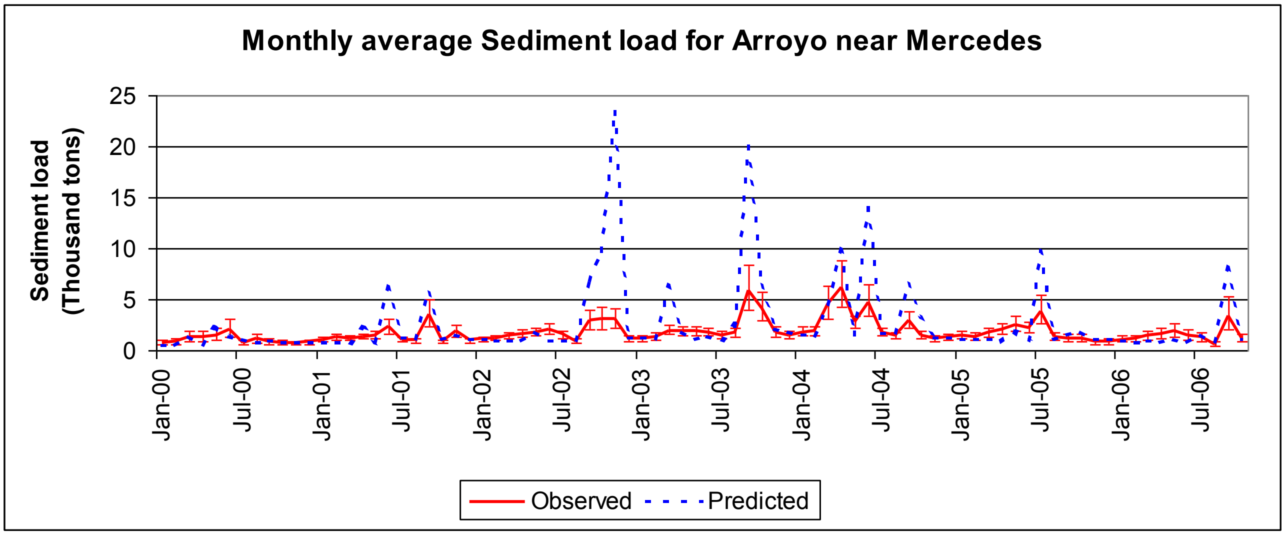

Figure A7. Monthly sediment load for Arroyo near Harlingen

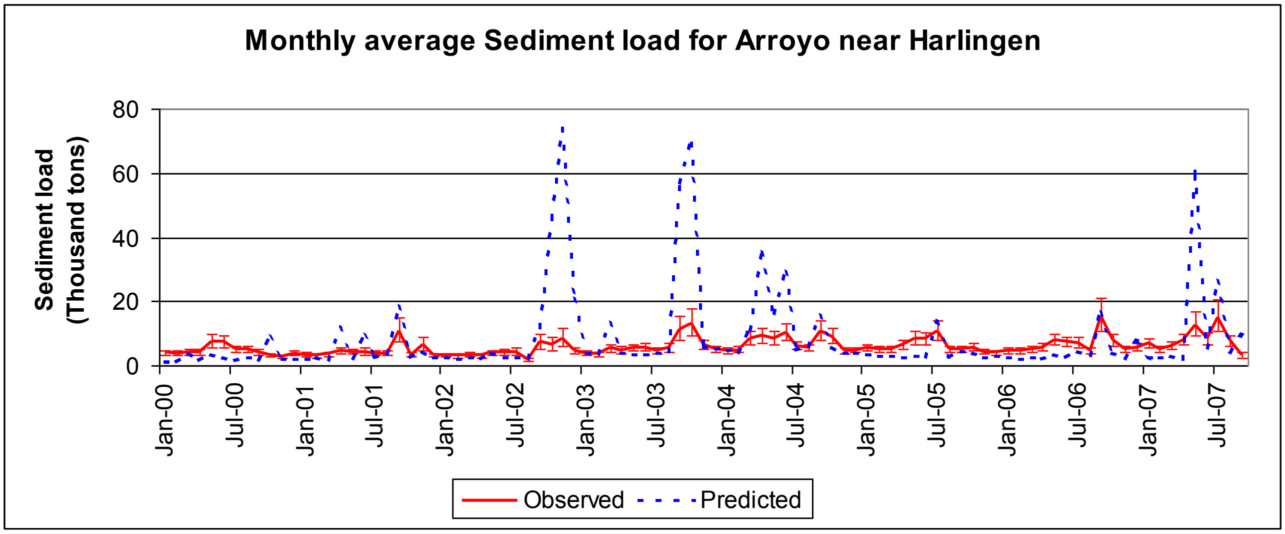

Figure A8. Monthly Orthophosphate load for Arroyo near Harlingen

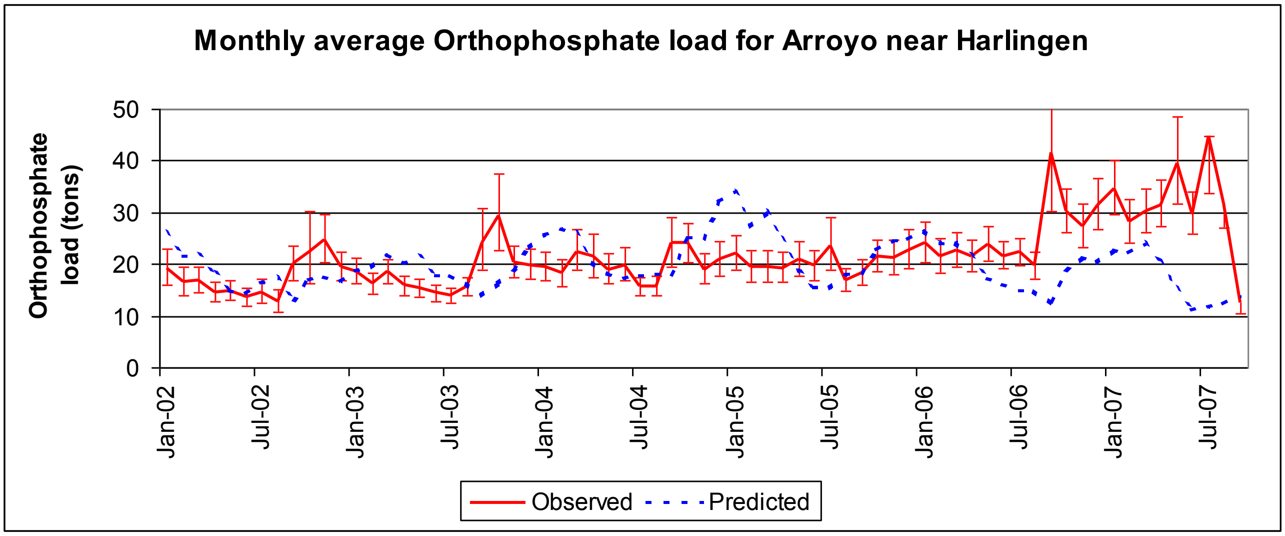

Figure A9. Monthly total phosphorus load for Arroyo near Harlingen

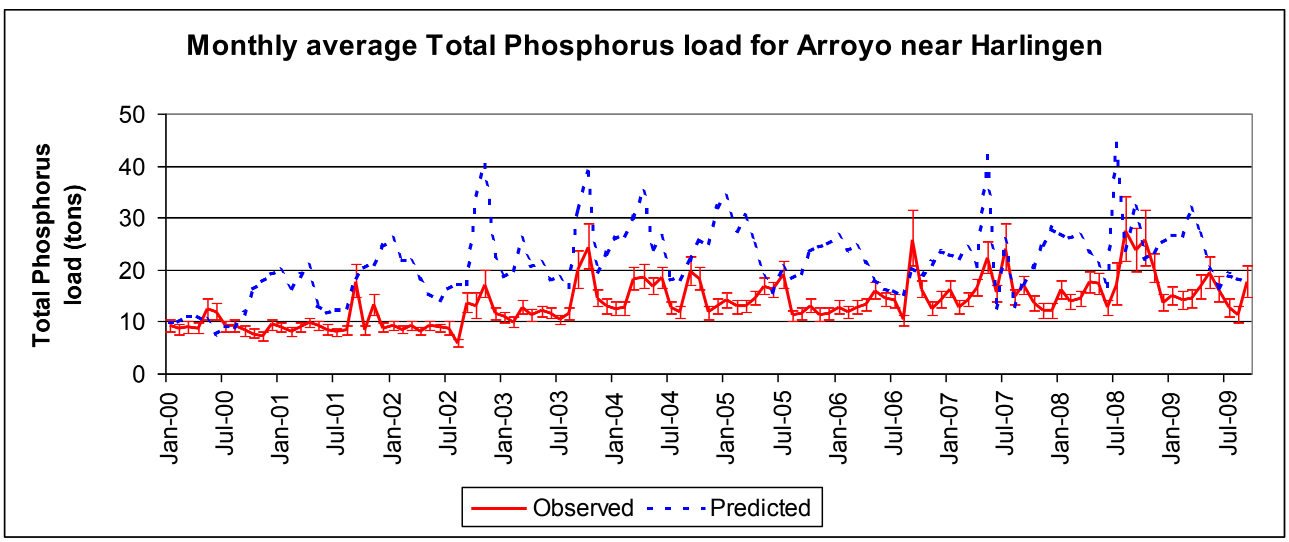

Figure A10. Monthly ammonia nitrogen load for Arroyo near Mercedes

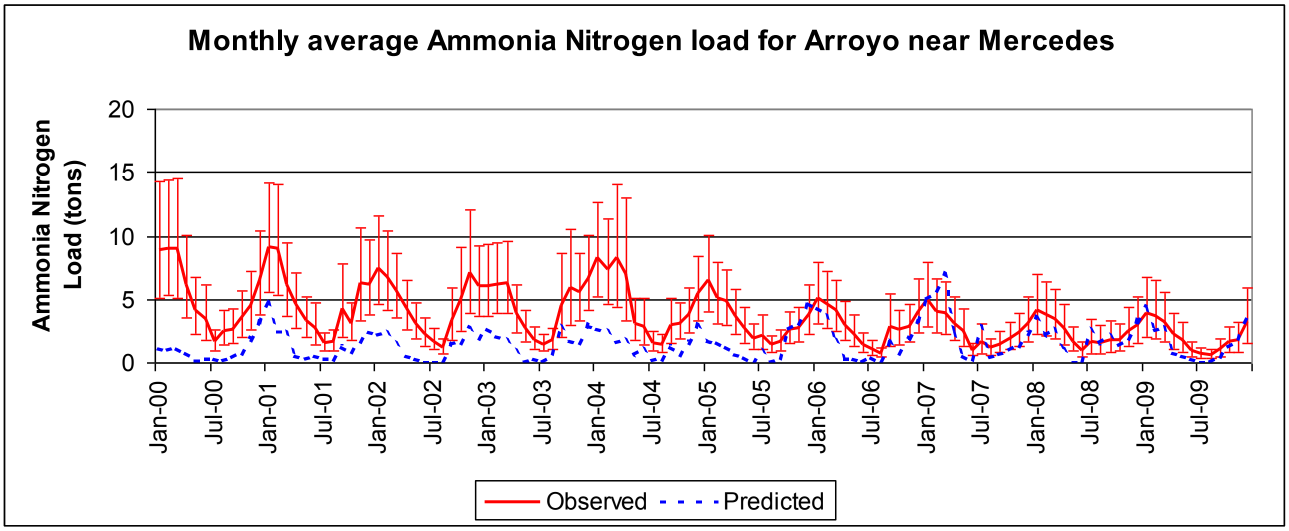

Figure A11. Monthly nitrate nitrogen load for Arroyo near Harlingen

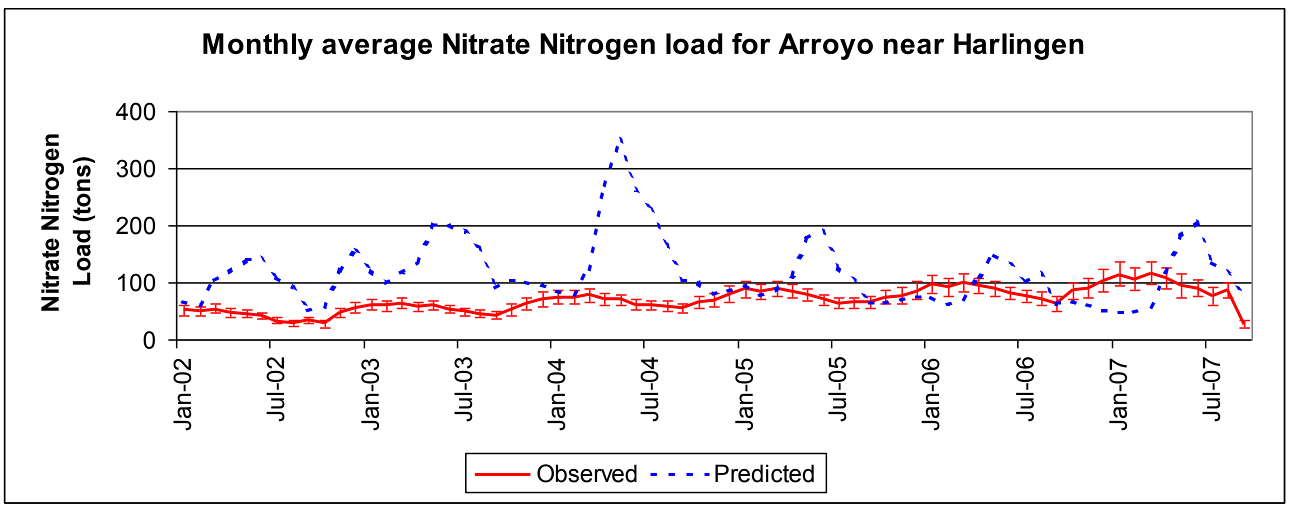

Figure A12. Monthly total nitrogen load for Arroyo near Harlingen

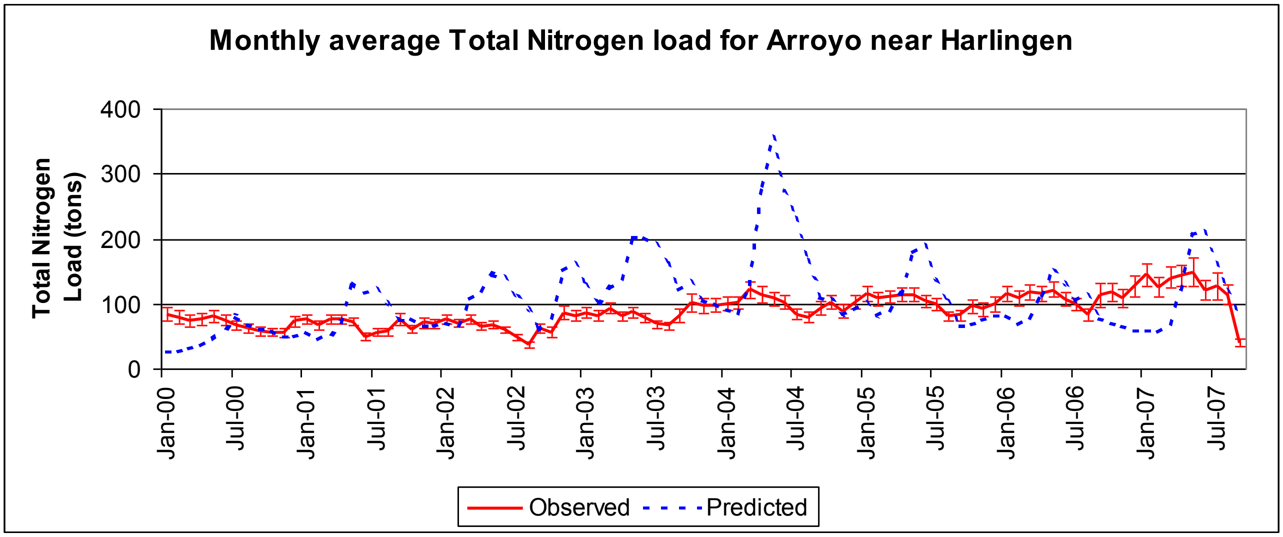

Figure A13. Mean Daily water temperature for Arroyo near Harlingen

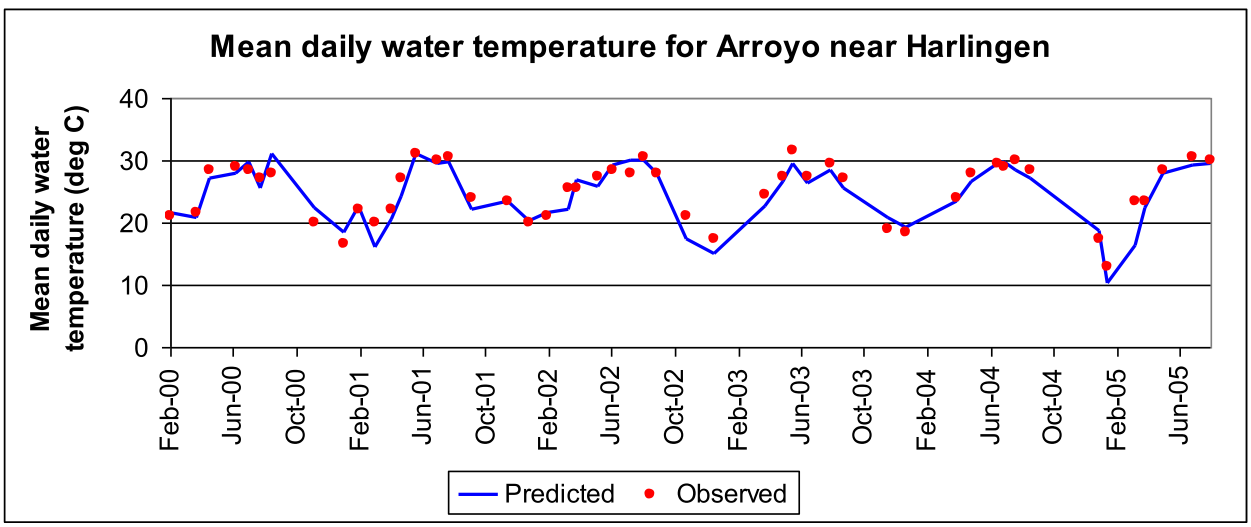

Figure A14. Mean daily dissolved oxygen for Arroyo near Harlingen

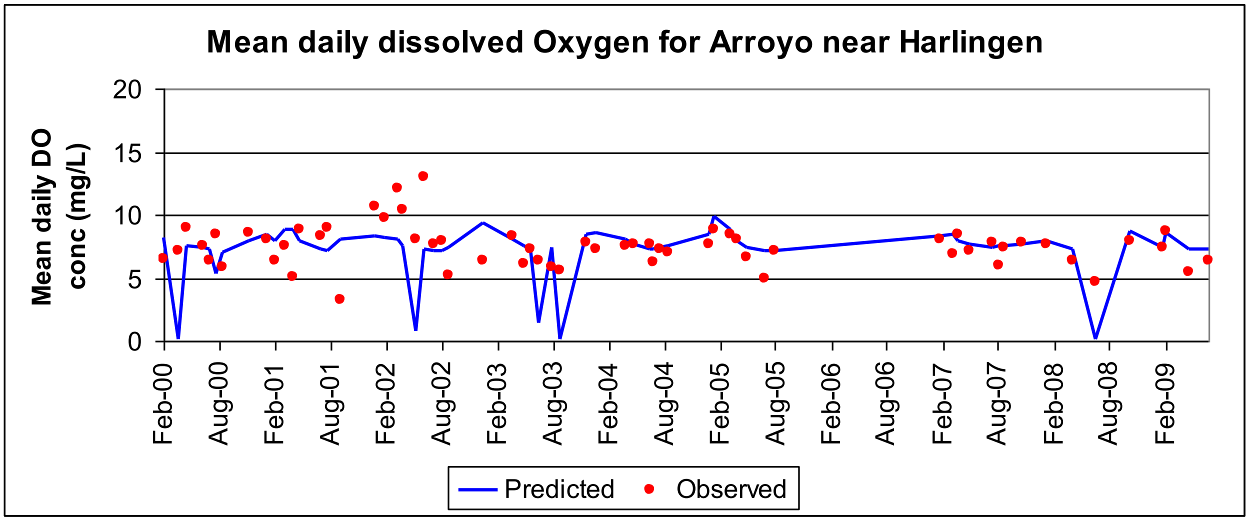

Figure A15. Pollutant load from different sources in the watershed model setup

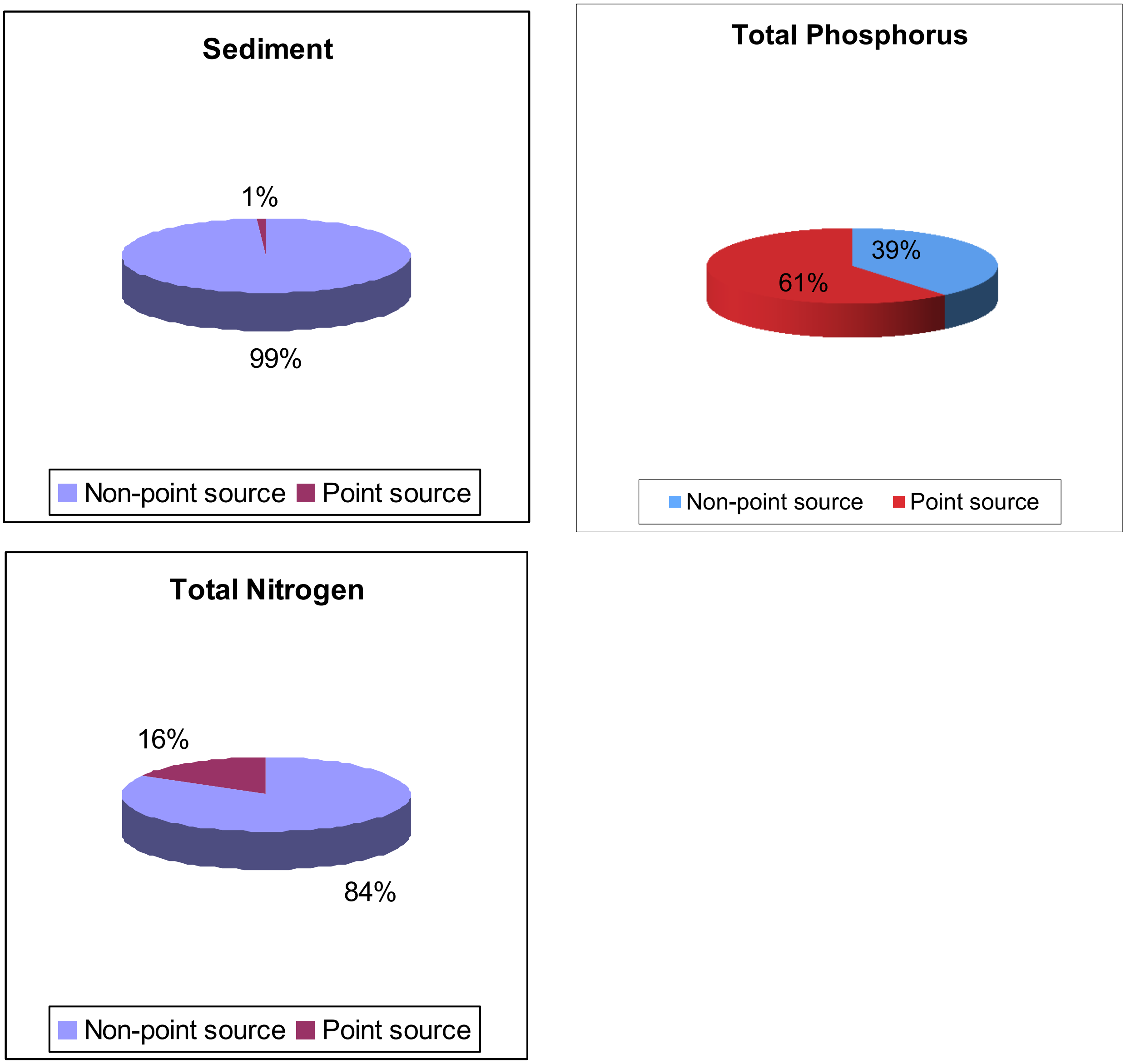

Table A1. Model parameters and their range considered for flow calibration

Parameter	Definition	Units	Spatial scale	Range of values	
				Min.	Max.
SURLAG	Surface runoff lag coefficient	days	watershed	0.001	15
AWC	Available water capacity	--	HRU	-0.04	+0.04
CN2	SCS runoff curve number for moisture condition II	--	HRU	-4.0	+4.0
EPCO	Plant uptake compensation factor	--	HRU	0.001	1
ESCO	Soil evaporation compensation factor	--	HRU	0.001	1
GW_DELAY	Delay time for aquifer recharge	days	HRU	0.001	100
GW_REVAP	Groundwater revap coefficient	--	HRU	0.02	0.2
GWQMN	Threshold water level in shallow aquifer for base flow	mm	HRU	0.01	100

Table A2. Mean monthly flow results for Arroyo Colorado

Monitoring station	Calibration period (2000-2003)		Validation Period (2004-2006)	
	Predicted (m^3/sec)	Observed (m^3/sec)	Predicted (m^3/sec)	Observed (m^3/sec)
Near Mercedes	3.47	3.76	3.79	5.08
Near Harlingen	5.24	6.89	5.81	8.20

Table A3. Model performance evaluation for flow calibration

Monitoring station	Calibration period (2000-2003)		Validation Period (2004-2006)	
	R^2	Nash and Sutcliffe Efficiency (%)	R^2	Nash and Sutcliffe Efficiency (%)
Near Mercedes	0.83	78.6	0.47	19.5
Near Harlingen	0.59	43.1	0.41	1.82

Table A4. Water quality data availability for Arroyo Colorado watershed

Parameter	Data Availability		
	Near Llano Grande at FM 1015 south of Weslaco	Near US 77 in South West Harlingen	Port of Harlingen
Stream flow	Available	Available	
Suspended Sediment	Available	Available	Available*
Total Nitrogen		Available	
Nitrate Nitrogen		Available	
Ammonia Nitrogen	Available	Available	Available*
Total Phosphorus		Available	
Ortho phosphate		Available	
Dissolved Oxygen		Available	
Water temperature		Available	Available*

* Very few samples; not considered for calibration

Table A5. Model parameters and their range considered for sediment calibration

Parameter	Definition	Units	Spatial scale	Range of values	
				Min.	Max.
ADJ_PKR	Flow peak rate adjustment factor for sediment routing in tributaries	--	watershed	0.0	1.0
PRF	Flow peak rate adjustment factor for sediment routing in main channel	--	watershed	0.0	1.0
SPCON	Linear parameter controlling sediment re-entrained in channels	--	watershed	0.0001	0.01
SPEXP	An exponent controlling sediment re-entrained in channels	--	watershed	1.0	2.0
CH_N2	Manning's n value for the main channel	--	reach	0.016	0.15
CH_COV1	Channel erodibility factor	--	reach	0.0	1.0
CH_COV2	Channel cover factor	--	reach	0.0	1.0
CH_N1	Manning's n value for the tributary channels	--	subbasin	0.025	0.15
Erosion K	Soil erodibility factor	--	HRU	0.0	1.0
LAT_SED	Sediment concentration in lateral flow	mg/L	HRU	0.0	--

Table A6. Model parameters and their range considered for nutrient calibration

Parameter	Definition	Units	Spatial scale	Range of values	
				Min.	Max.
N_UPDIS	Nitrogen uptake distribution parameter	--	watershed	0.0	40
P_UPDIS	Phosphorus uptake distribution parameter	--	watershed	0.0	40
NPERCO	Nitrogen percolation coefficient	--	watershed	0.01	1.0
PPERCO	Phosphorus percolation coefficient	--	watershed	10.0	17.5
PHOSKD	Phosphorus soil partitioning coefficient	--	watershed	0.01	300
PSP	Phosphorous sorption coefficient	--	watershed	0.0	1.0
RS2	Benthic source rate for dissolved phosphorus	--	reach	0.001	0.1
RS3	Benthic source rate for ammonia nitrogen	--	reach	0.001	0.1
RS4	Rate coefficient for organic nitrogen settling	--	reach	0.001	0.1
RS5	Rate coefficient for organic phosphorus settling	--	reach	0.001	0.1
BC1	Rate constant for biological oxidation of ammonia to nitrite	--	reach	0.1	1.0
BC2	Rate constant for biological oxidation of nitrite to nitrate	--	reach	0.2	2.0
BC3	Rate constant for hydrolysis of organic nitrogen to ammonia	--	reach	0.2	0.4
BC4	Rate constant for mineralization of organic phosphorus	--	reach	0.01	0.7
GWSOLP	Concentration of soluble phosphorus in groundwater	mg/L	HRU	0.01	1.0
HLIFE_NGW	Half life of nitrate in the shallow aquifer	days	HRU	30.0	200

Table A7. Comparison of predicted and observed mean of various water quality parameters

Average parameter values	Near Llano Grande at FM 1015 south of Weslaco		Near US 77 in South West Harlingen	
	Predictions	**Observations**	**Predictions**	**Observations**
Suspended sediment load (tons/year)	2,634.1	1,795.0	8,434.0	5,956.0
Ammonia Nitrogen (tons/year)	1.3	4.2	--	--
Nitrate Nitrogen (kg/day)			116.0	69.0
Total Nitrogen (kg/day)			107.0	89.0
Ortho Phosphorus (kg/day)			19.8	21.8
Total Phosphorus (kg/day)			21.4	13.5
Water temperature (°C)			24.6	25.3
Dissolved Oxygen (mg/L)			7.2	7.5